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Proximity Meteorological Observations for Wind-driven Grassland Wildfire Starts on the Southern High Plains

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ABSTRACT

Wildland fire behavior is highly dependent upon local meteorological conditions. While topography and the state of available fuels also influence fire behavior and spread, near-surface atmospheric conditions in proximity to wildland fires are the most dynamic determining variables for wildfire evolution. Recent episodes of drought across the southern High Plains have contributed to unprecedented wildfire activity in the region's grasslands, including within the Texas Tech University West Texas Mesonet (WTM) domain. The juxtaposition of this meso-network with the occurrence of numerous wind-driven wildfires has provided a unique dataset of proximity meteorological observations useful in analyzing fire start environments. This study presents statistical analyses of WTM 2-m relative humidity and 6-m wind speed, parameters utilized in local Red Flag fire weather warning criteria, along with 2-m temperature in temporal and spatial proximity to 99 wind-driven grassland wildfire starts which occurred between January 2006 and May 2010. Since the state of vegetative fuels also influences fire behavior, but is dependent upon local weather, the proximity observations are used to calculate fine dead-fuel moisture and to examine pre-conditioning potential per the preceding humidity recoveries for each documented fire start. A comparison of the meteorological observations to local Red Flag warning criteria, which was met or exceeded for critical values of relative humidity and wind speed in 64% of the surveyed fire starts, also is included. Furthermore, seasonal and diurnal tendencies for local wind-driven wildfire activity are noted.

1. Introduction

Episodes of long-term drought, interrupted by brief reprieves of periodic heavy rainfall, have characterized the climatology of the southern High Plains in recent years. An artifact of this climatic variability has been an enhanced cycle of vegetative growth and curing of abundant grassland biofuels that has contributed to increased levels of wildland fire activity (Van Speybroeck et al. 2007).

Between January 2006 and May 2010, hundreds of wind-driven grassland wildfires occurred in the domain of the Texas Tech University West Texas Mesonet (WTM)—one of the region's densest networks of meteorological surface observations (Schroeder et al. 2005). The unprecedented number and severity of recent wildfires in the southern High Plains have provided data useful in efforts to correlate proximity meso-β and meso-γ scale weather observations to conditions that promote rapid fire spread and subsequent wildfire development.

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This study presents analyses of observed meteorological WTM data obtained in spatial and temporal proximity to 99 wind-driven grassland wildfire starts. The presentation of these proximity observations and analyses is preceded by a discussion of seasonal and diurnal trends for local wildfire activity evident in the dataset. This survey, however, is largely focused upon the most commonly used meteorological variables in fire weather prediction: 2-m relative humidity (RH) and 6-m wind speed (adjusted from 10-m measurements). National Weather Service (NWS) policy defines critical values for these meteorological parameters that serve as explicit criteria for local Red Flag warnings (RFWs). The relationship between 2-m RH and 6-m wind speed for wildfire starts is investigated through a statistical correlation analysis, and is shown to be significant and slightly linear. The observations additionally are differentiated by the eventual fire size for each start to further illustrate how specific combinations of RH and wind speed may influence potential for fire growth.

Near-surface air temperature and RH, also help to determine fuel temperature and moisture, in turn contributing to subsequent fire behavior. Therefore, this study also considers proximity observations of 2-m temperature and 2-m temperature deviation from climatology. The concept of fire behavior's codependency on local weather and fuels is further pursued through the application of 2-m RH and 2-m temperature proximity observations toward calculations of fine dead-fuel moisture content (Rothermel 1983) for grassy fuels associated with the documented wildfire starts. The observed 24-hour 2-m RH recovery, or maximum overnight RH, preceding fire starts also is examined in order to investigate the potential pre-conditioned state of available fuels prior to ignition.

Lastly, the proximity observations of 2-m RH and 6-m wind speed are compared to local meteorological RFW criterion. Although recommendations for improved RFW criteria are beyond the scope of this study, the data illustrates how critical fire weather that promotes problematic fire behavior and wildfire growth in grasslands exists along a spectrum of RH and wind speed combinations that are not limited to the currently defined RFW criteria.

2. The weather-wildfire relationship

Wildfire evolution is closely related to environmental and meteorological conditions. Three specific, yet interdependent factors influence fire behavior: weather, fuel and topography (USDA cited 2008). Local topography, as well as the type and amount of available fuels, remain constant on short-time scales. Other fuel characteristics such as moisture and temperature, however, are variable and highly dependent on local weather conditions which can change dramatically on the order of only a few hours. As such, certain infrequent combinations of weather long have been noted as prerequisite to wildland fire (Brotak and Reifsnyder 1977). Furthermore, in the presence of receptive fuels, fire fighting and land-management officials recognize near-surface atmospheric conditions as the most dynamic variables to influence wildland fire behavior and severity (Heilman 1995). Precipitation, atmospheric moisture, stability, temperature, and changes in wind speed and direction all play important roles in determining fire behavior (Davis 1959 and Brotak 1976). RH and wind speed, however, are the most commonly used operational fire weather indicators.

Very large and often damaging grassland wildfires in the southern High Plains are frequently driven by strong, southwesterly or westerly downslope winds that promote extremely dry air and unseasonably warm near-surface temperatures. These meteorological conditions commonly are exacerbated by the passage of mid latitude cyclones, an enhanced variation of the "Chinook-type" synoptic pattern that long has been recognized as a contributor to weather which promotes wildland fire in the region (Schroeder et al. 1964). Particularly widespread and destructive wildfire episodes were observed across large portions of the southern High Plains in association with the passage of several such large-scale weather features coincident with periodic drought during the study period (Lindley et al. 2007). The profound societal impacts that resulted from such "wildfire outbreaks" during the study period, including more than 1.6 million acres (647 772 ha) burned and 15 human deaths within the WTM domain (NCDC 2006, 2008 and 2009), illustrate the danger posed by wind-driven grassland wildfires in the southern High Plains, and underscore the need for intensive meteorological study of the weather regimes in which they occur.

3. Methodology

This study utilizes the National Oceanic and Atmospheric Administration's (NOAA) network Weather Surveillance Radar 1988 Doppler (WSR-88D) coverage and Geostationary Operational Environmental Satellite-12 (GOES-12) infrared imagery to identify fire start times and locations. Remotely-sensed start times and locations were found using the initial detection of either biomass debris lofted within smoke plumes via radar reflectivity or infrared satellite "hot spots" detected in 4 km 11–3.9 µm channel imagery (Fig. 1) for each of the 99 wind-driven wildfire starts documented within the WTM domain (Huang et al. 2007 and Jones and Christopher 2010).

Wildfire starts included in the dataset evolved to range in size between 300 acres (121 ha) and 479 549 acres (194 063 ha), as reported by local and state officials. The mean fire size was 24 009 acres (9716 ha) while the median value was 2500 acres (1012 ha). All of the included fire starts either developed into "significant" grassland wildfires (defined by NOAA 2007) as ≥300 acres (121 ha), or exceeded the USDA (2006) Forest Service definitions for "severe" (1000 acres or 405 ha) wildland fires in the south-central U.S.

All of the examined wildfire starts occurred between 1 January 2006 and 10 May 2010. This study period included five local climatological fire seasons, which traditionally have been recognized to persist through the winter and early spring months of the region's cool season. A majority of the wildfires that occurred in the southern High Plains during this period, and 69% of the fire starts presented here, were associated with regional outbreaks of widespread wildfires occurring simultaneously across large areas of eastern New Mexico, Texas and Oklahoma. Wind-driven wildfires, which tend to occur during the cool season (winter and early spring) were examined. Lightning-initiated grass fires, which sometimes occur in more moist environments characterized by lower sustained wind speeds and less volatile, post green-up fuels during the region's warm season, were not considered. Such fires tend to be smaller in scale, of shorter duration, and historically have posed a lesser degree of public threat than the cool-season, wind-driven fires documented here. In contrast, this dataset includes the largest, most destructive, and deadliest wildfires in Texas history (Weaver 2006 and Brown and Smith 2007). The study period also is characterized by unprecedented wildfire frequencies significantly higher than the region's expected recurrence interval of 13–27 y for fires ≥10 km^2 (≥2471 acres or 1000 ha) as calculated by Malamud et al. (2005).

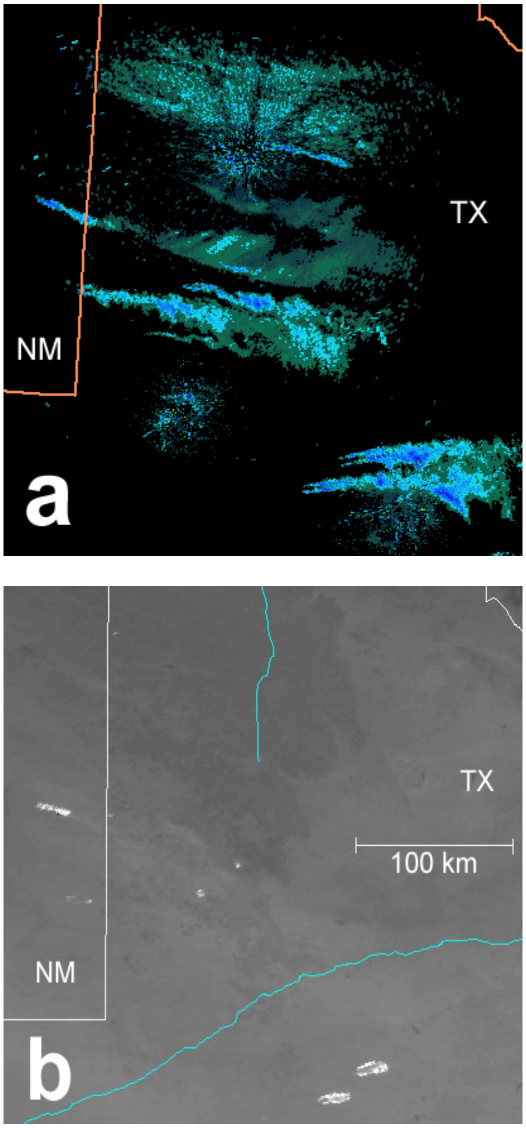

Figure 1: Smoke plumes from wildfire activity remotely-sensed via a) Doppler radar reflectivity and b) GOES-12 infrared satellite image at 2342 UTC 1 January 2006. *Click images to enlarge.*

Start times and locations for each wildfire, as detected by the aforementioned remote sensing methods, were compared to 5-min observations of 2-m AGL RH, 10-m AGL wind speed, and 2-m AGL temperature from the nearest WTM site

