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Key Points:
- Electrified pyrocumulonimbus are investigated for Black Saturday, demonstrating extensive deep convection and lightning activity
- Relationships between lightning activity and fire behavior are documented, with implications for remote sensing guidance and nowcasting
- First examination of fire ignition from pyrogenic lightning, indicating extreme distances for the risk of new ignitions

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Pyrocumulonimbus lightning and fire ignition on Black Saturday in southeast Australia

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Abstract A number of devastating wildfires occurred in southeast Australia on 7 February 2009, colloquially known as Black Saturday. Atmospheric responses to this extreme fire event are investigated here with a focus on convective processes associated with fire activity (i.e., pyroconvection). We examine six different fire complexes on Black Saturday, finding three clearly distinct pyrocumulonimbus storms, the largest of which reached heights of 15 km on that day and generated hundreds of lightning strokes. The first lightning stroke was recorded near the largest fire complex 5 h after fire ignition. One of the pyrocumulonimbus storms was initiated close to midnight due to mesoscale influences, consistent with extreme fire behavior observed at that time for that particular fire. As another example of fire-atmosphere interactions, a fire that started late on Black Saturday is examined in relation to ignition caused by pyrogenic lightning, with implications for understanding the maximum rate of spread of a wildfire. Results are discussed in relation to another pyrocumulonimbus event associated with the 2003 Canberra fires. Our findings are intended to provide a greater understanding of pyroconvection and fire-atmosphere feedback processes, as well as help enhance wildfire response capabilities. We also demonstrate the potential for using lightning, radar, and satellite remote sensing in combination with thermodynamic analyses as well as synoptic and mesoscale dynamics to provide enhanced real-time guidance for dangerous fire conditions associated with pyroconvection, as well as for the risk of new fire ignitions from pyrogenic lightning.

Plain Language Summary A number of devastating wildfires occurred in southeast Australia on 7 February 2009, colloquially known as Black Saturday. Atmospheric responses to this extreme fire event are investigated here with a focus on convective processes associated with fire activity (i.e., pyroconvection). We show that multiple fire plumes produced a number of distinct pyrocumulonimbus storms, some of which reached heights of 15 km on that day and generated a large amount of lightning. The first lightning stroke was recorded near the largest fire complex 5 h after fire ignition. This offers broad implications for understanding fire behavior exacerbation rates, given that deep convection can produce extreme variations in surface wind conditions. A fire that started late on Black Saturday is examined in relation to ignition caused by pyrogenic lightning, 100 km ahead of the fire front, with implications for understanding extreme fire spread rates. Our findings are intended to provide a greater understanding of pyroconvection and fire-atmosphere feedback processes, as well as help enhance wildfire response capabilities. We also demonstrate the potential for combining lightning and radar data to provide real-time guidance for dangerous fire conditions associated with pyroconvection, as well as for the risk of new fire ignitions from pyrogenic lightning.

1. Introduction

The fire regime of southern Australia is notable for the extremely dangerous conditions that can sometimes occur during the austral summer [*Luke and McArthur*, 1978; *Russell-Smith et al.*, 2007; *Bradstock*, 2010; *Sullivan et al.*, 2012; *Murphy et al.*, 2013]. Extreme fire-weather conditions on Black Saturday (7 February 2009) near Melbourne in southeast Australia led to the occurrence of wildfires that killed 173 persons, destroyed over 2000 homes, burnt more than 450,000 ha, and resulted in losses of over four billion Australian dollars [*Victorian Bushfire Royal Commission (VBRC)*, 2009].

This event involved the combined influence of a number of extreme weather features. No precipitation was recorded in the 4 weeks leading up to Black Saturday at the Melbourne Airport observing station, with a strong anticyclone dominating southeastern Australia's weather in the week prior to Black Saturday leading to a deep air mass of very hot air over this region [*Bureau of Meteorology (BOM)*, 2009]. On Black Saturday,

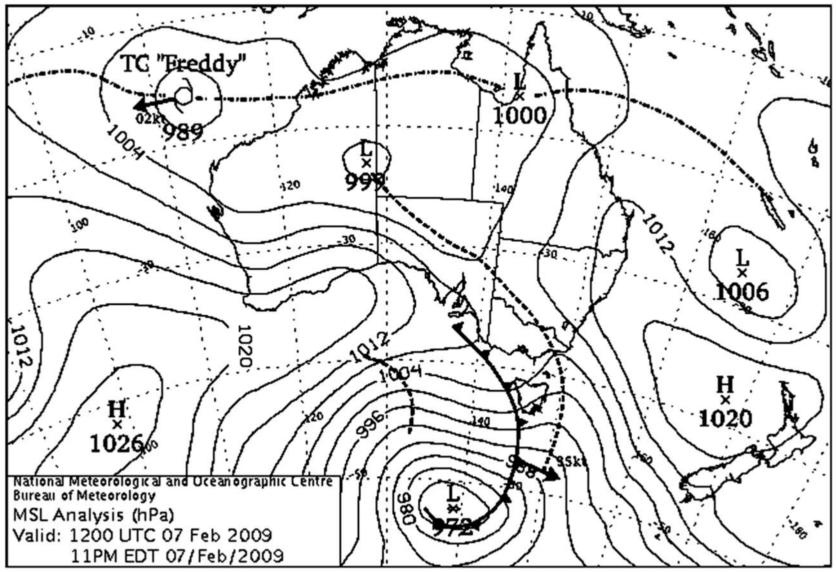

Figure 1. Synoptic features on Black Saturday, as represented by the mean sea level pressure (MSLP) analysis produced operationally by the Bureau of Meteorology. This is shown for 2300 LT on 7 February 2009.

there was an approaching cold front southwest of this region associated with a low-pressure system farther to the south as well as a high-pressure system to the east (Figure 1). This set of synoptic features typifies many of the historical extreme fire events in this region [*Reeder and Smith*, 1987; *Mills*, 2005a; *Fiddes et al.*, 2015; *Reeder et al.*, 2015]. The approaching cold front resulted in strong northwesterly winds that transported extremely hot and dry air to the region near Melbourne from farther inland, with the maximum temperature in Melbourne reaching 46.4°C—the highest recorded from 154 years of record [*BOM*, 2009]. The resultant extreme wind, heat, low humidity, and fuel moisture [*Sullivan and Matthews*, 2013] on Black Saturday combined to produce fire danger ratings reported to be as extreme as any in the historical record for southeast Australia [*BOM*, 2009]. Furthermore, a wind change associated with a surface trough ahead of the cold front (Figure 1) passed over the fire region during the late afternoon [*BOM*, 2009], leading to extremely dangerous fire behavior in terms of observed intensity, rate of spread, and spotting (i.e., the development of new fires, known as spot fires, ignited by burning debris transported by the fire plume) [*Cruz et al.*, 2012].

