Lindley, T. T., G. P. Murdoch, J. L. Guyer, G. D. Skwira, K. J. Schneider, S. R. Nagle, K. M. Van Speybroeck, B. R. Smith, and M.-J. Beierle 2014: Southern Great Plains wildfire outbreaks. *Electronic J. Severe Storms Meteor.*, **9** (2), 1–43.

Electronic Journal of
SEVERE STORMS METEOROLOGY

Southern Great Plains Wildfire Outbreaks

T. TODD LINDLEY,[*] GREGORY P. MURDOCH,[+] JARED L. GUYER,[#] GARY D. SKWIRA,[@]
KENNETH J. SCHNEIDER,[*] SETH R. NAGLE,[~] KURT M. VAN SPEYBROECK,[>]
BRADLEY R. SMITH,[&] MICAH-JOHN BEIERLE[%]

[*]*NOAA/NWS, Weather Forecast Office, Amarillo, Texas*
[+]*NOAA/NWS, Weather Forecast Office, Midland, Texas*
[#]*NOAA/NWS, Storm Prediction Center, Norman, Oklahoma*
[@]*NOAA/NWS, Weather Forecast Office, Lubbock, Texas*
[~]*NOAA/NWS, Weather Forecast Office, San Angelo, Texas*
[>]*NOAA/NWS, Southern Region—Regional Operations Center, Fort Worth, Texas*
[&]*Texas A&M Forest Service, Predictive Services, Longview, Texas*
[%]*Texas Tech University, Department of Natural Resources Management, Lubbock, Texas (former)*

(Submitted 5 August 2013; in final form 07 August 2014)

ABSTRACT

Destructive wildfire outbreaks are a preeminent natural hazard on the grass-dominated landscape of the southern Great Plains. These southern Great Plains wildfire outbreaks (SGPWOs) are characterized by tens of wildfires that evolve on spatial and temporal scales closely tied to the passage of midlatitude cyclones when dormant herbaceous vegetation is particularly dry and abundant. Ten SGPWOs inflicted tragic losses of life and property across eastern New Mexico, west Texas, and Oklahoma between December 2005 and April 2009. This study reviews the conditions that promoted these dangerous phenomena. Texas A&M Forest Service records reveal that enhanced seasonal wildfire activity and increased potential for SGPWOs typically occurs during El Niño Southern Oscillation cold phases (La Niña), especially when preceded by positive growing-season rainfall anomalies. The antecedent state of predominately fine grassland vegetative fuels associated with SGPWOs is quantified per Energy Release Component (ERC, fuel model G). Average ERC values >50 (>70$_{th}$ percentile) supported the 2005–2009 SGPWOs on the Great Plains of Texas. Meteorological composites that quantify mean synoptic patterns during SGPWOs are generated via Rapid Update Cycle analyses, and averaged vertical temperature, moisture, and wind profiles are presented. Further analyses of subsynoptic low and midlevel tropospheric temperatures and winds illustrate a tendency for wildfires to occur near 2-m and 850-hPa thermal ridges when overspread by 500-hPa wind maxima. The juxtaposition of these atmospheric features appears to be a useful meso-α-scale predictor of heightened wildfire risks. Recognition of the presented seasonal indicators toward a fire-prone regime influenced strategic preparations for the historic 2011 Texas wildfires. Operational use of composite pattern recognition-based forecasts in tactical decision support is demonstrated for the 27 February 2011 "firestorm", a particularly damaging SGPWO during an unprecedented fire season. Average ERC values >75 (>95th percentile) additionally supported prolonged burn periods with the passage of subsequent fire outbreak-bearing weather systems during the spring of 2011. Lastly, seasonal trends and the chronology of climatic and environmental signals prior to SGPWOs are highlighted, per a summary of conditions that preceded all of the 2005–2011 episodes.

____

Corresponding author address: T. Todd Lindley, National Weather Service, 1900 English Road, Amarillo, TX 79108. Email: todd.lindley@noaa.gov

1. Introduction

While not typically as intense or long-lived as forest fires, grassland wildfires present a major threat to life and property on the U.S. Great Plains (Clements et al. 2007). Between 2005 and 2009, ten episodes of widespread and damaging wind-driven wildfires occurred within the grass-dominated vegetative fuelscape of the physiographic region known as the southern Great Plains (SGP) (Fenneman 1917). These SGP wildfire outbreaks (SGPWOs) were distinctive both in their geographically widespread nature and in their severity. Cumulatively during these ten outbreaks, 287 fires burned approximately 2.6 million acres (1.1 million ha), 24 people were killed and 166 others were injured. The spatial and temporal evolution of wildfires during these outbreak episodes, and the atmospheric conditions supporting them, were associated with the passage of midlatitude cyclones during periods of abundant and particularly dry, dormant, herbaceous vegetative fuels (Fig. 1).

This manuscript consolidates and formalizes preliminary work by several of its coauthors in an effort to provide a comprehensive review of plains wildfire outbreaks. The primary impetus of this research, however, is the integration of meteorological composites that identify and quantify mean magnitude and relative location of large-scale weather features associated with SGPWOs. Rapid Update Cycle (RUC) (Benjamin et al. 2004) analyses are used to generate depictions of averaged geopotential height, wind, mean sea-level pressure (MSLP), temperature, and relative humidity (RH) in synoptic-scale composites valid at 2100 UTC, the approximate time of peak burning during each of the 2005–2009 outbreaks. An averaged vertical profile of temperature, moisture, and wind representative of the fire-outbreak environment also is included. The presented meteorological composites illustrate an average synopsis of ten SGPWOs. In order to identify subregional areas of enhanced wildfire threat within composite-like synoptic patterns, meso-α-scale analyses of low and midtropospheric temperature and wind fields are used in a forecast funnel (Snellman 1982) approach. This shows that intense fire activity occurs in proximity to near-surface (2-m) and low-level (850-hPa) thermal ridges overspread by midlevel (500-hPa) wind maxima.

Although weather long has been recognized as the most dynamic variable to influence wildland fire behavior (Heilman 1995), SGPWOs do not always occur when meteorological patterns approximate the composites presented in this study. As noted by Brotak and Reifsnyder (1977), non-weather considerations also determine wildland fire potential. Certain infrequent combinations of vegetative fuel and weather are prerequisite to significant wildfires, defined as fires ≥300 acres (≥121 ha) in grasslands (NOAA 2007). Such fires frequently exceed containment ability of local jurisdictions and require mobilization of distant resources for incident management. In addition to the day-to-day weather, other variable characteristics of a fire regime include climate and vegetation (Marlon et al. 2012). Complex interactions between these factors and local short-term meteorological conditions determine the spatial and temporal scales of

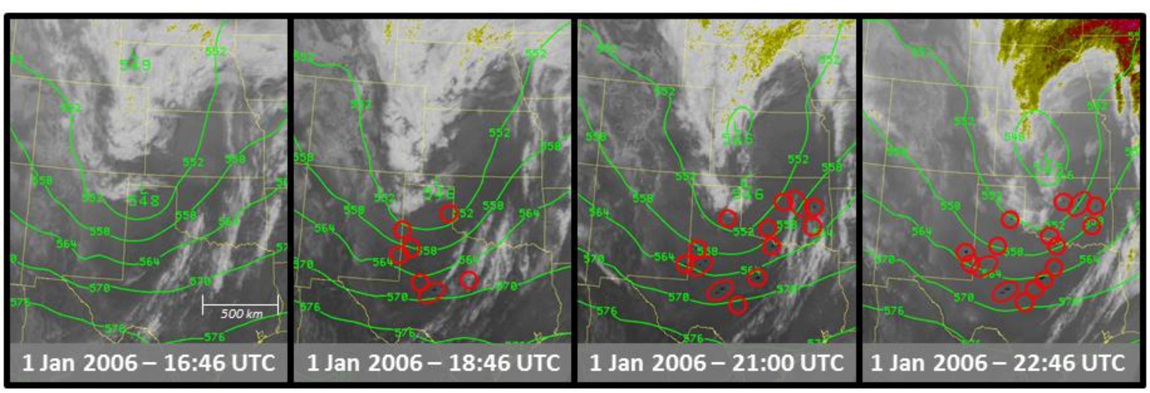


Figure 1: Infrared satellite imagery (11–3.9 μ) and 500-hPa geopotential heights (green contours) illustrating the passage of a wildfire outbreak-bearing midlatitude cyclone on 1 January 2006. Surface fire "hot spots" (Jones and Christopher 2010) are circled (red). *Click image to enlarge.*

significant fire potential. Thus, by necessity, any thorough discussion of the conditions that support SGPWOs also must consider the interdependent influences of seasonal climatic variability and herbaceous vegetative responses. Therefore, discussion of meteorological SGPWO composites is preceded here by documentation of antecedent climatic and environmental regimes associated with the 2005–2009 fire outbreaks. Texas A&M Forest Service (TA&MFS) seasonal wildland fire reports from 2000–2010 illustrate a tendency for enhanced wildfire activity and SGPWOs to occur in Texas during cold phases of the El Niño Southern Oscillation (La Niña). The energy release component for fuel model G (ERC, Bradshaw et al. 1983) is used to quantify responses in grass-dependent vegetative fuelscapes supporting SGPWOs. The 2005–2009 SGPWOs occurred when average ERCs across west Texas exceeded values of 50 (>70th percentile).

In addition, an example illustrating successful application of the presented concepts is demonstrated. Recognition of fire-effective signals in climatic variability, including observed trends in precipitation anomalies, ENSO, and ERC influenced strategic planning by Texas officials prior to the historic 2011 wildfire season. Composite pattern recognition-based forecast methods were employed by fire meteorologists in support of tactical operations prior to the 27 February 2011 "firestorm", a particularly damaging fire outbreak that occurred during that unprecedented fire season. Furthermore, between April and June 2011, vegetative fuels characterized by average ERC values >75 (>95th percentile) supported prolonged SGPWO burn periods. These especially critical antecedent conditions contributed to long-duration, multi-day outbreaks, as well as extended SGPWOs beyond typical onset of the growing season. Lastly, although a limited dataset precludes a thorough climatological treatment of plains fire outbreaks, the seasonality of SGPWOs is addressed briefly, and the chronology of environmental signals prior to the 2005–2011 SGPWOs is summarized.

Although this paper includes discussion of nonmeteorological factors related to SGPWOs, it is not intended to serve as a definitive reference on such topics. Instead, the scope of information presented here aims to provide fire forecasters with a comprehensive overview of the complex interactions between seasonal climatic variability, associated responses of predominantly grass-dependent vegetative fuels, and specific weather patterns that combine to pose a threat of SGPWOs. Although human population and culture directly affect the continuity of vegetative fuel regimes and the frequency of wildland fire ignitions (Guyette and Dey 2000), this study will focus upon the atmospheric and biophysical variables of wildland fire that are influenced directly by either climate or weather.

2. Outbreak definition and cases

Use of the term "outbreak" in meteorology traditionally has described widespread or high-end occurrences of adverse weather phenomena, such as equatorial intrusions of polar air (Glickman 2000) or episodes of numerous severe local storms and tornadoes (Pautz 1969; Galway 1977; Glickman 2000 et al.). Although references to wildfire outbreaks are common, as with other terminology in fire weather, definitions for fire outbreaks lack standardization (Bachmann and Allgoewer 2000).

Meteorologists preliminarily documented the SGPWO phenomenon and its relationship to passing midlatitude cyclones following particularly widespread and destructive fire outbreaks that occurred during the extreme (D3) 2005–2006 drought (Lindley et al. 2007). These early observations were supported by findings of upper-air troughs during high-impact wildland fires elsewhere by Pirsko et al. (1965); Bond et al. (1967) and Finklin (1973). Brotak and Reifsnyder (1977) additionally noted that occurrences of major fires typically were associated with intense midlevel troughs (per 500-hPa geopotential heights) and that a high degree of predictability for such features meant that dangerous fire conditions could be forecast sufficiently for preparations by fire officials. Formal research concerning grassfires and fire meteorology in the predominant grasslands of the SGP, however, historically has been absent from the literature. Thus, an awareness of climate-wildland dynamics and the specific atmospheric features that contribute to SGPWOs initially was not common knowledge among forecasters in the region. As a result, identification of synoptic-scale cyclones that pose a high wildfire risk initially was difficult to ascertain using numerical weather prediction (NWP) models (Lindley et al. 2006).

The ten 2005–2009 SGPWOs used to generate conceptual models in this study were characterized by nearly simultaneous ignition and spread of ten or more wind-driven fires spatially and temporally close to the passage of midlatitude cyclones. During each outbreak, wildfires burned ~10^4–10^6 acres ($4x10^3$–$4x10^5$ ha) across multiple states. The most severe fire activity occurred within fine short- and mixed-grass prairies of the SGP (Fig. 2). The range of wildfires during a few outbreaks in late 2005 and early 2006 expanded eastward to involve increasingly timbered vegetative fuels east of the 98th meridian in northeastern Texas and eastern Oklahoma. These fires occurred under exceptional (D4) drought (NDMC, USDA and NOAA, cited 2006).

The occurrence of these fires underscores the potential for SGPWO-related wildfires to occur beyond the grasslands and defined boundaries of the SGP in extreme conditions. Preliminary field observations of wind-driven fire spread in mixed grass prairie during outbreaks, however, suggest rates of spread (ROS) near 2.7 m s^{-1} (Smith 2011). These measurements far exceed maximum expected ROS in timber of 0.2 m s^{-1} from Rothermel (1972). Thus, the extremity of fire spread during SGPWOs poses a unique danger within the predominantly grassland vegetative fuel environment on the plains.

In addition to rapid fire spreads that consume massive burn areas, wildfires during SGPWOs exhibit behavior that renders most firefighting tactics ineffective (Fig. 3). A consequence of such rapidly spreading and intense fire behavior is the occurrence of devastating public impacts. Each 2005–2009 SGPWO caused extensive property damage, and 80% of the outbreaks resulted in human deaths and/or injuries. TA&MFS officials have referred to the SGPWO phenomenon as *"a 'perfect storm' for extreme fire"* and have used the term "*firestorm*" to describe the most widespread and destructive outbreaks to impact the state (Mutch and Keller 2010). Table 1 provides statistics and maps for each of the ten 2005–2009 SGPWOs (NCDC 2005; 2006a,b,c; 2008a,b; 2009).

3. Seasonal climatic & environmental trends

Thorough assessments of significant wildland fire potential within a specific ecosystem are commonly based upon both long-term (static) and short-term (dynamic) variables (Snyder et al. 2006). Static considerations of fire risk include the state of climate, general characteristics of the landscape that do not vary on short timescales, as well as population and socioeconomic conditions. Although these factors are important in determining the overall fire regime, this study instead focuses upon operationally useful dynamic seasonal and daily indicators of SGPWO potential. This section presents the antecedent seasonal climatic variability and vegetative fuel regimes associated with the 2005–2009 SGPWOs.

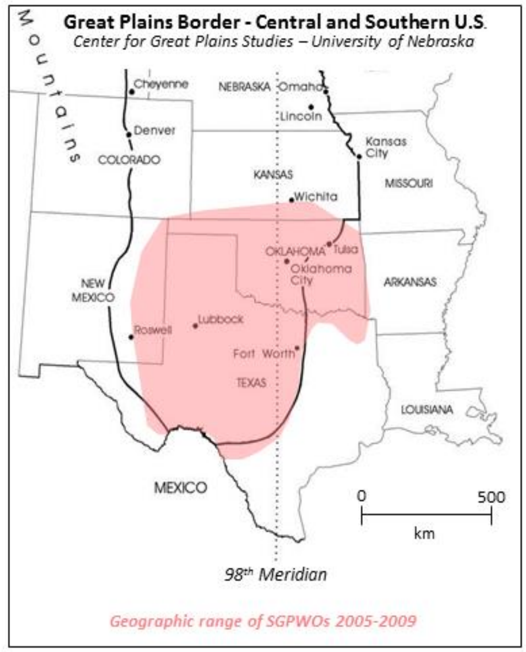
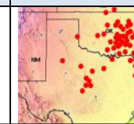
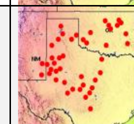
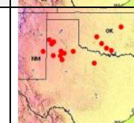
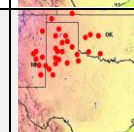
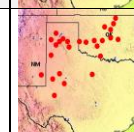
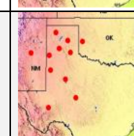
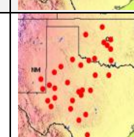
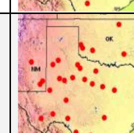
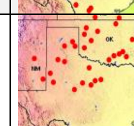
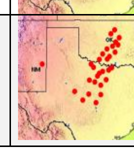


Figure 2: The central and southern Great Plains (black) and the geographic range of 2005–2009 SGPWOs (red). *Click image to enlarge.*

Figure 3: Extreme wildland fire behavior during a SGPWO that renders most offensive firefighting tactics ineffective. Photo courtesy of the Midland Fire Department, Midland, Texas. *Click image to enlarge.*

Table 1: Southern Great Plains wildfire outbreaks 2005–2009.

