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Precipitation associated with lightning ignited wildfires in Arizona and New Mexico

Beth L. Hall *
Desert Research Institute, Reno, NV

1. INTRODUCTION

From 1990 to 1998, over 15,000 naturally ignited wildfires were observed in Arizona and New Mexico on US Department of Interior and US Department of Agriculture's Forest Service land. This number represents less than 0.35% of all recorded cloud-to-ground (CG) lightning strikes that occurred during the fire season of April through October those years. Given the high aridity of this region, why do some lightning strikes ignite fires and others do not? Factors that influence the potential for wildfire ignition include the availability of ignition sources (in this case lightning), the availability of fuel from the presence of vegetation, and the dryness or low moisture content of those fuels. Precipitation associated with CG lightning can lower the potential of observed wildfires by either increasing the moisture content of the or by extinguishing the wildfire prior to detection. Wildfire ignitions in this region are often attributed to what is referred to as "dry" lightning, or lightning with little or no precipitation.

For natural wildfires, the primary ignition source is CG lightning. The availability of CG lightning (Barrow 1978; Price and Rind 1993; Meisner et al 1993) and the continuous channel, polarity, and multiplicity of the strike (Flannigan and Wotton 1991) influence the probability of wildfire ignition. The moisture content of the fuel will effect not only the efficiency of heat absorption, but also the likelihood of fuel temperatures reaching the critical point of ignition from a lightning strike without first having all of the energy from the strike expended by conversion of the available moisture into steam.

Several studies have examined how much fuel moisture is necessary to prevent a wildfire ignition. The finer fuels such as duff, dead pine needles (Viegas et al 1992) and slash (Meisner et al 1993) are most susceptible to ignition since they are most likely to be the type of fuels with the lowest moisture content. Flannigan and Wotton (1991) developed a Duff Moisture Code primarily designed to predict when these finer fuels would be dry enough to likely ignite if struck by lightning given the surrounding weather conditions. However, Renkin and Despain (1992) argue that it is the degree of departure from average moisture conditions that is indicative of what they referred to as "fire severity" in terms of both the number of ignitions and the area burned.

Atmospheric conditions exert the primary control of fuel moisture content (Rorig and Ferguson 2002; Price and Rind 1993; Meisner et al 1993). Though CG lightning activity is essential for ignition, the presence of precipitation and humid air near the surface will augment the fuel moisture content. Rorig and Ferguson (1999 and 2002) found that a mean dewpoint depression of 17.7°C at 85 kPa was associated with instability necessary for convection, and a mean temperature difference of 31.3°C between the 85 and 50 kPa were indicative of dry, low level conditions that would not only lead to a reduction of moisture content of available fuels, but also inhibit precipitation from reaching the fuels during the lightning storm.

This study used daily and hourly gridded precipitation derived from historical gauge data to compare the amount of precipitation associated with natural wildfires (WF) and CG lightning that was not associated with WF events. Observed natural wildfires (WF) were more often associated with less than 1.5 mm of precipitation on the day of the event than lightning strikes without an associated ignition (LWOI). This precipitation threshold amount provides the most representative separation between WF and LWOI populations. The results of this study can be applied to regional climate simulations or mesoscale gridded forecasts and analyses of daily precipitation amount to indicate areas where there is an increased probability of wildfire occurrence assuming the other factors of ignition source and fuel availability are present.

2. DATA

This study utilized data for the time period 1 April - 31 October during the years 1990 through 1998. These months represent the bulk of the fire season in this region. Though the region includes Arizona and New Mexico, only public lands of the US Department of Interior (DOI) (Bureau of Land Management, Fish and Wildlife Services, Bureau of Indian Affairs, and National Park Service) and US Department of Agriculture (DOA) (Forest Service) was considered due to the limitation of available wildfire occurrence data to these areas.

Wildfire data was acquired from the Program for Climate, Ecosystem, and Fire Applications (CEFA; http://cefa.dri.edu) fire database that consisted of fire records from the US DOI Form-1202 and the US DOA FS Report 5100-29. Fires were recorded in (or converted to) degrees latitude and longitude to the nearest hundredth of a degree. The temporal resolution is the local calendar day when the fire was discovered. Only fires with the general cause of 'natural' were included in the analysis.