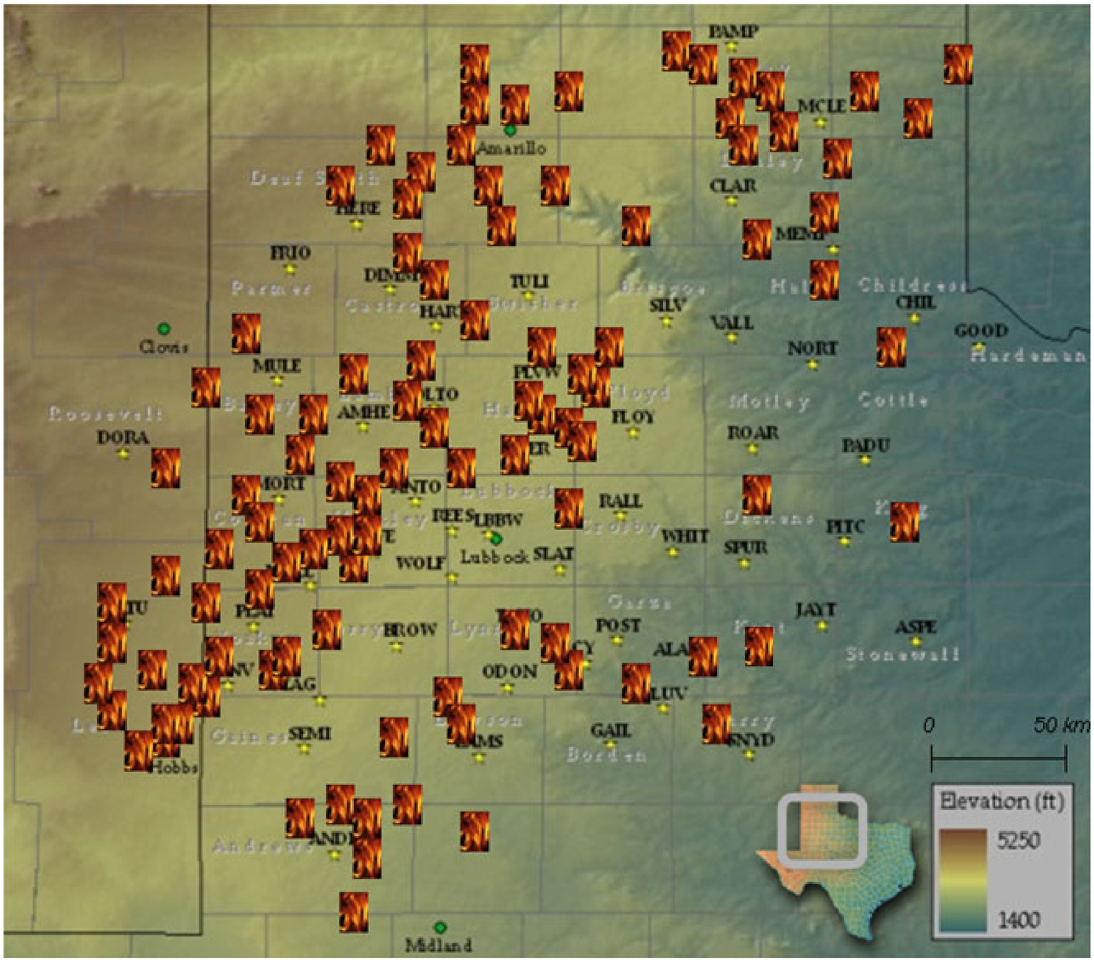

Figure 2: WTM domain with observation sites (yellow stars) and text identifiers (black text). Flame icons denote locations of 99 wind-driven wildfire starts determined by remote sensing for the period January 2006 to May 2010. The names of counties in which WTM sites are located also are labeled (gray text). *Click image to enlarge.*

(Fig. 2). Satellite-based detection of wildfires results from large differences in detected temperature and is not dependent on actual fire size. Also, potential limitations in satellite-based fire detection resulting from cloud obscuration were negated through the concurrent use of radar-detected plumes. The identification of wildfires in either radar or satellite imagery only was limited temporally by scan and data refresh rates (10 min for radar and 15 min for satellite). Accordingly, lag times in fire recognition and total temporal errors for the estimated start time proximity observation are <20 min, based on the 10-min to 15-min availability of radar and satellite imagery plus the 5-min resolution WTM data.

Temperature measurements (F) and 6-m AGL wind speeds (mph) are exclusively used by fire fighting and fire management personnel, and in fire weather forecasts, warnings, and observations. All WTM temperature and wind speeds are referenced similarly herein (metric units parenthesized in text).

Measured 10-m wind speeds were reduced to approximated 6-m values using a 0.886 conversion factor. Although a 0.800 conversion traditionally has been used to extrapolate 6-m wind speeds from 10-m measurements across the study domain, as dictated by the Region 3 Area Operating Plan (Southwest Coordination Center (SWCC) 2010), an attempt was made to quantify an appropriate 10-m 6-m conversion factor for this study.

Through cooperation between the NWS and Texas Tech University, a 6-m anemometer was installed at the Reese Center (REES) WTM site, 19 km west of Lubbock, TX and centrally located within the WTM domain. This additional anemometer was used to measure observed 6-m wind speeds and to derive an appropriate 10-m 6-m conversion factor for use in fire weather applications within the WTM domain. The three-cup style, R.M. Young Wind Sentry anemometer sampled every 3 s and measured a 5-min average wind speed, direction, and peak 3-s gust. Wind readings from 10 m, 6 m, and 2 m were analyzed to study variations of wind speed on the REES tower, and measurements collected during the diurnal burning period February 2009 through April 2009 were utilized to derive the 0.886 conversion factor. The 10-m–6-m relationship found at REES is consistent with findings by Bradshaw et al. (2003) in a similar field comparison.

The WTM's dense network of 59 automated observing sites provided a unique opportunity for sampling meteorological environments within proximity to wildfire starts. The mean distance between documented fires and the nearest WTM site was 24 km. With only 14 conventional surface weather observing platforms that provide hourly meteorological observations operational within the WTM domain as of this writing, both the spatial (24-km average) and temporal (<20 min) proximities for WTM observations to wildfire starts utilized here improve upon that possible by use of standard surface observing networks alone. These distances also are notably small when compared to "proximity observations" employed in previous meteorological studies that utilized defined proximities as high as 200 km and time scales up to 3 h (Guyer et al. 2006).

In addition to local meteorological factors, topography and the state of available fuels also influence wildland fire behavior. Some fuel characteristics, such as moisture, are variable and highly dependent upon local weather conditions. Therefore, this study utilizes WTM proximity observations to calculate fine dead-fuel moisture content (representative for 1-h and 10-h fuels) within BehavePlus 5.0.1 (Andrews et al. 2005 and 2007), and to document the preceding 24-h 2-m RH recovery and the potential for associated pre-conditioning of fuels.

With such consideration given to the state of relevant biofuels, it is important to consider the ecosystem and terrain of the WTM domain. The domain is comprised of two biophysical regions with elevations that range from 500 m MSL in the east to 1225 m MSL in the west. The Caprock, an abrupt, dominant, mostly north-south oriented escarpment, accounts for a 300-m rise in elevation within a zonal distance of only 25–50 km, and separates the two regions. The eastern third of the WTM domain, east of the Caprock escarpment, is dominated by mesquite-buffalograss vegetative fuel communities. West of the Caprock escarpment, the seemingly flat landscape predominately is covered in native grama-buffalograss vegetative fuel communities that are dissected by large spans of agricultural farmland. These grasslands rise up a gentle slope known as the Llano Estacado (Fig. 3). Grassy 1-h vegetative fuels (buffalograsses) are the primary fire carriers both east and west of the escarpment. Given these topographical and biophysical characteristics, an assumed slope between 0%-30% with a slight east aspect and no shade were incorporated into calculations of fine dead-fuel moisture content.

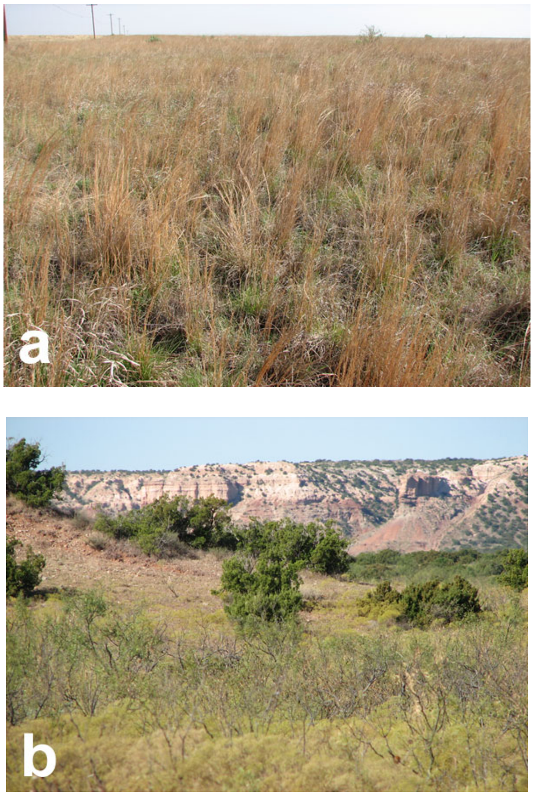

Figure 3: Vegetative fuels within the WTM domain: a) grama-buffalograss west of the Caprock and b) mesquite-buffalograss east of the Caprock. Photos courtesy of Brad Smith, Texas Forest Service. *Click images to enlarge.*

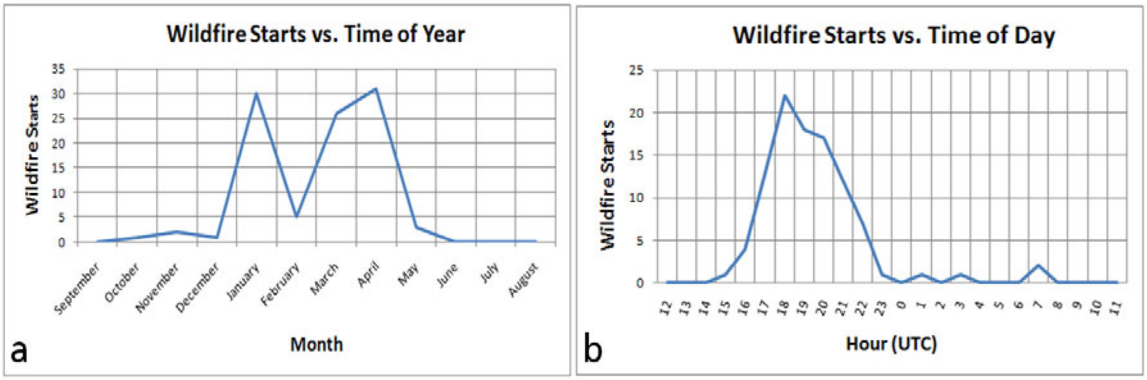

Figure 4: Graphs depicting wildfire starts relative to a) time of year and b) time of day. Time scales are arranged to depict a continuous winter and spring fire season by months and diurnal burning period by UTC hours. *Click images to enlarge.*

4. Observed seasonal and diurnal trends

The dataset of proximity observations for wind-driven wildfire starts presented here is too limited for use as a comprehensive long-term climatological survey of southern High Plains wildfire activity. The data, however, represent a sizable sampling of fire start environments during a 53-month period including five local fire seasons when wind-driven wildfires occurred at an unusually high frequency and intensity. As such, useful information can be determined regarding seasonal and diurnal tendencies for wildland fires in the region.

The occurrence of wind-driven wildfire starts was compared to time of year and day (Fig. 4). Nearly all (93%) of observed wildfire starts occurred during the months of January through April. These months of the region's cool season long have been recognized as the time of year when dry and windy weather patterns most frequently combine with dormant fuels to create favorable conditions for wind-driven grassland wildfires across the southern High Plains. Furthermore, Murdoch et al. (2009, unpublished manuscript) suggests that RH values and wind speeds in excess of local Red Flag criteria occur in west Texas and eastern New Mexico with increased frequency from December through March, then peak in April. This is well-correlated to the annual trends observed here, which also suggest a rapid increase of fire activity during the early winter, and a bi-modal peak of wildfires during winter and early spring. A relative minimum in fire occurrence was observed during February. It is not known if this mid-fire season minimum is an artifact of the small sample size of five seasons or a real climatological signal. February brings the highest frequency of dense fog within the WTM domain (Bomar 1983), and this could contribute to the relatively suppressed state of fire weather and the pre-conditioning of fuels.

In addition, most of the wildfire starts documented here occurred during the midday and afternoon hours. In fact, 94% of the observed fire starts occurred from 1600–2300 UTC, with a pronounced peak during the 1800 UTC hour. This timeframe corresponds to the climatologically expected, local diurnal burn period of maximum insolation, heating, drying, wind speed, and deep boundary-layer mixing.

5. Proximity observations and statistical analyses

a. 2-m RH and 6-m wind speed

The most commonly used meteorological variables in operational fire weather prediction are near-surface RH and wind speed. Thus, this investigation of proximity observations for wind-driven wildfire starts is focused upon these parameters.