Date	Wildfires	Acreage	Damages	Structures Lost	Deaths	Injuries	Map
27 Dec 2005	52	60 823 (24 614 ha)	$19 M	341	4	28	
1 Jan 2006	43	303 570 (122 850 ha)	$25 M	115	2	19	
12 Jan 2006	16	39 173 (15 852 ha)	$600 K	48	0	0	
12 Mar 2006	27	1 102 044 (445 981 ha)	$96 M	102	12	11	
6 Apr 2006	26	119 846 (48 500 ha)	$3 M	42	0	2	
15 Apr 2006	10	23 135 (9 362 ha)	$290 K	7	0	3	
25 Feb 2008	32	377 568 (152 796 ha)	$2.5 M	5	1	6	
14 Mar 2008	29	263 375 (106 584 ha)	$4.5 M	31	0	0	
4 Apr 2009	23	33 830 (13 690 ha)	$5.7 M	35	1	35	
9 Apr 2009	29	235 792 (95 421 ha)	$47.9 M	339	4	62	

a. El Niño Southern Oscillation (ENSO)

Climate influences wildland fire at the broadest scale, generally through effects on seasonal cycles such as weather and the distribution of vegetative fuels (Marlon et al. 2012). Drought is a recurring climatic feature of the SGP (Woodhouse and Overpeck 1998). Hoerling et al. (2009) suggests that climatic fluctuations on the SGP are sensitive to equatorial Pacific sea surface temperatures, and specifically identifies a vulnerability to drought on the SGP during cold phases of the El Niño Southern Oscillation (ENSO), or “La Niña”. ENSO is known to influence worldwide precipitation patterns, and has been shown to affect local weather conditions sufficiently to influence the frequency and extent of wildland fire (Simard et al. 1985; Jones et al. 1999; Beckage et al. 2003). Swetnam and Betancourt

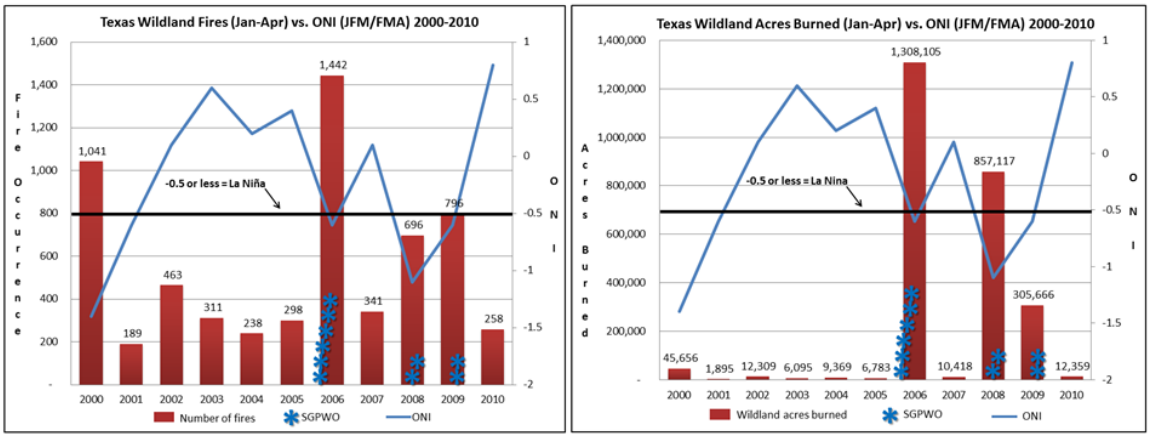


Figure 4: TA&MFS reported seasonal (January–April) wildland fires (left) and wildland acres burned (right) along with corresponding January–February–March/February–March–April (JFM/FMA) averaged ONI for 2000–2010. SGPWO occurrences also are plotted. *Click image to enlarge.*

(1990), Fye et al. (2003), Swetnam and Baiscan (2003), and Gedalof et al. (2005) have related La Niña episodes to reduced precipitation and abundant wildfire activity, particularly in the southwestern U.S.

Preliminary work by Van Speybroeck et al. (2007) initially related La Niña and associated SGP drought conditions to the 2005–2006 Texas fire disasters. Further evidence that supports an enhanced seasonal potential for wildfires on the SGP during La Niña is reflected in records of wildland fire in Texas. TA&MFS data show that both the number of wildfires and acreage burned across the state generally were higher during La Niña episodes between 2000 and 2010 (Fig. 4). Seasonal escalations of wildland fire in Texas, including the occurrence of SGPWOs, were noted during several of the region's climatological fire seasons (defined as January–April by Lindley et al. 2011a) when corresponding Oceanic Niño Index (ONI) values fell below the defined La Niña threshold of –0.5 (Trenberth 1997). In fact, 69% of all TA&MFS-documented fires during the 2000–2010 seasons, including 98% of all acreage burned, occurred during ONI-defined La Niña conditions. An exception occurred in 2001, the second consecutive fire season influenced by a long-lived La Niña episode. The authors suggest that persistent drought and a limited herbaceous response during the growing season reduced the availability of fine vegetative fuels and contributed to the observed lack of enhanced fire activity that year.

Similar seasonal trends that relate high fire activity to negative ONI also have been observed elsewhere in the western hemisphere (Chen et al. 2011). In addition, Johnson (1996) and Veblen and Kitzberger (2002) noted that ENSO is among global climatic cycles that have predictable seasonal influences on local fire regimes. While probably not a prerequisite for high-end fire events in the region, all of the 2005–2009 SGPWOs occurred during La Niña episodes. The data certainly suggest that climatic signals associated with ENSO cold phases have predictive utility as a seasonal indicator of enhanced wildland fire risks, and the potential for destructive wildfire outbreaks on the SGP

b. Vegetative fuels

In addition to local weather, ambient vegetative fuel conditions equally determine a fire regime by controlling fire intensity and the potential for fire spread (Whelan 1995; DeBano et al. 1998). The biophysical response of native vegetation to short-term or seasonal climatic variation is a critical environmental variable that influences significant fire potential and the likelihood of SGPWOs. Therefore, any comprehensive discussion of such widespread and destructive fire episodes must consider the antecedent state of wildland vegetative fuels.

The extreme fire behavior and spread associated with SGPWOs predominantly occurs within fine short- and mixed-grass prairies comprised of native buffalograss *(Buchloe dactyloides)* and blue grama *(Bouteloua gracilis)* communities that dominate the SGP ecosystem (Wright and Bailey 1982). Shrub-type fuels also contribute a significant component to the region's fuelscape (Fig. 5). Within the SGP fuel environment, grass is the primary catalyst for extreme rates of fire spread, while the presence of intermixed shrub influences fire intensity and resistance to control (Scott and Burgan 2005). Thus, the predominantly grass-dependent fuel regime on the SGP readily supports widespread wildfire outbreaks when sufficiently dormant and abundantly dry vegetation is exposed to fire-effective weather patterns.

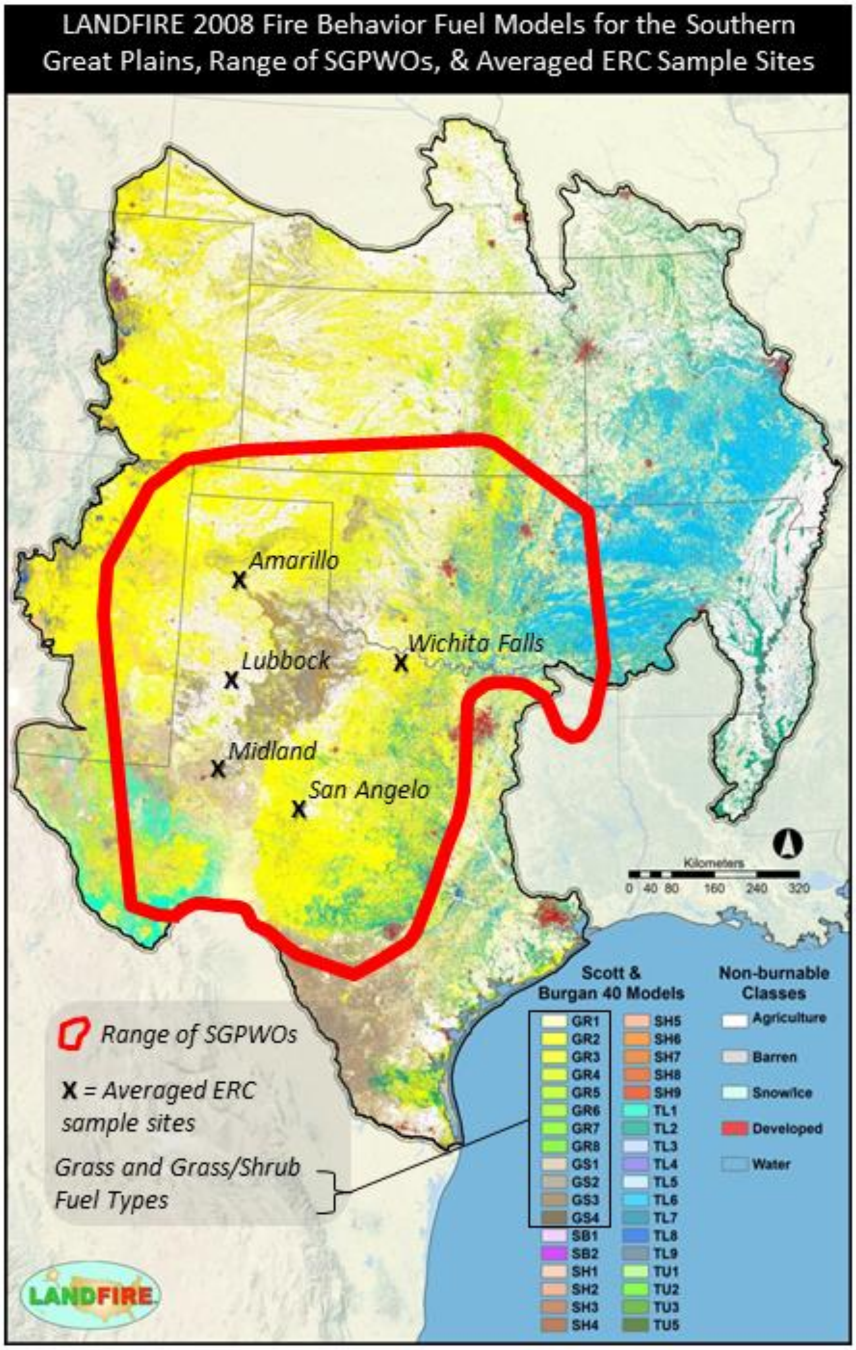


Figure 5: Landscape Fire and Resource Management Planning Tools Project (LANDFIRE) 2008 (Reeves et al. 2009) fuel models for the SGP. The geographic range of 2005–2009 SGPWOs (red outline) and sample sites for averaged ERC values also are shown. C*lick image to enlarge.*

In order to quantify the state of vegetative fuels associated with the 2005–2009 SGPWOs, this study uses ERC (fuel model G). ERC is a quantity directly related to the total energy (BTU) per unit area of vegetative fuel, or the potential heat release available for burning in the flaming zone of a fire for a specific fuel model (Bradshaw et al. 1983). Variables of ERC include weighted fuel loading (surface area-to-volume ratio) as well as a composite of live and dead large-fuel moistures (Cohen and Deeming 1985). The ERC is a cumulative index, and applies values from each of the previous seven days to successive calculations. The effects of day-to-day weather and fuel loading build over time as live fuels cure and dead fuels dry. Therefore, in the absence of widespread fire-mitigating moisture or wetting rainfall, ERC has low day-to-day variability during steady-state drying conditions, and is an excellent indicator of intermediate to long-term drying of vegetative fuels and (by extension) potential fire behavior.

The observed five-day averaged ERC representative of conditions near five cities on the Great Plains of Texas (Amarillo, Lubbock, Midland, San Angelo, and Wichita Falls) is plotted relative to 30-day averaged climatological mean and maxima values, as well as long term (20-y) 70th (ERC of 49), 90th (ERC of 64), and 95th (ERC of 73) percentile rankings for a period spanning 2000–2010 (Fig. 6). ERC data and percentiles are presented here in the same format that is used operationally by TA&MFS Predictive Services. When occurrences of SGPWOs are plotted on the ERC charts, the ten 2005–2009 outbreaks were associated with fuel regimes of ERC between 50 and 70, or exceeding the long-term-averaged 70th percentile. Daily-averaged and event-specific ERC values for each of the 2005–2009 outbreaks are detailed in Fig. 7.

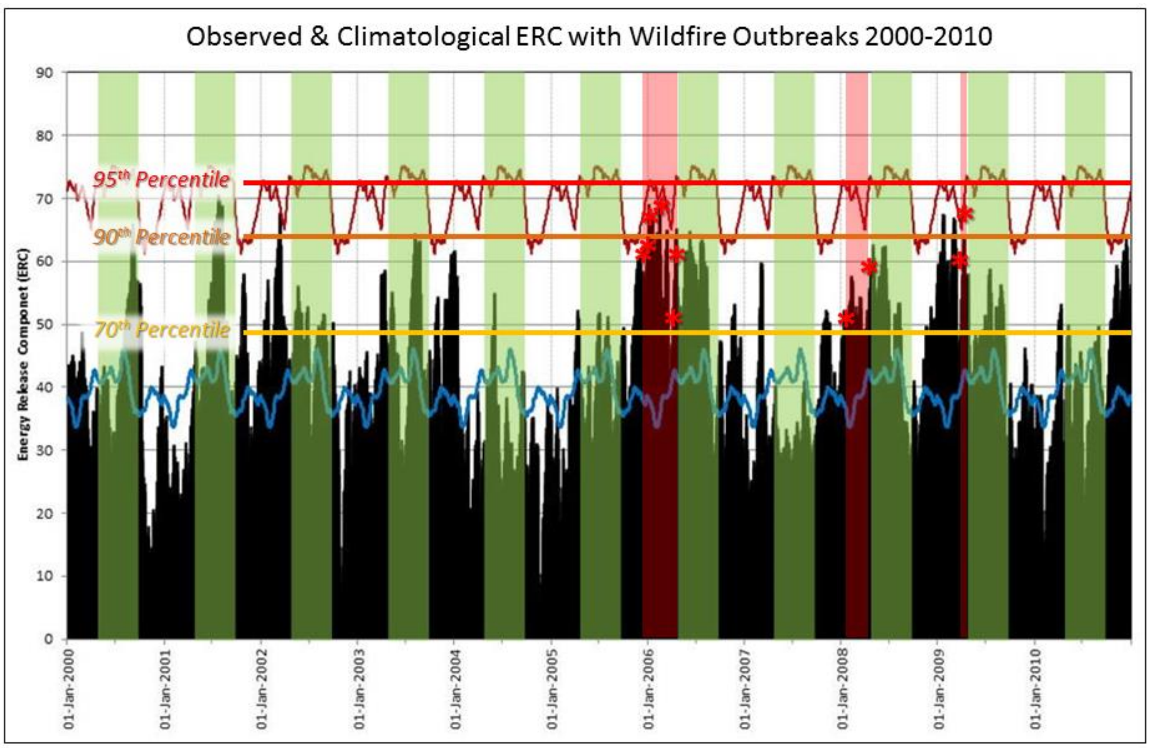


Figure 6: Observed five-day average ERC in west Texas (black) for 2000–2010 with 30-day averaged mean (blue) and maximum values (red). Long-term (20-y) 70th-percentile, 90th-percentile, and 95th-percentile rankings are denoted. Typical growing season (May–September) is shaded green. Periods of observed SGPWOs shaded red. Individual SGPWOs are marked by red "*". *Click image to enlarge.*

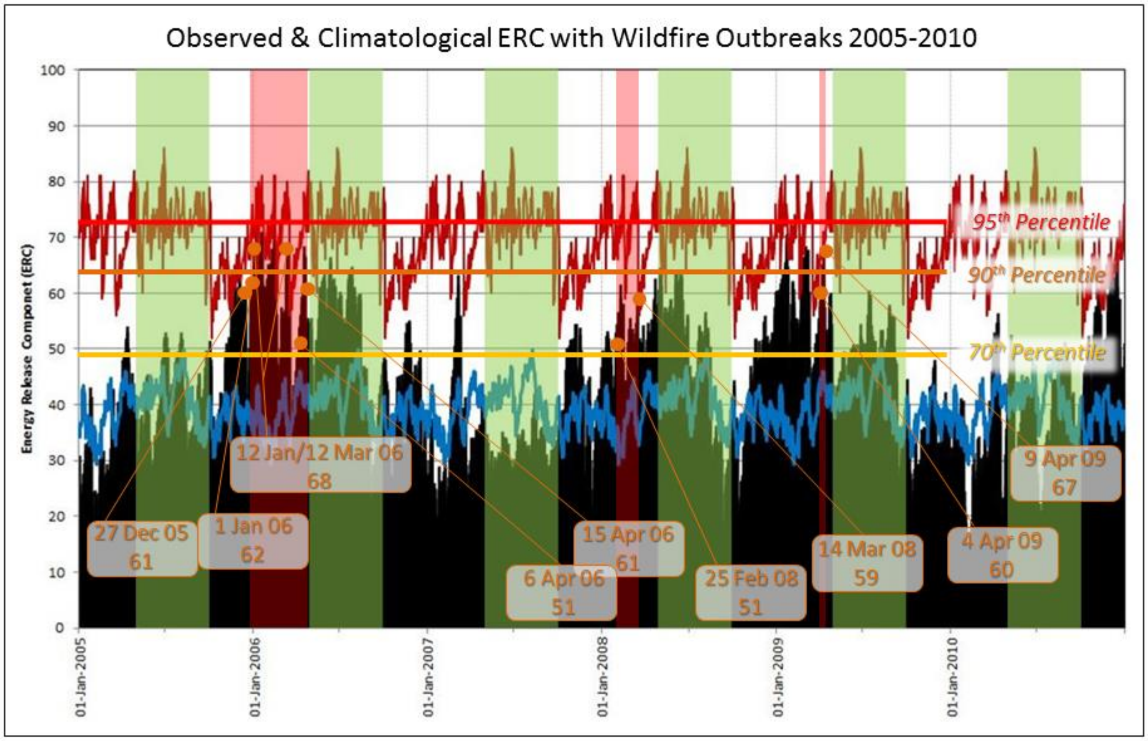


Figure 7: Observed daily average ERC in west Texas (black) for 2005–2010 with daily averaged mean (blue) and maximum values (red). Long term (20-y) 70th percentile, 90th percentile, and 95th percentile rankings are denoted. Typical growing season (May–September) is shaded green and periods of observed SGPWOs shaded red. ERC values associated with individual SGPWOs are detailed (orange). *Click image to enlarge*.

