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A Distinct Class of High Peak-Current Lightning Pulses Over Mountainous Terrain in Thunderstorms

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Key Points:

- Document a type of highly energetic, negative field polarity lightning processes in the United States only over mountain areas (>2,800 MSL altitude)
- Measurements indicate that these pulses occur during the upward propagation of terrain-initiated positive leaders
- Their similarity to other processes suggests that they may be associated with terrestrial gamma-ray flashes and elves

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Abstract

Cloud-to-ground strokes, narrow bipolar events, and energetic in-cloud pulses are known classes of high peak-current lightning processes that occur in thunderstorms. Here, we report one more distinct class of high peak-current events observed exclusively over mountainous terrain, usually above 2,000 m altitude, in the continental Unites States. These events, which we call mountain-top energetic pulses (MEPs), are bipolar pulses with negative radiated field polarities. MEPs are generated between the high mountain tops and compact overhead thunderclouds. Evidence supports the hypothesis that MEPs are produced by terrain-initiated upward positive leaders propagating in high electric fields due to the proximity of the low negative charge regions of the thunderstorms. This scenario further suggests the possibility that MEPs are associated with downward terrestrial gamma-ray flashes, and their high peak currents imply that they may produce elves.

Plain Language Summary

Several distinct classes of high peak-current lightning processes are known to occur in thunderstorms, such as cloud-to-ground (CG) strokes, narrow bipolar events (NBEs), and the recently revealed energetic in-cloud pulses (EIPs). Here, we report on another type of high-amplitude event that is generated almost always over mountainous terrain in the western United States. We term them mountain-top energetic pulses, or MEPs, which produce only radiated fields of negative polarity. The low-frequency radio waveform characteristics, associated lightning flash structures, as well as weather radar images of the storms suggest that MEPs occur during the propagation of upward, terrain-initiated, positive polarity lightning leaders. MEPs seem to require several conditions, namely a high ground altitude, a relatively short distance between the ground and overhead cloud, and terrain that can enhance the local electric field. MEP-producing processes are very different from CGs and NBEs but are similar to EIPs. It is known that positive EIPs are always or almost always associated with upward-propagating terrestrial gamma-ray flashes (TGFs). We conjecture that MEPs may be associated with downward-propagating TGFs. And because of the transient high-amplitude-radiated electromagnetic fields, MEPs may also produce ionospheric optical emissions in the form of elves.

1. Introduction

Analysis of the radio emissions from lightning discharges continues to provide new insight into lightning and atmospheric electricity processes, especially classes of energetic discharges that have particularly strong radio emissions. Cloud-to-ground (CG) return strokes with large peak-current or large charge moment changes (Lyons et al., 1998) produce transient luminous events between cloud tops and the ionosphere. Narrow bipolar events (NBEs) (Le Vine, 1980; Smith et al., 1999; Willett et al., 1989) demonstrate the existence of powerful very high frequency (VHF) radio frequency emissions inside thunderclouds and also serve as the initiation process for some lightning flashes (Lyu et al., 2019; Marshall et al., 2019; Rison et al., 1999, 2016), as well as initiation of blue flashes (Chou et al., 2018; Liu et al., 2018) and blue jets accompanied by elves (Neubert et al., 2021).

A previously reported analysis of the detailed low-frequency (LF) waveforms produced by high peak-current lightning pulses identified using National Lightning Detection Network (NLDN) data (Cummins & Murphy, 2009; Cummins et al., 1998) identified a class of lightning events termed energetic in-cloud pulses (EIPs) (Lyu et al., 2015), which occur shortly after lightning initiation and are clearly distinct from NBE and CG processes. Positive radiated field polarity EIPs are produced during the development of upward negative in-cloud leaders, and +EIPs are known to often and perhaps always be associated with terrestrial gamma-ray flashes (TGFs) (Lyu, Cummer, Briggs, et al., 2016; Lyu et al., 2021). The same analysis approach also identified negative radiated field polarity EIPs (Lyu & Cummer, 2018), which are also produced by propagating negative leaders, either less than 1 ms after the initiation of a downward negative leader or approximately 1 ms before a downward negative leader contacts the ground and produces a CG stroke. The possible association of −EIPs with downward TGFs still needs confirmation.

