1. Introduction

Large smoke plumes from active fires often become capped by cumulus clouds (pyroCu), which enhance the vertical lofting of smoke through latent heat release. Under certain conditions, this moist “pyroconvection” mechanism allows pyroCu to develop into a larger fire-triggered thunderstorm, known as pyrocumulonimbus (or pyroCb; American Meteorological Society 2016). The deep convective column provides an efficient method for lofting smoke particles well into the upper troposphere, drastically impacting the extent of downwind transport. Intense pyroCb activity can also inject a significant quantity of aerosol mass into the upper troposphere and lower stratosphere (UTLS), occasionally more than 7–10 km above the tropopause (Fromm et al. 2005, 2008a,b). At this altitude, aerosol particles can persist for long durations (Robock 2000), allowing for gradual spread over hemispheric scales. PyroCb are therefore likely to be a highly relevant and significant process governing the state of stratospheric aerosols and affecting global climate.

The current understanding of UTLS smoke injection from pyroCb is based on individual fires observed in the mid- and upper-latitude forests of North America,
Australia, and Asia (e.g., Fromm et al. 2006, 2010, 2012). PyroCb have been identified as the source of several UTLS aerosol layers previously presumed to be of volcanic origin (Fromm et al. 2010). Remote sensing–based studies reveal that pyroCb anvils have distinct, smoke-induced microphysical characteristics and longer lifetimes compared with traditional convection (e.g., Rosenfeld et al. 2007; Lindsey and Fromm 2008; Reutter et al. 2014). The mechanisms driving pyroCb development and ensuing UTLS smoke injection can be different from those linked to rapid fire spread (Peterson et al. 2015). However, the specific meteorological conditions driving pyroCb development remain highly uncertain, especially over large spatial and temporal scales.

All observed pyroCb to date are associated with large and intense fires. It is therefore not surprising that a hot surface temperature, strong surface winds, low relative humidity, and deep mixed layer are often associated with pyroCb activity (Fromm et al. 2006, 2012; Cruz et al. 2012). A variety of fire weather indices, such as the Haines index (Haines 1988) or continuous Haines index (Mills and McCaw 2010) have been employed to characterize the pyroCb environment (Fromm et al. 2012). However, Peterson et al. (2015) show that these surface and near-surface-based variables and indices have limited utility for forecasting or diagnosing extreme wildfire development, including formation of pyroCb. There are also conflicting assertions on the importance of atmospheric instability and the parameter or index used to quantify its magnitude (Trentmann et al. 2006; Fromm et al. 2010, 2012). A potential link to surface frontal boundaries (Fromm et al. 2005; Trentmann et al. 2006; Cruz et al. 2012) and/or upper-level disturbances (Johnson et al. 2014; Peterson et al. 2015) has been identified, but the specific role these features have in pyroCb development is currently unclear.

All convective cloud development requires a moisture source, usually from within the lower or midtroposphere. However, the unique link between pyroCb and intense fire activity suggests that water vapor released as a by-product of combustion may also play a role. The specific contribution of each potential moisture source during pyroCb development remains a highly controversial topic. Several studies suggest that latent heat production from combustion is a key driver of plume dynamics and subsequent pyroCb activity, with a negligible contribution from the ambient atmosphere (e.g., Potter 2005; Cunningham and Reeder 2009). In contrast, other studies show plume dynamics are primarily driven by sensible/radiant heat release, with the contribution of water vapor from combustion decreasing rapidly with height (Trentmann et al. 2006; Luderer et al. 2009). Model simulations of pyroCb plumes show potential for significant entrainment of ambient air in the midtroposphere (Trentmann et al. 2006). This suggests that midtropospheric water vapor can be a primary driver of pyroCb development.

Through a detailed analysis of the 2013 Rim Fire in California, Peterson et al. (2015) hypothesize that the meteorological environment commonly associated with high-based convection (dry thunderstorms) in the southwestern United States is likely a general precursor for pyroCb development. Fromm et al. (2006) also describe pyroCb activity in the vicinity of traditional high-based convection in southeastern Australia. High-based convection occurs when a layer with increased moisture and instability is advected over a dry, deep, and unstable mixed layer, typically along the leading edge of an approaching disturbance (e.g., Rorig and Ferguson 1999; Nauslar et al. 2013). The upper-tropospheric dynamics and synoptic pattern must also be conducive for rising motion and vertical development of convection (Wallmann et al. 2010; Nauslar et al. 2013). Mid- and upper-tropospheric conditions are therefore paramount for the development and maintenance of high-based convection, presumably including pyroCb activity. In contrast to severe thunderstorm outbreaks, the triggering mechanism for high-based convection usually stems from orographic heating/lifting or a weak disturbance in the midtroposphere (Wallmann et al. 2010). Increased thermal buoyancy from large and intense wildfires (e.g., Val Martin et al. 2012; Peterson et al. 2014) may also serve as a potential trigger for pyroCb (e.g., Peterson et al. 2015; Lareau and Clements 2016); especially during specific forms of surface fire spread (McRae et al. 2015).

Many techniques have been employed to identify individual pyroCb events of varying magnitude, including visual observations, satellite remote sensing of cloud-top brightness temperature near fires, and reverse trajectories from high-altitude smoke clouds observed by lidar during the days following a potential pyroCb (e.g., Rosenfeld et al. 2007; Fromm et al. 2005, 2008a,b, 2010). Satellite observations reveal that North American pyroCb typically initiate during midafternoon and terminate a few hours after sunset (Fromm et al. 2010). Many pyroCb are characterized by relatively small anvil clouds, persisting for less than one hour. In extreme cases, pyroCb develop expansive anvils that persist for several hours, occasionally comprising multiple convective pulses (Rosenfeld et al. 2007). However, despite this growing body of literature, pyroCb detection at large regional or global scales has been unsystematic and limited, suggesting that pyroCb activity is likely undersampled.

The U.S. Naval Research Laboratory (NRL) has developed a near-real-time pyroCb detection algorithm
based on geostationary satellite data (Peterson et al. 2017). The algorithm takes advantage of the unique microphysics of pyroCb, facilitating development of the first systematic event inventory across western North America during the primary fire season (June–August) of 2013. This companion study employs the combination of the pyroCb inventory and reanalysis data to examine the meteorological conditions during large and intense pyroCb events, with the goal of building the first conceptual model for their development. Periods of intense fire activity (90th percentile of hourly fire radiative power) that fail to produce pyroCb activity are also examined. Results highlight the role of atmospheric dynamics, midlevel moisture content, and atmospheric stability profiles in pyroCb development. Limitations of traditional fire weather indices and forecasting methodologies are also explored. This information is essential for understanding the impact of pyroCb and ensuing stratospheric smoke injection on the climate system, as well as development of future predictive capabilities.

