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Lightning-Ignited Wildfires in the Western United States: Ignition Precipitation and Associated Environmental Conditions

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Key Points:

- The widely-used 2.5 mm daily precipitation threshold to define "dry" lightning does not fully capture fire ignition risk across the WUS
- Ignition precipitation amounts range from 1.7 to 7.7 mm depending on ecoprovince and whether the fire was promptly-detected or a holdover
- Holdover fires occur when conditions are cooler and wetter compared to promptly-detected fires

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Cloud-to-ground lightning with minimal rainfall ("dry" lightning) is a major wildfire ignition source in the western United States (WUS). Although dry lightning is commonly defined as occurring with <2.5 mm of daily-accumulated precipitation, a rigorous quantification of precipitation amounts concurrent with lightning-ignited wildfires (LIWs) is lacking. We combine wildfire, lightning and precipitation data sets to quantify these ignition precipitation amounts across ecoprovinces of the WUS. The median precipitation for all LIWs is 2.8 mm but varies with vegetation and fire characteristics. "Holdover" fires not detected until 2–5 days following ignition occur with significantly higher precipitation (5.1 mm) compared to fires detected promptly after ignition (2.5 mm), and with cooler and wetter environmental conditions. Further, there is substantial variation in precipitation associated with promptly-detected (1.7–4.6 mm) and holdover (3.0–7.7 mm) fires across ecoprovinces. Consequently, the widely-used 2.5 mm threshold does not fully capture lightning ignition risk and incorporating ecoprovince-specific precipitation amounts would better inform WUS wildfire prediction and management.

Plain Language Summary Cloud-to-ground lightning with minimal rainfall, also known as "dry lightning," is a major wildfire ignition source in the western United States (WUS). Typically, daily-accumulated precipitation of less than 2.5 mm is used to identify dry lightning occurrence. However, there is limited knowledge of (a) the true precipitation amounts that occur with lightning-ignited wildfires (LIWs), and (b) how these amounts vary across different landscapes and vegetation types. We combine wildfire, lightning and precipitation data sets to quantify these ignition precipitation amounts across different regions of the WUS. Although we find a 2.8 mm median ignition precipitation for all LIWs, we show that "holdover" fires not detected until 2–5 days following ignition occur with significantly higher precipitation (5.1 mm) compared to fires detected promptly after ignition (2.5 mm). Holdover fires also occur with cooler and wetter environmental conditions. Further, ignition precipitation amounts associated with promptly-detected and holdover fires vary substantially across ecoprovinces. Consequently, the widely-used 2.5 mm threshold does not fully capture lightning ignition risk. WUS wildfire prediction and management could be improved through incorporating ecoprovince-specific precipitation amounts and accounting for differing characteristics of holdover fires.

1. Introduction

Cloud-to-ground lightning without substantial accompanying rainfall ("dry lightning") is a major source of western United States (WUS) wildfire ignitions during summer, when fuels are typically dry (Abatzoglou et al., 2016; Balch et al., 2017; Brey et al., 2018). In August 2020, a large dry lightning outbreak ignited numerous simultaneous wildfires in California (Kalashnikov, Abatzoglou, et al., 2022), contributing to the largest annual wildfire burned area in the state's modern history (Keeley & Syphard, 2021) and prolonged hazardous air quality conditions across the WUS (Kalashnikov, Schnell, et al., 2022; Zhou et al., 2021). Approximately 69% of WUS wildfire burned area is attributed to lightning-ignited wildfires (LIWs; Abatzoglou et al., 2016). LIW burned area is increasing (Cattau et al., 2020) and these trends are projected to continue under warming (Barros et al., 2021; Li et al., 2020). A better understanding of dry lightning and the environmental conditions shaping LIW risk can inform operational forecasting and future projections of LIWs.

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Dry lightning is produced by thunderstorms that typically initiate at high altitudes (>3 km) due to moisture advection in the mid-troposphere, with substantially elevated cloud bases compared to heavy rain-producing thunderstorms (Fuquay, 1962; Krumm, 1954; Nauslar et al., 2013; Rorig & Ferguson, 1999). These conditions coincide with increased mid-level instability and a dry lower troposphere, evaporating rainfall before reaching the ground and increasing LIW ignition risk (Kalashnikov, Abatzoglou, et al., 2022; Nauslar et al., 2013; Rorig & Ferguson, 1999; Wallmann et al., 2010). A daily precipitation amount of <2.5 mm is widely used to define dry lightning over the interior WUS and similar dryland environments globally in both research (Abatzoglou et al., 2016; Dowdy, 2020; Dowdy & Mills, 2012; Kalashnikov, Abatzoglou, et al., 2022; Rorig & Ferguson, 1999) and operational forecasting (SPC, 2022). Precipitation below this threshold is considered insufficient to prevent sustained wildfire ignition from cloud-to-ground lightning. However, other studies have shown varied precipitation amounts during LIWs. Using interpolated rain-gauge data, Hall (2007) found that most LIWs occur with <2 mm/day precipitation in the southwest US. Using atmospheric reanalyses for the same region, Pérez-Invernón et al. (2022) reported a median precipitation of 0.2 mm/hr accumulated during the hour of ignition. MacNamara et al. (2020) found median ignition precipitation amounts of 1.7 mm/hr and 2.9 mm/day using radar estimates over the WUS for LIWs in 2017. However, a comprehensive multi-year analysis of WUS LIW precipitation amounts does not yet exist.