WTM proximity observations of 2-m RH and 6-m wind speed for each of the 99 wildfires are presented in Fig. 5. A slight linear relationship between 2-m RH and 6-m wind speed for fire starts exists per a Pearson correlation coefficient (Nater et al. 1996) statistical analysis (r=0.36, P=0.0003), and the relationship between these variables is significant (P<0.05). While correlation is present, causality may not exist

(Bewick et al. 2003). The slight linear relationship between 2-m RH and 6-m wind speed is associated with extremely dry environments characterized by 2-m RH values near 5% with moderately strong 6-m wind speeds between 20 mph (8.9 m s^{-1}) and 25 mph (11.2 m s^{-1}), to more moist environments with 2-m relative humidities upward of 35% accompanied by very strong 2-m wind speeds around 35 mph (15.6 m s^{-1}). A majority (72%) of the wildfire occurrences are clustered within 6-m relative humidities of 4% and 12% with 2-m wind speeds between 13–39 mph (5.8–17.4 m s^{-1}), and 92% of the documented starts occurred when relative humidities were ≤20%.

Specific statistical distributions for the observed wildfire environments are best illustrated with box-and-whisker analyses (Fig. 6). Although observed fire starts occurred when RH ranged between 4% and 31%, half of the cases occurred with 2-m RH between 8% and 14%. The mean 2-m RH value observed in proximity to wildfire starts was 12% and the median value was 10%. Likewise, proximity 6-m wind speeds for wind-driven wildfires ranged from 13–39 mph (5.8–17.4 m s^{-1}). The first and third quartiles were 23 and 31 mph (10.3 and 13.9 m s^{-1}) respectively, while the mean 6-m wind speed was 27 mph (12.1 m s^{-1}) and the median value was 28 mph (12.5 m s^{-1}).

When WTM proximity observations of 2-m RH and 6-m wind speed for fire starts are compared to climatology, the anomolously dry and windy nature of the environments that support wind-driven grassland wildfires in the southern High Plains is evident. Since climatological values of RH and wind speed are variables neither frequently considered by nor readily available to forecasters, such comparisons may have limited operational utility. For the purpose of illustrating how observed fire start environments relate to the region’s baseline climatology, however, the proximity observations for 2-m RH and 6-m wind speed were compared to average, or “normal,” values of daily minimum RH and wind speed at Lubbock, TX (centrally located within the WTM domain) for the date of each wildfire event (Fig. 7). These analyses reveal that the observed wind-driven grassland fires occurred almost exclusively in environments characterized by strong deviations in RH (lower than normal) and wind speed (higher than normal) from climatology.

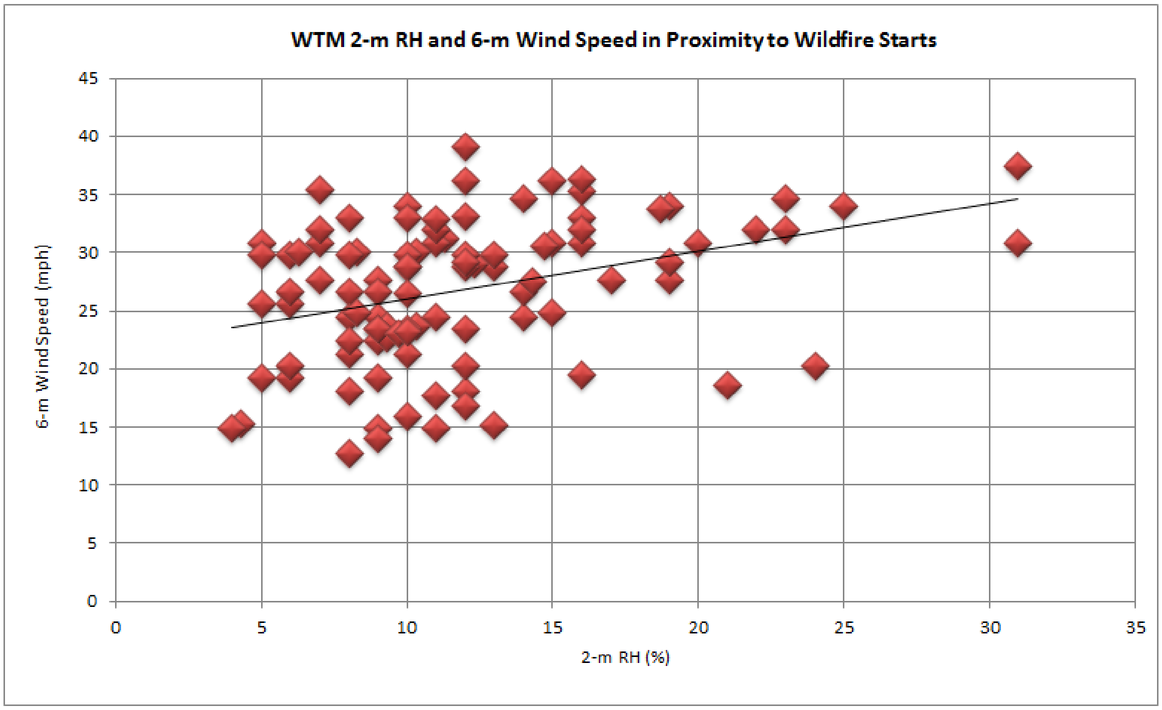

Figure 5: Scatter plot showing WTM proximity 2-m RH and 6-m wind speed observations for 99 wind-driven wildfires and the best fit linear trend line (black). *Click image to enlarge.*

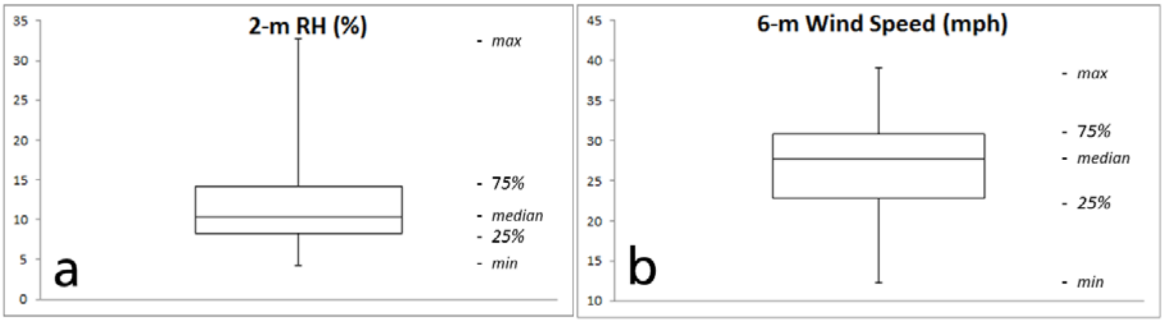

Figure 6: Box-and-whisker plots for a) observed 2-m RH and b) 6-m wind speed in proximity to wind-driven wildfire starts. *Click images to enlarge.*

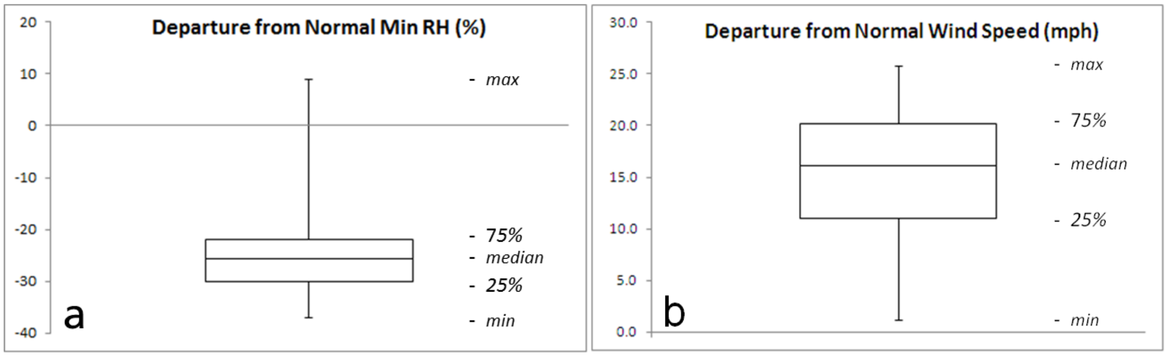

Figure 7: Box-and-whisker plots for proximity RH deviation from: a) normal daily minimum RH and b) climatological daily average wind speed. *Click images to enlarge.*

An operationally useful representation of the proximity 2-m RH and 6-m wind speed analyses, and the statistical relationship between combinations of these variables and fire starts, is derived by quantitatively contouring the data according to frequency of occurrence for observed wildfires. Through the application of an ellepsoidal analysis method (Fox 2002), categories and percentages provide forecasters a visual reference for combinations of RH and wind speed that have been observed in association with wildfire starts. In Fig. 8, the RH and wind speed scatter plot is presented with the range of meteorological environments observed to be associated with wind-driven wildfire starts categorized by “low” (10%), “moderate” (30%), or “high” (60%) distributions of fire start case events. The statistical centroid combination of 2-m RH and 6-m wind speed is highlighted as 12% and 27 mph (12.1 m s^{-1}) respectively. Fire weather forecasters can compare forecast values of 2-m RH and 6-m wind speed to the graph, in order to see how anticipated environments compare to the frequency of wildfire development during the study period.

Fig. 9 differentiates plotted fire starts by their eventual burn size. An examination of start environments for fires which eventually grew to burn areas ≥10 000 acres (4047 ha), ≥20 000 acres (8094 ha), ≥35 000 acres (14 164 ha), and ≥70 000 acres (28 328 ha) suggest that as eventual fire size increases, starts become increasingly focused within dry environments, or along the left portion of the trend line. For example, the distribution of proximity observations for fires eventually exceeding 10 000 acres (4047 ha) is virtually unchanged when compared to all wildfire starts ≥300 acres (121 ha). Fires that consumed areas ≥20 000 acres (8094 ha), however, occurred exclusively when 2-m RH values were <15% with 6-m wind speeds ≥15 mph (6.7 m s^{-1}); and fires that evolved to ≥35 000 acres (14 164 ha) similarly started with 2-m RH <15%, but only with 6-m wind speeds >20 mph (8.9 m s^{-1}). Start environments for ≥70 000 acre (28 328 ha) fires were characterized by 2-m RH of ~10% or lower, and 6-m wind speeds of ~25 mph (11.2 m s^{-1}) or higher.

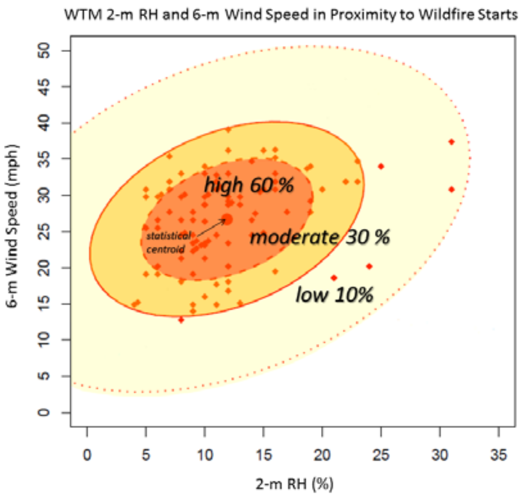

Figure 8: Wind-driven wildfire proximity observation scatter plot for 2-m RH and 6-m wind speed contoured with percentage and categorical occurrences of wildfire evolution. *Click image to enlarge.*

Although such analyses appear to have utility in determining potential fire growth for specific combinations of RH and wind speed, caution should be applied in associating eventual fire size as a proxy measurement of fire severity and in correlating fire size to specific combinationsof RH and wind speed. Local meteorological conditions may vary substantially during the lifespan of a wildfire. In addition, fire size can be dependent upon many non-meteorological variables, such as fire management practices and the availability of suppression resources. Also, the number of fire starts documented here decreases significantly for increasingly large fires. The non-normal distribution of eventual fire sizes in this database (Fig. 10), however, is typical (Malamud et al. 1998). The data analyses presented here supports an operationally useful assumption that meteorological environments promoting the most extreme wind-driven grassland fire growth potential exist along the dry (left) portion of the derived linear relationship-trend line, in environments characterized by 2-m RH <15% and 6-m wind speeds >20 mph (8.9 m s^{-1}).

b. 2-m temperature

Operational fire weather forecasts utilize near-surface RH as an easily predictable and observed proxy for fuel moisture and temperature. Both of these variables, however, also are highly dependent on ambient dry-bulb air temperature.

