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Understanding the critical elements of the pyrocumulonimbus storm sparked by high-intensity wildland fire

Michael Fromm[1✉], René Servranckx[2], Brian J. Stocks[3] & David A. Peterson[4]

High-intensity wildland fires can produce extreme flaming and smoke emissions that develop into a fire-cloud chimney, reaching into the upper troposphere or lower stratosphere. Termed pyrocumulonimbus, these storms are both conventional and counterintuitive. They have been observed to produce lightning, hail, downdraft wind hazards, and tornadoes as expected with severe convective storms, but counterintuitively, they are not associated with significant precipitation. Pyrocumulonimbus storms have been noticed outside wildfire expert circles following Australia's Black Summer in 2019/20, and have since repeatedly made headlines in the United States. However, much is unknown about their behavior, energetics, history, and impact on the Earth/atmosphere system. We address several questions and science challenges related to these unknowns. Our worldwide record of pyrocumulonimbus events from 2013 to 2021 shows that the phenomenon is neither new nor rare. Despite high occurrences in 2019 and 2021, these data do not support identification of a trend. Future studies require an expansive record of pyrocumulonimbus occurrence globally and regionally, both historically and continuously forward in time.

The term "pyrocumulonimbus"[1,2] is increasingly showing up in the press, social media, and even in casual conversations on the street. This cryptic name, and the abbreviation "pyroCb", were not even used in the scientific community prior to 2004[3,4]. It refers to a peculiarly violent atmospheric disturbance linked to extremely intense wildland fire and manifested as a thunderstorm-like cloud. This cloud has a more official--if unwieldy--name, "cumulonimbus calvus flammagenitus", according to the World Meteorological Organization[5]. Pyrocumulonimbus and pyroCb terminology, used herein to identify the fire-atmosphere phenomenon as opposed to the cloud name, entered the mainstream after Australia was besieged by the calamitous "Black Summer" of 2019/20, which featured bushfires of unprecedented number, size, and ferocity[6]. These bushfires produced a "super outbreak" of 18 pyroCb events at the dawn of the 2020 New Year[7], which is the most frightening example of extreme and unpredictable wildfire behavior spawning its own violent weather. Recent major pyroCb events in North America have increasingly made the pyroCb a headline item (https://www.nytimes.com/interactive/2021/10/19/climate/dixie-fire-storm-clouds-weather.html). The pyroCb cloud (Fig. 1a) is much less familiar than its "cousins", the universally recognizable generic cumulonimbus (Cb) thunderstorm (also in Fig. 1a) and the explosive Plinian[8] and sub-Plinian (https://www.nps.gov/articles/000/sub-plinian-eruptions.htm) volcanic-eruption cloud (Fig. 1b). Recent studies draw comparisons between pyroCb activity and volcanic eruptions[7,9], revealing that the particulate mass injected into the stratosphere by pyroCb activity can rival or exceed that of many volcanic plumes. The apparent novelty of the pyroCb

[1]Naval Research Laboratory, Washington D.C., USA. [2]Independent Researcher, Dorval, QC, Canada. [3]B.J. Stocks Wildfire Investigations Ltd., Sault Ste. Marie, Ontario, Canada. [4]Naval Research Laboratory, Monterey, CA, USA. ✉email: mike.fromm@nrl.navy.mil