Therefore, we quantify precipitation associated with LIWs across WUS ecoprovinces between 2015 and 2020 and examine associated environmental conditions. Some LIWs are not discovered for multiple days or weeks following ignition and are known as "holdover" fires (Schultz et al., 2019). For example, the 2021 Bootleg Fire in Oregon smoldered for more than 1 week before detection and ultimately grew into the state's third-largest wildfire on record (Gorman, 2021). Such holdover fires might be associated with different environmental conditions and precipitation amounts (MacNamara et al., 2020). We therefore investigate ignition precipitation amounts and environmental conditions associated with holdover LIWs separately from promptly-detected LIWs. Our findings advance the understanding of factors affecting LIW risk and are relevant to wildland fire prediction, suppression, and management across WUS sub-regions.

2. Materials and Methods

We conduct our analyses during May–September between 2015 and 2020, which corresponds to the summertime thunderstorm season over the interior WUS (Burrows et al., 2005; Kalashnikov et al., 2020; Rorig & Ferguson, 1999). Our analysis utilizes Bailey's ecoprovinces (USFS, 1995) to examine variations in precipitation amounts and environmental conditions associated with LIWs across different landscapes. Although each ecoprovince contains multiple vegetation types and land cover classifications, they represent regions of broadly similar climate, vegetation composition, and climate-fire relationships (Abatzoglou et al., 2016; Littell et al., 2009). We analyze the 16 ecoprovinces contained within the WUS.

2.1. Data

Wildfire data are from the National Interagency Fire Center (NIFC)—"Wildland Fire Locations Full History" data set (WFIGS, 2022). This database provides fire discovery locations, dates, final burned areas, and fire cause type (e.g., human or natural). We consider all fires labeled as "natural" and constrain our analysis to >1 ha fires (Fusco, Finn, Abatzoglou, et al., 2019). Wildfire records geolocated within 0.01° latitude and longitude (~1 km) of another fire on the same day are flagged as duplicates and removed. A total of 4,651 fires are identified using these criteria, representing a combined burned area of 5.79 million ha (Figure S1 in Supporting Information S1).

Cloud-to-ground lightning flashes are from the National Lightning Detection Network (NLDN; Vaisala, Inc.). We use daily accumulated precipitation from three gridded data sets: NOAA Multi-Radar/Multi-Sensor System (MRMS; 1-km); NASA's Integrated Multi-satellitE Retrievals for GPM (IMERG; 0.1°); and gridMET (Abatzoglou, 2013; 4-km). These data sets were chosen to represent the three primary input data types for quantitative precipitation estimation - radar, satellite, and interpolated surface gauges, allowing for assessing uncertainties. Since we use gauge-corrected MRMS data ("GaugeCorr_QPE_01H") available starting 7 May 2015, we exclude ignitions between 1 and 6 May 2015. We assess differences in ignition precipitation amounts when aggregated by percent tree cover (as of 2020) using the Moderate Resolution Imaging Spectroradiometer (MODIS) "Vegetation Continuous Fields" data set, and by fire size using the National Wildfire Coordinating Group (NWCG) fire size classes (https://www.nwcg.gov/term/glossary/size-class-of-fire).

To understand environmental conditions shaping LIW risk, we analyze daily surface variables representing atmospheric and fuel moisture conditions (vapor pressure deficit, maximum temperatures, 100- and 1000-hr dead fuel moisture on a 4-km grid) from gridMET since they can affect LIW ignition efficiency and overall burned area (Abatzoglou et al., 2016; Brey et al., 2020). Contemporaneous atmospheric conditions should affect moisture content and flammability of fine fuels. Meanwhile, the fuel moisture variables indicate the moisture content of medium (~3–8 cm diameter; 100-hr) to large (8–20 cm diameter; 1000-hr) dead woody debris.

2.2. Methods

Although the NIFC database provides latitude-longitude coordinates for each fire's discovery location, these may not represent the precise ignition location (Fusco, Finn, Abatzoglou, et al., 2019; Pérez-Invernón et al., 2022). Similarly, fire discovery dates are provided but they differ from ignition dates for holdover fires. Due to these spatiotemporal uncertainties, locations and dates of wildfire reports are refined using cloud-to-ground lightning data (Larjavaara et al., 2005; Schultz et al., 2019). To match wildfires with lightning, we use a 2 km radius around every wildfire location to search for lightning (MacNamara et al., 2020; Nauslar, 2014), and consider the closest lightning location as the most likely ignition source. Although some studies have used larger search radii (Larjavaara et al., 2005; Moris et al., 2020; Pérez-Invernón et al., 2022; Pineda & Rigo, 2017; Pineda et al., 2022; Schultz et al., 2019), the smaller radius should reduce uncertainty in matching wildfire locations to potential igniting lightning flashes. This search radius also captures the ~1.6 km locational uncertainty ascribed to US federal wildfire reports (Short, 2014). NLDN lightning data also contain locational uncertainties of ~0.25 km (Nag, 2014), which can be larger in the mountainous terrain of the WUS (Schultz et al., 2019).