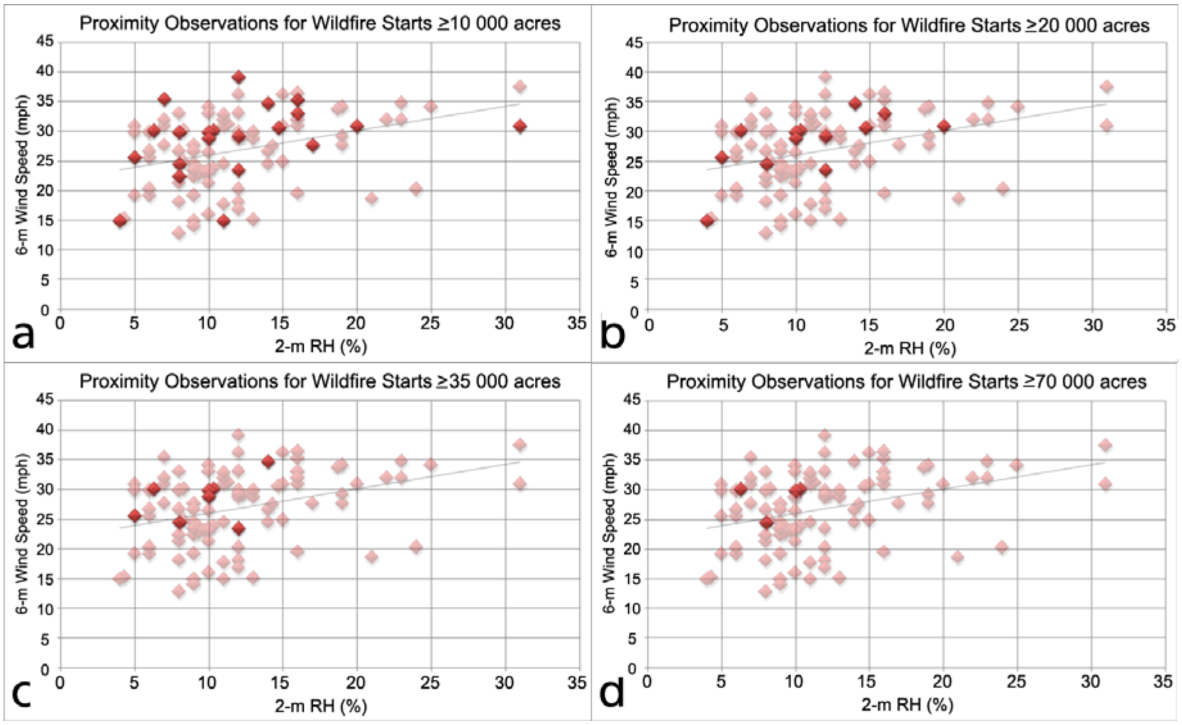

Figure 9: Scatter plots of WTM proximity observations for 2-m RH and 6-m wind speeds for 99 documented wildfire starts (light red), and in bold red, wildfires that burned: a) ≥10 000 acres (4047 ha), b) ≥20 000 acres (8094 ha), c) ≥35 000 acres (14 164 ha), and d) ≥70 000 acres (28 328 ha). *Click images to enlarge.*

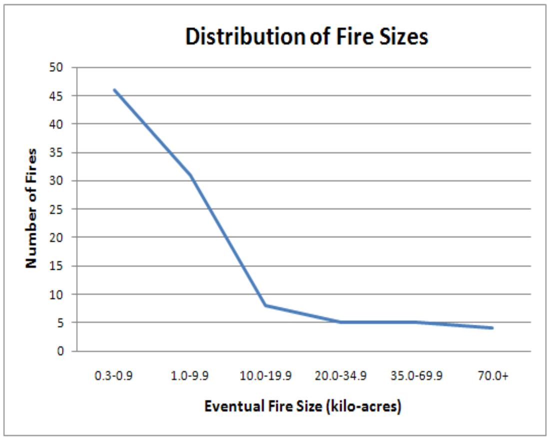

Figure 10: Distribution of eventual fire sizes for the 99 documented wildfire starts. *Click image to enlarge.*

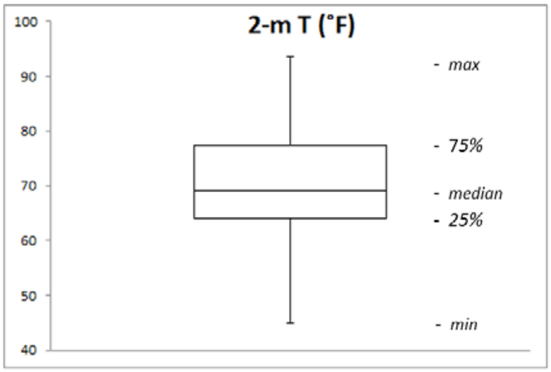

Figure 11: Box-and-whisker plot for observed 2-m temperature near wind-driven wildfire starts. *Click image to enlarge.*

As such, an examination of observed WTM proximity 2-m temperatures for wind-driven wildfire starts also is appropriate. A box-and-whisker analysis of proximity 2-m temperature observations (Fig. 11) reveals that the 99 fire starts occurred when near-surface air temperatures ranged between 45° F (7° C) and 92° F (33° C). Despite this large variation, half of the fires occurred with temperatures between 64° F (18° C) and 78° F (24° C). The average proximity 2-m temperature for the wildfire starts was 71° F (22° C), while the median value was 69° F (21° C).

Employing a similar analysis of the observed proximity 2-m temperatures, relative to climatology, offers a more operationally useful statistical signal (Fig. 12a). As with the previous analyses of proximity 2-m RH and 6-m wind speed relative to daily normal values, proximity observations of 2-m temperature were compared to the climatological daily average (normal) maximum 2-m temperature at Lubbock, TX for the date of each of the 99 documented wildfires. Although the dataset contained wildfire starts characterized by a range of deviations from normal between –26° F (–15° C) and 26° F (15° C), a strong correlation between wind-driven wildfire starts and above normal temperatures was noted. In fact, 77% of the fire starts were associated with temperatures above seasonal average daily maxima, and half of the starts occurred with 2-m temperature anomalies 2° F (1° C) and 14° F (8° C). Mean and median deviation values were strongly positive at 7° F (4° C) and 8° F (4° C) respectively. These statistics are influenced by two outlier negative deviations associated with anomalously cool nighttime wildfire starts on 2 April 2009, when damaging cold-frontal winds downed utility lines into receptive fuels. Further, wildfire starts peak during temperature anomalies of 5° F (3° C) to 20° F (11° C) (Fig. 12b). Unlike the prior

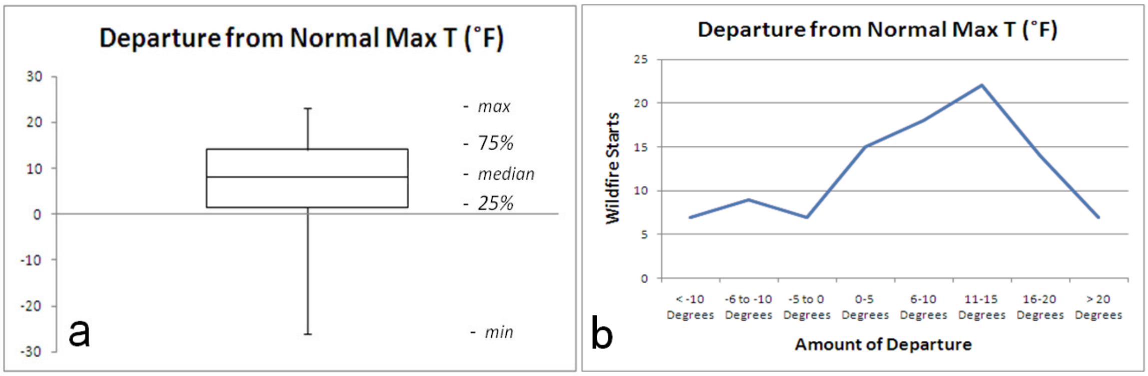

Figure 12: a) Box-and-whisker plot of proximity temperature anomalies and b) graph of wildfire starts versus those anomalies. *Click images to enlarge.*

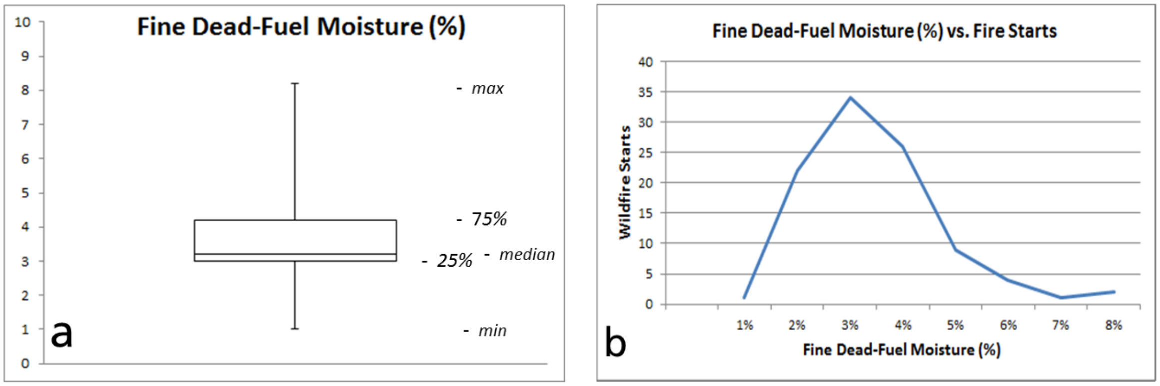

Figure 13: a) Box-and-whisker plot for fine dead-fuel moisture content associated with wildfire starts and b) a linear plot of wildfire starts relative to fine dead-fuel moisture content. *Click images to enlarge.*

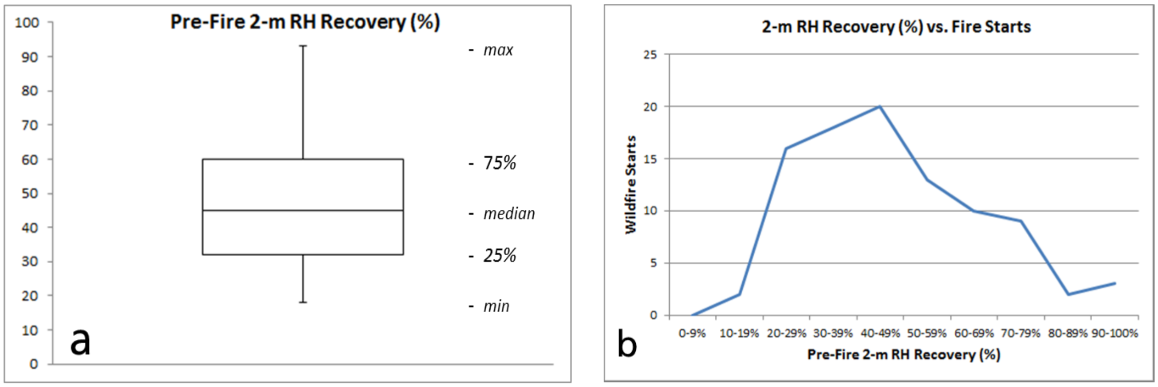

Figure 14: a) Box-and-whisker plot for maximum 2-m RH recovery prior to proximity wildfire starts; b) linear plot of wildfire start occurrences relative to specified ranges of 2-m RH recovery. *Click images to enlarge.*

comparisons of proximity 2-m RH and 6-m wind speed to climatological values, however, the daily average maximum temperature is commonly known by forecasters. Thermal anomalies, therefore, likely provide results more readily useful in the operational fire weather forecast and warning environment.

c. Application of proximity observations toward the state of vegetative fuels

Local weather conditions and the state of available vegetative fuels are equally important in determining wildland fire behavior. Measures of moisture content for the grassy 1-h fuels that are predominant throughout the southern High Plains, however, are highly dependent upon and particularly susceptible to hour-by-hour changes in near-surface temperature and RH (Cheney and Sullivan 2008). As a result, these atmospheric variables can yield useful information about the state of vegetative fuels. In a unique use of the WTM, observed RH and temperature at 2 m were applied toward calculations of fine dead-fuel moisture content, and toward documenting fire occurrence in relation to 24-h 2-m RH recoveries prior to each fire start.