4. Synoptic-scale composites

a. Logic and operational utility

The most extensive research on synoptic patterns associated with critical fire weather across the continental U.S., including the "Southern Plains Region", was in Schroeder et al. (1964). This research, however, was based solely upon airmass characteristics that promote a high ambient fire danger and did not use actual wildland fire occurrence as a verifying measure. With the initial documentation of SGPWOs that occurred in 2005–2006, fire meteorologists recognized that none of Schroeder's "Southern Plains Region" critical fire weather patterns served as an acceptable analog to the atmospheric pattern which promoted wildfire outbreaks in the region that season. The best matched pattern presented by Schroeder et al. was the "Chinook-type" characterized by strong downslope surface winds that overspread the SGP in association with a lee surface trough. That pattern, however, suggested that cold advection in the wake of passing Pacific fronts reduced fire danger over the SGP as midlatitude cyclones and their associated wind maxima translated over the region. This conclusion is in contrast to observations of the 2005–2009 SGPWOs that instead were characterized by the sudden and widespread ignition and spread of wildfires directly associated with midlatitude cyclone passages.

Following the SGPWOs of 2005–2006, fire weather forecasters immediately sought to identify common large-scale weather features associated with extreme fire episodes. Given the lack of documented knowledge concerning fire outbreaks on the SGP, and the complex nonmeteorological processes involved in wildland fire, preliminary work by Lindley et al. (2007) focused on the development of meteorological composite charts. They hoped that recognition of future synoptic patterns that resemble those associated with the 2005–2006 SGPWOs, combined with knowledge of the seasonal state of grass-dependent wildland fuels, would increase awareness of potentially high-impact fire conditions. Such awareness then could lead to improved forecasts, and result in better firefighting and emergency management preparedness in advance of future SGPWOs, as suggested by Brotak and Reifsnyder (1977).

Beebe (1956) demonstrated the utility of meteorological composites in operational pattern-recognition forecasts for tornadoes. Beebe noted that the similarity of synoptic-scale patterns during many tornado events was "striking", and that composite charts provide a means for identifying large-scale atmospheric features common to specific weather situations. Fire meteorologists also recognized a striking similarity of large-scale patterns associated with SGPWOs characterized by the passage of midlatitude cyclones and strong negative-geopotential-height and MSLP anomalies (Fig. 8). Thus, composite methodologies were pursued as a means to quantify the relative magnitude and location of common synoptic-scale atmospheric features associated with SGPWOs.

The utility of SGPWO composites in the enhancement of fire weather forecasts and warnings became apparent in 2008 and 2009, when composites derived from the 2005–2006 fire outbreaks were used with operational success prior to four subsequent SGPWO events that this study includes. Days before each of those SGPWOs, meteorologists recognized composite-like patterns in NWP cyclone passages, and relayed forecasts of high-impact fire events to local and state officials. Texas officials considered these forecasts "imperative" for public safety (Jones et al. 2013). The similarity of synoptic-scale patterns associated with SGPWOs is illustrated via 500-hPa geopotential height reanalyses (Kalnay et al. 1996) for each of the ten 2005–2009 outbreaks (Fig. 9).

While Beebe's tornado composites were independent of geographical location, SGPWOs occur within a physiographic region where atmospheric, biophysical and anthropogenic conditions interact to result in widespread and intense wildland fires. Thus, meteorological composites for SGPWOs are presented here relative to geography, since the background vegetative and population characteristics of the region are contributors to the fire regime.

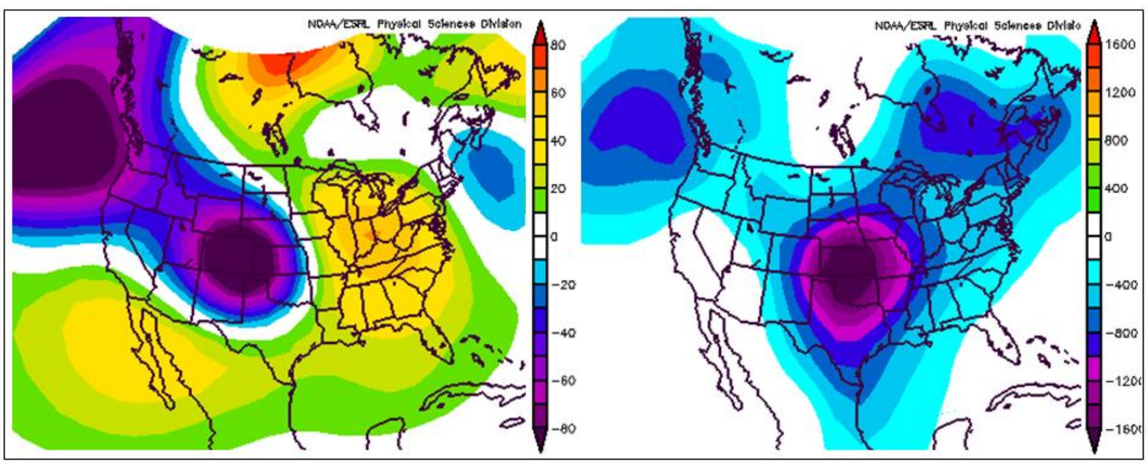


Figure 8: Composite 500-hPa geopotential height (m, left) and MSLP (Pa, right) anomalies associated with ten 2005–2009 SGPWOs. *Images provided by the NOAA/ESRL Physical Sciences Division at http://www.esrl.noaa.gov/psd/. Click image to enlarge.*

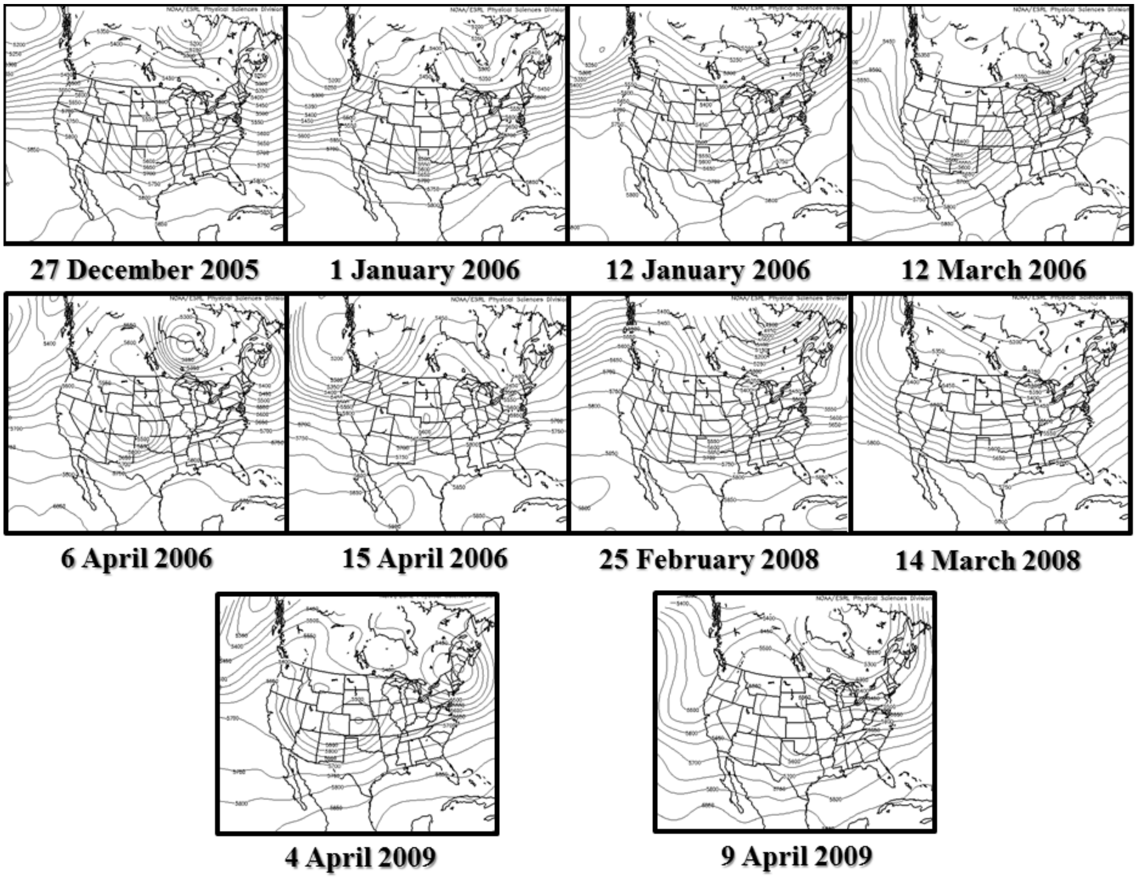


Figure 9: 500-hPa geopotential height reanalyses that show similarity between synoptic-scale upper-air weather patterns associated with ten 2005–2009 SGPWOs. *Images provided by the NOAA/ESRL Physical Sciences Division at http://www.esrl.noaa.gov/psd/. Click image to enlarge.*

b. Composite methodology

Meteorological composites derived from SGPWOs that occurred on 27 December 2005, 1 January 2006, 12 January 2006, 12 March 2006, 6 April 2006, 15 April 2006, 25 February 2008, 14 March 2008, 4 April 2009, and 9 April 2009 were created using RUC analyses post-processed on a 20-km grid. These composites show averaged atmospheric fields derived from initial-hour 2100 UTC analyses, the approximate peak-intensity burn period for each outbreak. GEneral Meteorological PAcKage (GEMPAK) (Unidata 2002) applications were used to plot computed mean grid values for a variety of parameters including: geopotential height and winds at the 300-hPa, 500-hPa, 700-hPa, and 850-hPa levels, 850-hPa temperatures, MSLP, 2-m temperature, 2-m RH, and 10-m wind. The mentioned low-level variables were deemed relevant, given that RH and wind are the most commonly used meteorological parameters in the prediction of wildland fire behavior and spread, and they are recognized as the primary variable factors to influence wildfire severity (Heilman 1995).

A composite vertical profile also was generated through use of 0000 UTC observed soundings from Midland International Airport, Texas (MAF). MAF is located near the core of the composite surface warm and dry sector, and was in that sector of each presented outbreak-bearing cyclone.

c. Wildfire-outbreak composites

Atmospheric composites for the peak intensity burn period of SGPWOs are consistent with the passage of a deep midlatitude cyclone over the Plains. GEMPAK graphics that depict the 300-hPa, 500-hPa, 700-hPa, 850-hPa, and near-surface level composites, as well as an averaged vertical sounding profile, follow (Fig. 10) along with a narrative description of each composite level.

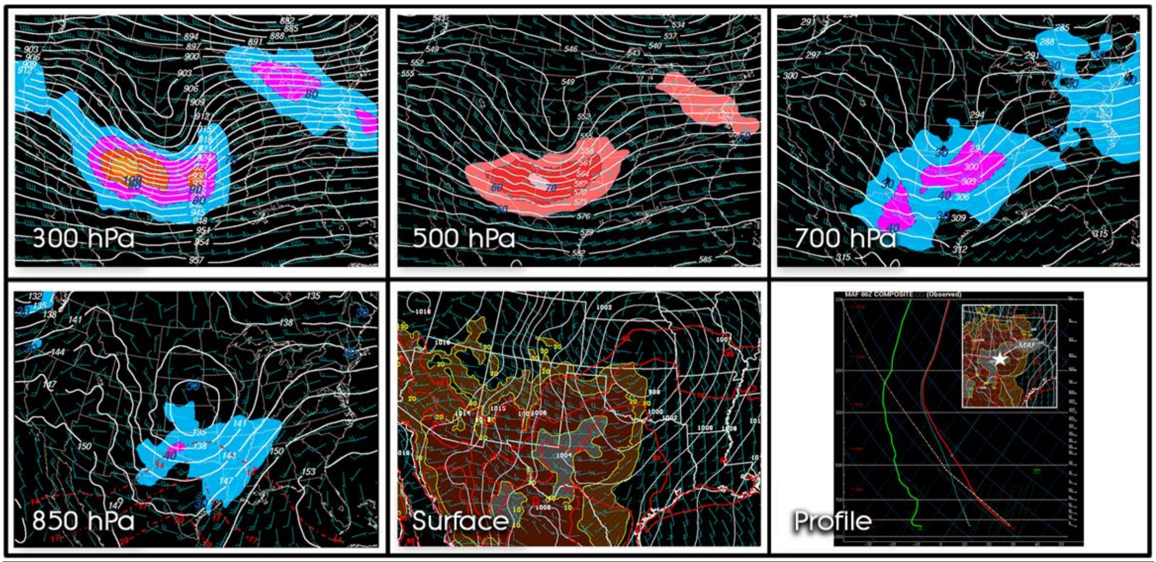


Figure 10: 2100 UTC RUC composites for the 300-hPa, 500-hPa, 700-hPa, 850-hPa, and surface levels along with an averaged vertical sounding profile at MAF from ten 2005–2009 SGPWOs. Format for upper air charts includes: geopotential heights (white contours in dam), winds (cyan barbs in kt), and isotachs (shaded) ≥70 kt (36 m s^{-1}) at 300 hPa, ≥50 kt (26 m s^{-1}) at 500 hPa, ≥30 kt (15 m s^{-1}) at 700 hPa, and 850 hPa. 850-hPa isotherms ≥14°C are shown (red dashes). Format for surface chart includes MSLP (white contours), 10-m winds (cyan barbs in kt), 2-m isotherms ≥60°F (16°C), and 2-m RH ≤30% (shaded). Format for the vertical profile includes: temperature (red), dewpoint (green), and wind (white barbs in kt). *Click images to enlarge*.

300 hPa: Composite geopotential heights between 903–909 dam are analyzed along a trough over the Nebraska Panhandle southward to western Kansas. Averaged wind speeds >70 kt (36 m s^{-1}) to 80 kt (41 m s^{-1}) are shown over all of the Great Plains portions of New Mexico, Texas, and Oklahoma, with a jet core >100 kt (51 m s^{-1}) over central New Mexico.

500 hPa: Minimum geopotential heights of 549 dam are characteristic of a sharp midlevel composite trough over western South Dakota southward to northwestern Kansas. The averaged wind maximum at 500 hPa exceeds 70 kt (36 m s^{-1}) over eastern New Mexico and west Texas, with a broad area of 50–60 kt (26–31 m s^{-1}) over the remainder of the SGP.

700 hPa: The composite analysis indicates a 294 dam trough centered near the Nebraska and Kansas state line, with a band of southwesterly to westerly winds >40 kt (21 m s^{-1}) over far western Texas and extending northeastward over eastern Oklahoma and adjacent areas of southeastern Kansas, southwestern Missouri, and western Arkansas.

850 hPa: A 135-dam low is depicted over north-central Kansas with 30–40 kt (15–21 m s^{-1}) southwesterly to westerly winds over areas of eastern New Mexico and west Texas eastward to the lower Mississippi River. A thermal ridge characterized by 14–20°C temperatures is depicted from central Oklahoma southward to the lower Rio Grande Valley of south Texas.

