Increasing intensity and frequency of cold fronts contributed to Australia’s 2019–2020 Black Summer fire disaster

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Abstract

Human-caused climate changes are increasing the risk of dangerous wildfires in many regions of the world. There are multiple, compounding aspects of climate change that are increasing fire risk, including large-scale climate changes driving hotter and drier conditions that are generally well observed and predicted. However, changes in synoptic-scale processes that can exacerbate dangerous fire weather and promote extreme pyroconvective events are often not well known in historical observations and are poorly represented in climate models, making it difficult to fully quantify and anticipate changing fire risk. In this study, we statistically test the association between synoptic-scale cold front passage and large fires in southeast Australia during Australia’s 2019–2020 ‘Black Summer’ fire disaster, and analyse daily gridded temperature data to detect long-term changes in the intensity and frequency of strong cold fronts over southeast Australia. We demonstrate that the passage of cold fronts over southeast Australia significantly increased the likelihood of large fire days during the entire Black Summer fire season. Additionally, the intensity and frequency of strong cold front events were anomalously high during the Black Summer, and this is part of a long-term significant increase in the intensity and frequency of strong cold fronts since the 1950s. These changes in fire-promoting cold front activity are expected to imminently emerge above the range of historical experience across large areas of southeast Australia if current trends continue. Our results provide new insights into a previously poorly constrained contributor to fire risk in southeast Australia, highlighting the potential of synoptic-scale weather changes to compound previously documented broad-scale climate changes in intensifying future forest fire risk.

1. Introduction

The 2019–2020 Black Summer forest fires across southeast Australia were unprecedented in their spatial extent, intensity and impacts (Abram et al 2021). The Black Summer fires swept across nearly 7.2 million hectares in southeast Australia and burnt a record-breaking area of nearly 5.6 million hectares in New South Wales (NSW) (Filkov et al 2020, Bowman et al 2021). The monthly total fire radiative power (FRP) in southeast Australia was the highest since records began in 2003 for every month from September 2019 to February 2020, and was associated with an unprecedented number of 29 pyrocumulonimbus (pyroCb) fire events (Abram et al 2021). The Black Summer fires resulted in far-reaching social, economic and environmental impacts by directly claiming 33 lives, producing wildfire smoke pollution associated with another 429 premature deaths and around $1.95 billion health costs, and potentially impacting 433 threatened fauna and flora species in NSW (Davey and Sarre 2020, Johnston et al 2020, State of NSW Department of Planning, Industry and Environment 2020).
The Black Summer fires have highlighted the need for improved understanding of the factors contributing to extreme fire risk. Among these factors, the influence of hotter and drier climate conditions under global-scale anthropogenic climate change has been well identified and is projected to further increase future fire risk in numerous regions of the world (Halofsky et al 2020, Richardson et al 2022). For southeast Australia, ongoing climate warming, the sustained severe drought during 2017–2020, and extreme phases of the Indian Ocean Dipole and Southern Annular Mode in 2019 all combined to drive record-high temperatures and rainfall deficits in the Black Summer (Abram et al 2021, van Oldenborgh et al 2021). This resulted in critically dry fuels across broad swaths of the landscape and induced record-breaking dangerous fire weather, which collectively facilitated the development of large and rapidly spreading wildfires (Nolan et al 2021).

Apart from broad-scale climate conditions, the development of large bushfire events in southeast Australia is also associated with synoptic-scale cold front activity. The pre-frontal trough of the approaching cold front over the Southern Ocean can draw hot and dry northwesterly airflow from central Australia towards southeast Australia, leading to further fuel drying and more dangerous fire weather (Dowdy et al 2017). The later cold front passage over the fire region can elevate wind speed and abruptly change the wind direction by bringing strong southwest- erly maritime winds, which can transform the flank of a bushfire into a much broader and fast-moving headfire and create more erratic fire behaviour (Cruz et al 2012). Moreover, these frontal weather systems can increase atmospheric instability and support the vertical development of fire plumes (Ndahila et al 2020). Such pyroconvection can trigger a coupling between the fire and the atmosphere, which may develop into extreme pyrocumulonimbus fire storms with widespread flaming areas and disastrous impacts (Di Virgilio et al 2019, Dowdy et al 2019).