Fine dead-fuel moisture content (Rothermel 1983) is a percentage defined as the sum of a reference fuel moisture and a moisture correction, and can be used for 1-h and 10-h fuels. The reference fuel moisture is a function of temperature and RH, and thus can be determined for each documented fire start by utilizing the WTM proximity observations of 2-m RH and 2-m temperature. The moisture correction value is a function of month, time of day, terrain slope and aspect, and fuel shading. Inputs for slope, aspect, and shade appropriate to the WTM domain's topographical and biophysical characteristics were noted in Section 3.

Values of fine dead-fuel moisture content associated with the documented wildfire starts ranged from 1% to 8% (Fig 13a). Half of all documented wildfire starts, however, occurred within a very narrow range of fine dead-fuel moisture values: between 3% and 4%. The mean fine dead-fuel moisture content associated with the 99 documented wildfire starts was 3.5%, while the median value was 3%. A linear plot of wildfire start frequency relative to fine dead-fuel moisture reveals a pronounced peak in wildfire occurrence when 1-h and 10-h fuel moisture values range between 2% and 5% (Fig. 13b).

RH recovery also can serve as a proxy for fuel moisture prior to the diurnal burn period. Low RH recoveries aid pre-conditioning of fuels for drying and subsequent burning. While 2-m RH recoveries were observed from 18%–93%, half of the fire start cases occurred following a narrower range of low to moderate recoveries between 32% and 60% (Fig. 14a). The mean and median RH recoveries were 47% and 45%, respectively. Fig. 14b shows a peak in fire start occurrence when the diurnal recoveries range between 20% and 50%. These values roughly correspond to dead-fuel extinction moisture[1] thresholds between 20% and 40% for similar grassy fuel types as determined by Scott and Burgan (2005).

6. Proximity observations and local meteorological RFW criteria

The NWS's RFW criterion within the WTM domain are governed by the Southwest Area Fire Weather Operating Plan (SWCC cited 2010) and are meant to identify critical combinations of dry fuels and weather conditions that support extreme fire behavior. The plan defines a RFW event as the simultaneous occurrence of: 1) RH $\leq$15%, 2) sustained 6-m wind speeds $\geq$20 mph (8.9 m s^{-1}), and 3) a 3-h duration of (1) and (2).

Most significant southern High Plains grassland fire starts, and all of those documented here, are anthropogenic. As such, the purpose of the NWS's RFW program is not to predict the development of wildfires; and the validity of RFWs is not based on the presence and/or absence of fire activity. Instead, RFWs are used by NWS forecasters to highlight imminent weather events that support extreme fire behavior and subsequent wildfire evolution (NOAA 2009). The analyses of proximity WTM observations for wildfire starts presented here are useful, however, as a statistical quantification of wind-driven grassland wildfire environments in the region. In that context, these data can be compared to the defined meteorological RFW criteria.

As per Fig. 15, 64% of the starts occurred within conditions that met or exceeded the local 2-m RH and 6-m wind speed criteria for RFWs, more than a third did not. Furthermore, considering the size distribution of events in Section 5a, some wildfires that burned areas $\geq$20 000 acres (8094 ha) started in environments outside of RFW criteria; yet the most extreme wildfires of $\geq$35 000 acres (14 164 ha) started exclusively within current RFW thresholds.

Recommendations for change to the NWS RFW program are beyond the scope of this study. The presented environmental data for wind-driven wildfires, however, suggest a spectrum of critical combinations of 2-m RH and 6-m wind speed that favor wind-driven grassland fires in the southern High Plains that is not confined to current RFW criteria. RFW criteria do reflect a majority of the documented wind-driven wildfire start environments, and appear to be good indicators for the most extreme environments that support massive grassland wildfires. This analysis, however, suggests that NWS fire weather services could be improved if policy addressed critical fire weather environments characterized by: 1) lower threshold 6-m wind speeds in extremely dry regimes, and 2) higher 2-m RH values in the presence of very strong winds. Such weather has been observed in association with a nontrivial percentage (23%) of wildfire starts that led to burns of $\geq$20 000 acres (8094 ha); and such fires clearly present a threat to life and property.

The plot in Fig. 16 suggests that more than two-thirds (69%) of the documented wind-driven wildfire starts occurred outside of the 3-h RFW criteria. In fact, 14% of the fire starts occurred before the onset of concurrently critical RH and wind speed, within the first 3 h of critical conditions (42%), or when defined critical

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[1] Dead-fuel extinction moisture defines values in excess of which sufficient moisture exists to suppress fire spread within a given vegetative biofuel (Rothermel 1972). A vegetative fuel will lack suppressive moisture, exacerbating its susceptibility to fire if overnight RH maxima either fail to exceed or barely meet extinction moisture values before the onset of expected diurnal heating and drying.

combinations of RH and wind speed failed to materialize (13%). However, 75% of the wildfire environments eventually met the defined critical thresholds >3 h. In all, 31% of the wind-driven wildfires started 3–9 h after the onset of RFW RH and wind speed conditions; and a notable drop in the frequency of starts was noted after critical conditions had been ongoing for 4-5 h.

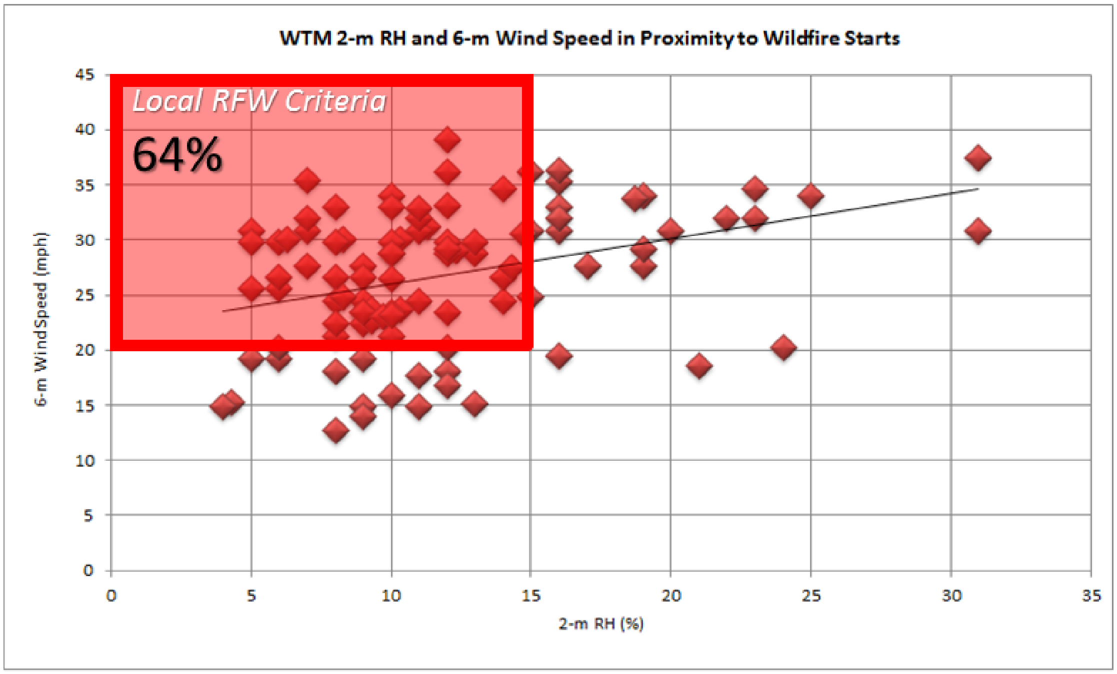

Figure 15: Scatter plot for WTM proximity observations of 2-m RH and 6-m wind speed, relative to local meteorological RFW criteria (red shaded box).

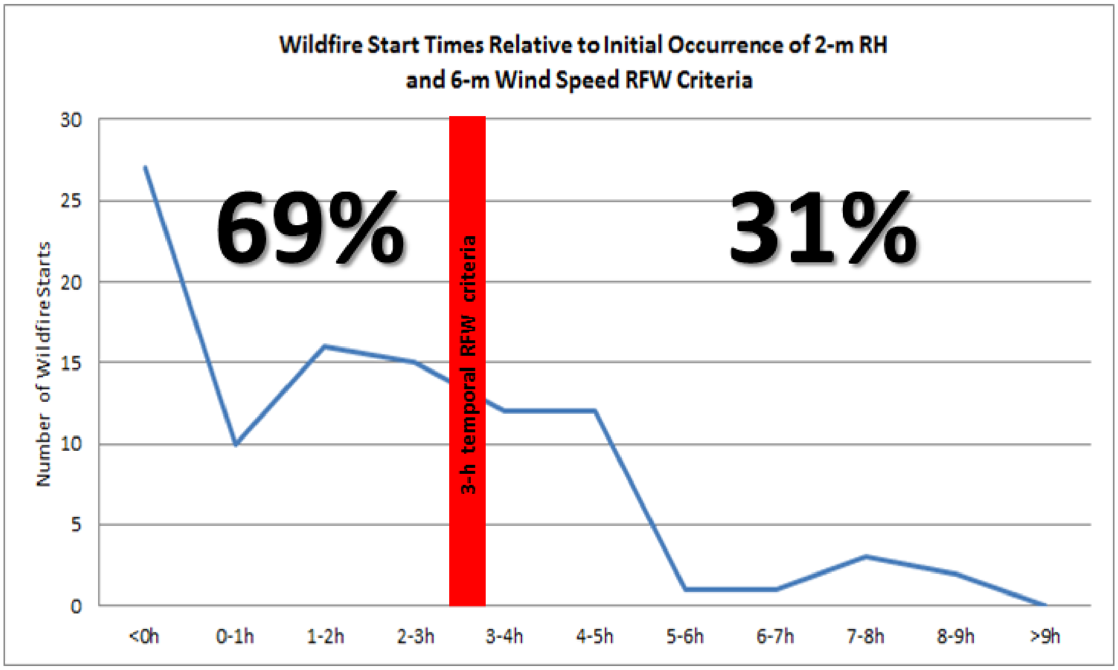

Figure 16: A comparison of wildfire start times to the initial occurrence of RFW 2-m RH and 6-m wind speed criteria.

7. Summary and conclusions

Local meteorological conditions are the most dynamic variables to influence wildland fire behavior. A relationship between weather and wildfire evolution in the southern High Plains is demonstrated through analyses of 99 WTM proximity observations for wind-driven grassland wildfire starts. Within this dataset, fire starts were shown to be characterized by a slightly linear and significant relationship (r=0.36, P=0.0003) between observed 2-m RH and 6-m wind speed. This correlation approximates a best fit linear trend line from extremely dry environments, with 2-m RH values near 5% and 6-m wind speeds between 20-25 mph (8.9-11.2 m s^{-1}), to environments with 2-m RH near 35% with 2-m wind speeds around 35 mph (15.6 m s^{-1}). Although it is difficult to draw conclusions about specific weather conditions and fire growth potential, starts for fires that eventually burned ≥20 000 acres (4047 ha) to ≥70 000 acres (28 328 ha) displayed a tendency to start in increasingly drier environments. Wildfire proximity observations of 2-m RH, 6-m wind speed, and 2-m temperature also revealed strong anomalies from climatology, with 77% of the starts being with temperatures above daily normal maxima.