We search for lightning on the day of wildfire discovery (Lag 0), followed by the day prior (Lag 1). LIWs detected on Lag 0 or 1 are termed promptly-detected. If no cloud-to-ground lightning is found within 2 km on Lag 0 or 1, we sequentially search up to 5 days prior to fire discovery (Lag 2–5) until lightning is found or the search is exhausted. This imposes at least a 24-hr delay between ignition and discovery for such LIWs, termed as holdovers, as late afternoon and evening ignitions may not be reported until the following morning (Pineda & Rigo, 2017). The lightning flash closest to wildfire discovery time is considered the ignition source. We select a 5-day lag as a majority of LIWs are reported within a few days of ignition (MacNamara et al., 2020; Schultz et al., 2019). This window excludes rare longer-duration holdovers with increased uncertainty in the location of their ignition source (Schultz et al., 2019). Fires not paired with lightning within this window are excluded from further analysis.

For each fire, we use the lightning location and day to extract the precipitation amount and environmental variables from the overlying grid cell. We primarily use MRMS because of its high spatial resolution (1-km) and its use in prior studies (MacNamara et al., 2020). Due to the areal coverage and proximity of ground-based radar beams, MRMS is expected to perform better when capturing convective precipitation over mountainous terrain of the WUS compared to gridMET and IMERG, particularly in areas with a sparse gauge network. Known limitations to using radar data over this region include a lack of adequate coverage in some areas (Vant-Hull et al., 2018) and possible overestimation of surface precipitation if rainfall evaporates before reaching the ground (Zhang et al., 2016). Therefore, we evaluate the sensitivity of our analysis to other precipitation data sets.

We compare the distributions of ignition precipitation amounts and environmental variables for promptly-detected LIWs with holdovers for each ecoprovince, and assess statistical significance of differences ($P < 0.10$) using the Mann-Whitney U test. For each ecoprovince and fire type, we use bootstrap resampling ($n = 1{,}000$ iterations) to test whether the median ignition precipitation is significantly different from 2.5 mm. Differences are considered significant if the 90% confidence interval of resampled medians does not overlap 2.5 mm.

3. Results and Discussion

3.1. Spatial Patterns of LIWs

Using our spatiotemporal search criteria, we matched 3,726 of the 4,651 (~80.1%) naturally-caused fires (>1 ha) across the WUS from the NIFC database with a cloud-to-ground lightning flash (Figure 1a). The percentage of matched fires is similar to MacNamara et al. (2020), who matched ~79.5% for 2017, but substantially higher than the ~59.6% over 2012–2015 reported by Schultz et al. (2019) using the same search radius but for larger fires

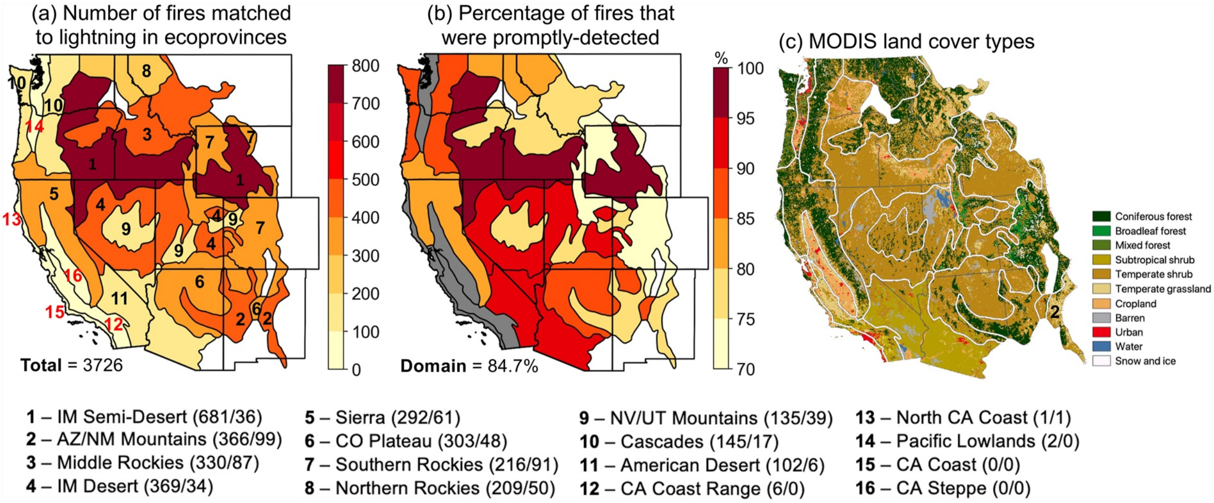

Figure 1. (a) Number of lightning-ignited wildfires (LIWs) in Bailey's ecoprovinces (May-September 2015–2020). Numbers in (a) are ranks reflecting number of LIWs. Ecoprovinces labeled with red (#12–16) are excluded from further analysis due to low LIW numbers. (b) Percentage of total LIWs that were promptly-detected. Abbreviated ecoprovince names are shown below (see Table S1 in Supporting Information S1 for details), with the number of promptly-detected/holdover fires in parentheses. (c) Moderate Resolution Imaging Spectroradiometer land cover types (250 m).