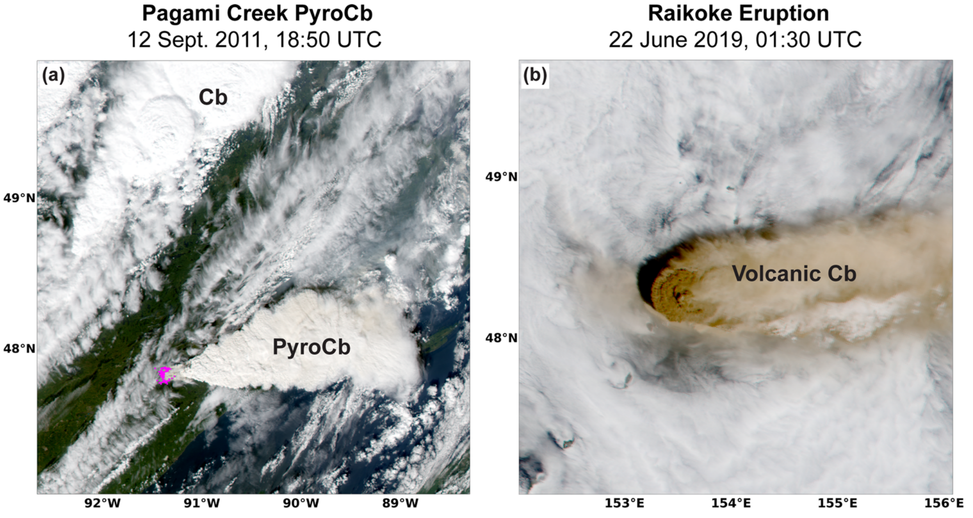

Fig. 1 Visual comparison between three types of overshooting thunderstorm convection. True color imagery highlights (**a**) traditional Cb and pyroCb using Aqua MODIS and (**b**) volcanic Cb using Terra MODIS. The pyroCb was spawned by the Pagami Creek fire along the border of Ontario, Canada and Minnesota, USA, on 12 September 2011. For a witness/survivor account, see https://queticosuperior.org/blog/video-tells-riveting-story-of-six-rangers-caught-by-pagami-creek-fire/. MODIS fire detections are displayed in pink. The volcanic Cb is from the Raikoke volcanic eruption on 22 June 2019 in the Kuril Islands of Russia.

phenomenon raises many questions. Just what is this peculiar atmospheric disturbance? Is it really new? Can the pyroCb-driven fire be controlled? Is it a harbinger of dangerous climate change? How much do scientists know about pyroCb development and ensuing impacts? In this paper, we address these questions and pose others, along with selected challenges.

The pyroCb storm described. Landscape fire is a global phenomenon, occurring wherever combustible biomass grows. Generally, wildland fire behavior can escalate to the status of high-intensity crowning fires, with considerable downwind spotting and erratic behavior, wherever fuel is sufficiently abundant in hot, dry, and/or windy meteorological conditions. These extreme fires have been described as “firestorms” in recent years[10], but this terminology is more colloquial than scientific. We describe the pyroCb as a “storm”, in accordance with the American Meteorological Society Glossary definition (https://glossary.ametsoc.org/wiki/Storm). The pyroCb storm is a peculiar disturbance coupling high-intensity wildland fire with an atmospheric response manifested by ice-capped cumulonimbus convection.

Wildland fire managers and scientists are largely able to predict and model the behavior of high-intensity crown fires, which commonly result in the development of a cumulous cloud (pyrocumulus or pyroCu) at the top of the smoke column. These fire situations are informally referred to as “column-dominated” or “plume-dominated”. The pyroCu is a direct result of a plume-dominated fire that features a large, upright, brown smoke plume capped by a column of whiteish, cumuliform cloud. PyroCu have been in the lexicon of wildland fire management personnel for decades. Such cloud-capped smoke columns represent a subjective, visual signal of wildfire attaining vigorous flaming and/or rapid fire-front expansion. PyroCu-level combustion implies exceptional heat-energy release, an integral quantity composed of flaming intensity, area, and duration. All contribute to the sustenance of a thermal updraft column feeding the pyrocloud.

A relatively small fraction of pyroCu continue developing into a pyroCb, which is the ultimate plume-dominated fire, reaching well into the upper troposphere or lower stratosphere (UTLS). Research into the mechanisms driving this transition has advanced significantly in recent years[11,12]. Increased spread rates and unexpected changes in fire direction have been documented, along with fire ignitions from lightning strikes downwind. There is also speculation that upper-level winds brought to the surface through low-level jets are a factor in the transition, although these are difficult to predict in terms of timing and location. Characterization of the pyroCu-pyroCb transition is still in its infancy, and remains a critical goal in terms of fire management strategies and safety.

PyroCb development implies a consequential increase of flaming and smoke emission. The input of extreme heat and smoke concentration are critical for both the height of the pyroCb storm and the signature smoke plume in the UTLS. The pyroCb combustion engine is defined by the inextricable contributions from the fire, smoke, cloud, and surrounding atmosphere. In-cloud latent heat release via hydrometeor formation augments the buoyancy brought by the fire’s rising thermal column. Peculiar to the pyroCb though is direct injection and seeding of the cloud column with smoke particles, creating a microphysical oddity: a vigorous convective column devoid of appreciable precipitation[13,14].