2. Study region, data, and methods

This study incorporates an inventory of 26 intense pyroCb events developed by Peterson et al. (2017), which is based on the lifetime of 88 intense wildfires observed across western North America during June–August 2013 (Fig. 1). The study domain is primarily based on fire-prone regions within the effective field-of-view for the Geostationary Operational Environmental Satellite observing western North America (GOES-W; currently GOES-15), with an equatorial subsatellite point of 135°W. This includes the western continental United States and northern Mexico (MCONUS), as well as the remote boreal forest of western Canada (Fig. 1). All fires in MCONUS were located in regions with
complex topography [mean elevation of 1800 m above sea level (MSL)], but the majority of the Canadian fires occurred on relatively flat terrain, with a mean elevation of 400 m MSL. Regardless of region, the North American Regional Reanalysis (NARR; Mesinger et al. 2006) vegetation layer indicates that all pyroCb were associated with fires located in dense forest or a mix of forest and chaparral vegetation (Fig. 1, green shading). This section describes the pyroCb inventory, a control inventory of intense fire activity in the absence of pyroCb, and the meteorological data used in the analysis of these events.

a. PyroCb detection and inventory

PyroCb detection for GOES-W begins with identification of deep convection near observations of active fires (described in the next section). Intense pyroCb (IPCB) must have large anvil ice clouds (Fig. 2), and therefore must exhibit a thermal infrared (11 μm) brightness temperature (BT₁₁) near an approximated homogeneous liquid-water freezing threshold (BT₁₁ < −38°C; Wallace and Hobbs 2006; Rosenfeld et al. 2007). However, to account for averaging of convection within the large pixel size of GOES-W (20–110 km²), the pyroCb algorithm employs an IPCB BT₁₁ threshold of −35°C (Peterson et al. 2017). All 26 events in the pyroCb inventory reach this IPCB BT₁₁ threshold, and therefore have a high likelihood of injecting smoke particles into the UTLS.

Extreme aerosol loading within a pyroCb induces a microphysical shift (from indirect aerosol effects) toward smaller cloud droplets and ice particles (Rosenfeld et al. 2007; Reutter et al. 2014; Chang et al. 2015), producing a much larger daytime near-infrared (4 μm) reflectivity than traditional convection (e.g., Rosenfeld et al. 2007). Application of a 4- and 11-μm brightness temperature difference (BTD₄–₁₁) therefore allows for separation of IPCB from more pristine traditional convection (Peterson et al. 2017). However, the dependence on 4-μm reflectivity currently limits pyroCb detection to daytime scenes (solar zenith angle < 80°). Two BTD₄–₁₁ thresholds are employed based on regional variability in convective clouds, which is driven by meteorological conditions. Output imagery for the Papoose Fire in Colorado (Fig. 2a) highlights the ability of these thresholds to separate the unique microphysics of IPCB activity from traditional convection. A cloud opacity test based on a modified split window (11- and 13-μm brightness temperature difference) is also applied to reduce potential cloud edge noise and detection errors from thin clouds passing over a hot fire. Imagery for the Pony/Elk fire in Idaho (Fig. 2b) highlights the removal of thin cloud-edge pixels by the opacity test in the IPCB anvil.

FIG. 2. Example GOES-W IPCB detection imagery for (a) the Papoose fire in Colorado and (b) Pony/Elk fire in Idaho. Red and orange shading indicates BTD₄–₁₁ for pixels with BT₁₁ below the IPCB threshold (BT₁₁ < −35°C). White shading indicates BT₁₁ for nonpyroCb clouds. The few pixels shaded in green represent deep convection (BT₁₁ < −20°C) that passes the pyroCb microphysics and opacity tests, but remains warmer than the IPCB BT₁₁ threshold.
region. (The entire suite of imagery products based on these methods is posted in near–real time at the NRL pyroCb website: http://www.nrlmry.navy.mil/pyrocb-bin/pyrocb.cgi.)

Following Peterson et al. (2017), the time corresponding with a specific pyroCb is defined as the first GOES-W scan meeting IPCB criteria. However, in this study, multiple pulses of IPCB activity within 6 h are considered a single event. The resulting IPCB inventory is based on processing of 15-min GOES-W imagery for daylight hours (roughly 6000 scenes), including additional scenes available during Rapid Scan Mode (http://www.ospo.noaa.gov/Operations/GOES/west/rso.html).

Table 1 provides details of IPCB observations for each region and surface elevation category. Of the 88 fires examined, 11 (13%) produced IPCB activity (Fig. 1, blue triangles), totaling 26 individual events. The majority of IPCB activity (23 events from 9 fires) was observed in MCONUS, with only 3 IPCB events observed in Canada (from 2 fires). The details of each individual IPCB event, including time, latitude, and longitude, are provided in Peterson et al. (2017).

As the viewing zenith angle (VZA) of GOES-W increases away from nadir, pixel size also increases from 24 to 39 km² in MCONUS (VZA < 60°) to 55–109 km² in the boreal regions of Canada (60° < VZA < 75°; Fig. 1, orange lines). Peterson et al. (2017) show that IPCB detection is possible in Canada, even at extreme VZAs (pixel size > 100 km²). However, a few IPCB events with small anvils may remain undetected, likely resulting in an underestimate of Canadian activity. Marginal pyroCb activity without an anvil (BT₁₁ ≃ −35°C; failing to reach the UTLS) and small pyroCu will not be detected in MCONUS or Canada using current GOES-W imagery.

**b. Control inventory of intense fire activity**

As highlighted by Peterson et al. (2015), intense burning and rapid fire spread do not always yield development of pyroCb. Therefore, a detailed understanding of pyroCb development also requires comparisons between observed IPCB events and a control inventory of intense burning without the associated presence of deep convection. This is accomplished by employing the GOES Wildfire Automated Biomass Burning Algorithm (WF_ABBA; Prins and Menzel 1994; Prins et al. 1998), which retrieves fire pixels by taking advantage of the spectral contrast between a pixel containing fire and the surrounding nonfire region using the same 4- and 11-μm infrared channels as the pyroCb detection algorithm. WF_ABBA also provides an estimate of instantaneous fire radiative power (FRP; units of MW) for detected fire pixels, which is a measure of radiant heat output and commonly used to approximate fire intensity (e.g., Kaufman et al. 1998; Giglio et al. 2003; Wooster et al. 2005; Schroeder et al. 2010; Peterson et al. 2013b). The true FRP value is occasionally higher than the GOES-W observation due to sensor saturation.