Surface: The MSLP analysis is consistent with the strong midlatitude cyclone depicted in geopotential height and wind fields aloft with a 988-hPa low centered near Salina, KS. Extremely dry air is noted west of a dryline that extends southward from the low over central Oklahoma and central Texas. Temperatures in the 70–80°F range (21–27°C), RH ≤20% and westerly downslope winds ≥20 kt (10 m s^{-1}) are analyzed in the low-level warm and dry sector of the cyclone, especially west of a thermal ridge over southeastern New Mexico, west Texas, and southwest Oklahoma. A large area of 2-m RH ≤10% is depicted over far southeastern New Mexico and much of west Texas coincident with westerly 10-m winds of 15–25 kt (8–13 m s^{-1}).

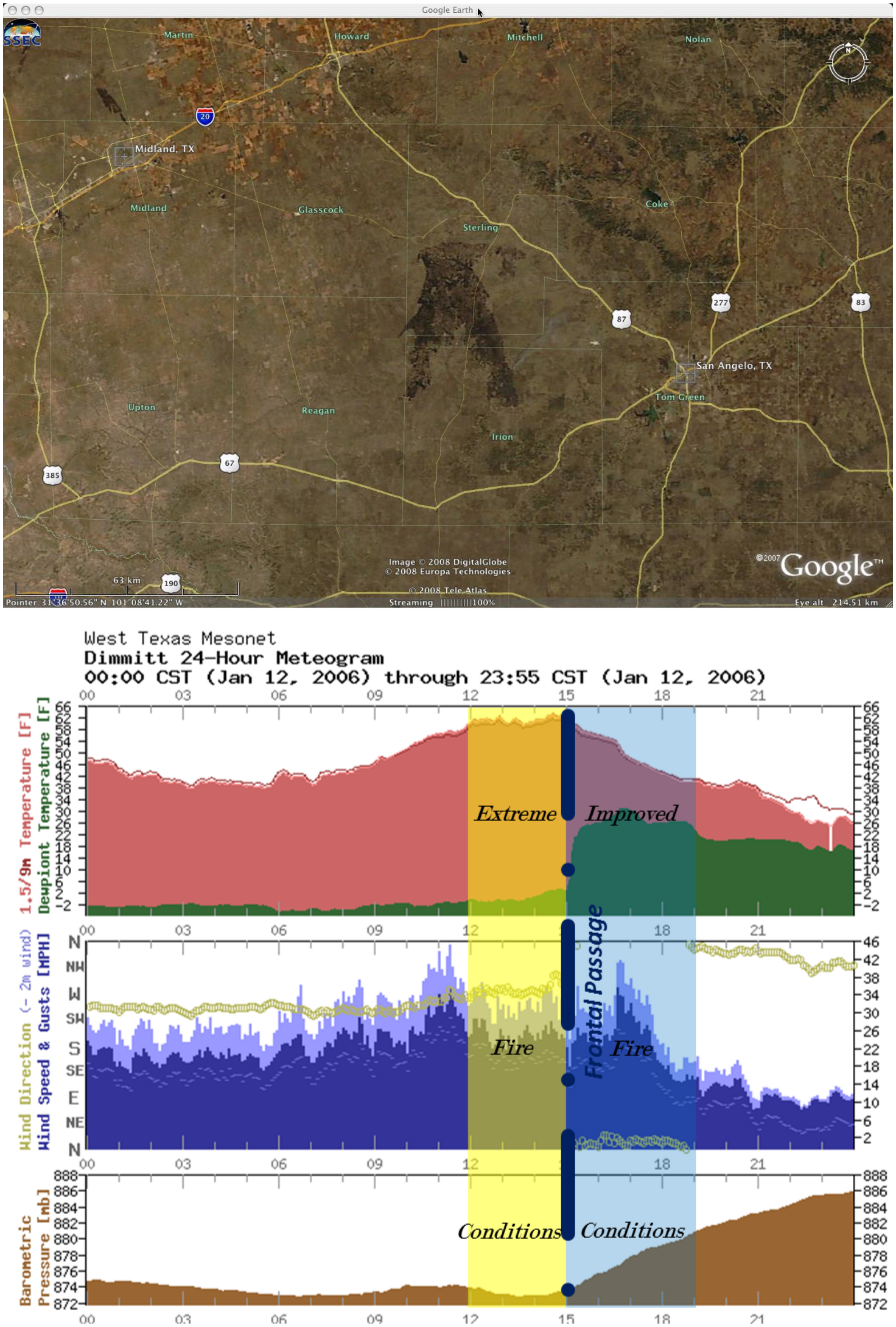


Figure 11: The "Glass Fire" burn scar west of San Angelo, TX, following a wildfire-wind shift interaction during a SGPWO and frontal passage on 25 February 2008 (left), and WTM meteogram for temperature and dewpoint (top), wind speed and direction (middle), and pressure (bottom) during a wildfire-wind shift interaction near Dimmitt, TX, during a SGPWO on 12 January 2006 (right). *Click image to enlarge*.

Vertical profile: The juxtaposition of warm, dry air and strong winds is associated with an unstable but dry atmospheric column characterized by 700–500-hPa lapse rates of 6.9°C km^{-1}, surface dewpoint depressions of 15–40°C, deep westerly flow with mean mixed-layer winds of 30 kt (15 m s^{-1}), wind speeds up to 100 kt (51 m s^{-1}) near 200 hPa, and deep boundary-layer mixing to near 675 hPa.

An important aspect of the SGPWO composites is the cold front over northwestern Oklahoma, the Texas and Oklahoma Panhandles, and northeastern New Mexico. This front is depicted in the surface composite (and to a lesser extent in the 850-hPa chart) as it advances into the fire-effective air mass west of the dryline and shifts composite westerly winds of 20–25 kt (10–13 m s^{-1}) within the warm, dry prefrontal air to northwesterly at about 15 kt (8 m s^{-1}). This frontal passage results in abrupt northerly wind shifts at the site of ongoing fires during SGPWOs. Such frontal wind shifts present a hazard by transitioning the southern flank of large ongoing fires into expansive head fires (Fig. 11). Changes in wind speed and direction long have been recognized as a reoccurring element common to many wildfire-related fatalities (National Wildfire Coordinating Group 1997). Texas Tech University West Texas Mesonet (WTM) (Schroeder et al. 2005) proximity observations for wildfire-wind shift interactions during SGPWOs, however, show that fire conditions generally improve in the postfrontal environment. Unlike many other geographical regions of the U.S. where frontal passages frequently signify the onset of dry air advection and critical fire weather, frontal passages during SGPWOs typically mark a gradual cessation of extreme fire conditions as cooler temperatures, increased RH, and decreased wind speeds settle over the outbreak area in wake of the front. These postfrontal weather changes can translate rapidly to increased fuel-moisture content in the fine herbaceous vegetative fuels on the plains, and further moderate the severity of fire behavior sufficiently to allow safe, traditional firefighting tactics.

An overview composite chart that depicts atmospheric features common to SGPWOs, as well as their mean location and intensity, is presented (Fig. 12). Satellite imagery from 14 April 2011 is shown in comparison to illustrate an actual fire-outbreak composite-like weather situation and SGPWO in progress.

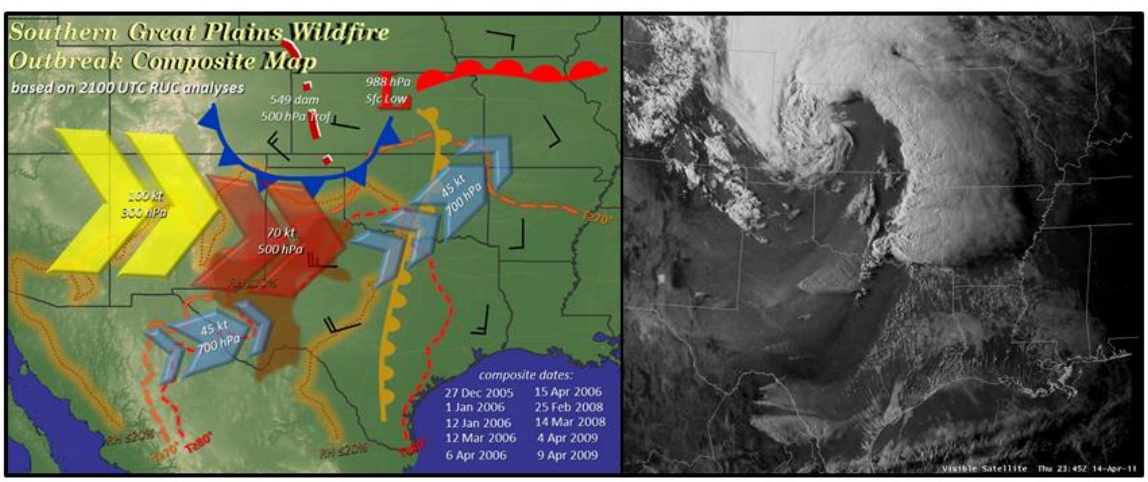


Figure 12: Overview composite chart valid at 2100 UTC for ten 2005–2009 SGPWOs (left), and visible satellite imagery of an SGPWO in progress at 2345 UTC 14 April 2011. *Click image to enlarge and for annotated satellite image.*

5. Meso-α-scale analyses

While the presented meteorological composites depict an average synopsis of SGPWOs, they do not provide adequate information for identifying site-specific fire threat forecasts from an ingredients-based perspective as described by McNulty (1978; 1995), Johns and Doswell (1992) and Doswell et al. (1996). Fire meteorologists acknowledge a need to evolve pattern-recognition techniques toward ingredients-based methodologies, but such methods are problematic in fire weather due to complex interactions between meteorological and ecological contributions to the fire regime. Unlike ingredients-based forecasts of other atmospheric phenomena, the occurrence of wind-driven wildfire on the SGP involves not only short-term meteorological variables such as wind and RH, but also biophysical responses in fine vegetative fuels to both weather and climate, and an anthropogenic component for ignition.

Further, a complex interdependency between these ingredients exists. For example, short-term changes in local weather rapidly influence the state of fine grass-dependent fuels (Cheney and Sullivan 2008). In addition, interactions between weather and routine human activity or man-made infrastructure result in wildland fire ignitions. Common ignition sources during SGPWOs include wind-damaged utility lines arcing into dry vegetation and wind-blown sparks generated from machinery and other human activities. These factors are ever-present, but largely unpredictable on fire-specific scales. Thus, a meteorological pursuit of ingredients-based forecast methods for wildland fire derived solely from observational data and NWP is complex, and possibly impractical.

Instead, this study uses a downscaled approach to pattern recognition methodologies in a manner consistent with forecasting funnel techniques (Snellman 1982). Meso-α-scale analyses of low-level (2-m and 850-hPa) thermal ridges and midlevel (500-hPa) wind maxima indicate meteorological environments that promote locally enhanced wildfire risks within larger composite-like patterns. The identification of these features, as well as their spatial and temporal proximity, dimensions and translation, can provide a forecast perspective on the evolution, intensity and areal coverage of wildfire outbreaks. Additionally, the lack of pronounced interactions between these low and midtropospheric features within the warm, dry sector of an otherwise composite-like midlatitude cyclone may diminish the fire effectiveness of its passage, even in the presence of receptive vegetative fuels.

Contributions from interacting low-level thermal ridges and midlevel wind maxima in determining heightened wildfire risks were illustrated during an SGPWO on 9 April 2009. The most severe combinations of RH and wind were expected, and occurred over west Texas and far eastern New Mexico. 2100 UTC RUC analyses depicted 2-m RHs ≤10% and sustained westerly 10-m wind speeds of 30 kt (15 m s^{-1}) over west Texas (Fig. 13). TA&MFS fuels data revealed ERCs in excess of the 70–80 range (~95th percentile) over west-central and far western Texas. A fuel-dryness index (dryness level) based on 100-h fuel moisture and ERC (Marsha 2008) depicted "extremely dry" vegetation in the area of lowest RH and highest

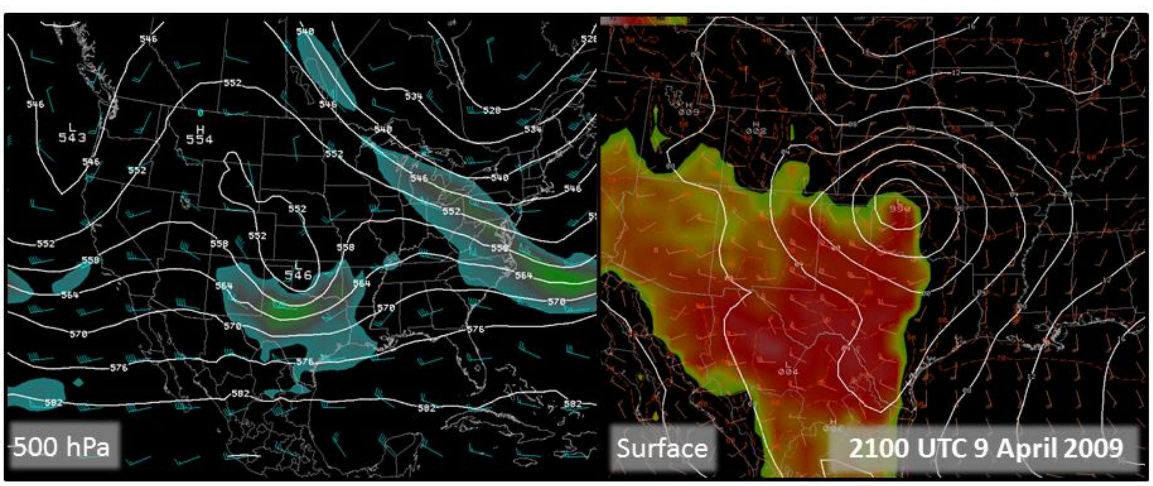


Figure 13: 2100 UTC 9 April 2009 RUC analyses of 500-hPa geopotential heights (white contours in dam), winds (cyan barbs in kt), isotachs ≥50 kt (26 m s^{-1}) (shaded), and surface analysis of MSLP (white contours in hPa), 10-m winds (orange barbs in kt), 2-m isotherms (red dashes in °F), and 2-m RH ≤30% (shaded). *Click image to enlarge.*

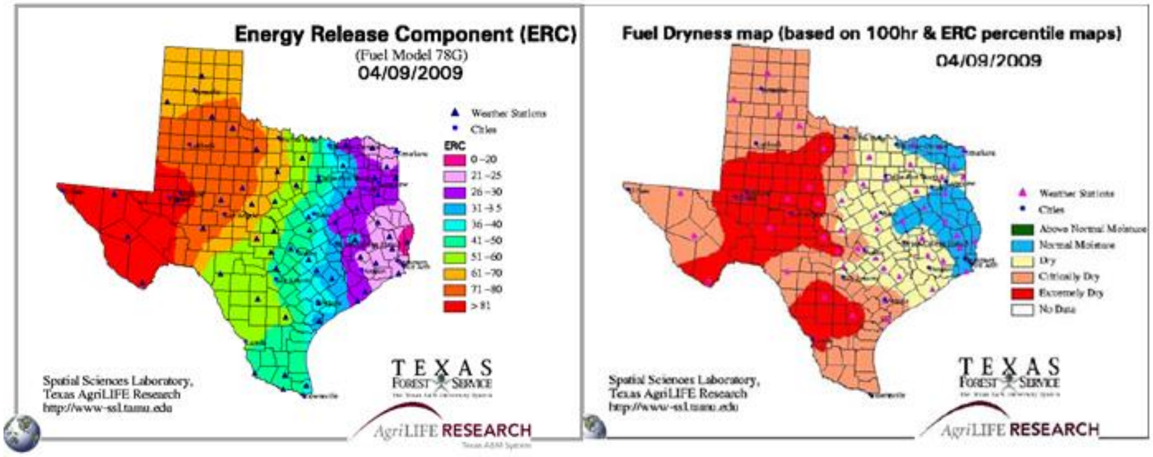


Figure 14: Texas ERC (left) and fuel dryness (right) valid on 9 April 2009. *Click image to enlarge.*

wind speed (Fig. 14). The anticipated combination of weather and wildland fuels prompted an "extremely critical" fire weather risk issued by the Storm Prediction Center (SPC) centered within the cyclone's warm, dry sector over west Texas (not shown; available per SPC's online archive at: http://www.spc.noaa.gov/products/fire_wx/overview.html).

A destructive SGPWO occurred on 9 April 2009, but the most widespread and damaging wildfires struck central Oklahoma and northern Texas. These fires developed where 2-m RH ranged from 10% to 25% and westerly winds were sustained at speeds of 15–25 kt (8–13 m s^{-1}). Fire activity was limited farther west where more favorable combinations of RH, wind and vegetative fuels were perceived. A preliminary analysis of the outbreak indicated that most fires occurred within relatively less-cured "transitional" vegetative fuels represented by ERCs between 50 and 70 (generally 70th–90th percentiles) and "dry" to "critically dry" fuel dryness (Smith 2009).