Here, we continue the detailed analysis of NLDN-detected high peak-current lightning events in the United States and identify another distinct process capable of producing exceptionally high peak currents (>150 kA). Remarkably, these events occur exclusively in high, mountainous terrain in the western United States, and accordingly, we term them mountain-top energetic pulses (MEPs). The MEPs reported here are only of negative radiated field polarity, and they can be distinguished from other high peak-current processes through details of the radiated LF waveforms as well as their unique geographical distribution. Evidence from the LF waveforms and VHF lightning mapping array (LMA) measurements favor MEPs being produced during the upward propagation of ground-initiated positive leaders into electrified clouds that are a very short distance (1–2 km) above mountainous terrain.

The high peak current and associated high-amplitude-radiated electromagnetic fields suggest that this class of events almost certainly produces ionospheric optical emissions and electron density perturbations in the form of elves (Barrington-Leigh & Inan, 1999; Inan et al., 2010). Since MEPs appear to be produced by positive polarity leaders propagating upward in high electric field regions due to terrain amplification and the proximity of negative charge regions of the thundercloud, we conjecture that it is possible that they are associated with downward TGFs, which are known to be occasionally produced by triggered upward positive leaders under similar circumstances (Bowers et al., 2017; Dwyer et al., 2004; Hare et al., 2016; Smith et al., 2018). The LF waveforms and occurrence contexts of MEPs appear similar in some ways to previously reported large bipolar events (LBEs) (Wu et al., 2014) that occur on the west coast of Japan, which have been conjectured to be associated with tall-grounded objects rather than high terrain. It remains an open question whether there are other places in the world where low thunderstorms and high terrain or grounded objects could produce this phenomenon.

2. Data Set and Geographic Identification of MEPs

Using the same approach as Lyu et al. (2015) and Lyu, Cummer, Briggs, et al. (2016), lightning pulse reports from the NLDN and the LF radio waveforms recorded by sensors in several locations across the U.S. were analyzed to identify the different lightning processes capable of generating exceptionally high NLDN peak current. Analysis of LF and NLDN data from 2015 to 2016 using LF waveform classification (Lyu et al., 2015) previously identified a total of 876 EIPs using a minimum peak currents of 150 kA and maximum propagation distance of 1,000 or 2,000 km (depending on years for the initial analysis) to at least one LF system (Lyu et al., 2021).

In that data analysis, there were an additional 218 high peak-current events, with NLDN peak-current magnitude from 150 kA (the lower threshold of our search) to 520 kA, that were not reported by Lyu and Cummer (2018) and that were clearly not CGs or NBEs. These 218 events, together with the −EIPs, were identified and presented in a previous conference report (Lyu, Cummer, Krebhiel, et al., 2016). But because of their distinct features comparing with −EIPs, these events were not included in Lyu and Cummer (2018). The most remarkable feature is their geographic distribution, as shown in Figure 1 along with the +EIPs and −EIPs that have been reported previously. The underlying map color denotes ground altitude above mean sea level, and all these 218 events were NLDN geolocated over regions with high mountains. For this reason, we call them MEPs.

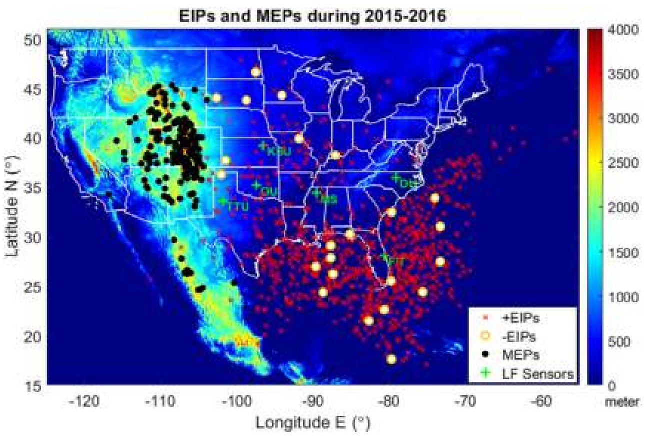

Figure 1. The National Lightning Detection Network (NLDN) locations of energetic in-cloud pulses (EIPs) and mountain-top energetic pulses (MEPs) identified during the years 2015 and 2016. The locations of +EIPs, −EIPs, and MEPs are marked by red crosses, white dots with yellow edges, and black dots, respectively. The locations of LF sensors used to measure the radio signals are marked by green pluses. The background color of the map varies from dark blue to dark red illustrates the altitude of the terrain from 0 to 4,000 m.