In contrast with traditional calculations of linear “fire line intensity” (Byram 1959), satellite retrievals provide FRP released over a pixel area. Combined FRP information from WF_ABBA (~4-km resolution) and the Moderate Resolution Imaging Spectroradiometer (MODIS) fire detection algorithm (MYD14/MOD14, ~1-km resolution; Giglio et al. 2003; Giglio 2010) are used to select clusters of active fire pixels, where a large total FRP is retrieved over an area of 625 km² during either a single day or a period of up to 5 days. A threshold of 140 000 MW is employed to select the 88 fires shown in Fig. 1 (Peterson et al. 2017), from which the IPCB and control inventories are derived.

The control inventory used in this study is based on high FRP events (HFRP; Table 1) observed during the time series of each individual fire. A consistent and representative hourly FRP time series is produced by normalizing fire detections from WF_ABBA (GOES-W) over a box marking the maximum fire boundaries (Peterson et al. 2015). HFRP events are identified by the 90th percentile of hourly FRP, including hours only where the observed minimum BT₁₁ is warmer than −20°C. This BT₁₁ threshold is warm enough to

<table>
<thead>
<tr>
<th>Category</th>
<th>All fires</th>
<th>IPCB fires</th>
<th>HFRP fires</th>
<th>IPCB events</th>
<th>HFRP events</th>
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</thead>
<tbody>
<tr>
<td>Fire surface elevation</td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<td>&lt;1000 m</td>
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<td>2000–3000 m</td>
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<td>4 (19%)</td>
<td>20 (95%)</td>
<td>8</td>
<td>55</td>
</tr>
<tr>
<td>≥3000 m</td>
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<td>2 (67%)</td>
<td>2 (67%)</td>
<td>8</td>
<td>5</td>
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<td>Geographic location</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MCONUS</td>
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<td>44 (92%)</td>
<td>23</td>
<td>145</td>
</tr>
<tr>
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<td>33 (83%)</td>
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<td>57</td>
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<td>All</td>
<td>88</td>
<td>11 (13%)</td>
<td>77 (88%)</td>
<td>26</td>
<td>202</td>
</tr>
</tbody>
</table>

*Based on the pyroCb inventory of Peterson et al. (2017).
exclude HFRP cases with deep convective clouds in the vicinity of the fire, but cold enough to allow HFRP events influenced by shallow convection, such as capping pyroCu (Peterson et al. 2015). Each HFRP event must also feature 12 h of separation between IPCB activity and any previous HFRP events. These criteria ensure there is only one HFRP event per day in the absence of pyroCb influence.

Of the 88 fires displayed in Fig. 1, 77 (88%) produced at least one HFRP event (Table 1). A total of 202 individual HFRP events were observed, with 145 observed in MCONUS (44 fires) and 57 observed in Canada (33 fires). Periods of high fire danger and vigorous burning are shorter in high-latitude boreal regions (e.g., Potter 2012), especially periods free of convective clouds. This results in fewer HFRP data points in Canada (Table 1). The 11 fires that failed to produce HFRP criteria were either impacted by consistent deep cloud cover or exhibited a short FRP time series without sufficient time between IPCB events (e.g., the Yarnell Hill Fire).

While the HFRP inventory successfully captures intense fire activity in the absence of deep convection, it does not account for rapid changes in subpixel fire characteristics prior to pyroCb development (McRae et al. 2015). Satellite retrievals of instantaneous, subpixel fire area and temperature are available, but require extensive processing and filtering (e.g., Peterson and Wang 2013; Peterson et al. 2013b, 2014). Potential relationships between these subpixel retrievals and IPCB development will therefore be explored in future research.

c. Meteorological data

Meteorological data corresponding to each IPCB and HFRP event are obtained from the NARR (http://nomads.ncdc.noaa.gov/data.php#narr_datasets), archived at the National Climatic Data Center (NCDC). Through data assimilation, the NARR blends a variety of observational data into Eta model output containing 29 pressure levels over a mesh across the North American continent of ~32-km grid spacing (Ebisuzaki 2004; Mesinger et al. 2006). In this study, 3-hourly NARR data are linearly interpolated to match the observation times of each GOES-W scene. The value for each variable is either the mean of all NARR grid box centroids located within the maximum fire perimeter boundaries or the closest centroid to the fire boundaries.

The standard NARR dataset is also used to derive variables relevant to forecasting fire weather conditions (e.g., Haines index; Haines 1988) and high-based convection (e.g., upper-tropospheric divergence and lapse rates; Nauslar et al. 2013). Thermodynamic profiles for each event are derived from the NARR’s 29 pressure levels, allowing for a variety of thermodynamic parameters to be calculated (described in section 4). This combined information is the basis for a detailed analysis of dynamic and thermodynamic conditions during IPCB development and HFRP events.

3. General meteorology

Generally speaking, pyroCb can occur at any point in a fire’s lifetime, occasionally as early as the first 48 h. In the study region (Fig. 1), the median and mean times of IPCB development are 4 and 7 days from the first FRP observation, respectively. While development can occur during sunset and nighttime, pyroCb activity peaks during the late afternoon and early evening hours (e.g., Fromm et al. 2010) at the same time as the diurnal peak in fire activity (Giglio 2007; Mu et al. 2011). The GOES-W pyroCb detection algorithm is also most effective during this time period. The majority of observed IPCB events (85%) in Table 1 initiate between 1900 and 0000 UTC, when the solar zenith angle is less than 60° (Peterson et al. 2017). The majority of these IPCB also develop in interior sections of the western MCONUS, where traditional convection often fails to reach the tropopause (Sassen and Campbell 2001). This feature helps distinguish regional microphysical perturbations in pyroCb using BTD4–11 compared with more vigorous convective storms. Since background ice particles at cloud top are otherwise relatively warm and large, smaller perturbed crystals in pyroCb anvils become more conspicuous (Peterson et al. 2017).

As described sequentially within the following sections, traditional means for assessing fire conditions, which would presumably become proxies for IPCB development, are incomplete. A more thorough consideration of regional and synoptic-scale meteorology is necessary to understand IPCB development relative to HFRP events.

a. Standard fire weather variables

Standard fire weather forecasts generally depend on three primary surface variables: relative humidity (RH), temperature, and wind speed (Potter 2012). These “dry, hot, and windy” criteria are used in many forecasting applications, and for building fire weather indices (e.g., Amiro et al. 2004; Peterson et al. 2013a; Field et al. 2015). Figure 3 shows the distributions of these three variables in the study region for each event type. IPCB develop with a surface-based mean (median) RH of 21% (20%) and temperature of 26°C (29°C). While the IPCB events were statistically hotter and drier compared to HFRP events, there is very little separation between the distributions. Surface wind speed (based
on a 3-hourly mean) shows the least distinction between event type and region, with mean and median values of about 5 m s\(^{-1}\) (9.7 kt) for all events. Standard dry, hot, and windy surface criteria are therefore unable to effectively distinguish between IPCB and HFRP events.