A consequence of the precipitation-poor pyroCb storm cloud is diminished drag resulting in largely unimpeded and thus extreme updrafts[15]. Through mass conservation, the rapid updraft, bolstered by latent heat release, requires surrounding air to flow rapidly into the column base and side. Ambient moisture surrounding the pyroCb may be entrained, enhancing hydrometeor nucleation and resultant latent heating[11]. The rapid and chaotic inflow at the base naturally stokes the fire, thereby feeding the already extreme flaming, closing the loop on pyroCb dynamics.

The result is a fire-cloud chimney reaching or overshooting the top of the troposphere, which is the most striking embodiment of a fire generating its own weather. PyroCb weather is both conventional (i.e. Cb-like) and counterintuitive. Conventional lightning, hail, downdraft wind hazards, and even tornadoes have been observed[13,14,16–18]. However, the lack of precipitation and associated scavenging[19] supports intensive downwind fire spotting at the surface and intense in-cloud smoke infusion, such that the skin of the pyroCb typically has a smoky tinge (Fig. 1a). The smoke concentration at the cloud top in the UTLS can be equivalent to that of opaque smoke plumes near the surface[4].

How the pyroCb impacts our environment. The effects of the pyroCb range from hazards confronting communities overcome by wildfire[20] to the potential radiative and chemical perturbation that a regional or hemispheric stratospheric smoke shroud might impose[21–24]. At ground level, pyroCbs represent the utmost danger from unpredictable and unexpected fire behavior. Severe updrafts and downdrafts can create rapid fire spread, tornadic circulations, lightning, and downwind spotting in many directions, resulting in unexpected fire growth[14,25].

The pyroCb phenomenon puts fire management personnel at direct risk, but also creates dire risks for the burgeoning number of communities and residents living in the constantly-expanding wildland-urban interface. Communities and firefighters confronting a pyroCb storm face disorientation and loss of situational awareness due to obscured visibility in dense smoke and nighttime-level darkness cast by the opaque, smoke-seeded pyroCb anvil cloud. Even pyroCu have been shown to essentially nullify incoming solar radiation[26], which facilitates extreme darkness beneath the cloud. Ember showers, exacerbated by strong wind, spread well beyond the obscured flame front into the smoky darkness, increasing danger and alarm. Hence, evacuations from pyroCb storms are fraught with tragedy, as occurred in Portugal on 17 June 2017[20]. PyroCb events in the wildland-urban interface are commonly associated with exorbitant property destruction and/or human fatalities. There are many examples, such as the Black Saturday pyroCb event in 2009, which led to the loss of 173 lives[25].

An urgent need exists to better understand the dynamics of high-intensity fire behavior, particularly the variables driving the transition from somewhat predictable high-intensity crown fire behavior (e.g. pyroCu) to the less predictable environment for pyroCb development. How much of this transition is driven by fuels and topography, and how much is due to meteorological conditions in combination with column dynamics? These questions remain unanswered and urgently require the development and refinement of coupled ground-atmospheric models[27,28] that identify the key variables and permit accurate forecasting and response to pyroCb development.

The same pyroCb dynamic that threatens communities also sometimes generates a stratospheric smoke plume with hemispheric implications. The Black Summer pyroCb super outbreak spawned a stratospheric smoke pall that garnered great attention worldwide. Smoke that was directly injected into the lowermost stratosphere, like many previous pyroCb plumes[13,29], persisted for more than a year[7] and exhibited extraordinary features. The smoke rose into the middle stratosphere, far higher than any previous smoke had been observed[23]. The most dramatic plume rise was embodied within spheroidal smoke volumes that took on anticyclonic circulations while rising diabatically to those unprecedented heights[23,30–32]. These smoke enclosures were termed "smoke with induced rotation and lofting" (SWIRL)[31]. Curiosity is therefore increasing about this seemingly new coupling between pyroCb activity and diabatic plume lofting that is really not new at all[29].

Prior to Black Summer, a pyroCb outbreak in the adjoining Pacific Northwest of the United States and Canada in 2017 also involved a stratospheric plume that exhibited diabatic lofting and the SWIRL[31,32]. So too did the above-mentioned Black Saturday[31]. The discovery of these pre-Black Summer SWIRLs was afforded by the new knowledge gained in the Black Summer smoke plume research. It is currently unclear how often these diabatically rising plume sub-elements have occurred historically[29]. Given that diabatic lofting of solar-heated stratospheric smoke plumes was central to the mechanism hypothesized in the Nuclear Winter[21] scenario, the observed manifestation of rapid stratospheric plume rise embodied by the SWIRL may represent a preferred or particularly efficient real-world pathway for modelers of Nuclear Winter scenarios to simulate. This would require coupling ground-level energy-release rates with atmospheric variables in a manner similar to simulations of pyroCb development and ensuing impacts.