It is important to note the uncertainties associated with this fire dataset. First, the date of discovery is not always the date of ignition, since a fire could have been ignited and smoldered for several days before advancing to a detectable stage. Therefore, WF data were cross-checked with the lightning data to discard all fires that had no lightning occurrence recorded on the

* *Corresponding author address*: Beth L. Hall, Desert Research Institute, Division of Atmospheric Science, Reno, NV 89506; e-mail: Beth.Hall@dri.edu.

day of discovery. Another potential source of uncertainty is geographical location coding errors. The data was quality controlled to remove such errors as fires mis-located over water bodies (Brown et al 2002).

Lightning data were obtained from the National Lightning Detection Network (NLDN) operated by Vaisala, Inc™. This network uses frequencies in the 1kHz to 1Mhz range to detect CG lightning discharges (Flannigan and Wotton 1990; Cummins et al 1998a; Cummins et al 1998b). Data is provided to the nearest fraction of a second in UTC time for latitude and longitude coordinates to the nearest thousandth of a degree. The NLDN data is believed to have a location efficiency of 500-600m and a detection efficiency from 80-90% at 5kA or higher in this region (Cummins et al 1998a; Cummins et al 1998b; Idone et al 1998; Orville et al 2002). Lightning data that was within 0.25 degrees (Cartesian distance) from a fire on the day of discovery was removed from the analysis in order to separate strikes that did not ignite a fire from those that may have. This distance was chosen since it corresponds to the spatial resolution of the daily precipitation dataset.

Precipitation data were obtained from hourly and daily gridded data sets developed by Higgins et al (1996; 2000). The gridded data set originated from the CPC Cooperative precipitation observation network, hourly and once-daily NCDC cooperative reports, and hourly GOES/Data Collection Platform (DCP) Centralized Automated Data Acquisition System (CADAS) precipitation reports. Quality control was performed on the data prior to distribution using radar and satellite information. The daily gridded data had a spatial resolution of 0.25x0.25 degrees. The daily time period for any specific date extended 24 hours beginning at 1200 UTC on the previous day. To correspond to the daily local time dimension of the fire data, a 7-hour shift was applied and each precipitation value was assigned to the previous day to represent precipitation over the 24 hours ending at 0500 LST. Hourly gridded precipitation data had a spatial resolution of 2.0x2.5 degrees and the time was converted from UTC to LST. Potential errors from this dataset include the possible underestimation or overestimation of precipitation amount from discrete spatial locations to a gridded value covering a large spatial area. Association of precipitation amount to each WF and LWOI event used a weighted bilinear interpolation function provided in the NCAR Command Language (NCL) software package. This function interpolates a precipitation amount based upon the distance from the lightning or fire event location to the surrounding grid points' center location.

Since one of the three main factors for ignition is fuel availability, vegetation data were used in the analysis to determine if there were different precipitation characteristics associated with finer (e.g., grass or shrub) versus heavier (e.g., tree) fuels. Vegetation cover type data was acquired from the Cover Type version 2000 data set developed by Schmidt et al (2002). This data set consists of the combination of two pre-existing remote sensing data sets: the Forest and Range Resource Planning Act's layer of the US Forest Type Groups (Powell et al 1992; Zhu and Evans 1992, 1994) that examined forest cover types, and the Land Cover Characteristics Database (Loveland et al 1991) that examined non-forest cover types. Both of these data layers were derived from the 1 km^2 resolution Advanced Very High Resolution Radiometry (AVHRR) satellite imagery, to produce a 1 km^2 resolution vegetation cover type dataset for the continental US. For this analysis, cover types were grouped into three classes: grass, shrub, and trees.

Past research has indicated a possible dependence of lightning activity and fire ignitions on elevation (Díaz-Avalos et al 2001). Therefore, discriminating WF and LWOI occurrence by ranges of elevation were analyzed. Elevation data were acquired from the US Geological Survey (USGS) 200m Digital Elevation Map (DEM) data set. Three ranges of elevation were selected for analysis: ≤ 1000 m, 1001 m to 1900 m, and >1900 m.