Strong cold fronts have been found to contribute to many of the worst fire events in southeast Australia’s history, including the 1983 Ash Wednesday fires (Mills 2005a), the 2003 Canberra fires (Mills 2005b) and the 2009 Black Saturday fires (Dowdy et al 2017). Nevertheless, very few studies (e.g. Peace et al 2021) have closely examined the potential role of cold fronts in the unprecedented 2019–2020 Black Summer fires. Moreover, previous studies focused on event-specific analysis of the occurrences of strong cold fronts on certain significant fire days (e.g. Cruz et al 2012) on 7 February 2009, ‘Black Saturday’), while little attention has been dedicated to monitoring and understanding any long-term variations in the characteristics of cold front events over southeast Australia (Sharples et al 2016). There is some evidence that the frequency of extreme frontal events could increase over southeast Australia in a high greenhouse gas future (e.g. Hasson et al 2009), but with large inter-model spread and caution around the ability of current climate models to reliably represent the synoptic-scale structures of strong cold fronts (Abram et al 2021).

Here, we conduct a comprehensive assessment of cold front activity in southeast Australia. Specifically, we first explore whether cold fronts had significant influences on large fires during the Black Summer. We then use the change in daily maximum temperature as an indicator for the passage of cold fronts, and analyse long-term gridded temperature data to explore if there have been any significant changes in the intensity and frequency of strong cold fronts over southeast Australia. Our findings deliver new understanding of historical changes in the synoptic-scale drivers of forest fires in southeast Australia, which provides valuable information for understanding the combined effects of weather and climate changes on future fire risk in a fire-prone region.

2. Data

2.1. Scope

The assessment of cold front activity was conducted for southeast Australia, which is defined here as the combined states of NSW, the Australian Capital Territory and Victoria. We focus our analysis on the fire season in southeast Australia, which includes the full Austral spring and summer from September to February (Canadell et al 2021).

2.2. Observational fire data

Remotely sensed FRP observations, retrieved from the Moderate Resolution Imaging Spectroradiometer (MODIS) instruments onboard the Terra and Aqua polar-orbiting satellites, were used as a proxy of fire intensity. FRP measures the rate of a fire’s radiant heat output and has a highly significant linear relationship with the fuel combustion rate (Wooster et al 2005). Hence, the daily total FRP for all fires in southeast Australia was calculated from September 2019 to February 2020 to indicate the strength of active fires on each day with respect to the amount of material consumed (Abram et al 2021). The monthly burnt area data derived from MODIS observations (Giglio et al 2018) were also obtained for southeast Australia from September 2019 to February 2020. Data for these months were combined to map the total area burnt during the Black Summer fire season.

2.3. Data on cold front passage

Following the method used by Picas and Grab (2020), the mean sea level pressure (MSLP) charts from the Bureau of Meteorology (BoM) were analysed to record the passage of cold fronts over southeast Australia during the 2019–2020 fire season. The BoM
analysis chart archive provides four MSLP charts for each day at 6 h intervals (Bureau of Meteorology 2022). A day on which at least one of the four MSLP charts marked the overpassing of a cold front over the land area of southeast Australia were identified as a day with cold front passage.

2.4. Temperature data

Daily maximum temperature data from the Australian Gridded Climate Data (AGCD; Bureau of Meteorology 2020) was obtained to define the indicator of cold front events (section 3.2). The AGCD daily maximum temperature dataset has a 0.05° × 0.05° native spatial resolution and is produced by interpolating high-quality data from temperature stations across the Australian continent through a hybrid gridding procedure (Evans et al. 2020). We explored using a coarser grid resolution of 0.25° × 0.25° as in previous studies (e.g. Jyoteeshkumar Reddy et al. 2021), but there were limited discernible differences in the magnitude and spatial patterns of the statistics of interest (supplementary figure S2). Therefore, we conducted analysis on the original 0.05° × 0.05° data for a more detailed view of the spatial patterns. Due to the sparse spatial coverage of the station network prior to the 1950s (Jones et al. 2009), we restricted the data used to the period 1951–2020 to balance the need for a sufficiently long data period in the analysis against reliability in the quality of the available gridded data.