Since fuel moisture is highly dependent upon short-term variations in RH and temperature, the WTM proximity observations were applied toward calculations of fine dead-fuel moisture content. Half of all documented wind-driven grassland wildfires started when 1-h and 10-h fuel moisture values were between 3% and 4%. Additionally, wildfire starts peaked when the preceding 24-h 2-m RH recovery ranged between 20% and 50%.

Nearly two-thirds (64%) of the documented wildfire starts occurred during combinations of 2-m RH and 6-m wind speeds that met or exceeded local RFW criteria. The data suggest, however, that critical values for parameters that promote rapid fire spread and subsequent wildfire development also exist outside of the currently defined RFW criteria. NWS fire weather services could serve interests for wind-driven grassland wildfires better if policy addressed extremely dry environments with lower-threshold winds, and higher RH in the presence of very strong winds. In addition, 69% of all fire starts did not meet the temporal RFW criteria: however, ≥3 h of RFW level RH values and wind speeds eventually were observed in 75% of the fire start cases.

This study provides a unique examination of proximity meso-β and meso-γ scale weather observations for wind-driven grassland wildfire starts. It is intended to aid prediction of critical fire weather conditions and to improve methods for operational fire weather forecasts and warnings. We also hope that this work will serve as a reference for, and will inspire, additional fire meteorology research in the southern High Plains, where the topic of grassland fire weather is largely absent from formal literature.

Future work should be focused on identifying the specific large-scale patterns that favor widespread wildfire episodes across the region, as well as understanding the complex interactions between biofuels and the near-ground atmosphere that support fires. Such research is essential to building knowledge and conceptual recognition of environments that promote dangerous, wind-driven grassland wildfires. The need for such expertise will increase in the years ahead as the NWS' incident-support role evolves and as demands increase for robust fire weather collaboration from local, state, and federal emergency management agencies.

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REVIEWER COMMENTS

[Authors' responses in *blue italics.*]

REVIEWER A (Jared L. Guyer):

Initial Review:

Recommendation: Accept with minor revision.

Overview: The authors make advantageous use of temporally and spatially dense West Texas Mesonet (WTM) observations to document a recent (2006-2009) period of sustained drought and prolific wildfires across the southern High Plains. This well-written paper was strong in its detailed documentation of individual wildfire starts via an array of observational/remote sensing techniques (WSR-88D, GOES etc.) in conjunction with 5-minute WTM observations of relative humidity, wind, and temperature. I have no qualm with the relatively small number of years (four seasons) contained within the dataset given the large number of fire starts (87) analyzed and high degree of temporal/spatial resolution as compared to other observational-based studies.

In addition to a nice climatology of the documented wildfires, I applaud the authors for acknowledging some potential for high-end biasing given the rather active period of study—"study period also spans fire seasons characterized by unprecedented wildfire frequencies significantly higher than the region's expected recurrence interval...." Furthermore, I think the manuscript makes appropriate service-relevant comparisons with existing Red Flag Warning (RFW) criteria, including notable observations that many (~66%) of these wildfires began prior to peak conditions/technical RFW criteria.

Overall, I think the scientific content and quality of presentation is very good, and it is difficult to have much in the way of substantive suggestions and/or conflicting opinions. Accordingly, my review comments are relatively minor and are largely either typographical or organizational in nature. I see this paper being a worthy and beneficial fire weather related addition to the EJSSM.

Substantive Comments:

Section 3: While it may be good information to discuss the Caprock, and it is certainly an important characteristic within the region, nothing is said of its practical relevance and/or direct importance to this study. While I don't necessarily recommend removing the paragraph from this section, I want to see if there is anything additional the author would like to mention regarding its relationship/importance to this study.

Intent was to provide the reader with background knowledge of the biophysical and topographical properties of the WTM domain, given that fuel and topography also are significant contributors toward fire behavior. This discussion gained significant relevance in the revisions, however, given the addition of observation-derived 1-hr and 10-hr fine dead-fuel moisture content. The need for slope, aspect and shading inputs into these calculations added context to providing a biophysical description of the WTM domain and its topographical features. Further, Mr. Beierle's expertise allowed us to provide additional details regarding the specific types of grassy fuels in question.

[Editor's Note: Beierle was added as tertiary author during this review cycle.]

Section 6: While paper length doesn't seem to be an issue, I would consider dropping the KBDI [Keetch-Byram drought index] section and associated graphic. While not poor information to include, it is probably unnecessary based upon my understanding and presumptions that it is inherently unlikely to be used across the southern High Plains given the limitations as noted by the authors (best in the Southeast U.S.) If the authors know of any appreciable usage of KBDI by local users, than certainly err on the side of including it.

The discussion of KBDI was initially included for the simple reason that it is used on the Texas Forest Service's fire intelligence website. The reviewer is correct, however, and following a similar suggestion *from Ms. Coen (Reviewer B), discussion of KBDI—as well as Drought Index and NFDR—has been omitted. Instead, consideration toward the state of fuels is now better handled by utilizing the proximity observations in calculations of 1-hr and 10-hr fine dead fuel moisture.*

Authors cite "west Texas region" throughout the paper. While I think this is largely an appropriate generalization of the region, Fig. 4 does imply as many as 15 fires in this study (around 17%) technically started in far eastern New Mexico. As one example, the authors state "A relationship between weather and wildfire evolution in the west Texas region." I think the region of study is well-understood, but you may want to at least consider inclusion of "far eastern New Mexico" and/or occasional usage of "southern High Plains" (or similar terminology) where appropriate.

We actually went back and forth on this ourselves, so thanks for bringing it up! Yes, a notable percentage of the fire starts occurred in far eastern New Mexico. In these instances, the nearest/proximity WTM sites likewise are located in New Mexico—where the WTM domain actually extends west of the state line. Ultimately, we decided that by changing our geographical references from "west Texas" to "Southern High Plains" we could more easily relate this study to upcoming research that will investigate larger scale weather patterns to wildfire outbreak episodes across all of the Southern Plains.

Otherwise, additional minor manuscript comments and typographical/reference corrections are included in an additional Word file.

[Minor comments omitted...]

Second review:

Recommendation: Accept with minor revision.

General Comments: I want to thank the authors for addressing prior comments and suggestions as appropriate. I feel that the already well-written paper has been considerably strengthened and polished. As previously stated, I see this paper being a worthy and beneficial fire weather related addition to the EJSSM. With that said, I have a couple of remaining comments/corrections for the authors.

[Minor comments omitted...]

REVIEWER B (Janice L. Coen):

Initial Review:

Reviewer recommendation: Accept with major revision.

Substantive: The paper is interesting in that it looks at a specific outbreak of fires and the surrounding environmental conditions, refreshingly using measurements from within a mesometeorological network.

[Embedded minor comments omitted below…]

P.2: Please consider the wording of paragraph beginning with "Wildfire evolution…" regarding local fuels and topography "remain relatively unchanged". Although the fuel type and amount remain relatively unchanged, the fuel moisture (which is also lumped under fuel characteristics) may change quickly and substantially. In fact, although illustrative, this concept of separate influences of weather, fuel, and topography on fire behavior is outdated, as we become more aware of their dynamic interdependence – topographic weather effects between weather and topography, weather effects on fuel state, etc.

The reviewer is correct in pointing out the "dynamic interdependence" between weather, fuel, and topography in relation to wildland fire behavior. In fact, these complexities frequently create a problematic disconnect for operational fire weather forecasters in diagnosing risks, and were partially the *motivation for this study. Often, forecasters are confident in their understanding of the expected weather conditions, but feel that they lack an understanding of the biofuel's susceptibility to fire when subjected to the anticipated weather, and the vegetation's overall contribution to fire danger. As such, the authors thank the reviewer for these comments and her assistance in clarifying this codependency, particularly between weather and fuels. The authors believe that this topic is best addressed with the addition of 1-hr and 10-hr fine dead fuel moisture content calculations based on WTM proximity observations of 2 m relative humidity and 2 m temperature, based on a later suggestion from this reviewer and discussed in more detail later in our responses. Otherwise, additional references and re-wording of the text have been added to address the complex interactions between weather and fuel.*

[Text-body blocks from manuscript omitted…]

We opted to maintain the use of [former]Figure 1 (the fire behavior triangle), as we believe it is still an excellent illustrative representation of the factors contributing to wildland fire behavior. Being that the graphic is a triangle, we hope that readers will be able to visualize the interdependent nature of the three variables: weather, fuel, and topography.

[Editor's Note: The figure in question later was removed at the editor's request.]

The concept of a "dynamic interdependence" between weather and fuel was again addressed in Section 3 with respect to the methodology for determining 1-hr and 10hr fine dead fuel moisture.

Section 3: Please identify and discuss the spatial resolution of the NOAA GOES-12 bands being used (on the order of tens of km?) and how this impacts the ability to identify the ignition location of fires—are the errors not comparable to the distance between stations within the much finer-scale mesonetwork?

The spatial resolution of the GOES-12 imagery used was 4 km, and this has been noted appropriately in the paper. This resolution is not considered a significant contributor to error and is an order of magnitude less than the spacing of WTM sites.

P. 3, paragraph beginning, "Start times…": "Start times … compared to … observations … from the nearest WTM site." So the nearest WTM site could be upwind, downwind, or displaced perpendicularly across the wind? Since the assumption is that local conditions affect the fire ignition, and that spatial variability matters, please discuss why you rejected selecting only a nearest station that might be (within some arc of) upwind from the ignition.

Yes, we simply utilized the nearest WTM site and did not restrict proximity observations to sites upwind of fire starts. This seems reasonable given that wind-driven grassland fires generally occur within unusually hot/dry downslope wind regimes. Unlike, for example, the usefulness in obtaining measurements from the inflow region of supercells to obtain proximity observations for tornadoes, in the case of wind-driven grassland fire starts, variations across the ambient air mass are small over spatial distances of a few tens of kilometers. In this case, our goal was simply to document the weather conditions at the closest WTM site nearest the time of the fire start. This was considered representative of local weather conditions that supported extreme fire behavior as evidenced by the development of wildfire. The authors believe that no additional information or utility would be gained by restricting proximity observations to only sites upwind of fire starts.

P.5 – Regarding the station proximity to fire raised in #6, the manuscript states, "spatial and temporal (<20 minutes) proximities for WTM observations to wildfire starts…". Given that the mean 6-m wind speed in Figure 7a is 12.1 m s^{-1} and the mean distance between starts is 25 km (p. 4-5), is the average temporal proximity not 25 km / (12.1 m s^{-1}), 34 min, instead of 20 min?

I am not sure I follow the reviewer's logic here. It is correct that the spatial proximity averaged out to 24 km (with the addition of 2009/10 cases, previously 25 km). The manuscript then states that temporal proximities were <20 min. This is based on the fact that fire detections were dependent upon remote sensing imagery that was received at intervals of 10 to 15 min, plus data from WTM observations every 5 *min. Thus our confidence is high that we sampled the weather conditions at the nearest WTM site within 20 min of each fire start.*

P.6 text: "Specific statistical values for the wildfire environments are best illustrated by examining box-and-whisker analyses for both parameters" + Figure 7a-b. The author is applauded for using statistical analyses to support assertions. The box-and whiskers (B&W) graph is useful and appropriate for exposing the desired quantities. I suggest introducing the analyses differently, rather than with the above quoted phrase that assumes readers will know what a (very information-rich) B&W plot is showing. Perhaps use the text to say the analyses/figure will show a representative value plus the variability in the distribution, and use the caption of Figure 7a-b to describe what the parts of a B&W plot show (mean or median, quartiles, total breadth of the observations). Lot of information in there!

The authors appreciate the reviewer's comments here! Hopefully the reviewer's concerns will be well-handled through suggestions made by Mr. Guyer (reviewer A). To address both reviewers need for clarification and great detailing attached to the box-and-whisker plots, nomenclature for each represented value was added to the actual box-and-whisker plot graphics. This should help readers [to] better interpret these data-rich figures.

P. 7: As I finished the paragraph beginning "Further, differentiating fire starts…", I was wondering what the variability of these meteorological conditions were across the domain. Could an additional figure establish the variability in time at several key stations?