The geographic distribution of MEPs is clearly different from that of EIPs. Most +EIPs and −EIPs are located over oceanic regions, with a small fraction of each scattered over land essentially uniformly. The ground elevation of MEP locations ranged from 1,526 to 3,998 m, with both mean and median of approximately 2,800 m. Eighty-eight percent of identified MEPs were over a location with ground elevations above 2,000 m. The majority are concentrated in the highest parts of the Rocky Mountains, but there are also more isolated events in high-altitude portions of Southern California, New Mexico, Nevada, and Mexico. It thus appears that MEPs, at least as observed in the United States, are produced by a lightning process that occurs only in locations with significant terrain height. However, the total lack of any MEPs in the eastern half of the United States (which is in the range of the LF measurements), where some mountains exceed 2,000 m altitude (e.g., Appalachian Mountains), suggests that high elevation is necessary but not sufficient. It is interesting to note that one MEP was located over the Black Hills of South Dakota, where upward lightning discharges are frequently initiated and observed from the towers in Rapid City (Warner et al., 2012).

In the following sections, we show that MEPs are different from other high peak-current lightning processes in two more ways. First, we analyze the fundamental LF waveform characteristics of MEPs compared to other types of high peak-current events and identify the key differences. Second, we analyze the radar reflectivity data from nearby NWS NEXRAD (Crum & Alberty, 1993) radars and the flash structures mapped by nearby LMAs (Rison et al., 1999; Thomas et al., 2004). The combination of instruments illustrates the meteorology of the thunderstorms as well as the structures of the discharge processes associated with MEPs.

3. LF Waveform Characteristics and Temporal Occurrence Context of MEPs

Low-frequency waveform characteristics give insight into the origin of MEPs and show that they are a class of discharge processes distinct from others based on more than their geography. First, the LF waveforms for all MEPs are negative polarity in the radiated fields, implying that they are produced during either downward negative leaders or upward positive leaders. Thus, MEPs are clearly different from +CGs, +EIPs, and +NBEs on the basis of field polarity. Moreover, the time scales of MEP pulses (typically 30–80 μs, with the mean value of 57 μs), while comparable to +EIPs (this will be discussed below), are significantly longer than those for −NBEs and also do not exhibit the same temporal isolation from other lightning activity (Lyu et al., 2015; Rison et al., 1999; Smith et al., 1999, 2002). We can thus say with near certainty that MEPs are not produced by the fast streamer breakdown that produces NBEs of both polarities (Rison et al., 2016).

Figure 2 shows LF waveforms for typical high peak-current +EIPs, −EIPs, −CG strokes, and MEPs recorded at comparable distances, highlighting their temporal occurrence contexts and their time scales. The MEP pulse itself is a relatively smooth and bipolar waveform, which implies a source current pulse that turns on and turns off with comparable time scales. The bipolar shape of MEP pulses is a closer match to both classes of −EIPs, and in fact, the general MEP pulse shape is notably similar to that for +EIPs shown in Figure 2a (both smooth, bipolar, and with a time scale of ∼50 μs, but obviously with the opposite polarity). In contrast, pulses from −CG events are less bipolar in nature, implying that the source current pulse does not turn off quickly but persists significantly longer. This suggests that MEPs are more likely to be pulses produced by an above-ground propagating leaders and not by leaders contacting the conducting ground.

The LF waveform activity surrounding the energetic events provides additional insight. A key feature of typical MEP waveforms is the onset of a sequence of smaller and fairly regular pulses several hundred microseconds before the MEP (mean of 580 μs). These pulses are reminiscent of the preliminary breakdown pulses that occur before +EIPs (Figure 2a) and PB-type −EIPs (Figure 2b), and they are different from the longer duration and less-organized pulses produced by heavily branched leaders preceding −CGs (Figure 2d). The