3. Climatology of Arizona and New Mexico

Figure 1 shows the seasonal time series of WF and LWOI events averaged over the 1990 to 1998 time period. A Stineman function was applied to the data that assigns a geometric weight to the current data point in the series and ±10% of the data range, in order to smooth the time series (Stineman 1980). Figure 1 shows that the main fire activity occurs between late-June through mid-August.

Unlike the climatology presented for WF events and CG lightning strikes that represented activity only on DOI and DOA land, precipitation climatology is presented for the entire states of AZ and NM due to the coarse nature of the gridded datasets. The season of peak precipitation generally coincides with the peak lightning season, which is shifted slightly forward in time by several weeks from the peak WF event season. There is an initial surge of precipitation in the first half of July, typically associated with early monsoon seasonal influences. Note the decrease in WF events at this time. The average number of WF events sharply decreases approximately half way through the peak

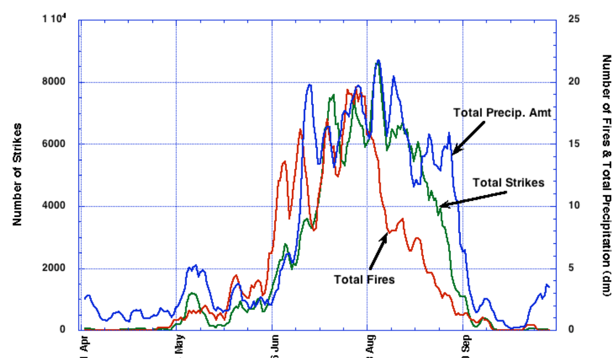

Figure 1. Smoothed daily median number of fires (red) and number of strikes (green) on DOI and DOA land, and total daily amount of precipitation (dm) (blue) over Arizona and New Mexico from 1 April through 31 October.

Figure 2. Total number of natural fires (red) and lightning strikes (green) on DOI and DOA land, and precipitation (dm) (blue) in Arizona and New Mexico per fire season (1 April through 31 October).

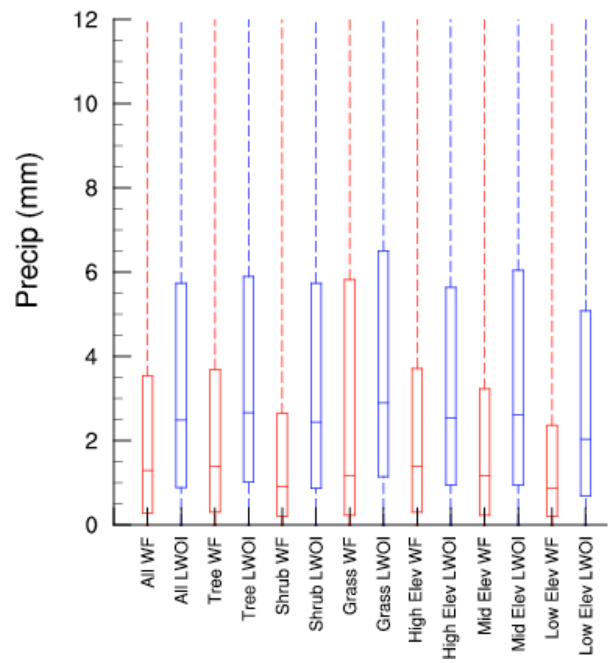

Figure 3. Box plots representing the amount of precipitation that occurred on the day of each lightning (blue) and fire ignition (red) events, by different classes. Note the vertical axis range is limited to 12 mm to better highlight the inter-quartile range (25-75% of the sorted data, indicated by the boxes).

precipitation and lightning seasons (i.e., early to mid-August). This could be due to a general increase in fuel moisture from the previous month of abundant precipitation, but could also be due to an increased number of "wet" lightning events associated with precipitation reaching the ground.

There is significant inter-annual variability of WF events in this region. Figure 2 shows the total number of WF events for each year. Peak years were 1994 (2766 WF events) and 1996 (2530), whereas the years with the lowest occurrence of WF events (1998 and 1991) had significantly lower numbers of fires.