In addition to synoptic-scale conditions such as prefrontal troughs and blocking highs (e.g., Figure 1, as well as discussed in various previous studies [*Mills*, 2005a; *Mills*, 2008; *Potter*, 2012a; *Engel et al.*, 2013; *Reeder et al.*, 2015]), dangerous fire behavior can also be associated with localized convective processes that can increase near-surface wind speed and directional variability thereby influencing fire rate of spread and intensity [*Haines*, 1988; *Rothermel*, 1991; *Banta et al.*, 1992; *Goens and Andrews*, 1998; *Potter*, 2012a, 2012b; *Peterson et al.*, 2015]. Convective processes can also lead to strong updrafts that increase the risk of spot fire occurrences [*Cheney and Bary*, 1969; *Ellis*, 2011; *Koo et al.*, 2010; *Potter*, 2012b]. Furthermore, the heat, moisture, and aerosol release from a fire can influence the fire plume [*Cunningham and Reeder*, 2009; *Luderer et al.*, 2009; *Clements*, 2010; *Potter*, 2012a, 2012b; *Tosca et al.*, 2015] and lead to the formation of convective clouds known as pyrocumulus (pyroCu), or pyrocumulonimbus (pyroCb) in the case of the more intense systems such as those observed on Black Saturday [*BOM*, 2009; *VBRC*, 2009; *Field et al.*, 2016]. A conceptual model, based on observations in Western North America, also highlights the importance of atmospheric conditions throughout the troposphere for pyroCb development [*Peterson et al.*, 2016]. PyroCbs can sometimes produce lightning, referred to as pyrocumulus electrification or pyrogenic lightning [*Fernandes et al.*, 2006; *Lang and Rutledge*, 2006; *Rosenfeld et al.*, 2007; *Johnson et al.*, 2014; *Lang et al.*, 2014], and other potentially dangerous phenomena such as hail and tornados [*Fromm et al.*, 2006; *Cunningham and Reeder*, 2009; *McRae et al.*, 2013].

The analysis presented here uses observations from a range of sources, including a network of lightning detectors, ground-based radars, satellite imagery, and station observations. Fire-atmosphere interactions are examined, focusing on pyroCb behavior and associated lightning activity. A new fire caused by

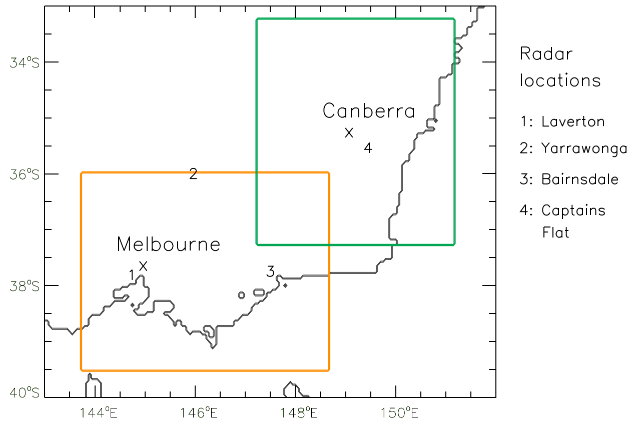

Figure 2. Map of southeast Australia showing cities (Melbourne and Canberra: cross symbols), radar locations, coastlines, latitude, and longitude. The inset boxes represent two regions of focus for this study, for Black Saturday (orange box) and the Canberra fire event (green box). The locations of radars referred to in this study are also shown.

pyrogenic lightning ignition and the determinate factors associated with this occurrence are examined here for the first time in the literature. A second southeast Australian pyroCb event, associated with the Canberra fires during January 2003, is examined with respect to electrification and contrasted with Black Saturday. Results are discussed in relation to improved model guidance and real-time intelligence for dangerous fire conditions associated with pyroCbs.

2. Data and Methods

Figure 2 presents a map of southeast Australia showing features of relevance to this study. This includes highlighting the regions of focus for the Black Saturday and Canberra fire events, respectively, as well as the cities of Melbourne and Canberra and the locations of radars from which data were obtained for use in this study.

Lightning observations were obtained from the commercial provider Global Position and Tracking System Pty. Ltd. Australia (GPATS). The observations are based on the time of arrival of the electromagnetic disturbance propagating away from the lightning discharge as recorded at a network of ground-based radio receivers [*Cummins and Murphy*, 2009] and contain information about the current magnitude and polarity, as well as the time and location of individual lightning strokes, noting that a single lightning flash as seen by a human eye can sometimes contain multiple lightning strokes (i.e., flash multiplicity). The detection efficiency of the GPATS system varies temporally (e.g., due to ongoing changes in the hardware and software used by the commercial provider of these data), spatially (e.g., due to proximity to receivers), and between different types of lightning (e.g., for cloud-to-ground strokes or cloud-to-cloud strokes) [*Kuleshov et al.*, 2006]. Consequently, the number of lightning strokes recorded by the GPATS system is used throughout this study as a lower bound measure of the total lightning strokes that occurred (i.e., the sum of the number of cloud-to-ground and cloud-to-cloud lightning strokes).

Data from three weather radars are used here to examine the Black Saturday fire event, located at Laverton (37.9°S, 144.8°E) in the city of Melbourne, Yarrawonga (36.0°S, 146.0°E) about 250 km northeast of Melbourne, and Bairnsdale (37.8°S, 147.6°E) about 250 km east of Melbourne. These data are examined here for times starting from 1800 LT, noting that the Laverton radar was inoperable prior to 1806 LT due to the extreme heat. A fourth weather radar is used to examine the Canberra fires, located at Captains Flat (35.6°S, 149.5°E) about 50 km southeast of Canberra in southeast Australia, with the Canberra pyrocumulonimbus event on 18 January 2003 selected here for comparison with Black Saturday due to the severe thunderstorm characteristics that were observed in association with that event [*Fromm et al.*, 2006, 2012; *Mills and McCaw*, 2010; *McRae et al.*, 2013, 2015]. Reflectivity data are used to derive echo-top altitudes, based on a 5 dB*Z* threshold, with prior radar analyses of pyroCbs [*Fromm et al.*, 2006, 2012; *Rosenfeld et al.*, 2007] showing how echo top data are informative for examining both the internal structure and the convective injection height of pyroCb events. The radar echoes come not only from cloud hydrometeors but also from debris lofted by the fires [*Jones*, 1950; *Lindley et al.*, 2011; *Baum et al.*, 2015].