In addition to the radiative implications of the pyroCb for our environment, the potential for a smoke plume to impact stratospheric chemistry is a frontier topic[24,33–36]. Depending on the mass and height of the plume, which comprises a peculiar set of reactive and trace gases[37–40] along with particulate matter, it can be hypothesized that chemical effects might be manifested globally. If the circumstances are such that the residual pyroCb plume is in a position to be drawn to polar latitudes and thereby reside within the wintertime vortex, the possibility of a "new" agent in the seasonal ozone-depletion mechanism would then exist. Hence, we are called to the great challenge of discerning and tracking high-altitude pyroCb plumes as they age and spread to high latitudes.

Historical recognition of the pyroCb. Although it may never be confirmed, a likely pyroCb plume shook the world in 1950, when communities across Canada to the Eastern Seaboard of the USA to western Europe were transfixed by nightlike skies and weird optical phenomena—a blue moon and green sun—were observed[41,42]. This "Great Pall of 1950" was traced to an extreme wildfire at the northern border of British Columbia and Alberta, Canada. The smoke plume was observed in situ at UTLS altitudes over Scotland[42] after alarming citizens of the United States and Canada.

Wildfire scientists and firefighters have been eyewitness to plumes from plume-dominated fire (both natural and prescribed) over many decades. Some of the pyro-clouds they were observing clearly bubbled to the uppermost troposphere. These early witnesses were unaware that the tallest columns they were watching, some even with a Cb-like cloud anvil, might have been behaving like a classic volcanic eruption column that injects material into the stratosphere. Their ground-based vantage point was inadequate.

In 1998, a wide array of remote sensing observations, from ground-based lidar to satellite-based vertical profilers, revealed widespread mysterious stratospheric particulate layers across the Northern Hemisphere. Previously, such mystery layers were assumed to have been volcanic in origin[43,44]. The puzzling 1998 stratospheric aerosols triggered an interdisciplinary forensic investigation among fire, volcano, and satellite remote sensing scientists to find the cause. These layers were hypothesized to be forest fire smoke[45,46], but the causal pathway for the smoke was still a mystery. The hunt leading to the pyroCb discovery was underway.

The evidence trail connecting mystery layers to the pyroCb involved a host of additional missed or misunderstood cloud and plume signals among a diverse set of satellite imagery products. For instance, the ultraviolet absorbing aerosol index[47] (UVAI), a daily, quasi-global satellite-image resource dating to 1979, was found to embody peculiar clues. On certain days, UVAI maps contained expansive features with extraordinary values deemed untrustworthy and hence flagged as erroneous[48]. These exceptional UVAI features, in combination with classic satellite visible and infrared cloud imagery, were eventually determined to be an invaluable signal of an optically thick smoke-cloud convolution in the UTLS[49], a veritable fingerprint of the a pyroCb-storm aftermath[50].

Research triggered by the mystery layers of 1998 and other years found that the unusual UVAI signature was a regular feature throughout the satellite era, hinting at an endemic phenomenon. Moreover, they were regularly convolved with classic weather-satellite cloud-image features also manifesting confounding radiometric signals. For instance, at window IR wavelengths (~11 μm), UVAI-coincident imagery told of a cloud as opaque as a thunderstorm anvil, yet embodying a decidedly gray visible reflectance, not the classic bright white. Another initially confounding satellite-image signal, now understood and critically informative, was an anomalously warm shortwave IR (~4 μm) brightness temperature of these oddly "cold and gray" clouds. The large brightness temperature difference between 4 and 11 μm is now explainable as an ice cloud heavily polluted with smoke. However, at the time of the forensic investigation into the connection between the stratospheric mystery layer and source, the "cold, gray" cloud signature puzzled satellite-image-interpretation experts. It was thought they might fit into a loosely defined category called "anomalous gray shades[51]". Once all of these coincident, perplexing UV-IR signals were finally understood, it became possible to routinely identify the marker of the "day-after-pyroCb" UTLS smoke plume and the active pyroCb storm cloud.