(>400 ha). These differences likely reflect variation in geographic locations, fire size, and reporting conditions in the years analyzed in each study.

There are substantial variations in LIW occurrences across ecoprovinces, with the highest number of 717 LIWs in the Intermountain Semi-Desert that covers a large portion of the northern Great Basin (Figure 1a). Other ecoprovinces had 108-465 LIWs, except for five ecoprovinces in western Washington, Oregon, and California that had substantially fewer LIWs (0–6) and were excluded from subsequent analyses. The spatial pattern of identified LIWs is similar to the pattern of reported naturally-caused fires in the NIFC database (Figure 1a and Figure S1 in Supporting Information S1). These patterns result from the greater lightning density in the interior WUS during summer compared to areas closer to the Pacific coast (Kalashnikov et al., 2020).

Of the 3,726 identified WUS LIWs, 3,157 (~84.7%) were promptly-detected while 569 (~15.3%) were holdovers (Figure 1b). The high percentage of promptly-detected LIWs is not surprising given that most fires are discovered soon after ignition, and a recent study over the southwest US found a median LIW holdover time of ~0.5 days (Pérez-Invernón et al., 2022). Similarly, Schultz et al. (2019) reported that ~78–80% of LIWs in the WUS were matched with a cloud-to-ground lightning flash on the same or prior day (see Figure 3 therein).

Across ecoprovinces, promptly-detected fires comprise 70%–95% of total LIWs (Figure 1b). The desert and semi-desert environments of the Great Basin and interior Southwest (ecoprovinces #1, #4, and #11; Figures 1b and 1c) have the largest proportion of promptly-detected LIWs (>90%). Conversely, the highest proportion of holdovers (~20–30%) is found in the largely mountainous, forested terrain of the Arizona/New Mexico Mountains (#2), Middle and Southern Rockies (#3, #7) and Nevada/Utah Mountains (#9). In the Southern Rockies (#7), nearly a third of all LIWs are holdovers. In forested environments, deeper layers of fine organic fuels can ignite and smolder under the canopy even in conditions that are not favorable for flaming combustion, decreasing the likelihood of quick detection (Flannigan & Wotton, 1991; Pineda & Rigo, 2017). In contrast, in semi-desert and desert environments, sparser and patchier dispersion of fuels reduce smoldering while lack of canopy cover enables quick detection, potentially explaining the relative rarity of holdovers.

3.2. Precipitation Amounts Associated With LIWs

Next, we evaluate systematic differences in precipitation amounts for promptly-detected and holdover LIWs (Figure 2). WUS-aggregated median holdover precipitation is more than double compared to promptly-detected LIWs (5.1 vs. 2.5 mm; $P < 0.10$), consistent with MacNamara et al. (2020). Further, eight of the 11 ecoprovinces have significantly higher median precipitation associated with holdover relative to promptly-detected LIWs (Figures 2a and 2b). Promptly-detected LIWs in most ecoprovinces have median precipitation amounts of