While some regional variability is expected, the distributions of the surface meteorology in Fig. 3 are very similar to the values described in the literature for all extreme characteristics of wildfires, including rapid fire spread, crowning, spotting, pyroCb, and even non-supercell, fire-generated tornados or “landspouts” (e.g., Cunningham and Reeder 2009; Werth et al. 2011; Cruz et al. 2012; McRae et al. 2013; Peterson et al. 2015). This suggests that standard dry, hot, and windy surface criteria are absolutely paramount for extreme wildfire development and maintenance of rapid fire spread. However, this is where the correlative relationship between these traditional indices and potential for convective initiation ends.

b. Synoptic pattern during intense pyroconvection

Inspection of the mid- and upper-level synoptic environment during all IPCB activity from June to August 2013 reveals that each event was associated with one of three distinct patterns: 1) monsoonal anticyclone, 2) West Coast disturbance, and 3) Canadian ridge breakdown. Examples are provided in Fig. 4. During May and June, the southwestern MCONUS experiences a transition from a midlatitude transient synoptic environment to the summer monsoonal pattern (e.g., Higgins et al. 1997; Johnson et al. 2007). Increased surface heating causes a northeastward migration, broadening, and flattening of the subtropical Pacific ridge (Sassen and Campbell 2001). This “monsoonal anticyclone,” in combination with a low-level thermal trough, facilitates moisture advection from the tropical eastern Pacific, Gulf of California, and/or Gulf of Mexico (Higgins et al. 1997). The position and intensity of the anticyclone fluctuates during the summer, shifting the direction of moisture transport and the location of convective development (Johnson et al. 2007). The majority of IPCB activity (16 events triggered by 6 fires) was observed during the monsoon onset phase (1 June–5 July), before precipitation increases fuel moisture.

Figure 4a displays the synoptic pattern for IPCB activity observed during the Yarnell Hill (Arizona) and Silver (New Mexico) fires on 30 June. The monsoonal anticyclone was centered over southern Nevada, allowing for midlevel moisture advection and development of traditional convection over the high terrain surrounding each fire. IPCB activity observed on 27 June, during the Silver fire, as well as the Papoose and West Fork fires (Colorado) was associated with a similar synoptic environment (Fig. 4b), with the center of the anticyclone shifted to the border between New Mexico and Colorado. This orientation reduces midlevel moisture advection, but is still suitable for development of traditional high-based convection at the extreme surface elevation of the fires (>3000 m MSL in Colorado; Table 1).

In the Pacific Northwest and much of California, IPCB activity generally develops over fires located along the leading edge of an approaching disturbance. This “West Coast disturbance” pattern is described in relation to the 2013 Rim Fire (19 August) by Peterson et al. (2015), and is illustrated in Fig. 4c. A cutoff area of low pressure near the coast allows for advection of subtropical midlevel moisture into central California, providing a thermodynamic environment favorable for high-based convection, especially in the vicinity of elevated terrain. The synoptic pattern on 12 August for IPCB activity during the Yarnell Hill (Arizona) and Silver (New Mexico) fires on 30 June. The monsoonal anticyclone was centered over southern Nevada, allowing for midlevel moisture advection and development of traditional high-based convection over the high terrain surrounding each fire. IPCB activity observed on 27 June, during the Silver fire, as well as the Papoose and West Fork fires (Colorado) was associated with a similar synoptic environment (Fig. 4b), with the center of the anticyclone shifted to the border between New Mexico and Colorado. This orientation reduces midlevel moisture advection, but is still suitable for development of traditional high-based convection at the extreme surface elevation of the fires (>3000 m MSL in Colorado; Table 1).

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In the boreal forests of western Canada, active fire seasons, periods of intense burning, and dry lightning strikes are commonly associated with the presence of a 500-hPa anticyclone (e.g., Skinner et al. 1999, 2002; Macias Fauria and Johnson 2006; Peterson et al. 2010; Potter 2012). However, fires tend to exhibit the most extreme characteristics as the corresponding ridge begins to break down, which is most commonly associated

![Synoptic Maps](https://example.com/synopticMaps.png)

**FIG. 4.** Example synoptic maps for IPCB events influenced by (a),(b) monsoonal anticyclone; (c),(d) West Coast disturbance; and (e),(f) Canadian ridge breakdown patterns. Black contours indicate NARR 500-hPa heights, plotted at 20-m intervals in (a)–(d) and 40-m intervals in (e),(f). Red contours indicate upper-tropospheric divergence, plotted every $1 \times 10^{-5}$ s$^{-1}$. Shading indicates the mean midlevel relative humidity and orange triangles indicate the locations of fires producing IPCB activity. The dashed white line in (e) indicates the axis of a short-wave trough.
with the arrival of a surface cold front and an upper-level trough (Nimchuk 1983; Westphal and Toon 1991). This pattern exhibits many similarities with the West Coast disturbance pattern. The primary differences in Canada are the relative lack of complex topography and closer proximity to the polar jet stream. This likely means that dynamic forcing mechanisms, including frontal boundaries, typically play a larger role in convective development.

Figure 4e shows the synoptic pattern for IPCB activity during a large wildfire in Manitoba on 1 July. The fire was located within a strong 500-hPa height gradient associated with an approaching short-wave trough and surface cold front, highlighting the classic “ridge breakdown” pattern. Figure 4f shows the synoptic pattern during IPCB activity in the Northwest Territories. In this case, the fire was located within the ridge portion of a “Rex Block” pattern (Rex 1950a,b), ahead of an approaching long-wave trough along the west coast of Canada. All three Canadian IPCB events (two fires) developed under similar synoptic environments. While regional variability is expected, all synoptic patterns highlighted in Fig. 4 induce favorable fire weather conditions near the surface, along with mid- and upper-level conditions favorable for convective sustenance.

c. Dynamic forcing

Development of deep convection requires an environment conducive to rising motion within the full depth of the troposphere. Calculations of divergence in the upper troposphere are commonly used to infer upper-tropospheric jet structure and the magnitude of quasi-geostrophic forcing mechanisms influencing vertical motion (e.g., Nauslar et al. 2013). In the southwestern MCONUS, upper-tropospheric divergence during IPCB development is typically a result of the summer monsoonal anticyclone (Figs. 4a,b), fed by intense diabatic heating over elevated terrain. The Pacific Northwest and Northern California are located between the monsoonal pattern and the storm track associated with the polar jet. Upper-tropospheric divergence and convective initiation in this region (Figs. 4c,d) typically results from a combination of terrain effects and mesoscale jet structures (e.g., Hamilton et al. 1998; Nauslar et al. 2013) embedded within the West Coast disturbance synoptic pattern (Peterson et al. 2015). Canadian IPCB events (Figs. 4e,f) develop in the absence of complex topography. Therefore, upper-tropospheric divergence is primarily a result of transient disturbances along the polar jet.