From year to year, the inter-annual variability of precipitation amount appears to have an indirect relationship to the number of WF events or CG lightning strikes (Figure 2). When there is above average precipitation during the fire season, there are fewer WF events; when there is below normal precipitation during the fire season, the level of fire activity appears to be driven by the level of CG lightning activity.

4. Precipitation thresholds associated with WF events

In order to determine if there is a threshold amount of precipitation typically associated with WF events, a daily precipitation amount was assigned to each event using the bilinear interpolation scheme mentioned in Section 2.

Figure 3 shows the data distribution of precipitation amounts for each classification of WF and LWOI events through graphical box plots, where the top and bottom edges of the boxes represent the 75^{th} and 25^{th} percentile value respectively, and the middle line represents the median. Note that for all scenarios, 75% of the WF events were associated with a precipitation amount less than 60% of the LWOI events. In other words, a larger percentage of WF events are associated with lower precipitation amounts than LWOI events.

The scenarios with the strongest distinction between precipitation amounts associated with WF events versus LWOI events are events that occurred in shrub vegetation and at low elevations, but not necessarily simultaneously. For both of these scenarios, more of the WF events (approximately 75%) were drier than approximately 50% of LWOI events. The scenario with the weakest delineation of precipitation amounts between WF and LWOI events was within the grass vegetation type. Here, the top edge of each event's box plot was relatively close to each other compared to the boxes in the other scenarios.

It is difficult to assess a unique threshold of precipitation that is associated with only WF events and not LWOI events given such wide ranges of rainfall amounts as is shown in Figure 3. However, one method is to identify the precipitation amount that separates the largest percentage of WF events from the largest percentage of LWOI events at intervals of 0.25 mm of precipitation.

The difference in the percentage of WF and LWOI events was computed for specific precipitation amounts was calculated using Equation 1, where α is the tested threshold precipitation amount. The numerator of each fraction is the number of cases that occurred at or below α; the denominator is the total number of cases that occurred. The amount of precipitation associated with the greatest difference in the percentage of cases for the two events is defined to be the precipitation threshold where amounts less than this are more likely to associated with WF events than LWOI events.

$$\%Diff_{\alpha} = \frac{WF_{\leq\alpha}}{WF_{Total}} - \frac{LWOI_{\leq\alpha}}{LWOI_{Total}} \quad \text{(Eq. 1)}$$

Table 1 presents the precipitation amount (mm) that showed the greatest difference in the percentage of the WF and LWOI populations. 53.6% of the WF events occurred at or below the precipitation threshold value of 1.5 mm, while only 36.2% of LWOI events occurred below this threshold. The grass vegetation class had the lowest threshold precipitation value. Regardless of elevation class, the majority of WF events were associated with a daily precipitation threshold of 1.3 – 1.5 mm.

The lowest precipitation thresholds occurred at low elevations. When all vegetation classes were combined at low elevation, a precipitation amount of 1.5 mm or less was the defining threshold. Sub-setting by vegetation class, resulted in a decrease in threshold value. WF events that occurred in tree, shrub, or grass vegetation classes at low elevations were typically associated with precipitation amounts of 0.5 mm or less, as opposed to the precipitation amounts typically associated with LWOI events. WF events at high elevations in grass were typically associated with higher amounts of precipitation (up to 1.8 mm).

Precipitation characteristics at an hourly scale used the coarse hourly gridded precipitation dataset. There were three time periods of interest for this part of the analysis: rainfall rate prior to the hours of the event, rainfall rate during the hours of the event, and rainfall rate after the hours that the event occurred. The same bilinear interpolation method was used to associate a precipitation amount to each fire and lightning event location. To correspond to the 24-hour period of a day as defined by the daily gridded dataset, hours prior to each event started at 5 AM LST and hours after each event went through the 4 AM LST hour the next day. For each of the time periods, the average precipitation amount for that time period was computed by dividing the total amount of precipitation by the total number of hours in that time period. For example, if a fire event was determined to occur sometime between 1300 and 1600 LST due to continuous lightning activity, then the precipitation rate prior to the event would have been based upon hourly precipitation from 0500 through 1200 LST, and the precipitation rate after the event would be based upon hourly precipitation from 1700 LST through 0400 LST the next day. Since the hour of ignition was estimated based upon when there were nearby CG strikes, there might have been several consecutive hours when WF events were assumed to have occurred, while each LWOI had its own unique hour.