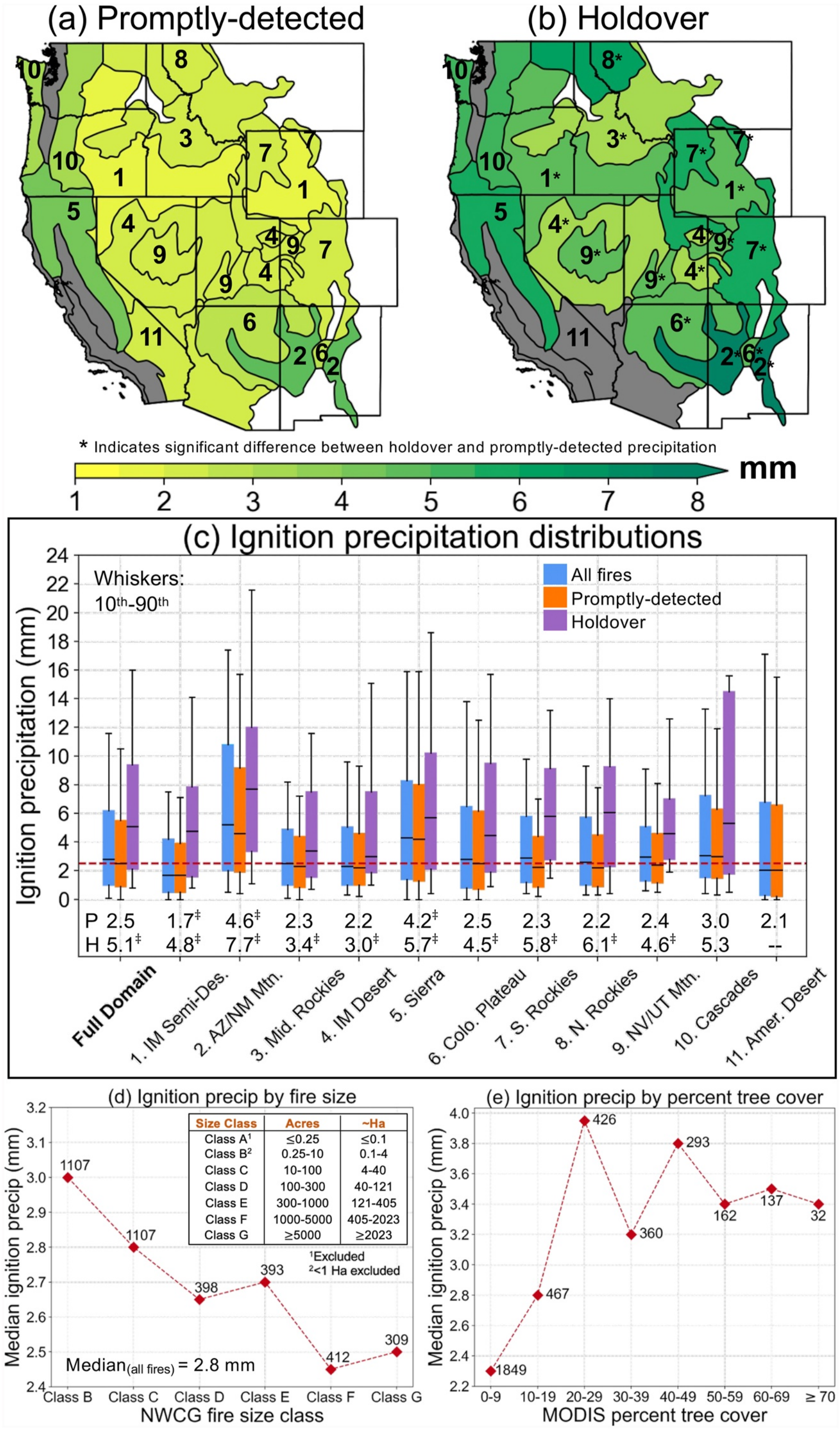

Figure 2. Median ignition precipitation amounts in each ecoprovince for (a) promptly-detected and (b) holdover lightning-ignited wildfires (LIWs). Asterisks beside ecoprovince ranks indicate statistically significant differences ($P < 0.10$) between the promptly-detected and holdover precipitation distributions based on the Mann-Whitney *U* test. (c) Distributions of ignition precipitation amounts for all (blue), promptly-detected (orange) and holdover (purple) LIWs. Red dashed line in (c) indicates 2.5 mm daily precipitation threshold commonly used for "dry" lightning. Numbers below distributions are median ignition precipitation amounts (mm) for promptly-detected ("P") and holdover ("H") LIWs. Markers (‡) indicate that precipitation amounts are significantly different ($P < 0.10$) from 2.5 mm based on bootstrap resampling ($n = 1,000$ iterations). Median ignition precipitation for all WUS LIWs binned by (d) National Wildfire Coordinating Group fire size class and (e) Moderate Resolution Imaging Spectroradiometer percent tree cover. Text accompanying datapoints shows number of LIWs in each bin. Note that the American Desert ecoprovince (#11) is excluded for holdovers in (b and c) and from statistical testing due to low sample size.

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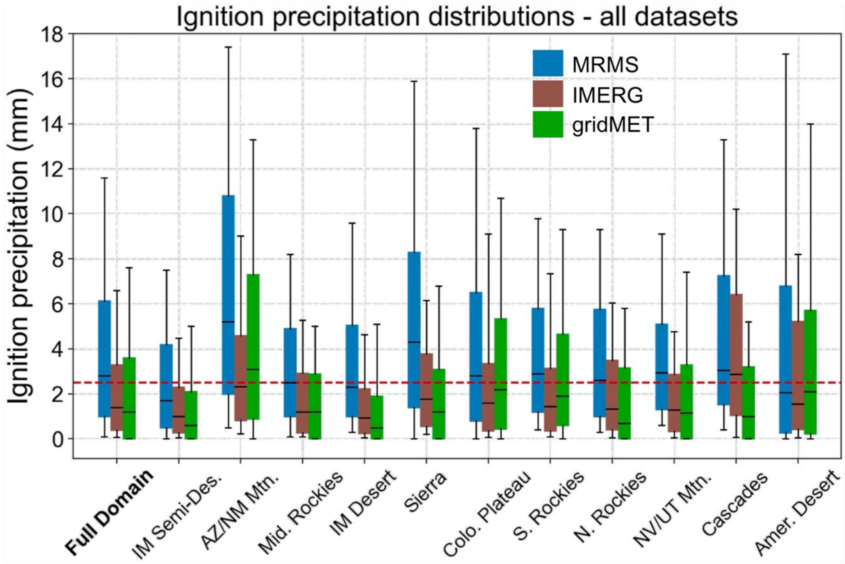

Figure 3. Distributions of ignition precipitation amounts for all lightning-ignited wildfires in the domain and across ecoprovinces using MRMS (blue), IMERG (brown), and gridMET (green). Red dashed line indicates commonly used 2.5 mm daily precipitation threshold for "dry" lightning. Whiskers indicate 10th–90th percentiles.