Because of regional variation in tropopause height, the upper troposphere is defined as 250 hPa in MCONUS and 300 hPa in Canada. Each synoptic pattern displayed in Fig. 4 produced upper-tropospheric divergence (Fig. 5a, positive values) during the majority of IPCB activity observed across western North America (Fig. 1). In contrast, more than 50% of HFRP events, specifically defined as devoid of deep convection, were generally observed with weak convergence in the upper troposphere (Fig. 5a, negative values).

While some upper-tropospheric divergence was typically present during IPCB development, its magnitude was much weaker in comparison with major severe thunderstorm outbreaks observed in the central MCONUS (e.g., Knupp et al. 2014). Similarly, large-scale quasi-geostrophic forcing mechanisms, including strong advection of absolute vorticity (Fig. 5b), were typically absent during IPCB development. Many IPCB events were therefore associated with weak rising motion (negative omega) in an environment only marginally favorable for convective development (e.g., Wallmann et al. 2010). Additional micro- and mesoscale influences, such as topography and/or intense heating from a large fire (explored in section 7), may be required to trigger pyroconvective development.

4. Thermodynamic profiles

Several previous studies have attempted to describe the thermodynamic environment during pyroCb activity using convective indices derived from nearby radiosondes.
However, these data are only available twice daily, and are often located a long distance from the fire in an environment with much different meteorology. By employing the NARR’s 29 pressure levels, thermodynamic profiles are derived at the location of each fire during each IPCB and HFRP event.

**a. Significance of the “inverted V” profile**

Figure 6 displays individual NARR-derived profiles for each IPCB and HFRP event observed at the 44 low elevation fires (<1000 m; Fig. 1, Table 1). The three IPCB profiles, all associated with Canadian fires, exhibited a relatively deep (mean of 1950 m) and near dry-adiabatic mixed layer (Fig. 6a). A large near-surface dewpoint depression, defined as the difference between temperature (Fig. 6a, red curves) and dewpoint (Fig. 6a, blue curves), gradually decreased with altitude, and remained relatively low in the midtroposphere. This elevated midtropospheric moisture content above a dry and unstable mixed layer is commonly referred to as an inverted-V thermodynamic profile (e.g., Wakimoto 1985; Evans et al. 2012; Tory and Thurston 2015). While the mean of all profiles corresponding to 68 HFRP events from the same fires also shows a reduction in dewpoint depression in the mixed layer, the mean midtropospheric layer (top of the inverted V) is drier, thus weakening the inverted-V signature (Fig. 6b).

All 41 midelevation fires (1000–3000 m MSL) were located within the interior of the western MCONUS (Fig. 1, Table 1). Significant daytime heating produced a much deeper dry mixed layer [3000 m above ground level (AGL)] compared with the lower elevation Canadian fires. The combination of these deep mixed layers and increased midtropospheric moisture (lower dewpoint depressions) produced well-defined inverted-V profiles for the majority of midelevation IPCB activity. However, midelevation profiles for HFRP events (Fig. 7b) were similar to their low-elevation counterparts, with reduced moisture (larger dewpoint depressions) in the midtroposphere. IPCB events observed during the three high elevation fires (>3000 m MSL) exhibited larger midtropospheric dewpoint depressions than those observed during low- and midelevation fires (Fig. 8a), thus producing a weaker inverted-V signature. High-elevation HFRP profiles were dry at all levels (Fig. 8b). The potential impact from
variation in surface elevation on midtropospheric moisture content is explored in greater detail in section 6. An inverted-V profile is significant because it highlights the same thermodynamic environment observed during traditional high-based convection and dry lightning activity in western North America (e.g., Wallmann et al. 2010). A variety of studies have shown similar thermodynamic profiles for individual pyroCb events in MCONUS, Canada, and Australia, usually via nearby radiosondes (e.g., Trentmann et al. 2006; Rosenfeld et al. 2007; Cunningham and Reeder 2009; deLaat et al. 2012; Fromm et al. 2012; Johnson et al. 2014; Lareau and Clements 2016). However, with limited sample sizes in previous work, the connection between pyroCb and high-based convection was only recently hypothesized (Peterson et al. 2015).

An inverted-V profile represents relatively dry and hot surface conditions, as well as a deep mixed layer favorable for strong smoke column updrafts in the presence of limited vertical wind shear (described in section 5). The width of an inverted-V base (large dewpoint depression) can be related to the moisture content of surface fuels, and thus the intensity with which they will burn (e.g., Van Wagner 1987; Haines 1988). These characteristics combine to promote intense burning and vertical smoke lofting, which are typical of “blow-up” fire events (McaRae and Sharples 2014). In contrast, supercell thunderstorms and associated tornado outbreaks typically coincide with moist conditions in the lower troposphere and drier conditions aloft (e.g., the “loaded gun” profile; http://www.theweatherprediction.com/thermo/soundings/gun/). This is a key distinguishing characteristic that corroborates why pyroCb have only been identified previously in specific geographic areas and climate zones.

b. Convective available potential energy

Several studies have employed convective available potential energy (CAPE) to estimate the buoyancy available for high-based convection (e.g., Peterson et al. 2010; Wallmann et al. 2010) and high-altitude smoke plumes (Potter 2005). The calculation of CAPE is either based on lifting a surface parcel, the most unstable parcel in the lower troposphere (e.g., lowest 300hPa), or a parcel with the mean properties of the lower troposphere (Bunkers et al. 2002; Wallace and Hobbs 2006). However, Fromm et al. (2010) show that...
several pyroCb are associated with little or no CAPE (surface based). When an inverted-V sounding profile is present, air parcels originate from within a hot and dry mixed layer and eventually encounter increased moisture near and mostly above the lifting condensation level (LCL), but no variant of CAPE considers entrainment (Holton 2004). CAPE calculations also fail to account for an increase in buoyancy produced by the intense heat of the fire (e.g., Potter 2005; Lareau and Clements 2016).