Figure 4 shows the distribution of average precipitation amounts for the three time periods relative to when the event occurred for both WF and LWOI events. For each time period, LWOI events are typically

Table 1. Thresholds of accumulated daily precipitation (mm) that marked the greatest difference in the percentage of NF events and the percentage of LWOI events.

Event Class	Ppt Amt (mm)	% Diff	% of WF	% of LWOI
All	1.50	17.5	53.6	36.2
Tree	1.50	18.2	51.7	33.5
Shrub	1.50	25.7	62.7	36.9
Grass	1.00	26.1	49.1	23.0
Low Elev	1.50	23.1	65.2	42.1
Mid Elev	1.50	22.3	57.3	34.9
High Elev	1.30	16.8	47.5	30.8
Low Tree	0.25	30.9	50.0	19.1
Low Shrub	0.50	31.1	61.0	29.9
Low Grass	0.50	33.2	60.0	26.8
Mid Tree	0.50	15.7	38.3	22.6
Mid Shrub	1.00	30.1	66.5	36.4
Mid Grass	1.50	25.5	66.7	41.2
High Tree	1.50	19.1	57.3	38.2
High Shrub	0.76	26.7	55.6	28.9
High Grass	1.80	27.4	70.4	43.0

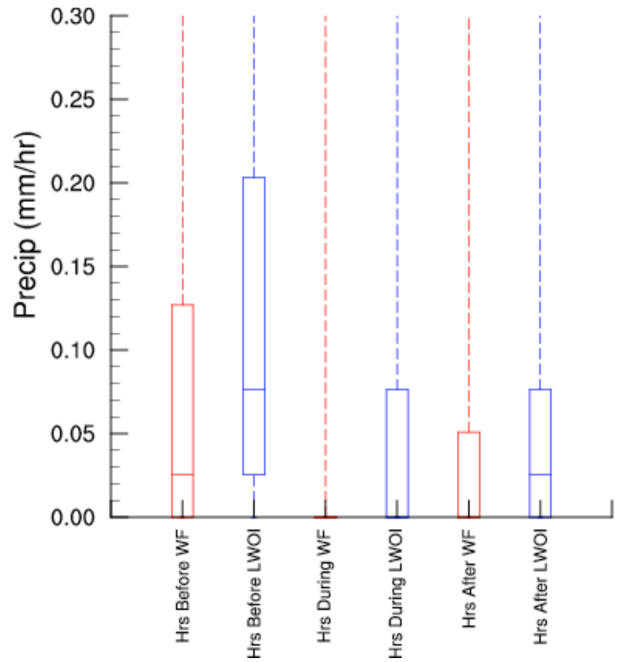

Figure 4. Distribution of average hourly precipitation rate (mm/hr) for WF events (red) and LWOI events (blue). There are three groups of box plots, where the first group represents the hourly precipitation rate that occurred at the event location from 5AM on the day of event up to the hour of the event. The second and third groups are similar to the first group, but represent hours during the event and hours after the event up through 4AM the next day, respectively.