Active fire observations are obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) on the Terra and Aqua satellites [*Giglio et al.*, 2009]. There were three satellite overpasses for the fire region on the afternoon and evening of Black Saturday, occurring for Aqua during the hour of 1500 local time (LT: 11 h ahead of UTC, including 1 h daylight saving) and for Terra during the hour of 2300 LT on 7 February 2009, as well as for Aqua during the hour of 0200 LT on 8 February 2009.

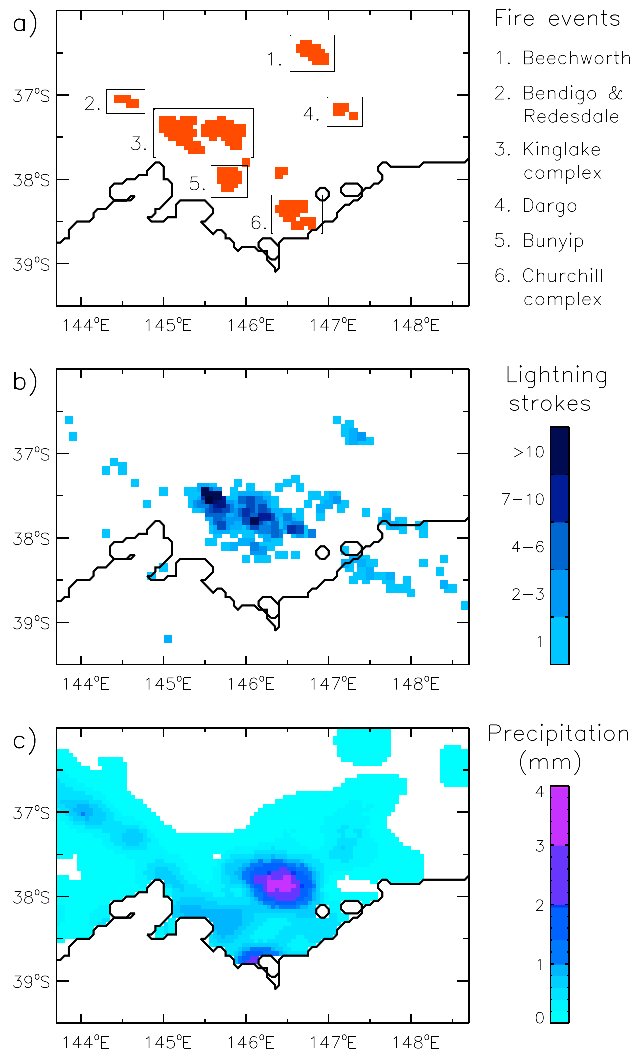

Figure 3. Fire, lightning, and precipitation observations on Black Saturday. (a) Active fire observations are shown, with six notable fire events listed. (b) Lightning stroke counts (strokes per 0.05° × 0.05° grid cell) are shown based on observations obtained from a ground-based network of sensors. (c) Precipitation data are based on a gridded analysis of observations over land. The fire and lightning data represent all observations within the time period from 1500 LT on 7 February 2009 to 0300 LT on 8 February 2009, while the precipitation data are based on daily observations for the 24 h time period from 0900 LT on 7 February 2009 to 0900 LT on 8 February 2009. Coastlines, latitude, and longitude are shown.

A gridded analysis of precipitation observations is used from the Australian Water Availability Project (AWAP) [*Jones et al.*, 2009], available on a 0.05° grid in both latitude and longitude, based on daily accumulated precipitation totals for the 24 h period to 0900 LT each day. This grid is also used for the aggregation and analysis of the other data sets considered throughout this study (i.e., the lightning, radar, and active fire observations), as these other data sets are available at finer spatial and temporal resolutions than the AWAP data.

3. Results

3.1. Black Saturday Observations

Figure 3 shows maps of fire, lightning, and precipitation observations on Black Saturday, with the domain of these maps as highlighted in Figure 2. Six notable fire events on that day are listed, with the largest being the Kinglake complex. These fire events were all ignited on Black Saturday, with the exception of the Bunyip fire which had been ignited a few days previously but grew rapidly on Black Saturday due to the extreme fire-weather conditions on that day (for details, see *VBRC* [2009]). The Kinglake complex comprises a merging of the Kilmore East fire and the Murrindindi fire which started on Black Saturday at around 1146 LT and 1445 LT, respectively, with the Kilmore East fire being the most significant of the fires on Black Saturday (resulting in 70% of the fatalities on that day and burning about 100,000 ha during the first 12 h after ignition) [*VBRC*, 2009; *Cruz et al.*, 2012]. The strongest lightning activity occurred southeast (i.e., downwind) of the Kinglake fire complex, with some other lightning activity in the broader region away from the fire events. Relatively little precipitation occurred in this region on Black Saturday, with only a small region of up to 4 mm precipitation occurring southeast of the Kinglake complex.

Figure 4 shows radar echo top heights at hourly intervals, for heights above 5 km, with the values representing the highest value recorded during that hour. The echo tops have maximum heights of 15 km during the hour of 1900 LT over the Kinglake fire complex and extending toward the southeast. This was during the period of most extreme fire behavior, with *Cruz et al.* [2012] reporting that the area affected by fire during the hour of 1800 LT (approximately 63,000 ha) was more than double the entire area burned by the fires prior to this time. *Cruz et al.* [2012] also report that the burn dynamics during the hour of 1900 LT were similar to those during the hour of 1800 LT, with somewhat weaker fire propagation from 2000 LT onward. In