Because of the unknown magnitude of sensible heating from each individual fire, CAPE values for each event in this study are determined by lifting the most unstable (MU) parcel below 400 hPa (MUCAPE). The height of the MU parcel ranged from the surface to 600 m AGL for more than 75% of observed IPCB events (mean of 350 m). The mean MU parcel height was only 200 m AGL for HFRP events. Figures 6–8 provide the mean MUCAPE values for each event type, showing that IPCB events exhibited higher MUCAPE than HFRP events, especially for low-elevation fires. This suggests that MUCAPE can be useful for identifying IPCB potential. However, all IPCB events occurred with less MUCAPE than traditional severe thunderstorms (e.g., Knupp et al. 2014), and several IPCB events from high-elevation fires developed with no MUCAPE. Therefore, while the presence of MUCAPE presumably increases the likelihood of convective development, it is not an absolute indicator of pyroCb development.

c. PyroCb condensation level

Having now established that the development of high-based convection and pyroCb is dependent on varying thermodynamic processes within the lower and midtroposphere, it is desirable to examine differences at each level relative to event characteristics. However, variation in surface elevation and latitude across the study region (Fig. 1) greatly affects each layer’s relative depth, thus preventing the use of a fixed standard pressure level to mark the boundary between layers. The most logical means to separate lower- and midtropospheric processes during pyroCb is the dynamic cloud base altitude, which is commonly inferred using calculations of the LCL.

Similar to the calculation of MUCAPE, the dynamic LCL for pyroCb activity is determined by lifting the MU parcel below 400 hPa. The resulting most unstable LCL (MULCL) can then be applied to separate lower- and midtropospheric analysis. However, an intense fire often increases the temperature of air parcels entering its plume (Potter 2005), producing higher saturation vapor pressures compared with the ambient background. This delays condensation thereby increasing the LCL height and associated cloud base (Luderer
et al. 2009; Lareau and Clements 2016). The MULCL therefore serves as a lower boundary for cloud-base altitude based on ambient lower-tropospheric conditions. Figures 6–8 display the mean MULCL (solid purple), as well as minimum and maximum values (dashed purple). While MULCL height is similar for IPCB and HFRP events, it is highly variable, especially for midelevation fires.

The dynamic MULCL altitude indicates the top of the lower-tropospheric layer (Figs. 6–8, green vertical bars) and the bottom of the midtropospheric layer (Figs. 6–8, pink vertical bars) for each individual IPCB and HFRP event. Any overlap shown in Figs. 6–8 results from variation in MULCL altitude within the bulk dataset. Because of variation in the depth of the troposphere produced by the large latitudinal extent of the study region (Fig. 1), the upper boundary of the midtropospheric layer is fixed at 300 hPa in MCONUS and 400 hPa in Canada. These levels are selected because they are located just below the mean height of upper-tropospheric features (e.g., jet stream) in each region. The following sections describe the relevant meteorology in each layer, progressing from lower to midtroposphere.

5. Lower troposphere

In addition to surface conditions favorable for intense fire activity (section 3a), lower-tropospheric conditions favorable for pyroCb development must support a robust convective smoke column capable of reaching beyond the MULCL. This situation is commonly referred to as a “plume-dominated fire,” where the fire is creating and sustaining its own favorable weather conditions (e.g., Rothermel 1991; Werth and Ochoa 1993). Plume-dominated behavior is primarily driven by increased lower-tropospheric instability (e.g., Potter et al. 2008) and reduced wind shear (e.g., Byram 1954).

a. Instability

In western North America, regional potential for plume-dominated behavior is most commonly quantified using the Haines index (HI): an integer scale (1–6) based on two equally weighted ingredients for moisture and stability, respectively derived from a lower-level (850 or 700 hPa) dewpoint depression and lower-atmospheric lapse rate (Haines 1988; Potter et al. 2008). The specific pressure levels used for HI calculations vary, depending on local topography. Originally based on mandatory pressure levels from soundings obtained in the late 1980s, the “low,” “mid,” and “high” elevation variants of the HI and their application are very subjective.

Figures 6–8 include respective HI layers for each fire elevation category as an orange vertical bar adjacent to the green vertical bar denoting the lower troposphere based on the dynamic MULCL definition. This display indicates that the HI layer is often too narrow to adequately measure the lower-tropospheric lapse rate. This is especially true for midelevation thermodynamic profiles (Fig. 7), where the midelevation HI variant often starts below the first profile layer, and does not account for the large depth of the mixed layer. Applying the high-elevation variant to these profiles increases the characterization of mixed layer depth, but would exclude the lowest levels of the profile. High-elevation fires (Fig. 8) are the only category where the HI layer compares well to the MULCL-based lower-tropospheric layer.

The HI has a fixed upper bound of 6, corresponding to the most extreme potential for plume-dominated behavior (Haines 1988; Potter et al. 2008). Figure 9a shows that the majority of IPCB and HFRP events in MCONUS exhibited at least moderate potential for plume-dominated activity (HI ≥ 5). An example of high- and midelevation HI variants is provided in Fig. 10a for IPCB activity during two large fires in the complex topography of Idaho on 12 August (as in Fig. 4d). Both variants yield at least moderate potential for plume-dominated behavior, but the depth of the lower-tropospheric layer and magnitude of instability are unclear. It is therefore challenging to decipher which HI variant is most

![Fig. 9](http://journals.ametsoc.org/mwr/article-pdf/145/6/2235/4779867/mwr-d-16-0232_1.pdf)
applicable. The HI upper limit can be extended for increased sensitivity to the most extreme fire danger (Mills and McCaw 2010). However, this “continuous Haines index” may also lack the fidelity to separate pyroCb from other extreme wildfire characteristics (Peterson et al. 2015).