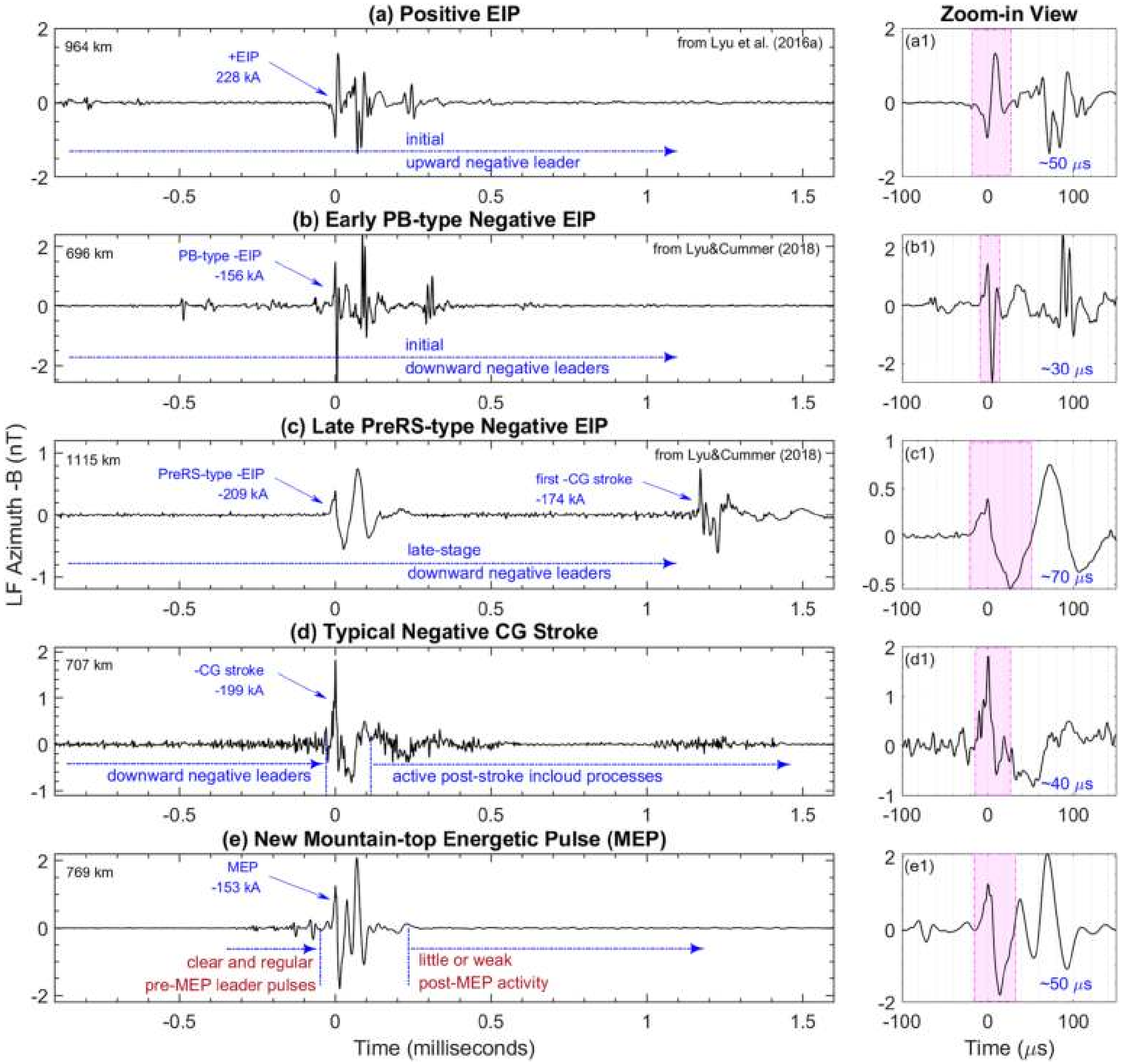

Figure 2. The low-frequency waveforms for typical +EIP, −EIP, −cloud-to-ground (CG), and mountain-top energetic pulses (MEP) events. (a) Replots an +EIP adapted from Lyu, Cummer, Briggs, et al. (2016). (b, c) −EIPs adapted from Lyu and Cummer (2018). (d, e) The temporal contexts of a typical negative CG stroke and MEP. The text in each panel describes the different stages of the leader process that produced the event. The figures on the right column illustrate the zoom-in view on the window of the main pulse, with the magenta windows marking the time scale of the main pulse.

regular time gap between the preceding leader pulses suggests the continuous and sustainable development of the leader, while the steady increase in amplitude of each pulse may indicate the existence of increasing local electric field at the leader tip associated with the development of the leader. Moreover, −CGs typically show noise-like LF activity after the return strokes, while +EIPs, PB-type −EIPs, and MEPs show just a few or no significant pulses immediately following the high peak-current pulses. These features are also in favor of MEPs being produced by above-ground propagating leaders. Double-pulsed ionospheric reflections are a signature of elevated sources, like NBEs (Jacobson et al., 2009; Smith et al., 1999, 2004), +EIPs (Lyu et al., 2015), and in-cloud leader pulses (Cummer et al., 2015). However, because of the low MEP source altitude above ground, no double pulse can be clearly resolved.