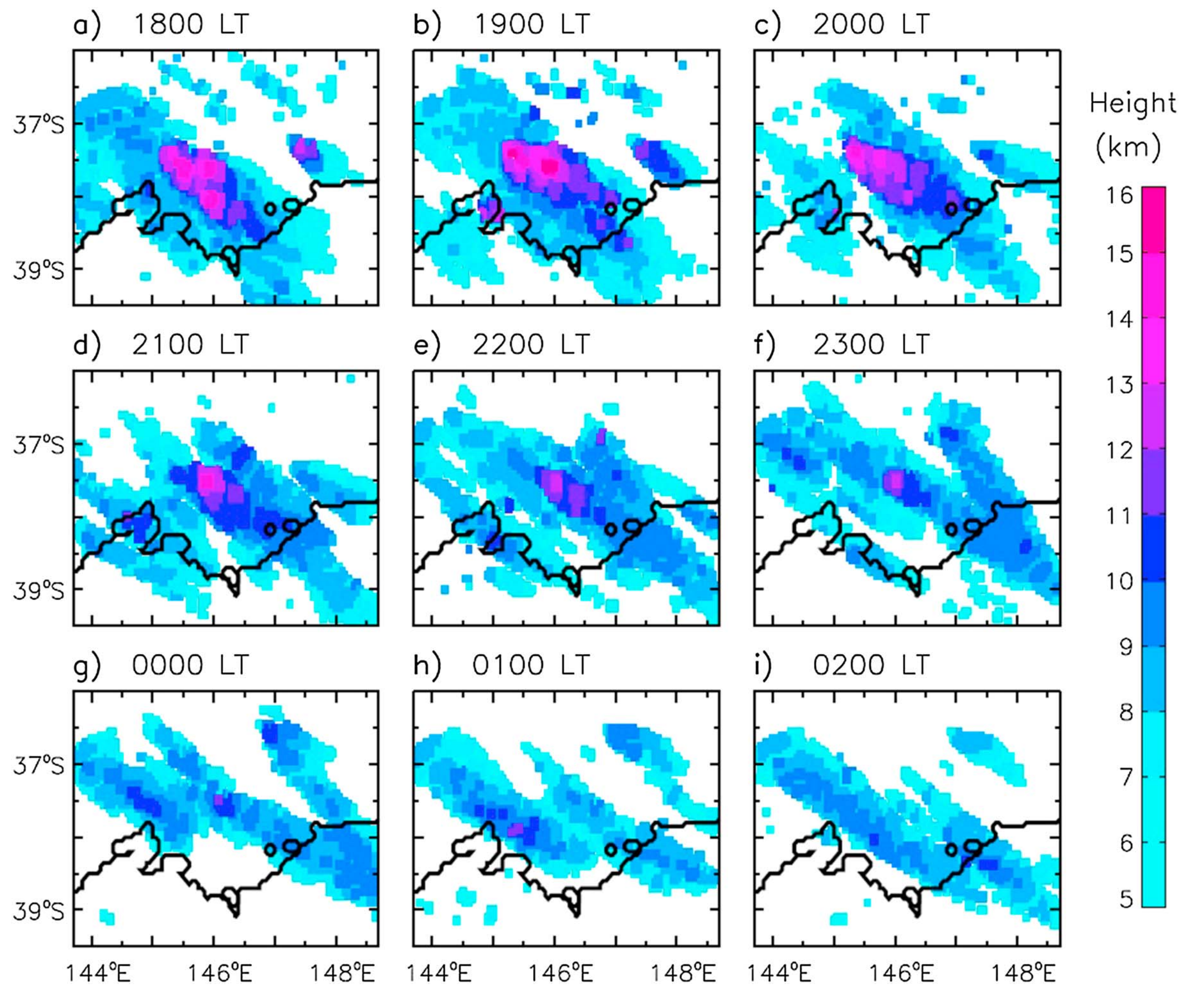

Figure 4. Echo top heights obtained from radar observations. Hourly values are shown from 1800 LT on Black Saturday to 0200 LT the following day, representing the highest echo top recorded during the 1 h period starting from the time shown. Coastlines, latitude, and longitude are shown.

addition to the Kinglake fire plume, a number of other plumes are evident from the radar observations. For example, the Dargo fire plume has echo top heights of about 12 km during the hour of 1800 LT (Figure 4a, around 37.0°S and 147.5°E) and somewhat lower values in subsequent hours. The Beechworth fire plume is also clearly apparent, reaching heights of 10 km during the hours near midnight LT (Figure 4g, around 36.5°S and 147.0°E).

3.2. Temporal Evolution of the Lightning Activity

Figure 5 shows the temporal evolution of the observed lightning activity as well as active fire observations. The first lightning stroke was recorded at 1650 LT in the region where the pyroCb occurred for the Kinglake fire complex, with lightning activity during the hour of 1700 LT also occurring only in that region, indicating the influence of the fire activity on initiating the lightning activity.

The majority of lightning activity during the hour of 1800 LT (Figure 5d) is clustered around the Kinglake fire complex (Figure 4), as well as some lightning strokes to the northwest mapping out a line similar to the location of the wind change at this time associated with the synoptic-scale prefrontal trough passing over the region at this time [see *Cruz et al.*, 2012] (Figure 1). As the wind change progressed across this region it produced rising air masses above its leading edge [*Engel et al.*, 2013], which plausibly provided the trigger for initiating deep convection (as indicated by the lightning activity) in locations away from the fire activity. During the following two hours (1900 LT and 2000 LT), lightning activity is only sustained in the region around the Kinglake pyroCb (a roughly elliptical region with a major axis of about 100 km in