Subsynoptic (meso-α-scale) meteorological analyses of the 9 April 2009 outbreak revealed that wildfires burned within an area of 4–7°C 2-m temperature anomalies. In contrast, minimal fire activity developed within the lower-RH, higher-wind and drier fuel environment over west Texas and eastern New Mexico, where 2-m temperatures ranged from near climatological average values to some 4°C below seasonal maximum temperatures (Fig. 15). These observations are consistent with Lindley et al. (2011a) who showed a peak in significant wildfire occurrence in environments characterized by positive 2-m temperature anomalies relative to climatological daily average maximum values. Further meso-α-scale analysis at 2100 UTC 9 April 2009, combined with 2115 UTC infrared satellite imagery, revealed that the most widespread fire activity occurred near the intersection of low-level thermal ridges and a midtropospheric wind maximum. Temperatures along the low-level thermal ridges ranged between 70–85°F (21–29°C) at 2 m and from 15–18°C at 850 hPa. These anomalously warm temperatures were overspread by a 70-kt (36-m s^{-1}) 500-hPa jet maximum (Fig. 16).

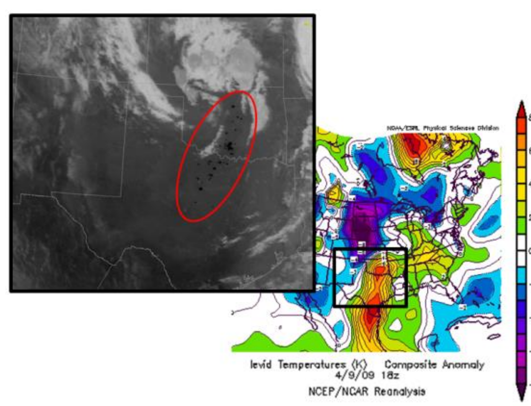


Figure 15: 2115 UTC 9 April 2009 infrared (11-3.9 μ) satellite image with "hot spots" (outbreak area circled in red) and 2-m temperature anomalies. *Image provided by the NOAA/ESRL Physical Sciences Division at http://www.esrl.noaa.gov/psd/. Click image to enlarge.*

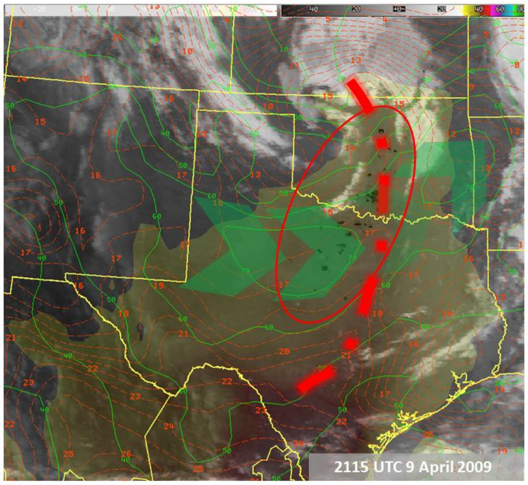


Figure 16: 2115 UTC 9 April 2009 infrared (3.9 μ) satellite image with fire "hot spots" (outbreak area circled in red) overlaid with 2100 UTC RUC analysis of 2-m temperature ≥70°F (21°C) (shaded), 850-hPa isotherms (red dashes in °C), and 500-hPa isotachs (green contours in kt). The 850-hPa thermal ridge (bold red dash) and 500-hPa wind max (green arrows) are denoted. *Click image to enlarge.*

6. Operational applications in 2011

The 2011 fire season on the SGP was unique both in its scope and duration, particularly in Texas where an unprecedented 4 011 709 acres (1 623 481 ha) burned and 2 947 homes were destroyed (TA&MFS, cited 2012 and Jones et al. 2013). During the course of this historic fire season, a series of eight devastating SGPWOs claimed three lives. Although 44% of all SGPWOs observed from 2005–2011 occurred in 2011, that year's outbreaks resulted in only 10% of SGPWO-related fatalities since 2005. The relatively low loss of life in 2011 wildfire outbreaks may be attributed partially to the advanced recognition of fire-favorable regimes and SGPWO composite-like weather patterns that influenced preparatory actions by Texas officials (Van Speybroeck et al. 2011).

Summaries of the seasonal dynamic conditions that primed the SGP fire regime for damaging outbreaks in 2011, the early warning diagnosis of the 27 February 2011 "firestorm", and the proactive measures taken to mitigate public impacts are included here to demonstrate proof-of-concept and the decision-support utility of the presented methods. As noted by Owen et al. (2012), few studies have illustrated how modern institutional changes, such as the creation of predictive services, and the incorporation of climate and weather research into wildland fire management, have affected operational practices positively. The events in Texas of 2011 are such an example.

a. Strategic—seasonal climatic and environmental observations

Remarkable seasonal variability occurred on the SGP between the summer of 2010 and spring of 2011 (Fig. 17). Summer 2010 brought excessive rainfall to much of the region, which culminated with the remnants of Hurricane Alex

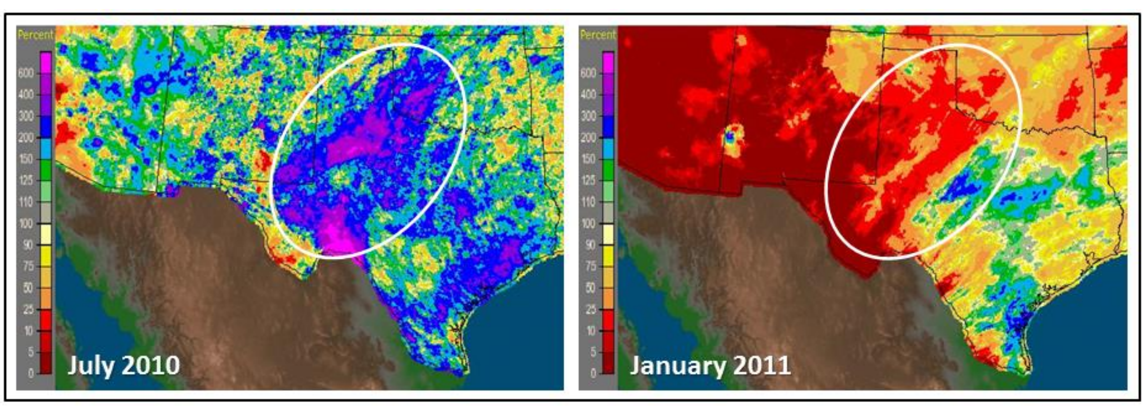


Figure 17: Precipitation departures from climatology for July 2010 and January 2011. An area of dramatic seasonal variability is highlighted by the white oval. *Click image to enlarge.*

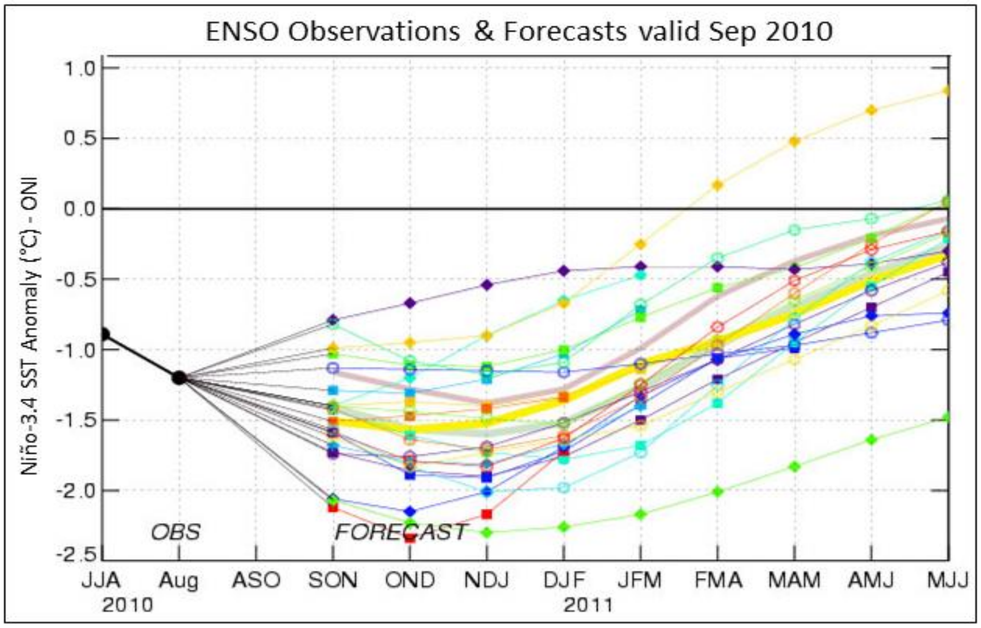


Figure 18: International Research Institute for Climate and Society (cited 2011) ENSO observations and forecasts per ONI valid September 2010. Three-month periods abbreviated (e.g., June–July–August shown as "JJA"). *Click image to enlarge.*

in July. This moisture left large areas of southeastern New Mexico, west Texas, and western Oklahoma with >200% (locally >300%) of climatologically normal monthly precipitation during the growing season. By late summer and fall 2010, however, ONI values <–1.0 already indicated La Niña conditions in the eastern equatorial Pacific, and negative trends were projected to persist through the upcoming winter and spring (Fig. 18). The ENSO cold phase contributed to renewed drought. By January 2011, areas that had an anomalously wet growing season began to experience <25% of monthly average precipitation. Fire meteorologists and fire analysts recognized that the enhanced vegetative-growth response that followed summer rains would result in an extreme predominance of dry fuels during the subsequent winter and spring fire season (Fig. 19).

With an imminent threat of an enhanced wildfire season identified as early as fall 2010, National Weather Service (NWS) fire meteorologists partnered with TA&MFS officials in actions to prepare the state of Texas for the potential of SGPWOs. These efforts included briefings for the Texas Division of Emergency Management, an NWS and TA&MFS co-hosted Fire Weather-Media Workshop, and a statewide Fire and Climate Planning Meeting. The state's preparation

Figure 19: Example of excessive grass-dominated fuel loads typical on the SGP of Texas in October 2010. Photo location denoted on map. *Click image to enlarge.*

ultimately focused on a collaborative educational campaign entitled "Texas Firestorm". This campaign featured a video which introduced the dangers of SGPWOs to local first responders and provided guidelines for dealing with fire outbreaks at the community level (TA&MFS, cited 2013).

As expected from negative trends in ONI, drought worsened over the SGP during the late winter and spring of 2011 (Fig. 20). At the beginning of January, moderate (D1) to severe (D2) drought already was occurring over the periphery of the SGP, mainly over southeastern

New Mexico and southwestern Texas (NDMC, USDA and NOAA, cited 2011). The state of drought rapidly deteriorated during the spring with expansive development of extreme (D3) to exceptional (D4) drought over a majority of the SGP portion of New Mexico, Texas and Oklahoma between March and June. As the drought worsened, ambient wildland fire potential increased. Averaged ERC values in west Texas intermittently began to exceed 70th-percentile values (≥50) as early as fall 2010, and initially reached ≥90th-percentile values (≥65) by early December 2010. Following a series of cold-air intrusions between late December 2010 and early February 2011, ERC values again reached the 60–70 range (~90th percentile) by late February. This increase in the vegetative fuel's susceptibility to fire was associated with the onset of SGPWOs on 27 February 2011, when an average ERC value of 62 (~90th percentile) was observed (Fig. 21).

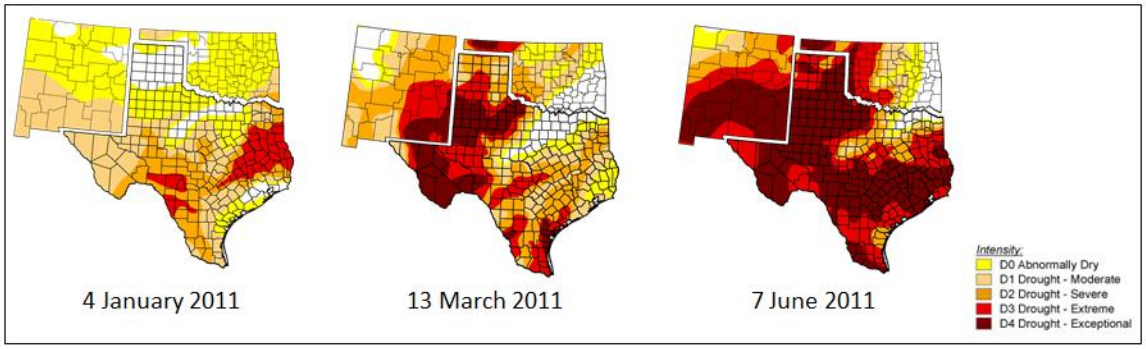


Figure 20: Progression of deepening drought across New Mexico, Texas and Oklahoma as shown by the U.S. Drought Monitor on 4 January 2011, 13 March 2011 and 7 June 2011. *Click image to enlarge.*

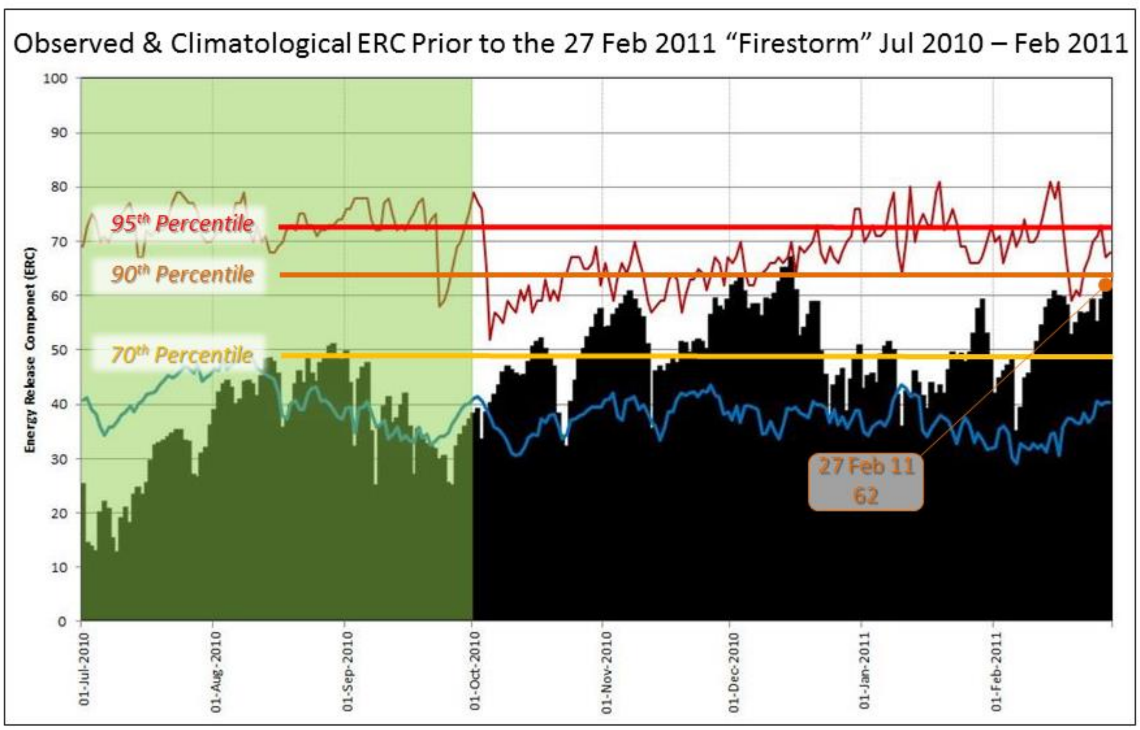
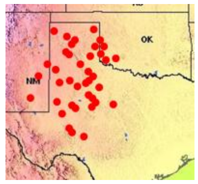


Figure 21: Observed daily average ERC in west Texas (black) for July 2010–February 2011 with daily averaged mean (blue) and maximum (red) values. Long term (20-y) 70th-percentile, 90th-percentile and 95th-percentile rankings are denoted. Typical growing season (through September) is shaded green. The daily average west Texas ERC for the 27 February 2011 "firestorm" is specified in orange (text). *Click image to enlarge.*

Table 2: 27 February 2011 southern Great Plains wildfire outbreak

Wildfires	39	Map
Acreage	284 911 (115 299 ha)	
Damages	$19 M	
Structures Lost	210	

b. Tactical—27 February 2011 "firestorm"

Utility of the synoptic pattern composite-based methods and meso-α-scale analyses presented in this study are demonstrated here through a review of operational fire weather forecasts prior to a particularly widespread and destructive wildfire outbreak that impacted eastern New Mexico, west Texas, and far southwestern Oklahoma on 27 February 2011. Fire and public-impact statistics associated with this event are shown in Table 2 (NCDC 2011).