<2.5 mm and as low as 1.7 mm in the Intermountain Semi-Desert (Figure 2c), which is characterized by sagebrush steppe ecosystems and has the highest proportion of promptly-detected LIWs (~95%; Figure 1b). In contrast, all ecoprovinces have median precipitation for holdovers ≥3.0 mm. Median ignition precipitation during holdovers in Northern and Southern Rockies, Arizona/New Mexico Mountains, and Intermountain Semi-Desert are at least 3 mm higher than for promptly-detected LIWs (Figure 2c). Ecoprovinces with the highest holdover precipitation—Arizona/New Mexico Mountains, Northern and Southern Rockies, and Sierra (5.7–7.7 mm)—are largely comprised of coniferous forests where canopy interception of precipitation and denser organic layers on the forest floor can sustain ignition in wetter conditions (Fischer et al., 2023; Flannigan & Wotton, 1991).

Across all WUS LIWs, the median ignition precipitation is 2.8 mm. However, this number varies for NWCG fire size classes (Figure 2d and Figure S2 in Supporting Information S1). Smaller fires (<40 ha; Class B and C) comprise the majority of LIWs and are associated with higher ignition precipitation (2.8–3.0 mm) whereas the largest LIWs (≥405 ha; Class F and G) occur with lower ignition precipitation (~2.5 mm), likely reflecting increased flammability due to less precipitation. Ignition precipitation amounts are also sensitive to percent tree cover (Figure 2e). LIWs ignite with higher accompanying precipitation (>3.2 mm) in areas with >20% tree cover compared to areas with <10% tree cover (~2.3 mm). These results indicate an increased risk of LIWs in forested areas at precipitation amounts that may be too "wet" for ignition in non-forest environments, where canopy interception of rainfall is absent (Wotton et al., 2005).

Our results suggest that the <2.5 mm precipitation amount commonly used to identify dry lightning is not adequate for capturing LIW ignition risk across most of the WUS, particularly for holdovers and LIWs in forested areas that can sustain ignition despite more accompanying rainfall. Approximately 72% of all WUS holdovers occurred with ≥2.5 mm precipitation (Figure S3 in Supporting Information S1). Further, median holdover ignition precipitation amounts are significantly higher than 2.5 mm everywhere except the Cascades, while promptly-detected precipitation amounts are close to 2.5 mm in most ecoprovinces (Figure 2c). For predicting and modeling LIW ignitions, these results imply that different precipitation amounts need to be considered to account for predominant vegetation type and holdovers, which comprise ~15% of WUS LIWs (Figure 1b).

Our findings of higher holdover precipitation amounts are robust across IMERG and gridMET (Figures S4 and S5 in Supporting Information S1). However, the radar-based MRMS shows systematically higher median precipitation for all ecoprovinces compared to the satellite-based IMERG or the gauge-interpolated gridMET (Figure 3). Aggregated across all WUS LIWs, the median ignition precipitation is 1.4 mm using IMERG and 1.2 mm using gridMET, compared to 2.8 mm using MRMS. Such uncertainties in ignition precipitation could arise from multiple factors including varying gauge density and radar coverage, instrumentation, measurement methods, and the influence of terrain and local meteorology. We note that MRMS might overestimate ignition precipitation amounts as radar beams cannot resolve virga (Zhang et al., 2016). Nonetheless, the finer spatial resolution and ground-based radar coverage of MRMS offers an advantage when capturing isolated convective episodes that can produce LIWs (Flannigan & Wotton, 1991; Pineda & Rigo, 2017), which may not be captured by the station network that gridMET is weighted toward or biased low due to averaging over the coarser grid of IMERG.

3.3. Environmental Conditions Associated With LIWs

To understand the influence of environmental conditions on promptly-detected and holdover LIWs, we compare atmospheric and fuel moisture conditions on identified lightning days for each LIW (Figure 4 and Figure S6 in Supporting Information S1). Vapor pressure deficit (VPD; −9.3 to −3.8 hPa) and maximum temperatures (T_{max}; −5.6 to −2.0°C) are significantly lower for holdover compared to promptly-detected LIWs across all ecoprovinces (Figures 4a–4d), and 100-hr fuel moisture (FM_{100}; +0.4 to +2.6%) is significantly higher (Figures 4e and 4f). Meanwhile, 1000-hr fuel moisture (FM_{1000}; +0.2 to +2.5%) is higher across all ecoprovinces and these differences are significant in all but the Intermountain Semi-Desert (#1) and Intermountain Desert (#4) (Figures 4g and 4h). The relatively cooler and more humid conditions associated with holdovers, along with higher fuel moisture, are consistent with previous work (Pineda et al., 2022).

The significantly higher FM_{100} in all ecoprovinces during holdovers (Figures 4e and 4f) indicates the importance of fuel moisture in medium-size (~3–8 cm) dead fuels on whether a LIW smolders or quickly spreads. These ecoprovinces are predominantly either coniferous forest or shrub steppe and have abundant fuels of this size (Figure 1c). Similarly, most ecoprovinces contain abundant large fuels (~8–20 cm) and have significant differences in FM_{1000} between holdover and promptly-detected LIWs (Figures 4g and 4h). These differences are larger in the typically drier ecoprovinces in the southeastern parts of the domain including the Arizona/New Mexico Mountains (#2; +2.0%) and the Colorado Plateau (#6; +2.5%; Figure 4g). This indicates that substantially wetter large fuels are needed in these regions for holdovers. Notably for the Colorado Plateau, substantially more precipitation is observed in the 7 days preceding holdovers compared to promptly-detected LIWs (+5.5 mm; Figure S7 in Supporting Information S1).