3. Methods

3.1. Relationship between fires and cold fronts during the Black Summer

A permutation Monte Carlo (MC) test was applied to statistically test whether the cold front passage coincided with large fire days in southeast Australia more often during the Black Summer compared to what would be expected by chance alone. Specifically, for the 182 days in the 2019–2020 fire season, the 50 days with FRP above 50 000 MW were identified as large fire days. Based on MSLP charts, we identified 60 days with cold front passage and counted the number of days during which cold fronts and large fires coincided. We then simulated 20 000 synthetic time series of 182 days and with random distributions of the same number of large fire days and cold front passage days as in the Black Summer (Abram et al. 2021). The total number of large fire days coincident with cold front passage in each simulated time series formed a sampling distribution under the null hypothesis of no association between cold fronts and large fires (Hodges 2008). If the actual value lies above the 95th percentile of this sampling distribution, then there is strong evidence (at the 5% significance level) to suggest that cold fronts had significant co-occurrence with large fires during the Black Summer.

3.2. Examination of cold front characteristics using temperature data

To explore changes in the characteristics of cold front events, we used the AGCD data to compute the change in daily maximum temperature from one day to the following day, denoted by ΔT hereafter. This was carried out from September 1951 to February 2020 for every 0.05° × 0.05° grid in southeast Australia. Note that using this definition of ΔT, positive values represent temperature falls on the following day, while negative values represent temperature rise. A strong drop in daily maximum temperature (i.e. a large positive ΔT) was used to indicate the passage of a strong cold front (Reeder et al. 2015). The ΔT indicator quantifies the influence of frontal activity on local temperature over a specific area and has been used to detect the occurrences of high-intensity cold front events in some previous bushfire studies in southeast Australia (e.g. Engel et al. 2013, Reeder et al. 2015). Using ΔT for cold front detection differs from studies that used the maximum magnitude of the land-ocean temperature gradient to indicate the strength of cold fronts, such as Mills (2005a) and Grose et al. (2014). We selected ΔT because the grids with large positive ΔT effectively captured the cold front movement shown on MSLP charts (supplementary figure S1). Different machine learning classification models also consistently showed that ΔT served as a more important variable than temperature gradient in predicting cold front passage over southeast Australia during the Black Summer (supplementary table S1).

To examine the long-term variations in the intensity of strong cold fronts, we calculated the average of the five most positive ΔT values for each fire season at each grid. Averaging the top five temperature drops can utilise the information from multiple strong events and provide a more comprehensive measure of intensity than the traditional block maxima approach that only takes the most extreme data point (Demirdjian et al. 2018). We also used a peak-over-threshold approach (Villarini et al. 2013) to define the frequency of strong cold front events. At each grid, we set the threshold for a strong temperature drop to be the 97.5th percentile of ΔT during the fire seasons from 1960–1961 to 1989–1990, and counted the total number of days exceeding this threshold in each fire season. Such spatially varying thresholds account for variability in the temperature influence of cold front passage in different parts of southeast Australia. The defined threshold shows a gradual decreasing pattern from over 12 °C at the southern coastal area of Victoria to below 8 °C in northeast NSW (figure 1). Notably, the threshold of 12.4 °C at the grid centred at 37.80° S, 144.95°E is highly consistent with the 12 °C threshold used by Reeder et al. (2015) to define strong cold fronts near this location. Choosing other climatological percentiles of ΔT as
Figure 1. Spatial distribution of threshold values (the 97.5th percentile of ∆T from the 1960–1961 to 1989–1990 fire seasons) for strong temperature drop events across southeast Australia. In this study southeast Australia refers to the combined states of New South Wales (NSW), the Australian Capital Territory (ACT) and Victoria. Red shading in the inset map shows the geographic location of southeast Australia.

the threshold provided consistent results in the characteristics of the frequency of strong events in southeast Australia (supplementary figures S3 and S4).