The remaining question is thus whether MEPs are produced during downward-propagating negative leaders or upward-propagating positive leaders. High peak-current pulses during downward negative leaders are seen in the form of PreRS-type −EIPs (Figure 2c), which unsurprisingly are usually (but not always) followed by high peak-current −CG events. In contrast, none of the 218 MEPs reported here were followed by a pulse consistent with a CG stroke. Additionally, probably because of the multiple branches of the negative leaders, the radio emissions preceding −CG strokes were much more active and complicated than that of the processes preceding the MEPs, suggesting the leader processes prior to MEPs could be different with that prior to the typical −CG stroke. We thus conclude that the LF waveform characteristics are most consistent with the hypothesis that MEPs are produced during terrain-initiated, upward-propagating positive polarity leaders. LMA measurements, described in more detail below, provide further evidence for this hypothesis.

4. Meteorological Context and Lightning Flash Structure of MEPs

The meteorological structure of MEP-producing storms and the structure of MEP-producing lightning flashes, as measured with a VHF LMA (Rison et al., 1999; Thomas et al., 2004), provide additional insight into the physical origin of MEPs. First, a statistical investigation of the thunderstorm cells that produced MEPs was conducted by estimating the size of the cells from radar data. The composite reflectivity field was used here which measures the maximum echo intensity from four tilt angles (0.5°, 1.45°, 2.40°, and 3.35°) of a single weather radar (Fuchs et al., 2018). For 61 MEP-producing cells with relatively short-range composite reflectivity data (<230 km), we estimated the size of the convection cells that produced MEPs by measuring the area of the 35 dBZ radar composite reflectivity region. Forty-eight of the 61 cells exhibited composite reflectivity greater than 35 dBZ (maximum of 50 dBZ), while the other 13 cells had composite reflectivity no more than 30 dBZ. The estimated horizontal size of the 35 dBZ echo region ranged from ∼10 to 200 km^2, with an average size of 72 km^2. And more than 66% of these 48 cells had a 35 dBZ echo area less than 50 km^2. This illustrates the compact and relatively weak convection of these MEP-producing cells, which suggests that it is likely the local conditions close to the MEP that drive the event, not thunderstorm complexes organized on the mesoscale.

LMA data further support the compact nature of the cells and lightning also shows that electric charge layers are very close to the mountain tops during MEP occurrence. Among the 218 MEPs analyzed in this study, 43 of them occurred within 200 km of the Colorado lightning mapping array (COLMA) coordinate center. Based on the COLMA data, these 43 events can be separated into three groups. In 12 cases, there were no mapped VHF sources within several seconds and 10 km from the MEP location. In 21 cases, only a few to several tens of VHF sources were mapped throughout the flash in a very compact horizontal region less than 5 km on a side, which did not provide much insight into the MEP-producing flashes. The other 10 MEPs were followed by reasonably well-mapped VHF sources. Two such examples are shown in Figure 3, with one MEP that was followed by weak and compact lightning activity, and one MEP that was followed by a larger and more active flash showing clear upward-moving lightning activity.

The MEP shown in Figure 3a was located 93 km horizontally from the COLMA center, which occurred in a relatively weak and scattered thunderstorm system, with 35 dBZ area no more than 30 km^2 (Figure 3c). This MEP occurred at the NLDN location with a ground geographical elevation of 3,212 m, illustrated in Figures 3a and 3d (marked as magenta crosses). A total of 83 VHF source points were mapped during this compact flash. The storm producing this MEP was observed with both horizontal and vertical dimensions of the 35 dBZ radar echo region less than 5 km. The source altitudes of the LMA sources suggest an altitude of the main negative charge region of ∼5 km (−10°C from the local sounding), as shown in Figure 3b. This indicates a relatively low-altitude main negative charge region during the MEP production, and thus a short 1–2 km distance between the main negative charge region and mountain tops.