In contrast, in the Intermountain Semi-Desert (#1) and Intermountain Desert (#4), FM_{1000} is not significantly higher for holdovers (Figure 4g). This is because large woody debris is scarce in these environments compared to forests, which likely diminishes their importance for LIW ignition and survival. Additionally, longer-term antecedent conditions (i.e., FM_{1000}) may be less important compared to short-term atmospheric conditions for differentiating between promptly-detected and holdover LIWs here. VPD and T_{max} are significantly lower for holdovers in these ecoprovinces (Figures 4a and 4c) and these differences can strongly influence moisture content of fine fuels common in these semi-arid to arid ecosystems, including invasive annual grasses such as cheatgrass (Davies & Nafus, 2012; Fusco, Finn, Balch, et al., 2019).

Our results indicate that the combination of fuel moisture and atmospheric conditions around ignition influence holdover LIW risk across ecoprovinces. Specifically, higher precipitation amounts (Figure 2) and cooler, more humid accompanying conditions with higher fuel moisture (Figure 4) during ignition are more conducive to holdovers. Hotter and drier conditions (e.g., higher VPD and T_{max}) such as those observed with promptly-detected LIWs are more favorable for flaming combustion that leads to faster-spreading fires and quicker detection. Although some fuel dryness is required to sustain ignition, cooler and wetter conditions can reduce the combustion to smoldering until conditions become more favorable thereby increasing the chance of a multi-day holdover.

4. Summary and Conclusions

We combined wildfire, lightning, and precipitation data along with atmospheric and fuel moisture indices to provide the first comprehensive multi-year assessment of ignition precipitation amounts and environmental conditions associated with promptly-detected and holdover LIWs across the WUS. Of the 3,726 LIWs examined, ~85% were promptly-detected. Holdovers are relatively rare (<10% of all LIWs) in desert and semi-desert ecoprovinces of the Great Basin and southwest US but are more common (>20%) in forested landscapes (Figure 1b). Holdovers occur with significantly higher median precipitation (5.1 mm) compared to promptly-detected LIWs (2.5 mm). Further, there is substantial spatial heterogeneity in promptly-detected (1.7–4.6 mm) and holdover (3.0–7.7 mm) ignition precipitation across ecoprovinces (Figure 2).

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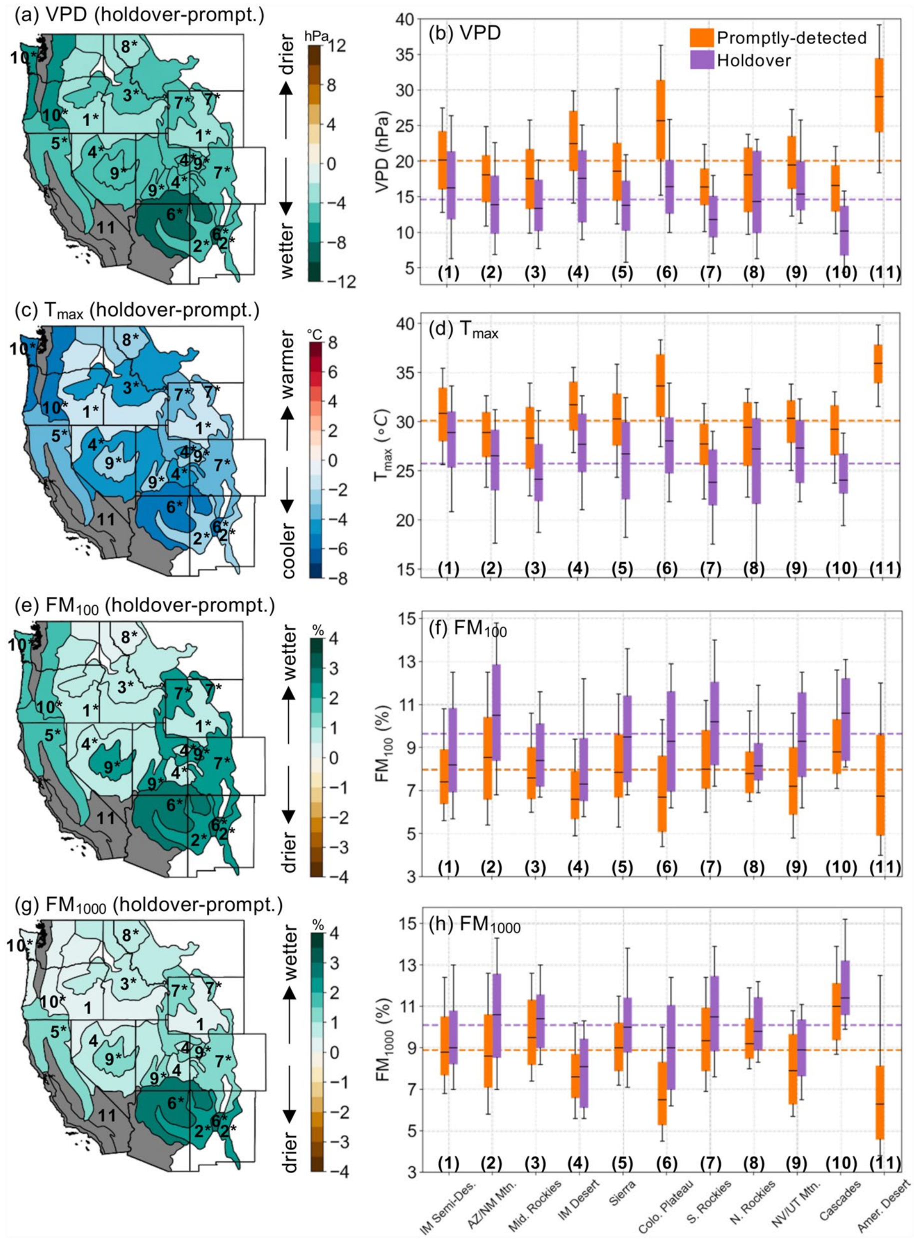