To assess how extreme the cold front activity in the Black Summer was compared to the historical record at each grid, we constructed decile maps of the intensity and frequency of strong temperature drops in the 2019–2020 fire season with respect to values in previous fire seasons since 1951–1952. We used ordinary least squares linear regression to analyse the trend in the intensity and frequency of strong temperature drops at each grid and the significance was tested with a two-sided t-test at the 5% level. For each grid, we further defined the signal of long-term changes in intensity and frequency by the value of the respective 30 year local regression (loess) filtered time series. We then calculated the grid-specific mean (μ) and standard deviation (σ) from the 1960–1961 to 1989–1990 fire seasons as the reference period and computed the number of reference standard deviations by which the long-term signal deviates from the reference mean, which we refer to as the z-score (Angélil et al. 2016). A z-score over 2 suggests that the long-term signal displays a significant departure from the normal states and shows potential emergence outside the range of historical variability (Grumm and Hart 2001).

4. Results

4.1. Characteristics of the Black Summer fire season

Cold fronts were significantly associated with large fire days during the Black Summer. Of the 50 defined large fire days in the 2019–2020 fire season, 23 days (46%) coincided with the passage of cold fronts over southeast Australia. This value lies above the 95th percentile of the MC simulation results of 21 days, with an estimated p-value of 0.019 (figure 2). This indicates that cold front passage significantly increased the chance of large fires in southeast Australia during the Black Summer, beyond what would be expected from chance alone (p < 0.05). This concurs with previous studies of major individual fire events where strong cold fronts contributed to disastrous escalations in fire activity (e.g. Mills 2005b, Cruz et al. 2012). It is the first time, however, that this statistically significant association has been demonstrated across an entire fire season.

The intensity and frequency of strong cold fronts were anomalously high to unprecedented across southeast Australia during the Black Summer. The decile maps of the intensity and frequency of strong temperature drops in the 2019–2020 fire season were dominated by values within decile 10, including many areas with the highest ever recorded values (figure 3). The intensity was the most extreme on record across large areas in southwest and eastern Victoria and southeast NSW (figure 3(a)). The frequency of strong temperature drops was the highest on record across central and eastern Victoria and was sitting mostly within decile 10 along the East Coast of NSW (figure 3(b)). Moreover, areas with anomalously high intensity and frequency of strong temperature drops overlapped quite consistently with the areas burnt in the Black Summer fires, that were concentrated in the mountainous and forested coastal region. For example, most burnt areas in eastern Victoria had the highest intensity and frequency of strong temperature drops on record, while the burnt areas in NSW mostly coincided with areas where the intensity
and/or frequency of strong temperature drops were in the uppermost decile (figure 3). These findings demonstrate that cold front activity during the Black Summer was unusually strong and frequent, and the coincidence of areas with anomalously high to unprecedented frontal activity with burnt area (figure 3) as well as the statistically significant connection between cold fronts and large fire days (figure 2) have demonstrated the important contribution of synoptic-scale frontal activity to the extreme fire activity throughout the 2019–2020 fire season.

4.2. Historical trends in the intensity and frequency of cold fronts
We next examined whether the extreme cold front characteristics in the Black Summer were associated with long-term changes in frontal activity. Figure 4 shows the significant \( p < 0.05 \) linear trends of the intensity and frequency of strong temperature drops across southeast Australia since the 1951–1952 fire season. The strongest trends in intensity are observed as several separate clusters along the East Coast, with a trend of over 0.4 °C per decade (figure 4(a)).

**Figure 2.** Histogram of the Monte-Carlo (MC) simulated numbers of large fire days coincident with cold front passage in southeast Australia using random timing of large fire days and cold front passage days during the Black Summer (grey bars). The blue vertical line represents the 95th percentile of the Monte-Carlo simulation results and the red vertical dashed line represents the actual observed value of 23 days during the 2019–2020 fire season.