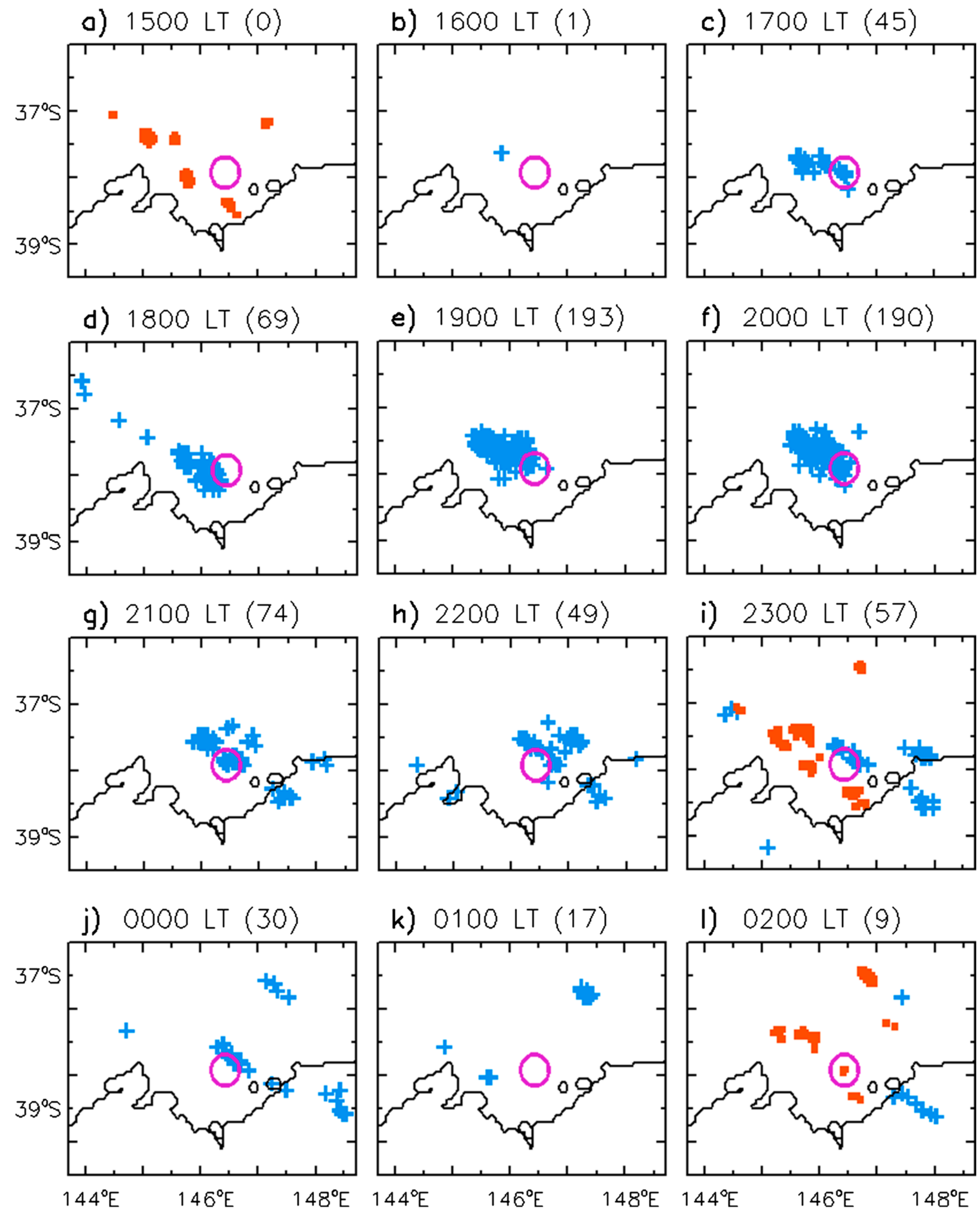

Figure 5. Temporal evolution of the lightning and fire activity. Lightning activity (blue plus symbols) and active fire observations from satellite overpasses (red regions) are shown during the hours of 1500 LT and 2300 LT on 7 February 2009 as well as 0200 LT on 8 February 2009. (a–l) Data are presented in hourly intervals from 1500 LT on 7 February 2009 to 0200 LT on 8 February 2009, representing all observations within 1 h periods starting from the specified times. The hour is listed at the top of each panel, followed in brackets by the total number of lightning strokes recorded during that hour in the region shown. Coastlines, latitude, and longitude are shown, as well as the location of a fire examined in relation to pyrogenic lightning ignition (purple circle) with the active fire observations for that case shown in Figure 5l.

length), with no lightning observed in surrounding regions, indicating the ongoing interaction between the Kinglake fire complex and the atmospheric processes throughout this time period.

The first fire ignition of the Kinglake complex occurred shortly before 1200 LT [*Cruz et al.*, 2012], 5 h prior to the first lightning observed in this region on Black Saturday. Such a short time interval from fire ignition to lightning generation offers broad implications for understanding fire behavior exacerbation rates, given that previous studies have shown that rapid and deep convection may be associated with dangerous variations in fire behavior [e.g., *Potter*, 2012b]. To put this time interval for Black Saturday into a more general context, a study of multiple pyroCb events in North America [*Peterson et al.*, 2016] reported that "generally speaking, pyroCb can occur at any point in a fire's lifetime, occasionally as early as the first 48 hours."

In addition to the Kinglake complex, the other fire event with lightning activity strongly clustered around it is the Beechworth fire. This fire was ignited at about 1800 LT on Black Saturday, with lightning activity in this region first observed at about midnight LT (6 h after ignition) and persisting until about 0200 LT the following morning (Figures 5j and 5k, around 36.5°S and 147.5°E). The Incident Controller for managing the Beechworth fire observed extreme fire behavior close to midnight, including reporting a "firestorm" approaching the town of Mudgegonga (around 36.5°S, 146.9°E) [*VBRC*, 2009]. These lightning data (Figure 5) indicate a significant change in convective processes within the Beechworth pyroCbs around midnight LT, consistent with the timing of the extreme fire behavior observed by the response personnel.

Engel et al. [2013] showed that shortly after 2300 LT a mesoscale bore passed over the Beechworth fire region introducing variability in atmospheric conditions at short spatial and temporal scales which can have large influences on fire danger. Rising air masses above the leading edge of the bore (as shown by *Engel et al.* [2013]) is suggested here to have likely helped initiate the deep pyroconvective processes required to electrify the Beechworth pyroCb, consistent with the initiation of the lightning activity around midnight LT. However, the bore is only one factor that helped initiate this lightning, given that lightning is not observed in the region away from the Beechworth fire plume, thereby indicating strong fire-atmosphere interactions in this case.

3.3. Fire Ignition From Pyrogenic Lightning

A new fire can be seen during the hour of 0200 LT on 8 February 2009 (Figure 5l, around 146.5°E and 38.0°S) that was not observed in previous satellite overpasses. This fire is listed as caused by lightning on Black Saturday in the Victorian State Government records of fire events based on postfire investigations by response personnel. These records refer to this fire event as the "East Tyers-Thompson" fire and state that it started at 1800 LT on Black Saturday due to lightning ignition. Complementary to the postfire investigations, the analysis of remotely sensed data presented here demonstrates a high risk of fire ignition from lightning in that region, including due to the high concentration of lightning activity produced by the Kinglake pyroCb in the region where this new fire occurred (Figure 5). Another important factor in determining whether or not a sustained fire will develop following a lightning ignition is the amount of precipitation that accompanies the lightning activity, with lightning accompanied by relatively little precipitation known as dry lightning [*Fuquay et al.*, 1967; *Latham*, 1991; *Rorig and Ferguson*, 1999]. The risk of fire occurrence from a lightning ignition in this region of southeast Australia is higher than average if less than about 3 mm of precipitation occurs and lower than average if more than about 5 mm of precipitation occurs [*Dowdy and Mills*, 2012a, 2012b]. Consequently, the relatively low amount of precipitation (Figure 3), coupled with the preexisting dryness of the fuels on Black Saturday [*Sullivan and Matthews*, 2013], indicate a substantial risk of sustained fire ignition from the observed lightning activity in this region (Figure 5).