Many more LMA sources were measured during the discharges associated with the MEP shown in Figure 3f. It was located 105 km from the COLMA center with the ground geographical elevation of 2,713 m. This MEP also occurred in a relatively weak convective region, although the horizontal size of the cell was larger than the one in Figure 3c. As for the previous case, there were no other evident sustained VHF sources mapped before this MEP-producing flash. The MEP was very close in time to the initiation of this flash, which followed by a clear upward process in 50 ms, with weak VHF lightning activity ∼1–2 km above the terrain altitude (also seen in Figure 3i). Then, an upward lightning expansion with vigorous VHF emissions was mapped between 5 and 8 km, similar to the upward triggered lightning mapped by Edens et al. (2012) over Langmuir Laboratory in New Mexico and the tower-initiated winter lightning in Schultz et al. (2018). The LMA data thus indicate that the main negative charge layer (Edens et al., 2012; Rust et al., 2005; Zheng et al., 2019) in this storm was at around 5 km (−12°C from the local sounding), and only ∼2 km above the

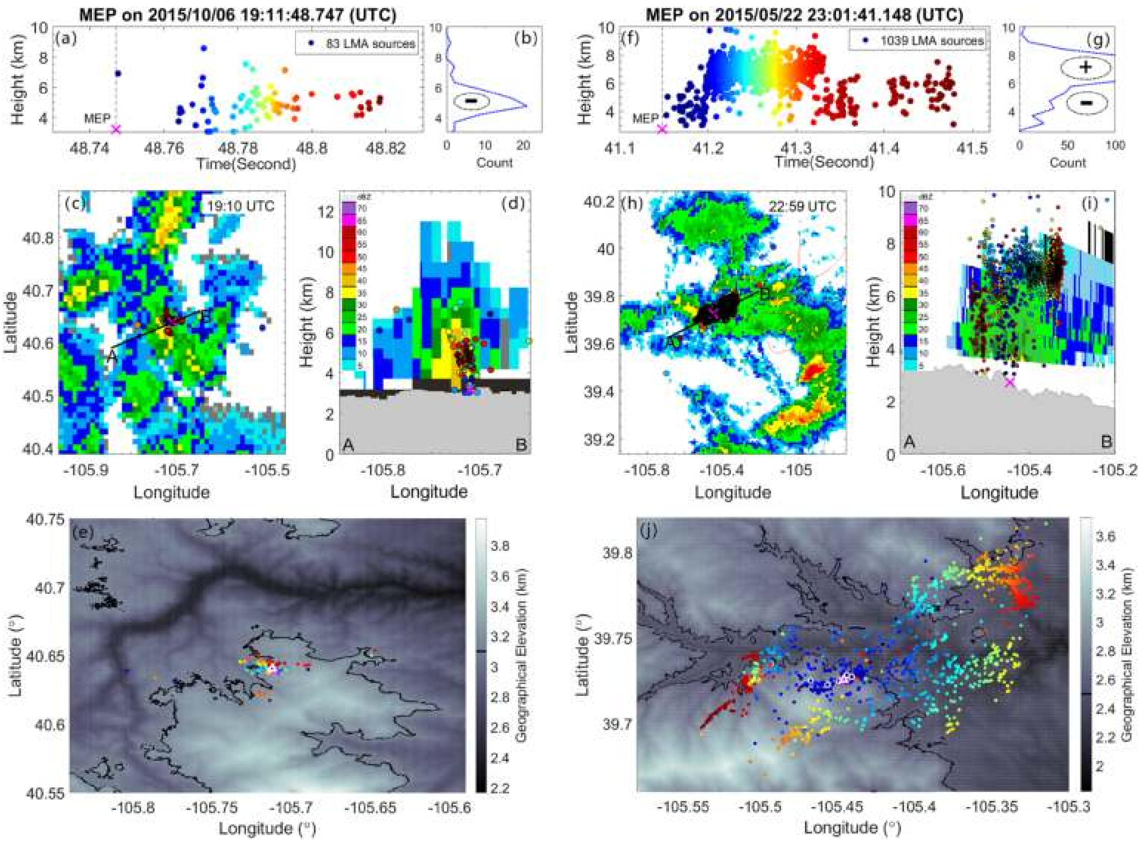

Figure 3. The lightning mapping array (LMA) images and radar echoes from two mountain-top energetic pulses (MEP)-producing flashes and thunderstorms. Panels (a) and (f) show the vertical position of LMA sources versus time for two MEPs on October 6, 2015, and May 22, 2015, respectively. Panels (b) and (g) show the vertical distribution of the LMA sources from the two flashes in (a) and (f), with the circled "+" and "−" illustrating the possible charge regions. Panels (c) and (d) show the plan view and the vertical view of the radar echo with the LMA sources for MEP in (a). Panel (h) and (i) show the plan view and the vertical view of the radar echo with the LMA sources for MEP in (f). Panels (e) and (j) illustrate the LMA sources over the geographical elevation of the local terrain, the black lines mark the elevation of 3,100 and 2,500 m, respectively. The color dots plot the LMA-mapped sources by more than six stations with chi-square less than 1. The color from blue to red indicates the time variation. The magenta "×" marks the time, ground altitude, and NLDN location of the MEP. The white triangle plots the first LMA source. The white circles in (j) show the following five LMA sources after the MEP.

local terrain, as shown in Figures 3g and 3i. The MEP occurred when positive leaders were limited to between the ground and the negative charge layer, well before any negative leader activity extended into the upper positive charge layer (at ~7–8 km), as shown in Figures 3f and 3i.

Among the 10 MEPs that were followed by clear IC processes, six of them were mapped with significant numbers of LMA sources centered on the MEP, similar to that shown in Figure 3j. For the other 4, it was difficult to resolve any horizontal progression of the leaders. All of these events are similar to reported ground-initiated, upward-propagating flash processes (Edens et al., 2012; Pineda et al., 2019; Schultz et al., 2018). Few VHF sources were mapped around the times of the MEPs at the very beginning of these flashes. This may be due to weak VHF radiation from the MEP-producing process, or because the low altitude of the VHF sources results in the mountains partly blocking the propagation of the VHF signals.