Since 2012, pyroCb detection and accounting has been carried out methodically via analyst-in-the-loop near-real-time satellite-image interpretation as described above[52]. The full results have yet to be published in peer-review literature, but the detection method and inventory of North American pyroCb activity is available for the 2002 and 2013 fire seasons[50,52]. The shortwave and window IR signals of active deep pyroconvection have been codified in an automated pyroCb-detection algorithm[52], which is used to monitor ongoing pyroCb activity in North America, northern Asia (eastern Siberia), Australia, and additional regions where pyroCbs have been observed (https://www.nrlmry.navy.mil/pyrocb-bin/pyrocb.cgi).

The 2013-2021 worldwide pyroCb record already answers several important questions (Fig. 2). For instance, that between 44 and 100 pyroCbs occurred annually across the globe, preferentially in North America, northern Asia, and Australia. Canada experiences the most prolific pyroCb activity, with 192 pyroCbs observed during this interval. It is reasonable to conclude from these data and the anecdotal evidence discussed above that the pyroCb storm is not new at all. Rather it is likely to be endemic in the Earth-atmosphere system.

The pyroCb transport pathway versus alternate scenarios. The pyroCb is now well established as a volcano-like direct, rapid, efficient stratospheric-injection pathway[4,7,13,14,16,49,52]. This chimney-like phenomenon has been characterized observationally for the most extreme pyroCb storms, including the contributing fire, pyroCb cloud development, and the ensuing stratospheric smoke plume. As discussed above, the pyroCb pathway is physically similar to the Plinian/sub-Plinian volcanic eruption. Both pathways terminate with the sudden stratospheric exhaust of particles and gases sufficiently massive to remain detectable for months or longer, e.g. [7,53]. Their scientific and societal importance is in proportion to their frequency, mass, and altitude.

Are there observed pathways other than the pyroCb leading to such sudden and/or massive stratospheric smoke plumes? Can multiple pathways operate in combination to affect such results? Massive stratospheric biomass-burning-emission plumes have been attributed to transport pathways independent of direct pyroconvective injection[46,54–59]. Most prominent among these alternatives is the generic Cb pathway, involving environmental smoke being drawn into the thunderstorm and efficiently exhausted in the UTLS. This same pathway was also implicated for the volcanic stratospheric sulfate plume originating with the eruption of Nabro volcano in June 2011[60]. A theme among the Cb-pathway studies[46,55,57,59] is that generic Cbs were observed in the vicinity of a pollution plume and thereby connectable to the stratospheric plumes in question[7,61].

A quite different pathway, diabatic self-lofting of a smoke plume from the troposphere into the stratosphere due to solar heating, has been theorized[21,62], and proposed as explanation for observed stratospheric aerosol plumes[56,63–65]. The pathway elements involve optically dense absorbing aerosols and multi-day meteorological conditions conducive to the smoke retaining high concentration (i.e. negligible wind shear and precipitation) while being heated and lofted[62]. However, two self-lofting case studies[56,63] involved stratospheric smoke that was linked to pyroCb activity with observed injection heights to the tropopause and beyond[14,29]. A third study[64] argued that self-lofted smoke