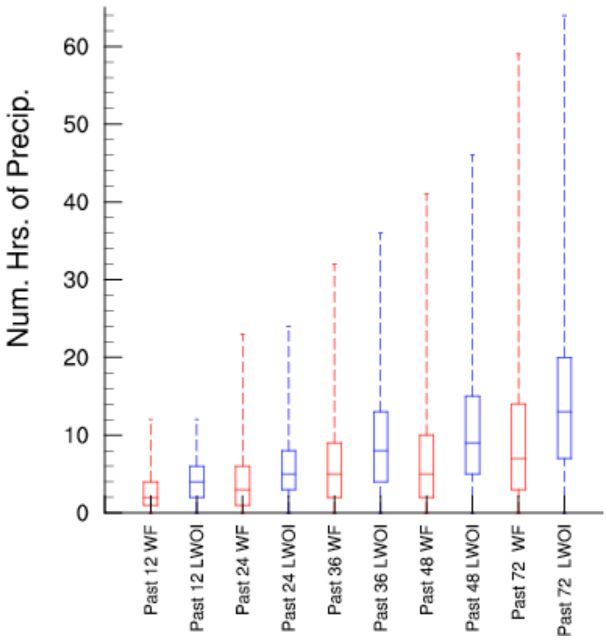

Figure 5. Distribution box plots representing how many hours over the past 12, 24, 36, 48, and 72 hours prior to the event (labeled on the x-axis) had precipitation for WF (red) and LWOI (blue) events.

associated with more precipitation than WF events. Though this may have been expected based upon the information presented in Figure 3, it was theorized that the time period with the highest amount of precipitation might be different between the WF and LWOI events. For example, if the highest precipitation amounts for WF events tended to occur prior to the WF event, but the highest precipitation amounts for LWOI events tended to occur after the LWOI events, this might suggest that LWOI could have extinguished WF events prior to a WF detection. However, both WF and LWOI events had their highest amount of precipitation occur prior to the events taking place. WF events have no associated precipitation at least 75% of the time (seen by the lack of a graphical box). This shows strong evidence that the majority of WF events are associated with “dry” lightning conditions where there is no precipitation during the hours of the event. In contrast, almost half of the LWOI events had some precipitation during the hour of the event and over 50% of the LWOI events had precipitation following the event.

To address the theory that the duration of precipitation rather than the amount of precipitation is more important to a WF ignition, hours of precipitation leading up to the event were counted within five time spans (12, 24, 36, 48, and 72 hours) leading up to the event. The objective was to determine if there was a time frame prior to the event where LWOI events clearly had more hours of precipitation than WF events. Figure 5 shows the distribution of the number of hours for each preceding time period for both WF and LWOI events. Figure 5 shows that LWOI events are associated with more hours of precipitation. For the 48 hours preceding events, 75% of WF events had 10 or less hours of precipitation compared with 14 hours with precipitation for the LWOI events. A caveat for this dataset is that total number of minutes with precipitation within each hour is unknown, only that sometime in each 60-minute period there was precipitation designated at that event location.

5. Discussion

The amounts and duration of accumulated precipitation, including the thresholds, should be used with caution for several reasons. First, precipitation amount assigned to each event was derived from relatively coarse grids, where interpolation from the center of the grid to the event location assumes that rainfall is a spatially continuous field over the grid cell. There is potential to have underestimation or overestimation of precipitation amounts at each event location. Box plots were used in the analysis to represent the sample population, and the quartile values are considered to be representative of the population. Values of the tails of each box plot (representing the 25% extremes of the data) may be under- or over-estimations.

Another potential source of uncertainty in this analysis is variable fuel density. Given the relatively sparse distribution of fuels in the study region, it is reasonable to assume that many LWOI events never made contact with vegetative fuel. Since ground truthing of fire occurrence for each CG strike is impractical, fuel distribution effects are evaluated broadly.

Analysis of precipitation timing indicated that both WF and LWOI events often had a higher precipitation rate prior to the event than during or after the event. At least 75% of the WF events were associated with zero precipitation during the likely hours of ignition, a strong indication of the effect of “dry” lightning. The results supported the argument that LWOI events have more hours of precipitation leading up to the event than do WF events.

6. Application of findings

The results of this study can be used to evaluate ignition potential for regional climate analysis and mesoscale forecasts. Also, since WF events seem to be associated with a lower precipitation threshold in grassy areas than other vegetation types, precipitation simulations and observations can be integrated with vegetation data to assist in identifying the most vulnerable ignition locations. Since most forecast model output is in a gridded data format similar to the precipitation data set used in this analysis, shading of a contoured region indicating 1.5 mm of daily precipitation or less could be used to highlight regions most susceptible to observed ignitions provided there are both available fuels and ignition sources.

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