Figure 4. Differences in environmental conditions during holdover and promptly-detected lightning-ignited wildfires (LIWs) for (a) VPD, (c) T_{max}, (e) FM_{100}, and (g) FM_{1000}. Asterisks indicate statistically significant difference ($P < 0.10$) between the promptly-detected and holdover distributions based on the Mann-Whitney U test. Boxplots of (b) VPD, (d) T_{max}, (f) FM_{100}, and (h) FM_{1000} for promptly-detected (orange) and holdover LIWs (purple). Whiskers indicate 10th–90th percentiles and dashed lines represent WUS-averaged values for promptly-detected (orange) and holdover LIWs (purple). Note that the American Desert ecoprovince (#11) is excluded for holdovers and from statistical testing due to low sample size.

Holdovers are accompanied by lower T_{max}, lower VPD, and higher FM_{100} and FM_{1000} compared to promptly-detected LIWs in a majority of ecoprovinces (Figure 4). We note, however, that daily-averaged values do not capture exact conditions during the hour of ignition, and hourly meteorological data at the spatial resolution used here are not available. Previous work shows that LIWs rarely become a holdover if ignition occurs during the morning-afternoon burning window, when fine fuels are primed for combustion (Pineda & Rigo, 2017). In addition to more precipitation, cooler and more humid environmental conditions along with late afternoon-evening ignition likely increase holdover probability. As holdovers represent ∼15% of all LIWs, accounting for their differing ignition precipitation and environmental conditions could advance prediction and identification of LIWs, and provide fire managers with information to retain resources after lightning events if conditions for holdovers are present.

Overall, our findings indicate that the widely-used 2.5 mm precipitation amount is only useful when characterizing LIWs in limited regions and a subset of scenarios. Ignition precipitation amounts are affected by climate and vegetation characteristics including tree cover, and differ by fire size. We suggest that spatially varying, vegetation-specific precipitation thresholds would more accurately characterize the risk of LIW ignition and holdover potential in different ecoprovinces of the WUS. Our results can inform prediction, modeling, and future projections of LIWs across this region to aid the suppression, management, and adaptation to these fires in a changing climate with increasing wildfire risk.

Data Availability Statement

MRMS data are from NOAA's National Severe Storms Laboratory, sourced from Iowa State University's Environmental Mesonet archive (https://mtarchive.geol.iastate.edu/). IMERG data were acquired from NASA's Goddard Earth Sciences Data Information Services Center (GES DISC; https://disc.gsfc.nasa.gov/datasets/GPM_3IMERGDF_06/summary?keywords=imerg). MODIS land cover data (250 m) is from the 2010 North American Environmental Atlas, made available by the Commission for Environmental Cooperation (http://www.cec.org/north-american-environmental-atlas/land-cover-2010-modis-250m/). Percent tree cover (as of 2020; 250 m) is from the MODIS Vegetation Continuous Fields dataset (MOD44B) sourced from the USGS Land Processes Distributed Active Archive Center (https://lpdaacsvc.cr.usgs.gov/appeears/). Ecoprovince polygons are sourced from the US Geological Survey (https://www.sciencebase.gov/catalog/item/54244abde4b037b608f9e23d). The NLDN lightning data are not publicly available at the resolution used herein, but can be purchased directly from Vaisala, Inc. (https://www.vaisala.com/en/products/national-lightning-detection-network-nldn) or Earth Networks (https://www.earthnetworks.com/product/lightning-data/). Datasets used to perform the analyses are available at the following Zenodo repository: https://doi.org/10.5281/zenodo.7761326 (Kalashnikov, 2023a). Source code to create publication figures can be accessed at the following GitHub repository: https://github.com/dmitri1357/Lightning-fire-precipitation (Kalashnikov, 2023b). Geospatial analyses were performed using the Python packages *GeoPy*, *GeoPandas*, and *rasterio*.

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