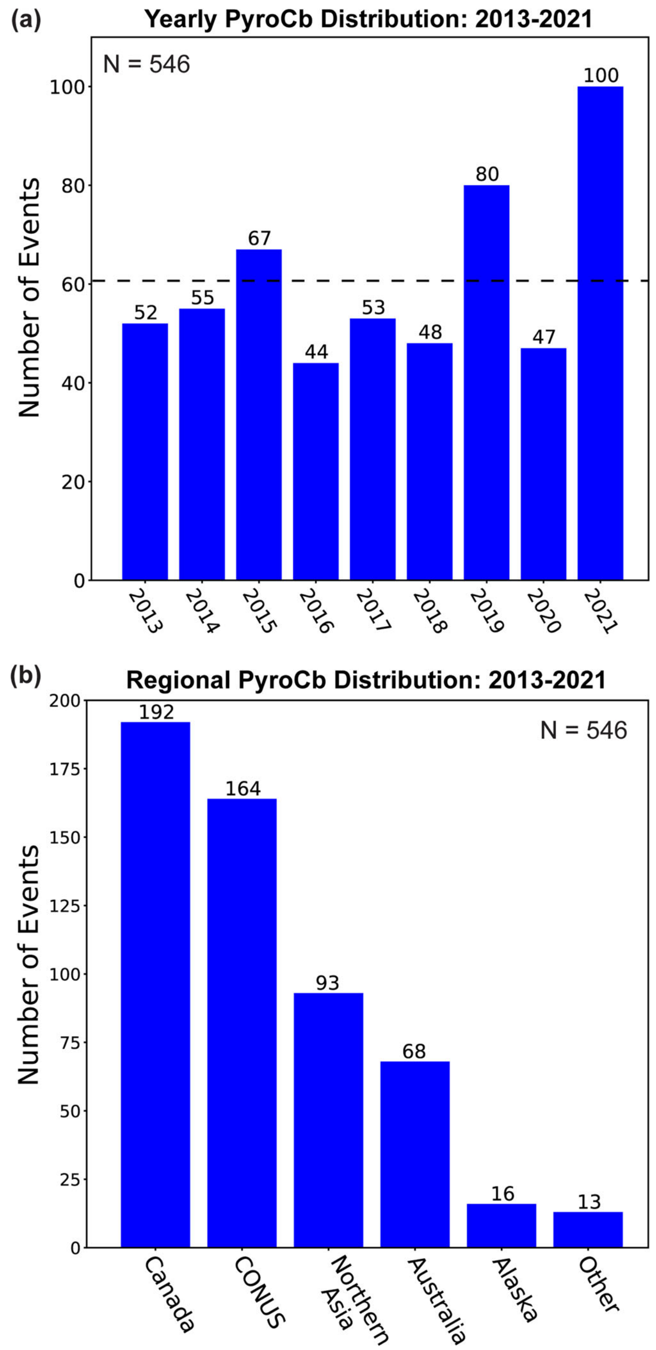

Fig. 2 Distribution of worldwide pyroCb activity by year and region for the period of 2013-2021. Both plots include 546 pyroCb events. The mean yearly pyroCb total (61) is displayed as a dashed line. "CONUS" refers to the conterminous USA states. "Northern Asia" comprises Russia (Siberia) and Mongolia. These data are part of a worldwide pyroCb inventory developed and maintained by a community[52].

polluted the stratosphere in Northern Hemisphere summer 2019 after the sulfate plume from the Raikoke volcano eruption[66] had already established a predominant, hemispheric presence[53,67,68].

Neither the generic Cb nor self-lofting pathways have been observationally established to rival the direct pyroCb pathway for smoke to reach the stratosphere[14,29,61]. It will be challenging to establish an end-to-end accounting for these alternate or combined pathways, all of which are more indirect, gradual, and complex when compared with the pyroCb "chimney". The alternate-pathway argument must present a source-receptor connection as plausible as that shown for the pyroCb[49]. Making a compelling observation-based case for a non-pyroCb pathway capable of matching the pyroCb's immediate and substantial injection into the UTLS will require the environment to be devoid of antecedent pyroCb plumes, volcanic influence, and concurrent pyroCb/volcanic activity.

PyroCb science uncertainties. It is apparent from the literature, peer-reviewed and otherwise, that pyroCbs are a recurring phenomenon. Annual pyroCb occurrence worldwide exceeds 40-50 distinct events and varies by a factor of two (Fig. 2). Although nine years is insufficient to glean a robust global trend, it would be tempting to draw such a conclusion had there been a compelling increase or decrease between 2013 and 2021. However, this is not the case. Two recent years, 2019 and 2021, coincide with large pyroCb counts, yet the total for 2020 is the second lowest in the record. The pyroCb record presented herein should be considered as an incentive for building a decadal inventory of pyroCb occurrence to facilitate trend analysis.

It is critical and eminently possible to embark on the construction of a systematic regional/global pyroCb climatology to the extent possible within the "satellite era," dating to 1979 when quasi-global coverage by polar-orbiting and geostationary satellite image data ensued. PyroCb detection is practical to the extent that these archives offer native pixel resolution at classic visible, shortwave (4 μm), and window (11–12 μm) IR wavelengths. In addition to pyroCbs, fire hot-spot and burn-scar climatologies can also be constructed. Day-after-pyroCb UTLS plume information via the UVAI archive also spans the satellite era. These long-term data sets need to be explored and analyzed in order to address critical questions surrounding decadal and regional patterns and trends in wildfire, pyroCb, and UTLS smoke plume occurrence.