An additional consideration in relation to the cause of this new fire is that it occurred about 100 km downwind of the Kinglake fire complex. This is too far for ember transport by the fire plume to be the cause of ignition, even considering the extreme ember transport distances observed on Black Saturday which resulted in spot fires occurring up to about 33 km ahead of the main fire front [*Cruz et al.,* 2012].

3.4. Comparison With Canberra Fire Event

A number of Australian pyroCb events have been documented in recent years [*Fromm et al.*, 2006, 2012; *Mills and McCaw*, 2010; *McRae et al.*, 2013, 2015]. The Canberra fire event on 18 January 2003 is particularly notable in that it resulted in pyroCbs that injected smoke into the stratosphere and perturbed stratospheric aerosol loading for at least 2 months [*Fromm et al.*, 2006]. Figure 6 shows the broad-scale meteorology on that day, including a large high in the Tasman Sea to the east of the continent as well as a midlatitude trough over southeast Australia with a cold front farther to the south of that region. Lightning activity associated with this event has not previously been examined in the literature. However, hail activity and a tornado (a nonsupercell type of tornado) associated with this pyroCb have been documented [*Fromm et al.*, 2006; *Cunningham and Reeder*, 2009; *McRae et al.*, 2013], noting that tornado or hail observations provide a means of defining severe thunderstorm occurrence (e.g., based on Australian Bureau of Meteorology operational practices). Given

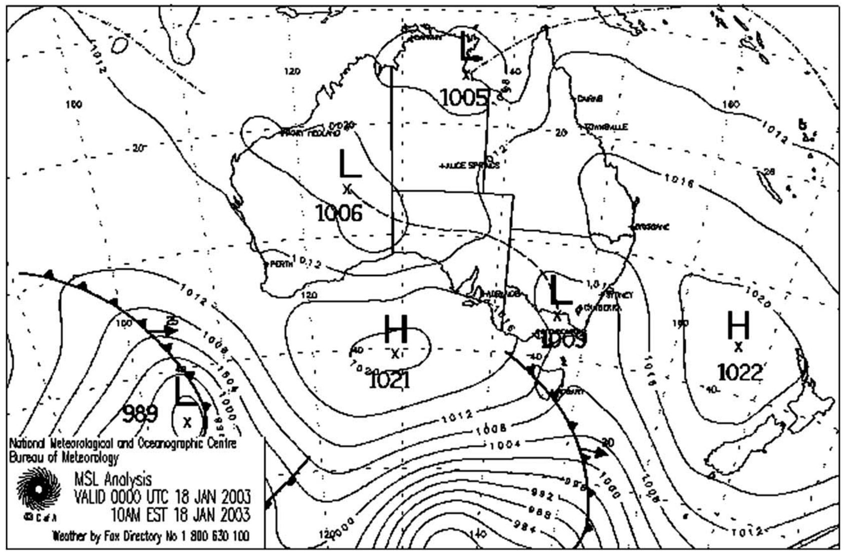

Figure 6. Synoptic features for the Canberra fire event, as represented by the mean sea level pressure (MSLP) analysis produced operationally by the Bureau of Meteorology. This is shown for 1100 LT on 18 January 2003.

these severe thunderstorm characteristics of the Canberra event, it is selected here for examination in comparison with Black Saturday.

Figure 7 presents observations similar to those shown in Figures 3 and 4 but for the region around Canberra on 18 January 2003. These include satellite observations of active fires, precipitation data, and lightning observations, as well as echo top heights (from the Captains Flat radar about 50 km southeast of Canberra).

Lightning activity was not observed in the region near the fire activity, with only four lightning strokes recorded over 100 km northeast of Canberra (Figure 7b), noting that this lightning activity was not downwind of the fires and occurred too far away to be associated with the fire activity. Additionally, no thunder was recorded as being heard on this day by the Canberra office of the Bureau of Meteorology in their thunderstorm observation records.

Although no lightning was observed in association with the Canberra pyroCb event, it could be possible that lightning activity occurred but was not detected. For example, a case occurred in the USA where the National Lightning Detection Network (NLDN) observed no lightning activity associated with a pyroCb, even though cloud-to-cloud (intracloud) lightning was observed by locally deployed lightning sensors [*Lang et al.*, 2014]. However, even considering the possibility that lightning did occur for the Canberra event but was not detected by the GPATS network (e.g., relatively weak intracloud lightning), there is a clear difference between Black Saturday and the Canberra event in terms of the characteristics of the lightning activity. This is potentially associated with the Canberra event having extremely dry conditions in some parts of the troposphere as compared to Black Saturday [*Cunningham and Reeder*, 2009; *McCaw et al.*, 2009] including the occurrence of a midtropospheric dry band for the Canberra event that led to abrupt surface drying resulting from vertical mixing [*Mills*, 2005b, 2008].

The relative dryness of the midtroposphere for the Canberra event as compared to Black Saturday is indicated by radiosonde observations during the middle of the day from Wagga Wagga (35.11°S, 147.36°E: about 180 km west of Canberra) for the Canberra fire event and from Melbourne Airport for Black Saturday (Figure 8). For example, the dewpoint temperature from 800 hPa to 700 hPa ranges from about −2°C to −7°C at Wagga Wagga as compared to values from about 0°C to 3°C at Melbourne Airport. The thermodynamic environmental conditions for the two cases show some broad similarities to each other, including an "inverted v" profile characterized by decreasing dewpoint depression with increasing height above the surface, consistent with the conceptual model of *Peterson et al.* [2016] of a dry and deep mixed layer with ambient midlevel moisture as typical factors associated with intense pyroCb development. The lifted condensation level (LCL) is 640 hPa for Wagga Wagga and 620 hPa for Melbourne Airport. Above