**Figure 3.** Decile map of (a) intensity and (b) frequency of strong temperature drops in the 2019–2020 Black Summer fire season compared to historical records since the 1951–1952 fire season. Stippling denotes the areas burnt in the Black Summer fires derived from MODIS observations.
Similarly, the frequency of strong temperature drops shows the strongest trends of over 0.6 days/decade in the coastal regions of NSW and eastern Victoria (figure 4(b)). This analysis suggests that strong cold fronts have become more common and more intense in southeast Australia over recent decades, particularly along the East Coast.

Under these long-term increasing trends, the intensity and frequency of cold fronts is moving close to, or emerging above, the upper bounds of historical experience across southeast Australia. To illustrate this, figure 5 shows the spatial distribution of the z-scores of the signal (30 year loess filter) of the intensity and frequency of strong temperature drops in the 2019–2020 Black Summer. The signal of loess filtered intensity is at least 1 standard deviation (+1σ) above reference mean across large parts of Victoria and emerges above the +2σ level of historical variability in mid-east NSW and eastern Victoria (figure 5(a)). The frequency signal also has a z-score above +1σ across the majority of southeast Australia, and with a less spatially coherent pattern reaches the +1.5σ to +2σ level of historical variability at inland NSW and small clusters along the East Coast (figure 5(b)). These observations indicate that the trends of increasing intensity and frequency of strong cold fronts over southeast Australia are causing long-term changes where cold front activity may imminent emerge above the range of historical variability, especially near the East Coast.

To further explore the potential emergence of signals, we examined individual time series of the intensity and frequency of strong temperature drops at two grid points, in northeast NSW and eastern Victoria.
respective, as illustrative examples (figure 6). Results for four additional example grid points are also presented in supplementary figure S5. These locations displayed strong intensity and frequency signals relative to historical variability (figure 5) and were also burnt during the Black Summer fires (figure 6(a)). The grid in northeast NSW (Site A) has shown a gradual increasing trend in intensity and frequency since the 1960s (figures 6(b) and (d)). The intensity signal has moved close to the +2σ threshold (figure 6(b)) while the frequency signal has emerged above the +2σ level of historical variability in the recent few years, with the Black Summer having a record-breaking number of 14 strong events here (figure 6(d)). For the grid in eastern Victoria (Site B), the long-term climate signal of intensity has increased rapidly since the early 2000s and emerged above the +2σ variability level recently (figure 6(c)), while the frequency signal has almost reached the +2σ variability level (figure 6(e)). In particular, this grid experienced its highest ever intensity (20.1 °C) and frequency (12 events) of strong temperature drops since the 1950s during the Black Summer.

Our analyses of the historical record of strong temperature drops (figures 3–6) provide collective evidence for a long-term systematic increase in cold front intensity and frequency in southeast Australia. Such long-term changes in cold front characteristics demonstrate a strong potential to imminently emerge above the range of historical variability and have manifested in the extreme frontal activity observed during Australia’s Black Summer.

5. Discussion

The role of cold fronts in generating dangerous fire weather and historical catastrophic fire events in southeast Australia has been well identified in literature (e.g. Cruz et al 2012). For the first time, we show that cold fronts significantly increased the occurrence of large fire days in southeast Australia during the entire 2019–2020 fire season, relative to what could be expected by chance. While previous studies have qualitatively matched large fires with observed cold front activity for specific events, this study utilised continuous satellite FRP observations to quantitatively confirm this linkage throughout the Black Summer. Future studies may explore other statistical techniques and other data sources on wildfires and cold front activity to further validate the contribution of cold fronts to large fire events during the Black Summer or other major fire seasons. Our findings establish the persistent contribution of cold fronts in the unprecedented Black Summer fire season for southeast Australia. This provides new evidence for the importance of incorporating synoptic-scale drivers of wildfires alongside large-scale climate changes in assessing fire risk for fire-prone regions of the world (e.g. Abatzoglou et al 2018).