An improved measure of lower-tropospheric instability, free from subjective pressure levels, can be produced by calculating the lapse rate from the surface to the dynamic MULCL (Figs. 6–8, green vertical bar). Plume-dominated potential increases as this lower-tropospheric lapse rate (LTLR) approaches dry adiabatic (−9.8°C km⁻¹), especially when the mixed layer is deep (Jenkins 2004). The example in Fig. 10b (1800 UTC) shows that both Idaho fires were located within a deep (3000 m) lower-tropospheric layer with a LTLR less than −8.0°C km⁻¹, at least 3 h before IPCB initiation (2100 UTC). Across the study region, the majority of IPCB development occurred with LTLR values less than −8.5°C km⁻¹, with HFRP events often linked to LTLR values greater than −8.0°C km⁻¹ (Fig. 9b).

d. Vertical wind shear

Intense fires burning in an environment with large vertical wind shear in the lower troposphere are likely to exhibit tilted and less concentrated smoke plumes, decreasing the likelihood of deep pyroconvection (e.g., Lareau and Clements 2016). Figures 6–8 provide the wind vector difference (or bulk shear vector) from the surface to the MULCL altitude for each event type. IPCB and HFRP events were both associated with low bulk shear values averaging 3–8 m s⁻¹ (6–16 kt). As shown by the mean wind profiles in Figs. 6–8, IPCB and HFRP events also developed with very little low-level directional shear. However, IPCB events generally exhibited the largest LTLR values (Fig. 9b), and therefore more lower-tropospheric instability, which presumably maximized potential for plume-dominated behavior. While the combination of a large LTLR and reduced low-level shear is important for plume-dominated behavior, it is unrepresentative of severe thunderstorm and tornado outbreaks east of the Rocky Mountains, which often coincide with larger low-level bulk shear values (occasionally >20 m s⁻¹), larger directional shear, and increased low-level moisture (Evans and Doswell 2001; Knupp et al. 2014). This is a primary characteristic distinguishing IPCB phenomenology relative to traditional vigorous convection.

6. Midtropospheric moisture and instability

A robust convective smoke column in the lower troposphere is not likely to produce IPCB activity unless conditions in the midtroposphere are also favorable for development of high-based convection (Peterson et al. 2015). The inverted-V thermodynamic profiles in Figs. 6–8 show that ambient midlevel moisture likely plays an important role in IPCB development, which supports the results of several modeling studies (e.g., Trentmann et al. 2006; Luderer et al. 2009). However, the amount of midtropospheric moisture required has
never been quantified nor clearly correlated with event occurrence.

By employing the dynamic MULCL-based definition of midtroposphere (Figs. 6–8, pink vertical line), mean midtropospheric RH (RH\textsubscript{MT}) and total precipitable water (TPW\textsubscript{MT}) can be calculated, thus providing relative and absolute measures of moisture content. Figure 11a provides distributions of RH\textsubscript{MT} values for IPCB and HFRP events as a function of fire surface elevation. These are the same elevation categories as the profiles in Figs. 6–8, with the midelevation category split into two 1000-m intervals. IPCB events corresponded with RH\textsubscript{MT} values ranging from 40% to 60% within the two lowest-elevation categories, but decreasing to 20%–40% for the highest-elevation category. Figure 4 highlights the spatial variability of RH\textsubscript{MT} found for several fires at varying elevations. As expected, Canadian IPCB events (fire elevation < 500 m) were associated with the largest RH\textsubscript{MT} values (Figs. 4e,f).

The inverse relationship with surface elevation is even more pronounced when using TPW\textsubscript{MT} (Fig. 11b). Low-elevation IPCB events corresponded with TPW\textsubscript{MT} values ranging from 7 to 14 mm, decreasing to 1–2 mm for high-elevation events. While few comparisons exist in the literature, Johnson et al. (2014) report TPW\textsubscript{MT} values (above 600 hPa) of 5.0 mm for pyroCb activity observed during a 2012 wildfire at an approximate elevation of 2000 m MSL in Colorado, which compares well to the midelevation TPW\textsubscript{MT} distributions. As fire surface elevation increases above sea level, a shallower and more elevated portion of the vertical profile is used to calculate TPW\textsubscript{MT}. In addition, less latent heating is required to develop convection capable of reaching the UTLS, especially with the deep lower-tropospheric mixed layers typical of IPCB events (Figs. 6–8). It is therefore difficult to highlight a single threshold of RH\textsubscript{MT} or TPW\textsubscript{MT} representative of IPCB development across all of western North America.

HFRP events also exhibited an inverse relationship between the two midlevel moisture metrics and surface elevation. However, the mean and median values for HFRP events were lower than those for IPCB events in all but the highest-elevation category (Figs. 11a,b). These results, along with the thermodynamic profiles in Figs. 6–8, reinforce the importance of ambient midlevel moisture during IPCB development, especially for fires at low surface elevations.

In addition to a moisture source, high-based convection requires unstable conditions in the midtroposphere, which can be quantified using several metrics. Equivalent potential temperature $\theta_e$, a function of both moisture and temperature, is used to identify potential instability (PI), which is present when $\theta_e$ decreases with height ($d\theta_e/dz < 0$). In this study, PI is approximated via the mean $d\theta_e/dz$ for NARR vertical levels contained within the midtropospheric layer (Figs. 6–8, pink vertical line). Similar to RH\textsubscript{MT} and TPW\textsubscript{MT}, an inverse relationship exists between PI and surface elevation (Fig. 11c). IPCB events originating from fires below 2000 m MSL coincided with PI values below or near
zero, suggesting a strong and/or deep midtropospheric layer where $d\theta_e/du$ was less than zero. While PI values became positive for high-elevation IPCB, they remained lower than their HFRP counterparts in every elevation category (Fig. 11c).

The collocation of PI with increased moisture content in the midtroposphere is paramount for development of high-based convection (Nauslar et al. 2013). Figure 12a highlights a region of substantial PI found coincident with RHMT values greater than 60% approaching a Canadian fire (surface elevation = 186 m) 1.5 h before IPCB initiation. These conditions, along with an approaching shortwave trough and dynamic forcing (Fig. 4e), allow for rapid convective development, including IPCB activity. In contrast, two Idaho fires influenced by the West Coast disturbance synoptic pattern (Fig. 4d) experienced much weaker PI, but with similar RHMT values (Fig. 12b). IPCB activity was likely able to develop over both fires due to the higher surface elevation (1500–2500 m).

Several additional methods have been developed to quantify mid- and upper-tropospheric instability. Primary examples include the upper-tropospheric lapse rate (UTLR; Wallmann et al. 2010) and high-level total totals (HLTT; Milne 2004). However, similar to the HI, these methods rely on fixed pressure levels, and therefore have limited utility for analysis and forecasting of high-based convection and IPCB across large regional domains with varying topography. UTLR values, defined here as the lapse rate between the MULCL and the top of the midtropospheric layer (400 or 300 hPa), are provided in Figs. 6–8. HLTT calculations are not considered in this analysis.