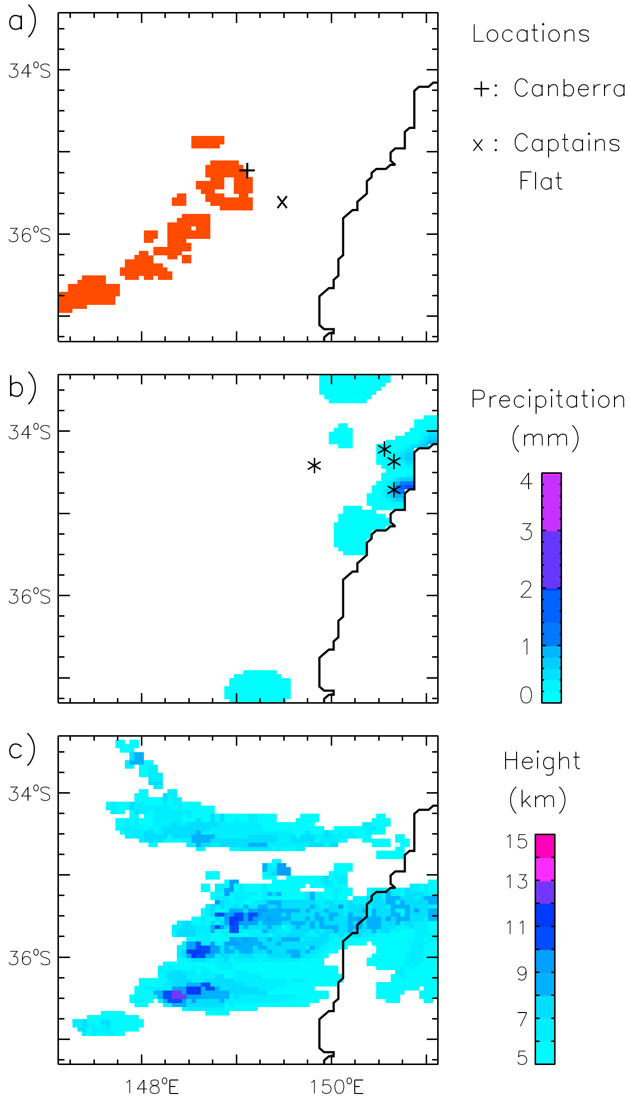

Figure 7. Observations for the Canberra fire event, 18 January 2003 in the Australian Capital Territory: (a) active fire observations, lightning (asterisk symbols), and (b) precipitation data, as well as (c) echo top heights from the Captains Flat radar. The fire and lightning data represent all observations within the period from 1500 LT on 18 January 2003 to 0300 LT on 19 January 2003. Precipitation data are based on daily observations over land for the 24 h time period from 0900 LT on 18 January 2003 to 0900 LT on 19 January 2003. Echo top heights are for the period from 1800 LT on 18 January 2003 to 0200 LT on 19 January 2003. Coastlines, latitude, and longitude are shown.

the LCL at around 500–600 hPa, the dewpoint depression is larger for Wagga Wagga (ranging from about 15°C to 25°C) than for Melbourne Airport (ranging from about 5°C to 10°C), while noting that at around 400 hPa the dewpoint depression is higher for Melbourne Airport than Wagga Wagga. Drier conditions for the Canberra event as compared to Black Saturday are also indicated by the precipitation observations presented here, with no precipitation recorded in the region near the Canberra fires (Figure 7b), compared with 1–4 mm precipitation in the region where the Kinglake pyroCb occurred (Figure 3c).

Although both of these fire events had deep convection reaching the stratosphere, as well as the “inverted v” type of atmospheric profile (Figure 8), the lightning data have illuminated a dichotomy between these two extreme pyroconvection events. We have suggested here that drier conditions in the lower and middle troposphere for the Canberra event as compared with Black Saturday could have potentially been an unfavorable factor for the generation of lightning activity, while acknowledging that there are a range of uncertainties associated with these processes (e.g., associated with the relative amount of entrainment and detrainment at different tropospheric levels that the surface parcel from the fire will experience as it is lifted). It is also noted that the atmospheric profiles shown in Figure 8 represent particular locations and times that are not exactly coincident with the actual pyroCb development in each case. Consequently, care is taken here to avoid making generalized conclusions based on these results from only 2 days (i.e., for Black Saturday and the Canberra event). To further examine this apparent conundrum that the lightning observations have highlighted, examinations of other similar cases throughout the world are intended for greater understanding of the processes leading to electrified pyroconvection.

4. Discussion

The analysis presented here provides evidence that extensive pyroCb activity occurred on Black Saturday, including a number of distinct electrified pyroCb clusters, the largest of which reached heights of around

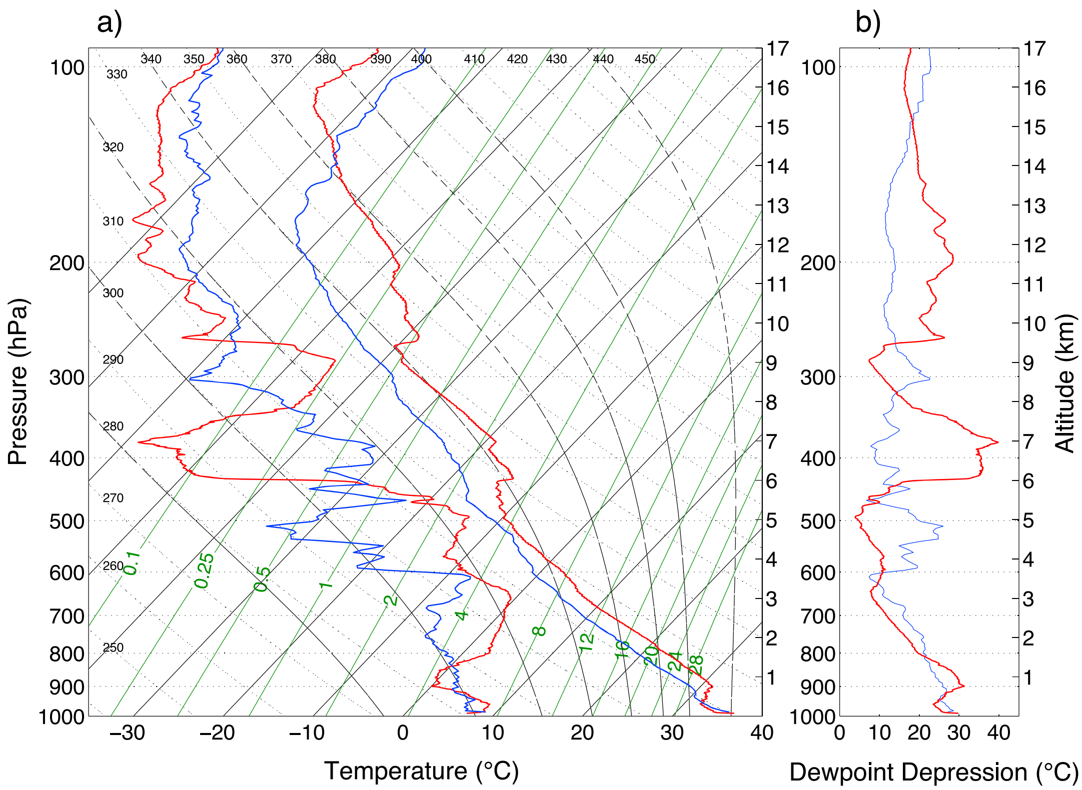

Figure 8. Radiosonde observations showing vertical profiles of (a) temperature and dewpoint as well as (b) dewpoint depression. This is shown for the Canberra fire event (blue) based on observations from Wagga Wagga at 0000 UT on 18 January 2003, as well as for Black Saturday (red) based on observations from Melbourne Airport at 2300 UT on 6 February 2009.