The authors do not see the value in, or even a feasible methodology for adding this information. It is conceivable that WTM meteorograms could be investigated to look at variability of weather conditions in proximity to wildfires, but given how grassland fires have been observed to modify their immediate environment per FIREFLUX, such data would likely not be representative of the near-fire environment. [S]uch observations could be the topic of future work! Therefore our methodology of documenting the proximity conditions for initial fire starts is likely the best available methodology for investigating weather conditions observed to be associated with the onset of extreme fire behavior and/or wildfire evolution. Otherwise, we don't see how the variation of meteorological conditions across the domain would be relevant to an individual wildfire start, or how they could even be displayed short of providing a series of meteorograms from x-number of WTM sites for each of the 99 fire start cases. That option doesn't seem plausible.

P. 8: "Also the number of fire starts documented here decreases significantly for increasingly large fires. Thus the non-normal distribution of represented fire sizes in this database makes assumptions…." (1) What is the distribution of fire sizes? Consider a (log? Log-log?) plot of this. (2) The distributions of sizes I have seen are always non-normal (an example is the power law relationship shown by Malamud et al., 1998, in *Science*, **281**, 1840-1842) indicating a few percent of fires become very large.

A linear plot of eventual fire sizes was added to the manuscript, and this seems to have made a very nice addition in supplementing this portion of the paper. As such, the citation for Malamud et al. 1998 was additionally incorporated.

Section 5: Several statements here address the background of RFW use, comparison to NWS RFW criteria, how recommendations for change to RFW criteria are beyond this study, etc. The text could be tightened considerably, and other text moved (i.e. introduction of RFW criteria to the introductory material, discussion of the context of this work and possible guidance for RFW adjustments or not to the Discussion section).

Initially, a major motivating factor for this research when we first began documenting proximity observations for wildfire starts in 2006 was to test the validity of the current RFW criteria. This work has apparently provided the first efforts to compare meteorological observations to wind-driven grassland fire starts in the plains, and thus this is the first time the RFW criteria have been examined relative to observed fire activity in the region. Influencing change to current RFW criteria, however, is a complex process that would involve collaboration and policy changes across a spectrum of governmental agencies for a large, *biophysically diverse area which encompasses west Texas, New Mexico, and Arizona. The preliminary results of this study have been presented each of the last two years at the Southwest Area Fire Weather Operating Plan meeting, and it is possible that changes in policy (at least for the grasslands of Region 3) may occur with sufficient observations and review. Although the authors hope that this study provides a scientifically rigorous dataset and analysis for weather conditions in proximity to wind-driven grassland fires, we do not presume that changes in policy will be instituted based solely upon these results. While the current meteorological RFW criteria appears well-suited as an indicator of weather conditions associated with a majority of and the most extreme wildfire events, the data also suggests that improvements in NWS fire weather services could be made by adjusting policy to address sub-RFW environments that support fires ≥10,000 to ≥20,000 acres. With that said, it is hoped that this research will help to initiate policy changes that would improve forecast and warning services for the full spectrum of critical fire weather in the plains. Therefore, we hope that the reviewer will be content with maintaining discussions and comparisons to the local RFW criteria within an independent section of the manuscript.*

Of the 33 references, 25 are nonstandard references, either [un]refereed conference papers or technical reports, or NWS documents, which is extremely high. The EJSSM guidelines recommend that the "principal source" references (e.g., the original source of information) be used whenever possible. Generally, refereed publications are more acceptable for this purpose than unrefereed material. Thus, if the author uses an unrefereed reference, this may not be considered acceptable support. The availability of unrefereed manuscripts is also an issue with their use in support of an assertion.

As discussed in our general responses to the editor and reviewers, finding refereed literature dealing with the meteorology of grassland wildfires in the Southern High Plains is a challenge. What little work that does exist on the topic is mostly found in conference preprints and NWS/Forest Service technical reports. That said, an effort was made to reduce the number of gray-literature citations. Through narrowing the focus of the paper and eliminating discussion of the relationship between La Niña and drought, a number of references to local studies were omitted.

While the earlier sections relating primary meteorological variables to wildland fire starts are a strong part of the paper, in my opinion, the paragraph on P. 11 beginning, "The fourth variable utilized in local RFW criteria is the National Fire Danger Rating System," detracts from the worth of the manuscript. NFDRS itself is composed of three factors concerning the Ignition Component, the Spread Component, and the Energy Release Component, each of which depends on other primary variables such as wind speed and various types of fuel moisture (some of which in turn depend on other primary meteorological variables); so I'm not sure there is any clear significance or knowledge to be gained by examining this. While a specific NFDRS may be a part of the NWS RFW conditions, the manuscript states that its purpose is not to address changes to RFW guidelines.

Our original intent in including NFDRS relative to observed fire starts was to look at all aspects of the RFW criteria. For precisely the reasons noted by the reviewer, the authors have informally argued that the NFDRS is biased too much by the forecast weather conditions and not particularly applicable to the grassland ecosystems of the Southern High Plains. From our observations, it would appear that fuel dryness (generated by the TFS) or perhaps the Grassland Fire Danger Index would be better suited to incorporate into our local RFW criteria, but that may be the topic of future work. Ultimately, the authors agree with the reviewer and the discussion of NFDRS has been removed in favor of a strictly meteorological/observational-based analysis.

I suggest major revisions to [former] Section 6. First, looking at the big picture, I think it is problematic because it is not clear that measures of degrees of drought are appropriate when applied to grasslands, in which the fuel response time to varying moisture conditions is expected to be short (grass is considered '1 hour' or '10 hour' fuels)—as the manuscript states, KBDI was developed for forested 100-hr fuels. And, even the next variable examined, the relative humidity recoveries during the preceding 24 h, may be too long before the fire ignition (according to the manuscript, midday through afternoon), although it appears useful in indicating the current air mass characteristics. In any case, I believe that the fundamental and perhaps only variable that merits examination in Section 6 is the fuel moisture (primarily the 10- and perhaps 1-h dead-fuel moisture (DFM), although the live component may be important as well (I am not an expert on this ecosystem). Some RAWS stations report 10-h DFM measurements, or diagnose them (using NFDRS algorithms) from preceding meteorological conditions. Section 6 would benefit from adhering to the rigorous formulaic examination of the appropriate primary physical variables, as the earlier sections did.

The authors appreciate these comments, and we believe that this feedback led to one of the most significant improvements to the manuscript made during the first round of revisions. The included discussion on levels of drought and KBDI relative to each fire start was an effort to account for the state of available fuels associated with each fire. As discussed previously, the codependency of fire behavior on weather, fuel, and their complex interactions made it necessary to address the issue of vegetative fuels in some form or fashion. Our initial efforts at this were based on the availability of archived indexes found via online U.S. and Texas Forest Service resources.

Being meteorologists, however, and having limited expertise in dealing with fuels, we were somewhat perplexed with the lack of useful signal in any of the drought/fuel related indices. Following the reviewer's comments, we sought guidance from Mr. Brad Smith, Fire Behavior Analyst, Texas Forest Service. With his assistance, we learned that it would be possible to derive values for 1-h and 10-h dead-fuel moisture based on our existing database of proximity observations. By utilizing the expertise of Mr. Smith and our newly added co-author (Mr. Beierle), we were able to input observed 2-m relative humidity and temperature along with time-of-year/day, slope, aspect, and shading into BehavePlus to generate values for fine dead fuel moisture content per the reviewer's suggestions. Given that this fuel information was derived straight from the proximity observations, the former Section 6 was omitted and both fine dead fuel moisture and relative humidity recovery were added to the main presentation of proximity observations and analyses. The authors believe that this extends the paper's strength in meteorological observations into the discussion of fuels.

We would like to maintain the discussion of preceding RH recovery. The reviewer may be correct in stating that the response time for moisture within the grassy 1-h fuels may generally be too rapid for 24-h recoveries to be meaningful, however, the authors believe that sufficient anecdotal evidence for influence on fire risk exists to introduce the observations here. For example, an instance of extremely critical fire weather was observed across the WTM domain on 28 Feb 2007, following dense morning fog and 100% RH recoveries. As a result, the fuel's susceptibility to fire appeared to be reduced and the diurnal burning period was shortened, despite afternoon RH values as low as 3% and sustained wind speeds up to 35 mph. In spite of these conditions, no fire starts were observed within the WTM domain. The authors suspect that the frequency of dense fog during the month of February may additionally be a contributing factor toward the climatological minimum in significant fire activity observed for the month. Further, although the fire starts documented here were observed following a wide range of overnight recoveries—including a few >90%—the frequency of wildfire starts shows a pronounced peak when RH maxima only recovered into the 20% to 50% range as shown. It is not known if this is an artifact of the ambient air mass characteristics, or if the poor recoveries are a direct meteorological influence on the fuel's vulnerability to fire. Probably the most logical and supported conclusion is that poor overnight humidity recoveries below the fuel's extinction moisture guarantees that the fuel will not have sufficient moisture to suppress fire. This statement continues to be supported by the fact that fire start instances peaked near the expected extinction moisture thresholds for our grassy fuels.

Again, the authors thank Ms. Coen for her thorough and thoughtful review of this manuscript.

[Minor comments omitted...]

Second review:

Recommendation: Accept with minor revision.

General Comments:

- I think they have put the RFW connections in a much better context.

- I appreciate their responsiveness to the issues I pointed out and am satisfied at how they made changes or carefully explained why they did not.

- There are still a lot of references to unreviewed reports, etc., but the manuscript is better in that way.

I have no further suggestions for changes.

Again, the authors would like to thank Ms. Coen for her review of this manuscript and for the positive nature of her criticism which certainly helped to improve this work.

[Minor comments omitted...]

REVIEWER C (Michael D. Fromm):

Initial Review:

Recommendation: Revisions required.

The basis of this report is the connection between the RH and wind at the time of an identified fire start. The correlation is visualized as scatter plots and box-and-whisker diagrams. However, the objective use of these diagrams is compromised by the omission of a "control" set of RH, wind [and] temperature metrics. In other words, it is essential for the analysis as visualized (e.g. in [former] Figures 6 and 7) to be shown in the context of overall variability of these weather data. e.g. what is the general variation of RH where the fires were detected, but independent of fire? Only in this way can the reader usefully assess the association of fire with these metrics.

The basis of this work is not to establish a relationship between relative humidity and wind speed (although in revision it is shown that a slight linear relationship does exist), but instead to document combinations of these two meteorological variables observed near the start of significant grassland fires. Yes, temperature appears to be a third contributing variable toward critical fire weather, and temperature's correlation to relative humidity is well known. In our study, wind speed is simply a covariant that is typically related to the likelihood of ignition and post-ignition fire propagation and spread. In the revised manuscript, our plots and text describe the correlation between relative humidity and wind speed but the correlation is not direct and statistically inappropriate for regressive analysis. The authors believe that the variability of relative humidity, wind speed, and temperature associated with fire starts is well documented.

Independent of the issues raised above, the substance of [former] Figures 6 and 7 is questionable. The statistical significance of the result visualized is never substantiated. In the absence of that, the visual impression I have is that there is not "trend" as described by the authors. There is a core of fire starts around a clump in RH/wind space with a few others forming a sort of tail. For such an analysis to be robust a careful statistical confidence test should be applied.

A Pearson correlation coefficient statistical analysis was applied to the dataset. This analysis revealed that a significant and slightly linear relationship does exist between relative humidity and wind speed as observed in proximity to fire starts, with r=0.36 and P=0.0003. This suggests that the use of a linear trend line is entirely appropriate. However, causality may not exist and the correlation is most likely due to the relationship of temperature. The authors are appreciative of the reviewer's comments in this respect, and believe that the suggestion for inclusion of more robust statistical analysis such as this strengthened the overall integrity of the paper. As a part of this process, a more technically correct ellipsoidal analysis method was employed to generate [former] Figure 8.