5. Possible MEP Mechanisms and Related Lightning Events

The MEPs reported in this study appear similar in some ways to high peak-current events that occur on the west coast of Japan that have been called LBEs (Wu et al., 2014). This similarity offers further insight into the two classes of events. First, both are negative radiated field polarity, implying negative downward or positive upward charge motion. The average initial width of MEP pulses is 19 μs, consistent with the average LBE initial pulse width of 15 μs. Second, the LBEs reported by Wu et al. (2014) were all located on land along the western Japanese coast, where cloud tops are known to be especially close to ground level and are possibly associated with tall-grounded objects. This is electrically similar to the MEPs reported here, with electrified clouds close to the elevated mountainous ground level and with topography capable of enhancing local electric fields in the same manner as tall-grounded objects. One notable difference is that LBEs are sometimes followed by stroke-like discharges (Wu et al., 2014), while MEPs appear not to be (or very rarely are).

Accounting for the high geographical ground altitude of the MEP locations (2–3 km), the vertical gaps between the mountain tops and the main negative layer were generally less than 3 km. This short distance suggests the possible existence of strong, terrain-enhanced electric fields between ground and low clouds. We posit that necessary (but not sufficient) conditions for MEP (and perhaps LBE) production include the terrain or tall-grounded objects to enhance the local electric field, and an overhead negative charge region at most a few kilometers above the ground. Together these requirements can create unusually strong electric fields between cloud and ground, which rarely would appear over flat ground that is not unusually close to the cloud base. MEPs thus appear to be produced when leaders propagate in a region of an unusually high electric field.

Are MEPs produced by downward negative or upward positive leaders? It is not possible to say with certainty with the data presented here. The similarity between +EIP and −EIP pulses, which are known to be produced by propagating negative polarity leaders (Lyu et al., 2015; Tilles et al., 2020), and MEP pulses indicates that the possibility that they are produced by downward negative leaders cannot be ruled out. However, the almost complete lack of any located LMA points before and during the MEP, as well as the LMA-mapped flash structures themselves (Edens et al., 2012; Pineda et al., 2019; Schultz et al., 2018), points in favor of their connection to upward positive leaders. Positive leaders radiate more weakly at VHF than negative leaders (Shao & Krehbiel, 1996) and are thus much harder to detect. We examined LMA data for −CG flashes close in time and space to these MEPs, and in almost all cases the descending negative leaders were detected with many LMA points. The regularity and steadily increasing amplitude of the LF pulse sequence observed prior to the MEPs is also atypical for downward negative leaders. Additionally, the absence of any cases of −CG strokes that might be expected to follow a strong MEP pulse produced by a downward negative leader at most a few kilometers above the ground further supports the origin of MEP being terrain-initiated upward positive leaders. However, the origin of MEP pulses certainly merits further research.