7. PyroCb conceptual model summary

The detailed meteorological analysis provided in the preceding sections shows that a conceptual model for IPCB development (Fig. 13) must be based on a synoptic environment that is at least marginally favorable for high-based convection, which is characterized by an inverted-V thermodynamic profile near the surface. Every IPCB event begins in the lower troposphere (Fig. 13, yellow box) with a large and/or intense fire capable of developing a deep convective smoke column. Intense burning is maintained by dry, hot, and somewhat windy conditions at the surface, corresponding with a high or extreme fire danger rating from the suite of surface-based fire weather indices (e.g., Van Wagner 1987; Haines 1988; Mills and McCaw 2010). Fuel loads, localized fire dynamics, terrain factors, and their combined interaction may also play a role (e.g., McRae et al. 2015). The lower-tropospheric layer (surface to MULCL) is usually deep (typically 2000–4000 m), dry, and unstable (LTLR $<-8.5^\circ$C km$^{-1}$), with minimal wind shear (both speed and directional). This increases the potential for plume-dominated behavior, which in turn increases the likelihood of the plume reaching beyond the MULCL.

Near and above the MULCL, a midtropospheric moisture source is paramount, often coincident with a layer of PI ($d\theta_e/du < 0$). This increases the potential for moisture entrainment, condensation, and latent heat release within the rising smoke plume, driving it higher into the mid- to upper troposphere, and initiating pyroCb development (Fig. 13). However, the quantity of
midlevel moisture and magnitude of PI required for development are strongly dependent on the surface elevation of the contributing fire, with lower-elevation fires requiring greater PI and relative moisture. Mid- and upper-tropospheric dynamic forcing is usually weak, but can play an important role for fires with minimal orographic lift, especially in close proximity to the polar jet (e.g., Canadian fires). Many IPCB events have therefore been linked to at least some upper-tropospheric divergence.

This conceptual model explains why IPCB events are often observed in close proximity to or embedded within traditional high-based convection (e.g., Fromm et al. 2006; Peterson et al. 2015, 2017). For example, IPCB activity during the Papoose fire in Colorado (28 June) was nearly surrounded by traditional convection (Fig. 2a), with additional IPCB events observed in the same region (New Mexico Silver fire; Peterson et al. 2017). However, in a few cases, increased thermal buoyancy associated with intense FRP will act as its own triggering mechanism. The most common manifestation of this effect is an IPCB event developing earlier in the day and/or over lower terrain than traditional convection. IPCB activity observed during the Pony/Elk fire in Idaho (10 August) was associated with a mean surface elevation of 1593 m MSL (Fig. 2b), while nearby traditional convection occurred over terrain with elevations of 2000–3000 m MSL. Similarly, both IPCB events observed during the California Rim Fire (19 and 21 August) developed over lower terrain than traditional convection (Peterson et al. 2015). Intense FRP may also provide the extra convective heating and buoyancy needed to break a capping inversion, which would be most likely within the warm sector of an approaching disturbance during Canadian ridge breakdown. IPCB events may therefore occasionally develop in the absence of traditional triggering mechanisms when an otherwise favorable thermodynamic and synoptic environment is in place. This potential relationship between FRP, convective heating, thermal buoyancy, and IPCB development remains an important topic for future research.

In western North America, meteorology favorable for high-based convection is frequently observed during the entire primary fire season (May–September). This suggests that IPCB activity can also be expected every fire season. Several fire-prone regions in Asia (e.g., Siberia) and Australia also exhibit conditions favorable for high-based convection during the fire season, which likely explains the perennial occurrence of IPCB activity in these regions. Any region with a low frequency of high-based convection (e.g., the Gulf Coast) therefore has a reduced likelihood of IPCB activity. The meteorology highlighted in the conceptual model (e.g., inverted-V profile) is uncommon in tropical regions, which likely explains why IPCB events are rarely (if ever) observed at low latitudes.

8. Conclusions

This study describes a conceptual model for intense pyroCb (IPCB) development using the combination of meteorological reanalysis data and a remote sensing–based inventory of 26 events (Peterson et al. 2017) observed in western North America during the primary fire season (June–August) of 2013. One of the key components of this model is a deep, dry, and unstable lower-tropospheric mixed layer surmounted by a moist and unstable midtropospheric layer, which is typical of traditional high-based convection (dry thunderstorms) found over elevated terrain in semiarid regions. Variation in topography and thermal buoyancy produced by intense fire activity are also key factors in IPCB development. Traditional surface fire weather variables and lower-tropospheric indices (e.g., Haines index) do not provide enough information to quantify IPCB potential.
by themselves. Periods of intense burning [high fire radiative power (HFRP)] that fail to produce IPCB activity usually lack a midtropospheric moisture source, which is the strongest selector for IPCB activity in the conceptual model. IPCB events have other distinctions from HFRP events, including greater instability in the lower troposphere and more favorable dynamics (divergence) in the upper troposphere.

Conditions driving IPCB development are shown to be fundamentally different from other severe weather events, including supercell thunderstorms and associated tornado outbreaks. This suggests that the IPCB conceptual model does not describe the most favorable environment for deep overshooting convection. However, it is the only meteorological environment that will support intense fire activity occurring at the same time as deep, moist convection. The IPCB conceptual model therefore reconciles the most efficient mechanism for injecting relatively large quantities of aerosol particles into the upper troposphere and lower stratosphere, aside from volcanic eruptions.

High-based convection is frequently observed across western North America every fire season. Conditions favorable for high-based convection often coincide with ongoing large wildfires. This implies that IPCB, far from the niche phenomenon they initially appeared to be (e.g., Fromm et al. 2000; Fromm and Servranckx 2003), are very likely significant and endemic features of the regional summer climate. Meteorological conditions favorable for high-based convection and IPCB are also observed in other highly fire-prone regions of the world. Therefore, annually recurring IPCB events may very well represent a new and potentially significant modulator of the lower stratospheric aerosol layer, with a potential impact on global climate and circulation. A companion paper (Peterson et al. 2017) describes a practical methodology for identifying IPCB operationally, which will allow for routine and retrospective monitoring and inventorying of such events to help constrain this source in other fire-prone regions worldwide.

The IPCB conceptual model is also highly relevant to other hazards from high-based convection, including dry lightning strikes, microbursts, and dust storms (haboobs). For example, the deep and dry lower-tropospheric layer (high MULCL) observed during IPCB activity is supportive of strong downdrafts and microbursts during traditional high-based convection (e.g., Wakimoto 1985). When considering that intense fire activity and IPCB are often located near traditional convection, potential for erratic fire behavior, such as a rapid shift in spread direction, greatly increases (e.g., Johnson et al. 2014; Hardy and Comfort 2015). This information is paramount for improved fire suppression efforts. In addition, the next generation of geostationary satellites (e.g., GOES-R; see online at http://www.goes-r.gov/) will greatly improve IPCB and fire detection capabilities, especially in regions with large satellite viewing angles (e.g., Canada). Therefore, the combination of meteorology from numerical forecast models and improved exploitation of satellite observations can be employed to develop future IPCB prediction and monitoring capabilities.

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