My recommendation is that the authors consider switching from fire start to a metric—like rate of spread—to associate with weather data for threat conditions. They also need to deal directly with the issue of fire cause before discussing their analysis, if indeed fire start is considered an important aspect of this analysis. It is also essential to fully contemplate the purpose of red flag warnings in order to best frame the type of fire weather analysis they perform in connection with observed fire behavior.

The authors disagree with these recommendations and assertions. First, the suggestion of dealing with a rate of spread metric instead of fire start is neither feasible nor relevant. The documented wildfires presented here did not occur in a controlled or well-sampled environment such as the FIREFLUX experiment, thus quantified fire-scale measurements for observed spread rate do not exist. As an example, it was very problematic to obtain basic measured and/or estimated eventual fire size information for many of these fire cases, especially for the less significant fires that burned areas on the order of 100s of acres and that were managed solely by local jurisdictions. It is possible that rate of spread could be estimated using an application such as BehavePlus, but many assumptions regarding specific micro-scale variables such as local fuel-types and moisture, wind speed, and terrain inputs would have to be made in order to calculate a reasonable estimate within the available models. Instead, it seems that the authors' methodology of documenting proximity meteorological conditions for environments supportive of wildfire ignition, not spread, is most supported and appropriate given the existing dataset. The authors maintain that investigations of such meso-β and meso-γ scale weather observations as related to significant wildfire starts are an appropriate comparison to RFW criteria for service-oriented and operational use.

The source of ignition for the documented wildfire starts is irrelevant to this study, as it is also irrelevant in the operational fire weather forecast and warning process. As stated in the text, the start sources for wind-driven grassland fires are of an anthropogenic nature given that they occur in cool season environments that are unfavorable for lightning. For the reviewer's information, the most common start sources observed in the WTM domain are utility lines downed from strong gradient winds. Other starts originate from a variety of sources including: vehicles, construction or oil field activities, outdoor lighting, discarded cigarettes, and arson. The specific cause of any given wildfire is not always known, however, and it is not important in terms of operational fire weather forecasting. What is important is the recognition of environmental weather and fuel conditions that support the growth and subsequent spread of wildland fire following an ignition, since significant wildfire evolution will not occur in the absence of such conditions. This is why RFWs are not verified based on the occurrence or non-occurrence of wildfire—because anthropogenic sources for fire ignition are ever-present and not reasonably predicted, but the critical fire weather that promotes wildland fire growth following a source for ignition is. It is not the cause of the fire that is important in our analyses; it is instead observations of wildfire starts relative to proximity weather that is important here.

That said, why is it essential for the authors to fully contemplate the purpose of RFWs to best frame our analyses? RFWs and their purpose are explicitly defined as NWS products used to highlight episodes of critical fire weather and dry fuels that promote extreme fire behavior, and those definitions are already clearly stated in the manuscript. For the WTM domain, defined meteorological RFW criteria are relative humidity values ≤15% and 6-m wind speeds ≥20 mph. These definitions also are already stated in the manuscript. In framing the presented analyses, the authors show that critical fire weather is not limited to these defined combinations of relative humidity and wind speed. The authors additionally suggest that policy makers within the myriad of governmental agencies involved in wildland fire planning and land management should consider ways of addressing the full spectrum of weather conditions that support significant wildfires in the grasslands of the Southern High Plains.

Again, the authors thank Mr. Fromm for his thought-provoking review of this manuscript.

Second review:

Recommendation: Revisions required.

General Comments: Lindley et al., (hereafter referred to as "auth") have made substantial revisions to their paper and responded to each reviewer. I have not assessed the responses to the other reviewers. This second review is based strictly on the response to my first review and a thorough study of the revised paper.

Regarding their response to the reviewer…

Unfortunately the author response to my review is incomplete. The document that was presented as their response does not contain my entire review, in particular two paragraphs that gave concrete criticism. I expected a more complete point-by-point response to each area I considered needing improvement (even if it meant making a rebuttal point more than once).

Our Round 1 response contained the Round 1 review in its entirety and addressed every point as presented to us. The Round 1 review we received was only four total paragraphs, of which we provided responses to three- with the only paragraph omitted from our response simply stating:

> *"There are technical concerns I have with this report, but are not listed at this time. These are not essential to itemize, considering the fundamental concerns raised above."*

Two paragraphs "that gave concrete criticism" are not absent from our response. The reviewer may not have been satisfied with our responses, but our attempted rebuttal for the entire review is present. From our perspective, the Round 1 review did not contain specific technical or substantive suggestions for change. Instead, the only true actionable item was the suggested addition of a statistical test for significance which we provided in revisions.

In a rebuttal statement auth write "The basis of this work is not to establish a relationship between relative humidity and wind speed…" However their scatter plots and especially the fitted trend line in several figures of the original manuscript suggest otherwise to this reviewer. It was based on the heavy use of the scatter plot analysis that I concluded that one of auth's aims was to explore how these to variables interrelated when fire starts were observed.

Okay, I believe I am starting to see where a disconnect exists between the reviewer and the authors here. I believe it is a matter of semantics, but the reviewer's position is logical. The authors show scatter plots and trend lines that ultimately can be construed as relating RH and wind, however, finding an explicit relationship between these variables is not the intent of the study. Instead, the purpose is to investigate combinations of RH and wind speed in proximity to fire starts.

In one rebuttal statement auth state, "The authors believe that the variability of relative humidity, wind speed, and temperature associated with fire starts is well documented." That presumably was made in response to my suggestion to relate the meteorological data shown in the paper to a general or "control" set of wind, RH, and T data. It may be well documented, but it is by no means self evident to all those who might read the Electronic Journal of Severe Storms Meteorology. Hence the reader at least needs to know by citation what documents to study. I saw no such citation in this paper, and did not detect any attempt by auth to provide a background discussion of this topic. In the paper they use comparative adjectives such as "extremely dry" and "moderately strong" (wind) which imply the need to establish (explicitly or by reference) the norms for the study area.

The authors believe the Round 2 revisions address this better. Please see our comments concerning the addition of RH and wind speed climatology in response to the substantive concerns below. The authors hope that the reviewer will find more context in the RH and wind speed values presented as well as more explicitly defined values of RH and wind speed accompanying comparative adjectives more acceptable. Examples include: "extremely dry environments characterized by 2 m relative humidity values near 5%" and "moderately strong 6 m wind speeds between 20 mph (8.9 m s-1) and 25 mph (11.2 m s-1)".

Regarding the revised version of the manuscript, I list substantive concerns followed by technical/minor concerns.

As with the original manuscript, I was left wondering what the unique contribution of the WTM data was to the characterization of fire weather. It is not a foregone conclusion that high-resolution data networks offer a strong advantage over regular WSO and WSFO reporting stations for this application; and no attempt is made to demonstrate the value added. If indeed auth had no intention of studying this aspect, then this work could have been built on regular station data. In my assessment, it was implicit in the title and abstract that auth intended to take advantage of this "unique data set." Hence somewhere in their report the reader should be able to learn if/how the unique data set delivered results or insights that justified the study.

Yes, the authors fully intended to take advantage of the "unique data set" provided by the WTM. The WTM, when combined with the unusually high frequency of wild land fire activity, provided a dense network of observations (spatially and temporally) for studying wind-driven grassland fire-start environments. With observations available every five minutes from a network of automated sites spaced roughly on a 30-km grid, the density of proximity observations far exceeds that possible with ASOS, AWOS, and RAWS networks. This is now more explicitly stated in the text.

[Text-body blocks from manuscript omitted…]

Auth state that they constrain their study to the "cool season" but do not define it or differentiate it from the "warm season." Moreover, the "cool season" constraint is made confusing (to me) by showing analyses like [former] Figure 5a (a 12-month analysis) without suitably marking the "cool season," or instead restricting the analysis to the months of the "cool season."

Wording that would suggest that this study database of wildfires was "constrained" or "limited" to the cool season intentionally has been removed. Instead, an explanation that wind-driven wildfires in the region generally occur during the cool season has been included. This study included all of the wind-driven wildfires that occurred in the study period/domain. It just happens that such fire events only occur when fuels are either transitioning toward a cured state, or in a fully cured state. As a matter of climatology, this occurs during the cool season. The authors made an effort to more explicitly define the cool season in revisions to the "winter and early spring months" as appropriate throughout the paper.

Also, the purpose of [former] Figure 5a is exactly to serve as an illustration of the local fire season. The authors believe that it shows convincingly that almost all of the wind-driven grass fires documented during the study period occurred during the winter and spring months of the cool season…as now more clearly stated in the text.

Section 5a (page 6). Auth introduce a linear statistical model to establish the type of and strength of the correlation between RH and wind speed in the presence of fire starts. They show, on the strength of the statistical significance test, that the result is significant but the correlation coefficient itself is weak ("slight" in their terminology). In terms of explained variance, their result suggests ~13% (r^2). What seems to be absent here is a discussion of how much weight the user of their analysis should give to this slight linear relationship. They make an attempt to use the [former] Figure 6 correlation space to assess one fire metric (final size) and conclude that caution be applied. Thus it seems that, having established the correlation, auth should interpret the statistical result in terms of how it can be otherwise applied.

The authors have tried to more explicitly state our interpretation of the RH/wind speed analyses and the weak linear relationship between these variables in proximity to fire starts. [D]iscussion was added at the end of Section 5a.

Also, we carefully re-worded an earlier portion of Section 5a that introduces the ellipsoidal analysis. This chart represents what the authors see as potentially the best operational use of the RH/wind speed analyses, and a line has been added to allude to this.

One shortcoming of the revised manuscript is that auth do not relate RH and wind speed to "climatology" as they do for temperature in Section 5b. E.g., the concern stated immediately above could be addressed by showing how the fire-start RH and wind environment relates to the "climatology" of those variables. I acknowledge the dependency of RH on T, but it is still achievable to construct an RH "climatology" relevant to the fire-start environment by, for instance, selecting only the times of day bounded by the peak fire-start hours (as shown in [former] Figure 5b) and using only "cool season" days for the climatology data set. The same can be said for wind. Although the details of such an implementation are left to auth, I strongly suggest that the absence of any such “climatology” or background state seriously inhibits one’s ability to interpret the fire-start meteorological data.

Climatological values of RH and wind speed are not data readily available or frequently referred to by forecasters during the forecast and warning process, and concern over their limited operational utility was the reason for omission in the original manuscript. The authors, however, do see the use in such climatological-based references as requested by the reviewer as background information that will help forecasters and other readers appreciate the anomalously dry and windy conditions that promote wind-driven wildfire evolution in the Southern High Plains grasslands. Thus a brief discussion of the WTM proximity observation’s deviation from average daily RH minima and daily average wind speed was added, along with box-and-whisker plots detailing the statistical values for such deviations. Hopefully this will additionally satisfy the reviewer’s desire to see a “control” set of RH and wind values from his previous Round 1 review.

In several parts of the manuscript “relative humidity recovery” is used. However, it is never defined and units are not stated. The term suggests to me that “RH recovery” is a recognized metric but it is not in my vocabulary. Please either fully define relative humidity recovery, or cite other works to establish it, or both.

Yes, “relative humidity recovery” is a well-recognized metric used extensively in operational fire meteorology and in fire behavior analysis. It is simply the maximum relative humidity value observed during the nighttime recovery period. Since it is a relative humidity, it is a percentage. The first sentence of this section has been reworded to more explicitly define the term.

Section 6 (p12) Auth state that “non-wind-driven lightning starts were excluded…” How was this exclusion done?

“Excluded” was a poor word choice. The study database was inclusive of all significant wind-driven wildfire events within the study domain and period. Simply stated, lightning-initiated fire starts do sometime occur in the Southern High Plains, but these fires rarely evolve into significant wind-driven wildfires – and in fact none such occurrences were observed here. The null mention of lightning started fires has been removed from Section 6 with a simple emphasis on wind-driven grassland fires added in its place, and the reference to such fire activity in Section 3 has been modified to include a discussion of such fires as not “included” or “considered” as previously mentioned above and in our response concerning cool vs. warm season events.

[Minor comments omitted...]

Again, the authors thank Mr. Fromm for his review of this manuscript.