15 km on that day. As noted by *Bannister* [2009, 2014], fire agencies were very concerned about the potential for pyroCb formation on Black Saturday, even though forecast models did not indicate a high risk of thunderstorm development, as normal model thunderstorm guidance does not represent the heat and moisture release from the fire. Consequently, pyroCb-specific model guidance (e.g., as could be developed based on coupled fire-atmosphere modeling [*Clark et al.*, 1997; *Cunningham and Reeder*, 2009; *Potter*, 2012b]) and real-time intelligence (e.g., based on improved remote sensing capabilities) would greatly add to the forecaster service to fire agencies. The analysis presented here indicates considerable potential to use a range of remotely sensed data in fire management applications, including combining lightning observations with ground-based radar and satellite observations for improved pyroCb monitoring and modeling (e.g., nowcasting). Additionally, the Himawari-8 and Himawari-9 satellites recently launched by Japan provide imagery at 10 min intervals over a longitudinal region surrounding Japan that includes Australia [*Kurino*, 2012], representing a considerable advance in remote sensing capabilities in this region.

Previous studies demonstrate significant changes in fire behavior in response to synoptic conditions on Black Saturday including in response to the prefrontal trough and associated change in wind direction [*BOM*, 2009; *VBRC*, 2009; *Cruz et al.*, 2012; *Engel et al.*, 2013]. The results presented here build on these findings in showing that there was a significant atmospheric response to this change in fire behavior, including the occurrence of pyrogenic lightning activity tightly clustered around the fire plume of the Kinglake complex. Additionally, the new fire ignited by this pyrogenic lightning, examined in section 3.3, further highlights the feedback loops of influence between the atmosphere and fire behavior on Black Saturday associated with these pyroconvective processes. In addition to indicating this strong coupling on Black Saturday between the atmosphere and the fire activity, the lightning observations also suggest considerable differences in pyroCb characteristics between Black Saturday and the Canberra fire event. Differences between pyroCb events, such as for the Black Saturday and Canberra cases, indicate considerable potential for improved understanding of pyroconvection based on combining different data sets as presented here (including in relation to lightning, radar, precipitation, and satellite observations).

Complementary to previous studies focusing on the role of combustion-released moisture and heat in driving pyroconvection [*Cunningham and Reeder*, 2009; *Luderer et al.*, 2009; *Clements*, 2010; *Potter*, 2012a, 2012b; *Tosca et al.*, 2015], the results for Black Saturday demonstrate that synoptic-scale dynamics are also important to consider, including in relation to the initiation of deep pyroconvective processes: e.g., as occurred around the time of the prefrontal trough passing over the Kinglake fire region (examined in section 3.2). In relation to mesoscale dynamics, the initiation of deep convection around midnight LT for the Beechworth pyroCb (as indicated by the lightning observations) does not match the midafternoon peak in the severity of the near-surface fire weather conditions in this region [*VBRC*, 2009; *Cruz et al.*, 2012], whereas the occurrence of rising air masses above the leading edge of the bore that passed over this region (as shown previously by *Engel et al.* [2013]) is consistent with the timing of the onset of lightning activity close to midnight. In addition to mesoscale dynamics associated with this bore, strong fire-atmosphere interactions likely also played a role in triggering this pyroCb, given that lightning is not observed in the broader surrounding region away from the Beechworth fire plume.

Fire ignition by pyrogenic lightning has been reported by fire management authorities for a number of recent wildfires, including the Fort McMurray fire in Alberta, Canada, in May 2016 and the Waroona fire in January 2016 in Western Australia [*Ferguson*, 2016]; however, this phenomena has not previously been examined in the scientific literature. The examinations presented here for Black Saturday demonstrate that fires ignited by lightning generated within the fire plume can occur at much larger distances ahead of the main fire front —of the order of about 100 km—than fires ignited by burning debris transported by the fire plume (up to about 33 km [*Cruz et al.*, 2012]), noting that this also has implications in relation to understanding the maximum rate of spread of a wildfire.

The Black Saturday fire plumes were observed at stratospheric altitudes in the subsequent days as detailed in a number of studies [*Siddaway et al.*, 2010; *Pumphrey et al.*, 2011; *Glatthor et al.*, 2013], and although these studies did not examine the stratospheric injection event specifically, they all speculated that pyroCb activity was likely the cause. However, a remarkable aspect of the pyroCb phenomenon is that it has often been overlooked and its effects misattributed [*Fromm et al.*, 2010]. For example, *De Laat et al.* [2012] examined the Black Saturday conditions and concluded that "extensive deep pyroconvection is not observed and unlikely to have developed due to unfavorable meteorological conditions" and proposed a diabatic process for lofting between the middle troposphere and stratosphere. Hence, it is essential to fully explore events such as these to properly characterize the fire behavior, pyroCb dynamics, and resultant influence on conditions in the upper troposphere and lower stratosphere (UTLS). It is also important to accurately characterize this transport process so that cloud, chemistry, and climate models have a firm basis on which to evaluate the pyrogenic source term, pathway from the boundary layer through cumulus cloud, and exhaust from the convective column.

A greater understanding of pyroCb activity is important, given that fire-atmosphere feedback processes can exacerbate the conditions associated with dangerous fire behavior. It is intended that our findings will have benefits for fire response capabilities, based on improved preparedness and real-time monitoring of the potential for dangerous fire conditions associated with pyroconvection. Additionally, understanding the combined effects of heat, moisture, and aerosols on cloud microphysics is important for a range of weather and climate processes, including in relation to improved modeling and prediction capabilities.

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