What other processes might be associated with MEPs? The exceptionally high peak currents for these events indicate that they almost certainly produce electromagnetic pulse-driven optical emissions and ionization in the ionosphere in the form of elves (Barrington-Leigh & Inan, 1999; Inan et al., 2010). The strong geographic concentration of lightning events that radiated exceptionally strongly at VLF, termed superbolts (Holzworth et al., 2019), high in the Andes Mountains and other mountainous regions, like Rockies over North America, east coast of Japan, coastlines along Norway, and Mediterranean Sea, suggests that MEPs might be the origin of some superbolts. Perhaps the most interesting possibility is one that is admittedly more speculative: MEPs could be associated with TGFs (Briggs et al., 2010; Fishman et al., 1994; Marisaldi et al., 2010; Neubert et al., 2020; Smith et al., 2005). It is already known that exceptionally strong pulses produced in upward-propagating negative leaders in the form of +EIPs are always or almost always TGFs (Lyu, Cummer, Briggs, et al., 2016, Lyu et al., 2021). These +EIPs occur when existing and relatively long (several kilometers) negative leaders are propagating in the high electric fields between the main negative and upper positive charge layers, and the +EIP pulse itself appears to be at least partly produced by the electron acceleration in the TGF-generating process (Dwyer & Cummer, 2013; Tilles et al., 2020). We also know that TGFs can be produced by rocket-triggered or tower-initiated positive leaders when they approach regions of high negative charges and produce very strong electric fields over significant lengths (Bowers et al., 2017; Dwyer et al., 2004; Hare et al., 2016; Smith et al., 2018).

We thus conjecture that MEPs might be the natural version of this process of TGF production by triggered lightning, in which a terrain-initiated upward positive leader propagates in the high and partly terrain-enhanced electric field region between the high terrain and a compact electrified cloud with low cloud base. Such TGFs would be directed downward into the propagating end of the positive leader. This suggests a possible approach to detect larger numbers of downward TGFs produced by natural lightning processes in regions of the world where this special combination of and high terrain or tall-grounded objects and electrified clouds close to ground occurs. One such region is the high mountains of the western portion of the United States, and it seems likely that another is the west coast of Japan in the wintertime (Wada et al., 2020; Wu et al., 2014). There may well be others.

6. Conclusions

We report here a class of high peak-current pulses that appear distinct from those previously identified. Its most remarkable feature is that it is confined within the United States to the high mountains of the west. It occurs almost exclusively at altitudes above 2,000 m, and all 218 of them analyzed here have negative radiated field polarity. We thus call this event a negative polarity MEP. The LF waveform characteristics compared to known types of energetic pulses, the LMA measurements of MEP-producing lightning flashes, and radar images of the compact cells that produce MEPs all suggest that MEPs are very high peak-current pulses that occur during the propagation of upward, terrain-initiated, and positive polarity lightning leaders. However, the possibility that MEPs are produced during downward negative polarity leader propagation cannot be ruled out.

Several conditions appear to be required to generate MEPs, namely a high ground altitude, a relatively short (~2 km) altitude difference between the ground and compact electrified clouds, and terrain that is capable of enhancing the local electric field. These conditions can produce unusually strong electric fields for leader propagation between the cloud and ground. Similar conditions appear to be involved in the production of previously reported LBEs in winter thunderstorms in Japan, and it seems possible that MEPs and LBEs are related in some way.

The specific combination of a propagating leader in a 2–3 km long high field region is already known to be associated with TGFs through in-cloud +EIPs, and the similarity of the LF waveforms of MEPs and +EIPs is notable. Moreover, upward positive leaders have been reported to produce ground-detected TGFs. We thus speculate that these MEPs may in fact be downward-directed TGFs and that they may occur regularly in locations around the world that meet these conditions. Clearly, more work is needed to understand the origin of and phenomena associated with MEPs.

Data Availability Statement

The data used in this study are available at the link https://doi.org/10.5281/zenodo.4896021.

Acknowledgments

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