PyroCbs occurring in the dark of night represent not only a peculiar hazard, they are also harder to identify from space. Even though nighttime pyroCbs are relatively infrequent[50], they are nonetheless of equal importance regarding detection. One of the pyroCbs marking the catastrophic Black Saturday cluster (Victoria, Australia) occurred near midnight[14]. Moreover, post-sunset pyroCbs have made notable contributions to the two largest stratospheric smoke plumes observed to date[7,29]. PyroCb anvils elicit an exploitable microphysics-based cloud-top signal, specifically an unusually large brightness temperature difference between two thermal IR wavelengths[69] regardless of time of day. However, at present, this metric has not been adequately defined and constrained, primarily because the preponderance of daytime pyroCb occurrence relegated it to a lower research priority. To date, the analyst-in-the-loop approach has delivered some success in nighttime pyroCb detection. The future, over-arching goal centers on improved innovation of satellite-based, pyro-cloud discernment over a full diurnal cycle.

Recognizing the overtly unusual nature of the pyroCb's efficient chimney-like smoke pathway to the UTLS, it is natural to ponder the storm's internal dynamics and microphysics. The state of knowledge in this regard is incomplete. Notable hints into the internal peculiarity of the pyroCb engine have been established, in terms of updraft speed[15], circulation[17,18], lightning[13,70], and microphysics[13]. Strategically building on this foundation will involve blending the knowledge base manifested in a pyroCb-detection climatology with wildfire data and penetrative data, such as operational and research cloud radar archives. It is also essential to continue the recent advancement in obtaining ground and airborne field measurements near and within active pyroCb activity[71,72]. Our new lens on the pyroCb danger, dynamics, and inherent coupling of biomass burning with the UTLS challenges scientists to uncover the historical imprint of pyroCbs to answer questions of where and when they develop and how they behave.

Understanding the role of the pyroCb in the weather-climate system is a natural science instinct that is still in its infancy. Recent studies include several containing discussion and/or numerical simulation of the physical evolution, dynamical interplay, ozone chemistry, and radiative impacts of stratospheric, pyroCb-generated smoke plumes[22,24,64,65,73,74]. Perhaps the key challenge going forward is the collection and maintenance of relevant stratospheric aerosol and gas observations from regional to hemispheric scales with the adequate spatio-temporal resolution to characterize the drivers of dynamical, chemical, and radiative perturbations of the earth-atmosphere system attributable to pyroCb activity.

Summary and perspective. Extreme wildfire events are endemic across the global landscape. However, the proportion of these associated with the pyroCb storm has yet to be established. Understanding the relevance of pyroCb activity to invested individuals, communities, and the global climate system is far from complete. Existing literature characterizing the pyroCb's unique character, unpredictable danger, and similarities to a volcanic eruption provides a foundation and motivation for systematic exploration. The spatiotemporal scales involved are huge, as are the uncertainties. Hence, the call to scientific action is demonstrable and laden with the responsibility to accurately quantify the pyroCb's impact on personal safety, community threat, and global change[75]. Critical to this initiative is a range of observational and modeling approaches, spanning scales from fire-scape to global. Substantial improvements in satellite observations that quantify instantaneous wildfire size and intensity are required for identifying key triggers for pyroCb development. PyroCbs themselves must be better examined. This includes a methodical, quantitative survey of satellite data on a global and decadal scale. Field experiments dedicated to the pyroCb phenomenon are essential, with in situ and remotely-sensed measurements of fire characteristics, fuels, pyrocloud microphysics, along with ensuing smoke-plume particle properties and chemistry. Coupled observations and simulations of UTLS pyroCb-plume lifetime and earth-atmosphere impact are required for an adequate understanding of the role of this still-mystifying phenomenon in the climate system.

Data availability

Data sharing not applicable to this article as no datasets were generated during the current study. Granular data values for Fig. 2 are provided therein. Satellite data used for Fig. 1 were acquired from NASA, https://www.earthdata.nasa.gov.

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Author contributions

M.F. wrote the outline and storyboard for this Perspective article. R.S. and M.F. are the originators of and main contributors to the analyst-in-the-loop global pyroCb databases. R.S. assisted with composing the pyroCb-discovery history account. B.S. provided the content on the wildfire management aspect of the article. D.P constructed the figures and provided details on the automated pyroCb-detection aspect. All authors shared equally in text editing and reviewer/editor response.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to Michael Fromm.

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