The 27 February 2011 "firestorm" evolved in a similar manner to the 2005–2009 SGPWOs. Days in advance, NWP depicted a composite-like pattern that featured the passage of a deep midlatitude cyclone over the southern Rockies and Great Plains. The 2100 UTC 27 February 2011 RUC 500-hPa analyses depicted a 545-dam low over northern New Mexico. An associated 100-kt (51-m s^{-1}) jet maximum over southern New Mexico extended eastward over west Texas in a manner consistent with the SGPWO composites (Fig. 22). The corresponding surface analysis showed:

- a 993-hPa surface low over the Oklahoma Panhandle,
- a broad area of downsloping 10-m southwesterly wind speeds of 30–35 kt (15–18 m s^{-1}) and
- 2-m RH as low as 5–10% within the cyclone's warm and dry sector, from southeastern Colorado southward over most of west Texas.

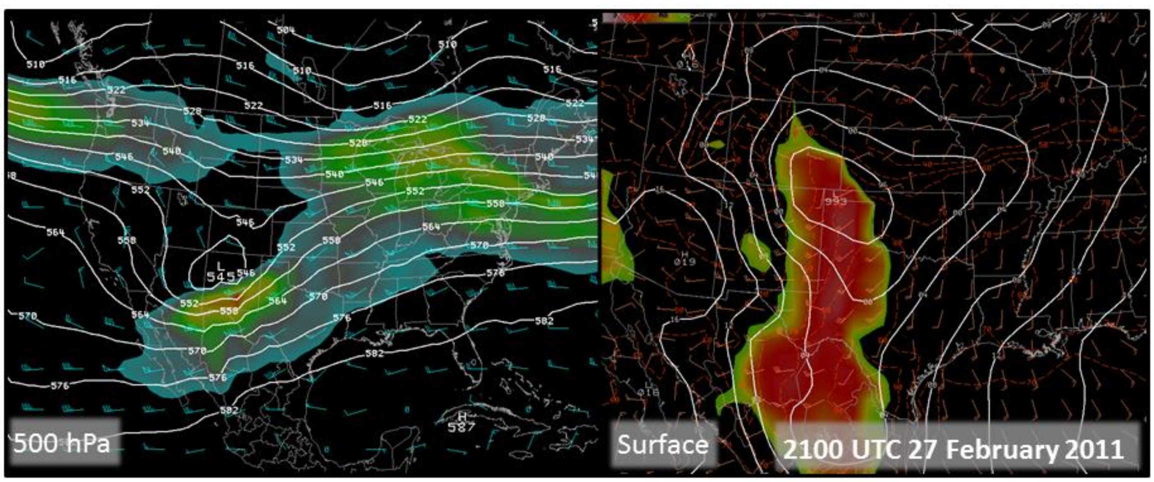


Figure 22: 2100 UTC 27 February 2011 RUC analysis of 500-hPa geopotential heights (white contours in dam), winds (cyan barbs in kt), and isotachs ≥50 kt (26 m s^{-1}) (shaded) and surface analysis of MSLP (white contours in hPa), 10-m winds (orange barbs in kt), 2-m isotherms (red dashes in °F), and 2-m RH ≤ 30% (shaded).

This pattern was identified early in the forecast process as a favorable comparison to the SGPWO composites. The midlevel trough and its associated surface low, however, were displaced ≈500 km southwest of the said synoptic features in the idealized fire-outbreak conceptual model. Yet, the magnitude and relative location of the observed midlatitude cyclone and associated wind maxima were aligned well, spatially and temporally, to support favorable combinations of near-surface RH, wind and temperature for intense wildland fire activity.

Recognition of the SGPWO composite-like pattern in NWP solutions, combined with knowledge of the vegetative fuel state characterized by average ERCs near the 90th percentile, allowed meteorologists and fire analysts to communicate the risk of a potential 27 February 2011 wildfire outbreak to Texas officials as early as 22 February. As consistency in NWP solutions and forecaster confidence increased with subsequent runs, fire meteorologists determined that an SGPWO was likely on 27 February. Graphical threat outlooks highlighting the area of enhanced risk were drafted through collaboration of NWS forecasters in Amarillo, Lubbock, Midland, and San Angelo (e.g., Fig 23). These graphics were disseminated at 1600 UTC 25 February 2011, >48 h beforehand, in support of local and state-level authorities involved in making tactical response decisions.

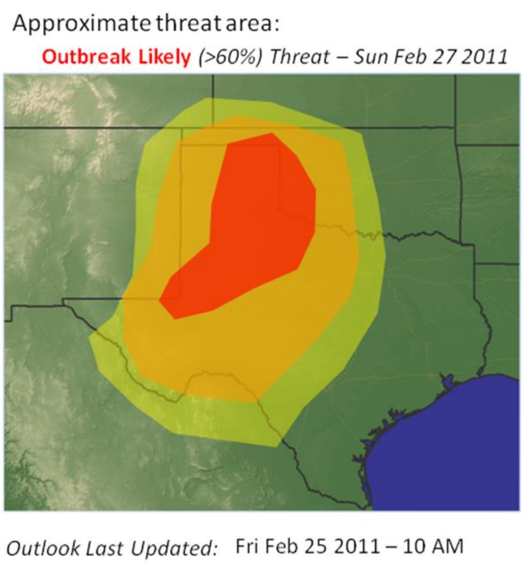


Figure 23: Graphical wildfire outbreak outlook disseminated to local and state-level decision makers at 1600 UTC 25 February 2011.

Those outlooks focused upon the expected evolution of low-level thermal ridges and an incoming midtropospheric wind maximum. A low-level thermal ridge initially was expected to develop over the Plains near the Texas–New Mexico state line. The ridge was predicted to amplify and move eastward over west Texas throughout the day, as winds aloft increased in association with the eastward advance of a midtropospheric wind maximum. Based on these forecasts, the TA&MFS mobilized a major allocation of firefighting resources (TA&MFS, cited 2011) to the highest threat area. This deployment of resources, some of which originated from states as far away as Arizona and Tennessee, included:

- six single-engine air tankers,
- one heavy air tanker,
- 25 bulldozers,
- four wildland fire strike teams,
- 27 fireline supervisors, and
- a six-person fire-prevention team.

In addition, advanced preparations for the outbreak reached the highest level of Texas government, and prompted the following 25 February 2011 statement from Texas Governor Rick Perry (Perry 2011):

"It is crucial that we take steps to prepare for and respond to extreme wildfire conditions across our state and protect threatened communities…Wildfires can start quickly, spread quickly and destroy quickly. I urge all Texans to heed warnings from their local officials, adhere to burn bans and make plans to keep their families out of harm's way."

To prepare for the significant fire threat posed by the impending wildfire outbreak, Governor Perry preemptively activated the Texas Intrastate Fire Mutual Aid System (only the third activation in state history) which authorized the mobilization of additional firefighting resources from the state's metropolitan areas to the forecasted outbreak zone.

On 27 February 2011, a few wildfires first developed between 1600–1800 UTC over southeastern New Mexico, as 500-hPa winds of 70–80 kt (36–41 m s^{-1}) initially overspread the emerging low-level thermal ridge characterized by 850-hPa temperatures of 15–17°C. A 2100 UTC meso-α-scale analysis of low- and mid-level temperature and wind fields combined with 2155 UTC infrared satellite imagery, showed that the peak of the fire outbreak was focused over west Texas. Fire was maximized as 500-hPa winds increased to 80–90 kt (41–46 m s^{-1}) and overspread sharply amplified low-level thermal ridges comprised of 2-m temperatures between 70–85°F (21–29°C) and 850-hPa temperatures of 16–22°C (Fig. 24).

c. SGPWOs in extreme fuel regimes—April–June 2011

The 27 February 2011 "firestorm" was only the first in a series of SGPWOs that year. A historically volatile state of vegetative fuels was observed on the SGP in 2011 and contributed to temporal deviations in the evolution of a few SGPWOs between April and June. The composite-based conceptual models in this study proved valid for the peak burning periods of each 2011 fire outbreak. This section demonstrates operational utility of forecast methods derived from the 2005–2009 SGPWO composites, and is not intended to add cases from the historic 2011 fire season to the existing composite dataset. All of the 2011 fire outbreaks also were associated with the passage of deep midlatitude cyclones and were consistent with the meteorological composites. This consistency is illustrated via analyses of 500-hPa geopotential height and MSLP composites representative of the 2100 UTC peak burn period for 2011 SGPWOs on 27 February, 22 March, 3 April, 10 April, 14 April, 26 April, 24 May, and 20 June (Fig. 25). These analyses compare favorably to the 2005–2009 SGPWO composites in section 4c.

The susceptibility of vegetative fuels to wildland fire in the region escalated as drought deepened in the spring of 2011, when average ERCs reached climatological (20-y) record values ≥75 in April. This historically volatile state of vegetative fuels contributed to an environment supporting a prolonged fire season that persisted beyond the typical onset of green-up in May and June (Fig. 26). Wildfire outbreaks on 26 April (ERC of 73), 24 May (ERC of 81), and 19–20 June (ERC of 89) were the latest SGPWOs (relative to the climatological fire season) observed since studies of the phenomenon began in 2005.

In addition to late-season SGPWOs, the extremely dry and abundantly loaded state of vegetative fuels dictated protracted outbreaks with the passage of several fire-effective weather systems between April and June 2011. Near-record or record values of observed average ERC contributed to prolonged extreme fire conditions during SGPWOs on 9–10 April 2011 (ERC of 68 on 10 April), 14–15 April 2011 (ERC of 73 on 15 April), and 19–20 June 2011 (ERC of 89 on 19 June). In these episodes, peaks in wildfire activity occurred not only during the immediate passage of parent midlatitude cyclones, but also:

- with the initial infringement of strong wind fields upon low-level thermal ridges in advance of approaching outbreak-bearing midlatitude cyclones, and
- within the postfrontal air mass immediately following cyclone passages.

In each of these instances, extreme wildland fire conditions persisted through 36–42-h timeframes and spanned two diurnal burn periods. Low RH and high winds were influenced by both lee-side and upstream peripheries of outbreak-bearing weather systems. Although less severe than those associated with the actual passage of the parent cyclones, these peripheral conditions became fire-effective when combined with the historically critical state of predominantly herbaceous vegetative fuels.

The multiday evolution of the April–June 2011 outbreaks deviated temporally from the large-scale atmospheric SGPWO composites. Nevertheless, a preliminary analysis of the April 2011 “firestorms” (Lindley et al. 2011b) revealed that the composites were valid for the time of peak burn intensity during each protracted outbreak episode. The number of active wildfires peaked in advance of the 10 April cyclone and in the wake of the 14 April cyclone. However, total burn areas per day during both outbreaks suggest that the most intense fire growth, spread, and behavior was associated with the cyclone passages. Those contained the most fire-effective alignment of low-level thermal ridges and overspreading wind fields aloft (Fig. 27a-c).

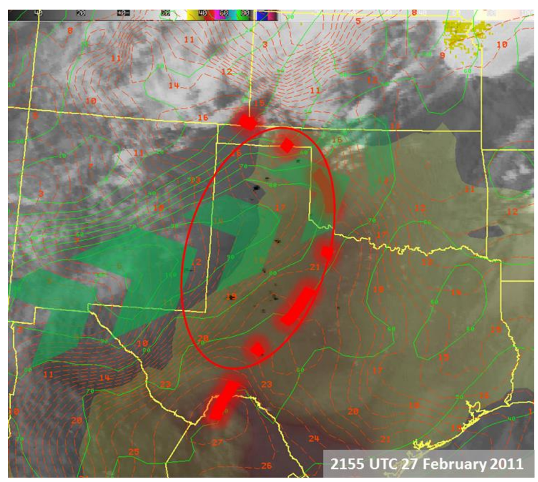


Figure 24: 2155 UTC 27 February 2011 infrared (3.9 *µ*) satellite image with “hot spots” (outbreak area circled in red) overlaid with 2100 UTC RUC analysis of 2-m temperature ≥70°F (21°C) (shaded), 850-hPa isotherms (red dashes in °C), and 500-hPa isotachs (green contours in kt). The 850-hPa thermal ridge (bold red dash) and 500-hPa wind max (green arrows) are denoted. *Click image to enlarge and to view the outbreak evolution at 1745, 1955, 2155, and 2345 UTC.*

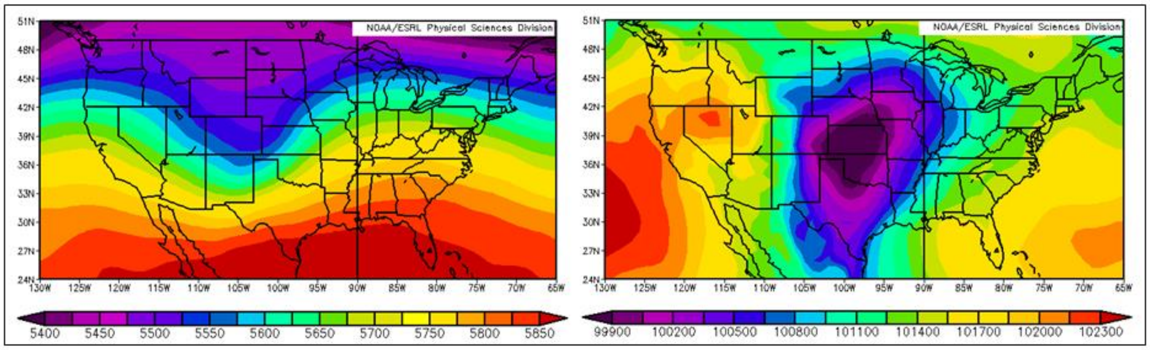


Figure 25: Composite analyses of 500-hPa geopotential heights (left, dam) and MSLP (right, Pa) valid for the peak burn period of eight 2011 SGPWOs. *Images provided by the NOAA/ESRL Physical Sciences Division at http://www.esrl.noaa.gov/psd/. Click image to enlarge.*

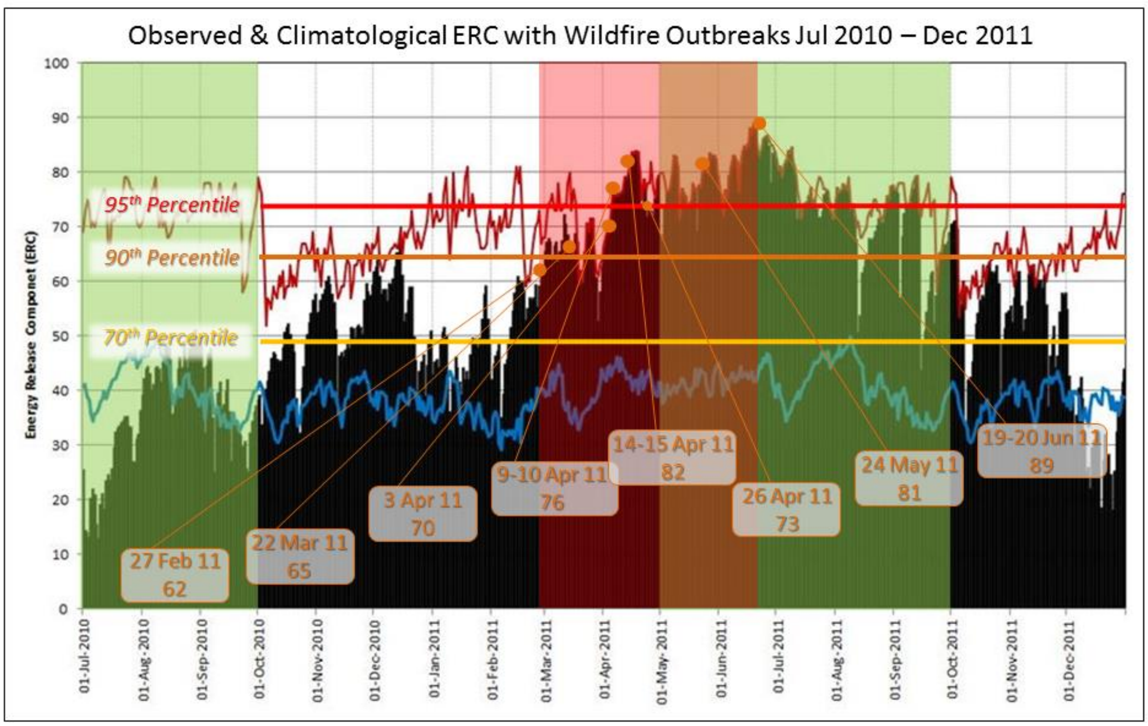


Figure 26: Observed daily average ERC in west Texas (black) for July 2010–December 2011 with daily averaged mean (blue) and maximum (red) values. Long term (20-y) 70th percentile, 90th percentile, and 95th percentile are denoted. Typical growing season (May–September) is shaded green and the period of observed SGPWOs is shaded red. Orange shade shows an extension of fire and SGPWO activity beyond expected seasonal green-up. ERC values associated with individual SGPWOs are detailed in orange (text). *Click image to enlarge.*