The Black Summer had a highly unusual to unprecedented intensity and frequency of strong temperature drops, indicative of the passage of strong cold fronts across southeast Australia. Areas showing anomalously high intensity and occurrence of strong cold fronts also coincided with the areas burnt in the Black Summer. Extreme synoptic-scale cold front activity brings strong surface winds that enhance fire spotting and heat transfer to unburnt dry fuels, facilitating fuel consumption and rapid fire propagation (Sharples et al 2010, Sullivan et al 2012). Additionally, the passage of low-pressure systems and associated cold fronts has been shown to interact with the mountainous terrain of southeast Australia to produce a foehn effect that brings warm and dry descending
Our work further suggests that any influence of more frequent strong cold fronts in the future may also be intensified by the growing magnitude of individual events. If current trends do continue, our findings indicate that the intensity and frequency of strong cold fronts will imminently emerge beyond the range of historical experience (figures 5 and 6). This will necessitate fire management planning that extends beyond the range of historically observed fire weather extremes, both in terms of the intensity of individual events and the number of extreme events across a fire season. Together, our findings demonstrate the importance of accurately modelling not only future climate changes, but also the associated weather changes that climate change will cause, in order to properly understand and quantify future fire risk.

There are several factors that could influence the validity of our findings and require careful consideration in future research. First, the quality of the gridded daily temperature dataset (AGCD) is subject to uncertainties in the gridding procedure and non-homogenisation of input data (Jyoteeshkumar Reddy et al 2021). Our analysis should be repeated on other observational datasets (e.g. in-situ station records) and reanalysis products to validate the changes in cold frontal characteristics we identify using AGCD. Additionally, there is large interannual variability in the intensity and frequency of strong temperature drops in southeast Australia (figure 6). Removing data from the Black Summer still provides consistent linear trends but demonstrates weaker signals relative to background variability (supplementary figures S6 and S7). Hence, the characteristics of cold front intensity and frequency should be monitored into the future to allow more robust detection and mechanistic understanding of the long-term changes and the state of emergence in these critical fire weather events.

Overall, our findings provide new evidence for significant increasing trends in cold front intensity and frequency in large parts of southeast Australia. To our knowledge, this is the first attempt to characterise historical changes in cold front activity over southeast Australia and it complements the limited research on changes in synoptic weather events in other fire-prone regions (e.g. Lee and Sheridan 2018). For southeast Australia, the newly established trends in synoptic-scale cold front activity would be expected to interact with previously identified broad-scale climate change trajectories of rising temperatures, declining cool season rainfall and increasing likelihood of fire-promoting natural climate variability (Abram et al 2021), leading to rapidly intensifying fire risk. Hence, our findings highlight the need to closely investigate synoptic weather changes in regions susceptible to wildfires to better anticipate future fire risk under climate change and support region-specific fire management practices.
6. Conclusion

This study comprises a comprehensive assessment of cold front activity (as represented by large temperature drops) across southeast Australia as an important synoptic-scale driver of forest fire risk. Cold front passage is found to have significantly increased the likelihood of large fire days in southeast Australia during the 2019–2020 Black Summer fire season. The anomalously high intensity and frequency of strong cold fronts over southeast Australia likely contributed to the unprecedented burnt area, FRP and pyrocumulonimbus occurrences in the Black Summer as cold fronts are known to enhance fuel combustion and atmospheric instability. The extreme cold front activity during the Black Summer forms part of a significant long-term increasing trend in the intensity and frequency of strong cold front events, particularly along the mountainous, forested and highly populated east coast region of southeast Australia, and these trends show imminent emergence above historical variability. Our findings offer new insights into current and possible future changes of synoptic-scale cold front activity in southeast Australia, which may combine with expected changes in mean climate and natural climate variability to further intensify future potential for extreme wildfires. Our study highlights the need for a more complete understanding of the compound effects of synoptic-scale weather changes and broad-scale climate changes on future wildfire risk in global fire-prone regions. This will ultimately enable more informed fire management and improved preparation for extreme fire events and fire seasons similar to Australia’s 2019–2020 Black Summer.

Data availability statement

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

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Conflict of interest

The authors declare that they have no conflict of interest.

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