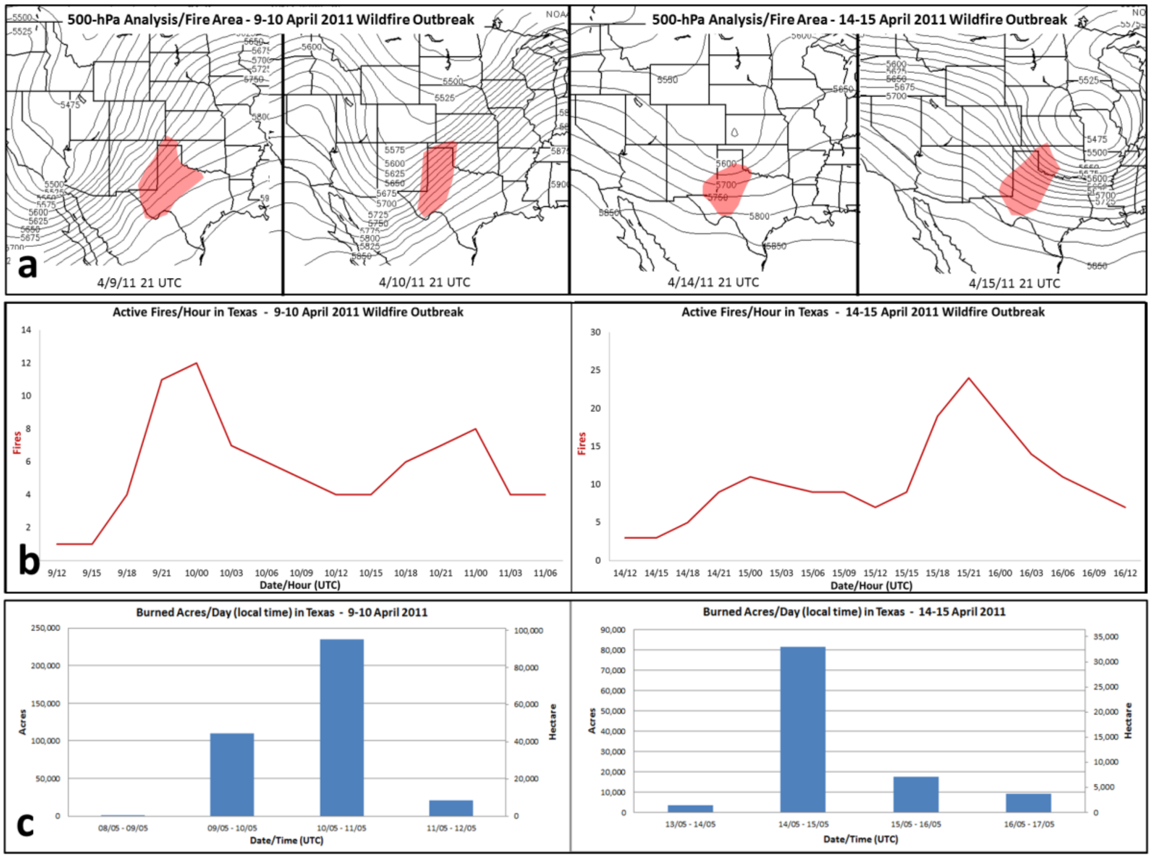


Figure 27: Analyses of two multi-day SGPWOs, including: a) 2100 UTC synoptic 500-hPa charts (isohyspes in dam) for 9–10 April 2011 (left) and 14–15 April 2011 (right) with outbreak areas (red shade), b) 3-h plot of active wildfires, and c) total burn area per day for corresponding dates. *Click images to enlarge.*

7. SGPWO seasonality and chronology of climatic and environmental signals

The 2005–2011 dataset of SGPWOs is too limited to derive a definitive climatology. A plot of monthly SGPWO occurrences (Fig. 28), however, reflects the seasonal trend of significant wildfires noted by Lindley et al. (2011a, dataset expanded to include 2010–2011). They found that 93% of observed wildfire starts in the region occurred during January–April. Similarly, 83% of all SGPWOs documented herein occurred during those months. A late-December outbreak was observed in 2005, and as noted in the previous section, two late-spring SGPWOs occurred in May and June 2011. Nearly half (44%) of the 2005–2009 SGPWOs occurred in April. Winter and early spring long have been recognized as the time of year when dry and windy weather patterns most frequently combine with dormant, grass-dominated vegetative fuels to support SGP wildfires.

While climatological trends of significant wildfire activity and SGPWOs are useful in identifying the time of year in which wildland fire is most likely to occur on the SGP, not every cool season constitutes a heightened threat. Between 2000 and 2011, SGPWOs only occurred during four seasons when specific rainfall and seasonal climatic variability resulted in particularly fire-prone vegetative fuel regimes. Figure 29 highlights a chronological sequence of unique seasonal climatic and environmental factors observed prior to the 2005–2011 SGPWOs via precipitation anomalies, ONI, and ERC spanning 2000–2011.

A review of the antecedent climatic and vegetative regimes that supported the 2005–2011 SGPWOs reveals environments characterized by a seasonal enhancement of herbaceous vegetation, subsequently subjected to the drying stresses of renewed drought. Veblen and Kitzberger (2002) identified a similar seasonal variability in their examination of the inter-hemispheric fire histories of both North and South America. Above-average precipitation promotes fire through enhanced growth of herbaceous plants that become abundant fine fuels for widespread burning. Therefore, the first climatic requisite of an increasingly fire-favorable environment is the occurrence of positive growing season precipitation anomalies.

The summers of 2005, 2007, 2008, and 2010 contained monthly average precipitation totals between 1.5–2.5 in (38–64 mm) above climatological averages on the Great Plains of Texas. These short-duration wet periods established increased vegetative fuel loads and continuity. By the late summer and autumn following each wet growing season, negative ONI trends indicated the onset of La Niña conditions. With ONI values between –0.8 to –1.5 before and during each subsequent SGPWO-bearing fire season, pronounced La Niña episodes were associated with negative monthly precipitation anomalies that averaged between –0.5 in (–13 mm) and –1.6 in (–41 mm) across the Great Plains of Texas throughout the subsequent dormant winter and spring. Deepening drought then cured the grass-dominated vegetative fuelscapes enhanced by the preceding summer rains. This drying is evident in averaged ERC values that show seasonal maxima between 50 and 90 (>70th percentile) during the 2005–2006, 2008, 2009, and 2011 fire seasons, when SGPWO episodes occurred.

The chronological sequence of common climatic and environmental regime indicators observed prior to the 2005–2011 SGPWOs include: 1) positive growing-season precipitation anomalies, 2) negative ONI values associated with La Niña development, 3) negative precipitation anomalies and the onset of varying degrees of drought, and 4) enhanced regional ERC values (>70th percentile). Each of these appears to have influenced the region's environment for seasonal enhancements in wildland fire, including SGPWOs. All of the 2005–2011 SGPWOs were preceded by this unique chronology of climatic and environmental factors, and no such fire outbreaks have occurred during the 2000–2011 study period in their absence.

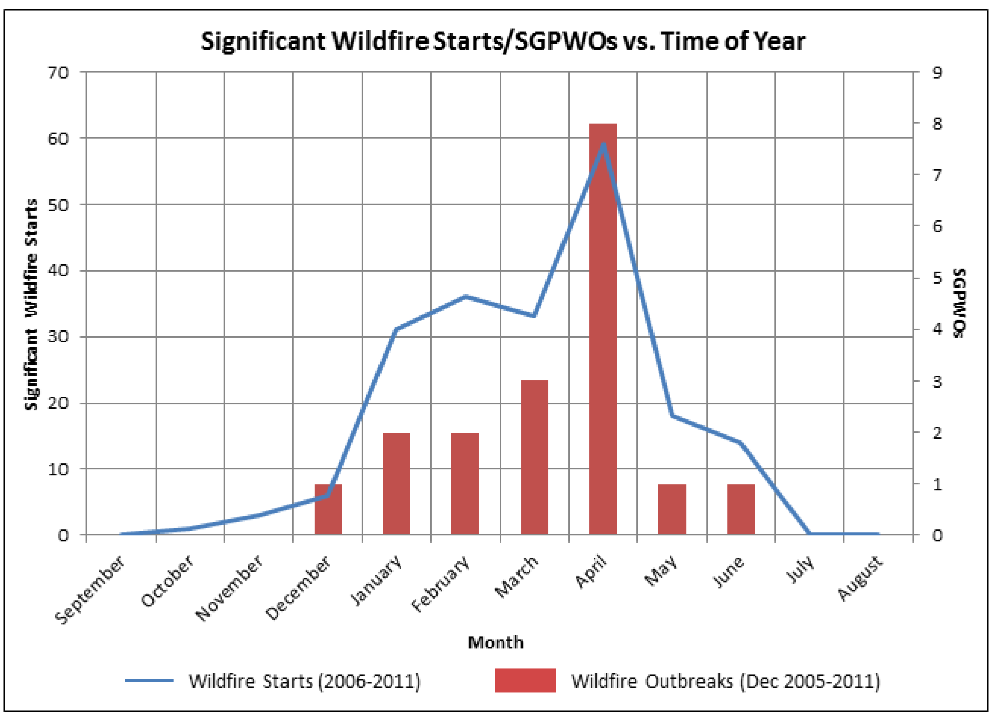


Figure 28: Significant wildfire starts within the West Texas Mesonet domain (2006–2011) and SGPWOs per month (December 2005–2011). *Click image to enlarge.*

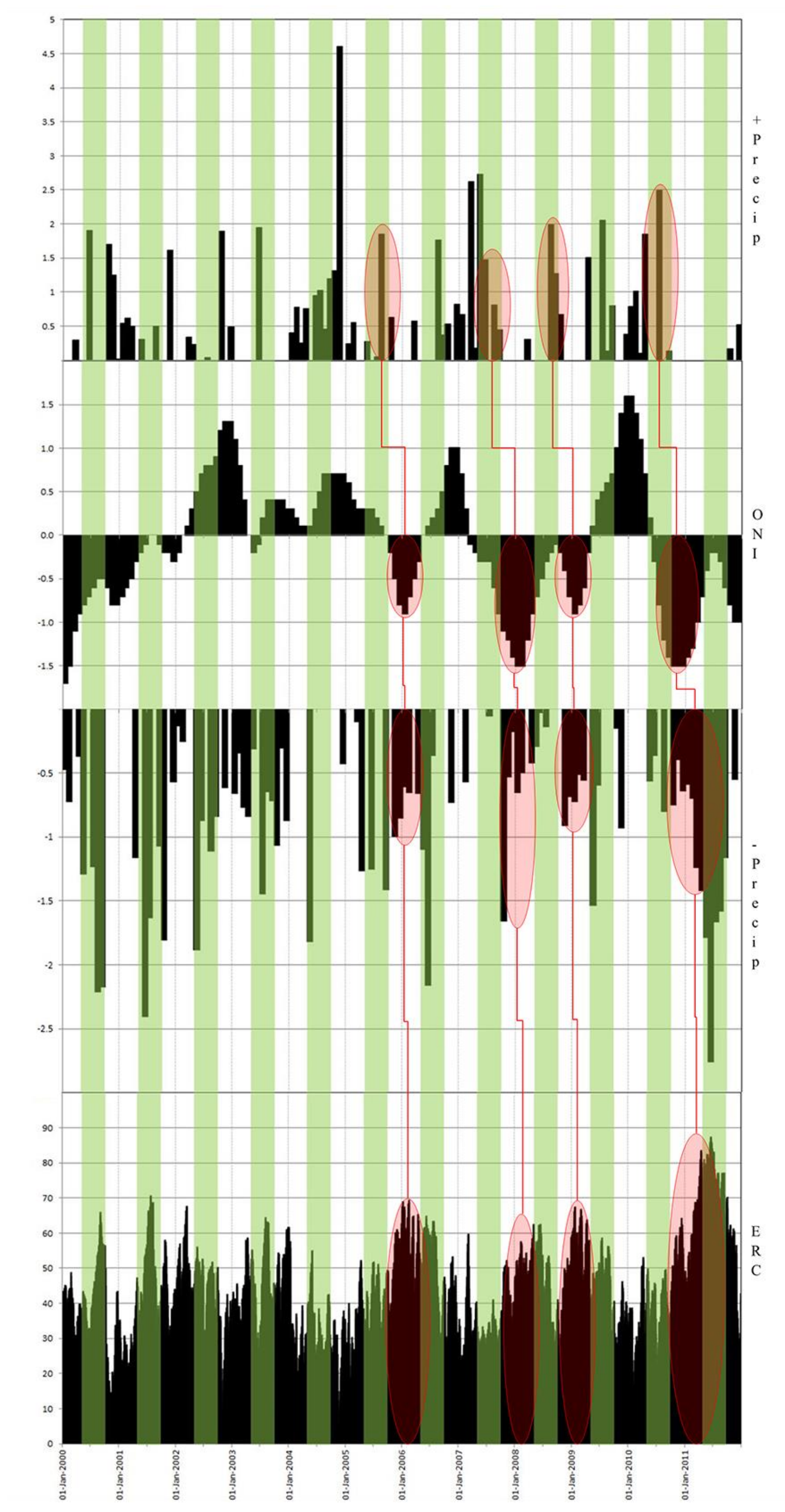


Figure 29: Chart series of averaged west Texas values for (from top to bottom): positive precipitation anomalies, ONI, negative precipitation anomalies, and ERC from 2000–2011. Typical growing season (May–September) in green shade and progression of favorable indicators that preceded four SGPWO-bearing fire seasons highlighted in red. *Click image to enlarge.*

8. Summary and conclusions

This study reviewed the seasonal climatic and environmental regimes, as well as large-scale weather patterns associated with destructive wildfire outbreaks on the SGP. Climatic variability and resultant seasonal responses within predominantly herbaceous vegetative fuel environments, as well as atmospheric composites for ten SGPWOs that occurred between 2005 and 2009, were documented.

TA&MFS wildfire reports from 2000–2010 reveal a tendency for enhanced fire seasons and SGPWOs during periods of negative ONI, or when La Niña conditions are present in the eastern equatorial Pacific. These observations reinforce studies that relate drought and wildland fire on the SGP and elsewhere to ENSO cold phases. Average ERC values across the Great Plains portion of Texas were used to quantify the state of vegetative fuels associated with the 2005–2009 SGPWOs, where regional fuel regimes had average ERCs >50 (>70th percentile).

Meteorological composites of synoptic-scale weather patterns associated with SGPWOs also were presented. These composites, derived from 2100 UTC RUC analyses of the ten 2005–2009 wildfire outbreaks, were valid for the approximate peak burn period of each outbreak. Analogous to Beebe's (1956) composite charts for tornado events, those presented here document the mean location and intensity of common atmospheric features during SGPWOs. In addition to meteorological composite charts for the 300-hPa, 500-hPa, 700-hPa, 850-hPa, and surface levels, a composite vertical profile of temperature, moisture, and wind representing the wildfire outbreak environment was shown. A downscaled approach to pattern recognition-based forecast methods then was applied consistently with Snellman's (1982) forecast funnel technique, showing that meso-α-scale analyses of low-level (2-m and 850-hPa) thermal ridges and midlevel (500-hPa) wind maxima can indicate areas of enhanced wildfire risk within synoptic composite-like patterns.

The dramatic seasonal variability of 2010–2011 illustrated the use of recognizable climatic and environmental signals in strategic planning and implementation of mitigating efforts prior to the historic 2011 SGPWOs. Operational use of meteorological composites and meso-α-scale temperature and wind analyses was demonstrated for the 27 February 2011 "firestorm". Particularly volatile fuels with average ERC values >75 (>95th percentile) supported prolonged burn periods during several 2011 SGPWOs, as well as anomalously late-season SGPWOs in May and June, past the climatological vegetative green-up.

Lastly, observed seasonal trends that preceded the 2005–2011 SGPWOs were summarized as a unique chronology of factors that increased fire-outbreak potential. This included: 1) positive growing-season precipitation anomalies that enhance vegetative growth in grass-dominated fuelscapes, 2) negatively trending ONI indicating the onset of La Niña, 3) negative precipitation anomalies, and 4) high averaged ERC >50 (>70th percentile) during subsequent dormant seasons.

Fire weather forecasters in the SGP should understand these climatic and environmental regimes so as to increase confidence and predictive skill for SGPWOs. As demonstrated by the successful 2011 "Texas Firestorm" campaign, and the mobilization of resources prior to the 27 February SGPWO, once the existence of fire-prone antecedent conditions is recognized, strategic planning can increase the effectiveness of tactical responses when outbreak-bearing weather systems are identified. The methods presented in this study allowed fire meteorologists to provide essential forecasts to key decision makers and were used to coordinate local, state and federal resources in Texas prior to the damaging SGPWOs of 2011.

Future research is needed to understand fully how meteorological and ecological variables interact to affect wildfire potential in the grass-dependent SGP fuelscape. Although reliable historical records of fire frequency are not readily available due to the lack of fire scar-carrying trees (Ford and McPherson 1996), subjective observations suggest that changes in population and land usage have altered the region's fire ecology and will continue to do so. Thus, an increased knowledge of how anthropogenic landscape changes of the SGP have influenced the likelihood of damaging wildfires may allow meteorologists and fire analysts to provide improved long-term risk mitigating guidance to community planners and key decision makers.

Of particular interests to meteorologists should be the tendency for significant fires to occur in anomalously warm temperatures, and the observed lack of fire in cool environments characterized by similar combinations of RH and wind. Such research would improve the meaningfulness of the NWS's red flag warning program. Instead of being dictated by static meteorological criteria and fire-danger ratings that inadequately quantify the state of Plains grasslands, the issuance of red flag warnings should identify more accurately the combined weather and fuel regimes that represent a high significant-fire potential.

ACKNOWLEDGEMENTS

The authors would like to thank the following individuals for their correspondence, support, technical assistance and editorial reviews: José Garcia, Edward Andrade, John Cockrell, and Justyn Jackson all of the NWS in Amarillo, TX, Justin Weaver, Steve Cobb, Ron McQueen, Mark Conder, Joe Jurecka, and Jeff Vitale all of the NWS in Lubbock, TX, Brian Curran of the NWS in Midland, TX, Tom Spencer and Mark Stanford of the TA&MFS in College Station, TX, and Denver Ingram of the Southern Area Coordination Center in Atlanta, GA. In addition, Sharon Tarbet assisted in the editorial process.

REFERENCES

Bachmann, A., and B. Allgoewer, 2000: The need for a consistent wildfire risk terminology. *Proc. Joint Fire Sci. Conf.: Crossing the Millennium: Integrating Spatial Technologies and Ecological Principles for a New Age in Fire Management*, Boise, ID, University of Idaho and International Assoc. of Wildland Fire. Moscow, ID and Fairfield, WA. Vol. I, 67–77.

Beckage, B., W. J. Platt, M. G. Slocum, and B. Panko. 2003: Influence of the El Nino-Southern Oscillation on fire regimes in the Florida Everglades. *Ecology*, **84**, 3124–3130. [Available online at http://www.uvm.edu/~bbeckage/Manuscripts/Beckageetal.Ecology.2003.pdf.]

Beebe, R. G., 1956: Tornado composite charts. *Mon. Wea. Rev.*, **84**, 127–142.

Benjamin S. G., and Coauthors, 2004: An hourly assimilation-forecast cycle: The RUC. *Mon. Wea. Rev.*, **132**, 495–518.

Bond, H. G., K. MacKinnon, and P. F. Noar, 1967: Report of the meteorological aspects of the catastrophic bushfires in southeastern Tasmania on February 7, 1967. Bureau of Meteorology, Melbourne, Australia, 17 pp. [Available online at http://trove.nla.gov.au/work/19379014?selectedversion=NBD3984280.]

Bradshaw, L. S., R. E. Burgan, J. D. Cohen, and J. E. Deeming, 1983: The 1978 national fire danger rating system: Technical documentation. USDA Forest Service Rep. INT-169, 44 pp. [Available online at http://www.fs.fed.us/rm/pubs_int/int_gtr169.pdf.]

Brotak, E. A., and W. E. Reifsnyder, 1977: An investigation of the synoptic situations associated with major wildland fires. *J. Appl. Meteor.*, **16**, 867–870.

Chen, Y., J. T. Randerson, D. C. Morton, R. S. DeFries, G. J. Collatz, P. S. Kasibhatla, L. Giglio, Y. Jin, and M. E. Marlier, 2011: Forecasting fire season severity in South America using sea surface temperature anomalies. *Science*, **334**, 787–791.

Cheney, P., and A. Sullivan, 2008: *Grassfires: Fuel, Weather and Fire Behaviour*. CSIRO Publishing, 150 pp.

Clements, C. B., S. Zhong, S. Goodrick, J. Li, X. Bian, B. E. Potter, W. E. Heilman, J. J. Charney, R. Perna, M. Jang, D. Lee, M. Patel, S. Street, and G. Aumann, 2007: Observing the dynamics of wildland grass fires: FireFlux-A field validation experiment. *Bull. Amer. Meteor. Soc.*, **88**, 1369–1382.

Cohen, J. D., and J. E. Deeming, 1985: The national fire-danger rating system: Basic equations. USDA Forest Service Rep. PSW-82, 16 pp. [Available online at http://www.fs.fed.us/psw/publications/documents/psw_gtr082/psw_gtr082.pdf.]

DeBano, L. F, D. G. Neary, and P. F. Ffolliott, 1998: *Fire's Effects on Ecosystems*. John Wiley & Sons, 333 pp.

Doswell, C. A. III, H. E. Brooks, and R. A. Maddox, 1996: Flash flood forecasting: An ingredients-based methodology. *Wea. Forecasting*, **11**, 560–580.

Fenneman, N. M., 1917: Physiographic subdivision of the United States. *Proc. Nat. Academy of Sci.*, **3**, 17–22.

Finklin, A. I., 1973: Meteorological factors in the Sundance fire run. USDA Forest Service Rep. INT-6, 46 pp. [Available from National Forest Service Library, 240 West Prospect Rd., Fort Collins, CO 80526-2098.]

Ford, P. L., and G. R. McPherson, 1996: Ecology of fire in shortgrass prairie of the southern Great Plains. *Symp Proc. Ecosystem Disturbance and Wildlife Conservation in Western Grasslands,* D. M. Finch, ed. USDA Forest Service Rep. RM-GTR-285, 20–39. [Available online at http://www.treesearch.fs.fed.us/pubs/35630.]

Fye, F. K., D. W. Stahle, and E. R. Cook, 2003: Paleoclimate analogs to twentieth-century moisture regimes across the United States. *Bull. Amer. Meteor. Soc.*, **84**, 901–909.

Galway, J. G., 1977: Some climatological aspects of tornado outbreaks. *Mon. Wea. Rev.*, **105,** 477–484.

Gedalof Z., D. L. Peterson, and N. J. Mantua, 2005: Atmospheric, climatic, and ecological controls on extreme wildfire years in the northwestern United States. *J. Appl. Ecol.*, **15**, 154–174.

Glickman, T. S., Ed., 2000: *Glossary of Meteorology*. 2nd ed., Amer. Meteor. Soc., 855 pp.

Guyette, R. P., and D. C. Dey, 2000: Humans, topography, and wildland fire: The ingredients for long-term patterns in ecosystems. *Proc. Workshop on Fire, People, and the Central Hardwoods Landscape*, Richmond, KY, USDA Forest Service, 29–35.

Heilman, W. E., 1995: Synoptic circulation and temperature patterns during severe wildland fires. Preprints, *9th Conf. on Applied Climatology*. Dallas, TX, Amer. Meteor. Soc., 346–351.

Hoerling, M., X.-W. Quan, and J. Eischeid, 2009: Distinct causes for two principal U.S. droughts of the 20th century. *Geophys. Res. Lett.*, **36**, L19708.

International Research Institute for Climate and Society, cited 2011: ENSO prediction plume. [Available online at http://iri.columbia.edu/our-expertise/climate/forecasts/enso/archive/201109/SST_table.html]

Johns, R. H., and C. A. Doswell III, 1992: Severe local storms forecasting. *Wea. Forecasting*, **7**, 588–612.

Johnson, E. A., 1996: Fire and vegetation dynamics: studies from the North American boreal forest. Cambridge University Press, 144 pp.

Jones, C. S., J. F. Shriver, and J. J. O'Brien, 1999: The effects of El Niño on rainfall and fire in Florida. *Florida Geographer*, **30**, 55–69.

Jones, J., A. Saginor, and B. Smith, 2013: 2011 Texas wildfires: common denominators of home destruction. Texas A&M Forest Service, 50 pp. [Available online at http://texasforestservice.tamu.edu/uploadedFiles/FRP/New_-_Mitigation/Safety_Tips/2011%20Texas%20Wildfires.pdf.]

Jones, T. A., and S. A. Christopher, 2010: Satellite and radar observations of the 9 April 2009 Texas and Oklahoma grassfires. *Bull. Amer. Meteor. Soc.*, **91**, 455–460.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR Reanalysis 40-year Project. *Bull. Amer. Meteor. Soc*., **77**, 437–471.

Lindley, T. T., M. Conder, J. Cupo, C. Lindsey, G. Murdoch, and J. Guyer, 2006: Operational implications of model predicted low-level moisture and winds prior to the New Year's Day 2006 wildfire outbreak in the southern Plains. *Electronic J. Oper. Meteor*., 2006-EJ7. [Available online at http://www.nwas.org/ej/2006-EJ7/.]

Lindley, T. T., J. L. Guyer, G. P. Murdoch, S. R. Nagle, K. J. Schneider, and G. D. Skwira, 2007: A meteorological composite of the 2005/06 wildfire outbreak in the Southern Plains. Preprints, *7th Symp. on Fire and Forest Meteorology*, Bar Harbor, ME, Amer. Meteor. Soc., 10.4.

——, J. D. Vitale, W. S. Burgett, and M.-J. Beierle, 2011a: Proximity meteorological observations for wind-driven grassland wildfire starts on the southern High Plains. *Electronic J. Severe Storms Meteor.*, **6** (1), 1–27.

——, G. D. Skwira, G. P. Murdoch, and J. L. Guyer, 2011b: Preliminary meteorological analysis of the 2011 "Texas firestorms". *9th Symp. on Fire and Forest Meteorology*, Palm Springs, CA, Amer. Meteor. Soc., 2.2.

Marlon, J. R., and Coauthors, 2012: Long-term perspective on wildfires in the western USA. *Proc. Nat. Academy of Sci*., **109**, E535–E543.

Marsha, T., cited 2008: Assessing daily fire potential. Northwest Coordination Center, 8 pp. [Available online at http://www.nwccweb.us/content/products/fwx/publications/Assessing_Daily_Fire_Severity1.pdf.]

McNulty, R. P., 1978: On upper tropospheric kinematics and severe weather occurrence. *Mon. Wea. Rev*., **106**, 662–672.

——, 1995: Severe and convective weather: a Central Region forecasting challenge. *Wea. Forecasting*, **10**, 187–202.

Mutch, B., and P. Keller, 2010: Case study: Lives lost—lessons learned, the victims and survivors of the 2005–2006 Texas and Oklahoma wildfires. Wildland Fire Lessons Learned Center, 133 pp. [Available online at http://wildfirelessons.net/documents/OK_TX_2005_06_Case_Study.pdf.]

National Wildfire Coordinating Group, 1997: Historical wildland firefighting fatalities 1910–1996, 2d ed. National Interagency Fire Center, PMS #822, NFES #1849, 41 pp. [Available online at http://www.nwcg.gov/pms/docs/fat_pdf.pdf.]

NDMC, USDA and NOAA, cited 2006, 2011: U.S. drought monitor map archive. [Available online at http://droughtmonitor.unl.edu/MapsAndData/MapArchive.aspx.]

NCDC, 2005: *Storm Data.* Vol. 47, No, 12. [Available from National Climatic Data Center, 151 Patton Ave., Asheville, NC 28801–5001.]

——, 2006a: *Storm Data.* Vol. 48, No, 1. [Available from National Climatic Data Center, 151 Patton Ave., Asheville, NC 28801–5001.]

——, 2006b: *Storm Data.* Vol. 48, No, 3. [Available from National Climatic Data Center, 151 Patton Ave., Asheville, NC 28801–5001.]

——, 2006c: *Storm Data.* Vol. 48, No, 4. [Available from National Climatic Data Center, 151 Patton Ave., Asheville, NC 28801–5001.]

——, 2008a: *Storm Data.* Vol. 50, No, 2. [Available from National Climatic Data Center, 151 Patton Ave., Asheville, NC 28801–5001.]

——, 2008b: *Storm Data.* Vol. 50, No, 3. [Available from National Climatic Data Center, 151 Patton Ave., Asheville, NC 28801–5001.]

——, 2009: *Storm Data.* Vol. 51, No, 4. [Available from National Climatic Data Center, 151 Patton Ave., Asheville, NC 28801–5001.]

——, 2011: *Storm Data.* Vol. 53, No, 2. [Available from National Climatic Data Center, 151 Patton Ave., Asheville, NC 28801–5001.]

NOAA, 2007: National Weather Service instruction 10–1605, 97 pp. [Available online at http://www.nws.noaa.gov/directives/sym/pd01016005curr.pdf.]

Owen, G., J. D. McLeod, C. A. Kolden, D. B. Ferguson, and T. J. Brown, 2012: Wildfire management and forecasting fire potential: The roles of climate information and social networks in the southwest United States. *Wea. Clim. Soc*., **4**, 90–101.

Pautz, M. E., 1969: Severe local storm occurrences, 1955–1967. ESSA Tech. Memo. WBTM FCST12, Washington, DC, 77 pp.

Perry, J. R., cited 2011: State resources pre-deploying in response to extreme wildfire threat. Press release, Office of the Governor, 25 February 2011. [Available online at http://governor.state.tx.us/news/press-release/15750/.]

Pirsko, A., L. Sergius, and C. Hickerson, 1965: Causes and behavior of a tornadic fire-whirlwind. USDA, Forest Service Rep. PSW-61, 13 pp. [Available online at http://www.fs.fed.us/psw/publications/documents/psw_rn061/psw_rn061.pdf.]

Reeves, M. C., K. C. Ryan, M. G. Rollins, and T. G. Thompson, 2009: Spatial fuel data products of the LANDFIRE project. *Int. J. Wildland Fire*, **18**, 250–267.

Rothermel, R. C., 1972: A mathematical model for predicting fire spread in wildland fuels. USDA Forest Service Rep. INT-115, 41 pp. [Available online at http://www.fs.fed.us/rm/pubs_int/int_rp115.pdf.]

Schroeder, J. L., W. S. Burgett, K. B. Haynie, I. Sonmez, G. D. Skwira, A. L. Doggett, and J. W. Lipe, 2005: The West Texas Mesonet: A technical overview. *J. Atmos. Oceanic Technol*., **22**, 211–222.

Schroeder, M. J., and Coauthors, 1964: *Synoptic Weather Types Associated with Critical Fire Weather*. USDA Forest Service Pacific Southwest Forest and Range Experiment Station, 503 pp. [Available from NOAA Central Library at 1315 East–West Highway, SSMC3, 2nd floor, Silver Spring, MD 20910.]

Scott, J. H., and R. E. Burgan, 2005: Standard fire behavior fuel models: A comprehensive set for use with Rothermel's surface fire spread model. USDA Forest Service Rep. RMRS-GTR-153, 72 pp. [Available online at http://www.nwccweb.us/content/products/mobguide/rmrs_gtr153.pdf.]

Simard, A. J., D. A. Haines, and W. A. Main, 1985: Relations between El Niño/Southern Oscillation anomalies and wildland fire activity in the United States. *Agric. For. Meteor.*, **36**, 93–104.

Smith, B., 2009: Overview of the April 9th, 2009 north central Texas wildfire outbreak. Texas Forest Service, 29 pp. [Available online at http://ticc.tamu.edu/Documents/PredictiveServices/Outlooks/outbreak09.pdf.]

——, 2011: Rockhouse Fire documentation for April 9th 2011: Observational notes. 2 pp. [Available online at http://ticc.tamu.edu/Documents/PredictiveServices/FireBehavior/Rockhouse_Fire_documentation_for_04092011.pdf.]

Snellman, L. W., 1982: Impact of AFOS on operational forecasting. Preprints, *Ninth Conf. on Weather Forecasting and Analysis*, Seattle, WA, Amer. Meteor. Soc., 13–16.

Snyder, S. L., D. Spano, P. Duce, D. Baldocchi, L. Xu, and K. T. Paw U, 2006: A fuel dryness index for grassland fire-danger assessment. *J. Agric. For. Meteor.*, **139**, 1–11.

Swetnam, T. W., and J. L. Betancourt, 1990: Fire—Southern Oscillation relations in the southwestern United States. *Science*, **24**, 1017–1020.

——, and C. H. Baisan, 2003: Tree-ring reconstructions of fire and climate history in the Sierra Nevada and southwestern United States. *Fire and Climate in Temperate Ecosystems of the Western Americas*, T. T. Veblen, W. L. Baker, G. Montenegro, and T. W. Swetnam, eds., Springer-Verlag, 158–195.

TA&MFS, cited 2011: Texas Forest Service strategically plans for wildfire response. Press release, 27 February 2011. [Available online at http://txforestservice.tamu.edu/main/popup.aspx?id=12894.]

——, cited 2012: TFS newsroom: Current Texas wildfire situation. [Available online at http://txforestservice.tamu.edu/main/article.aspx?id=12888.]

——, cited 2013: Texas Firestorm. Predictive Services educational campaign. [Available online at http://texasforestservice.tamu.edu/main/article.aspx?id=12296.]

Trenberth, K. E., 1997: The definition of El Niño. *Bull. Amer. Meteor. Soc.*, **78**, 2771–2777.

Unidata, 2002: GEMPAK User's guide version 5.6.G. U. S. Dept. of Commerce. [Various documentation available online at http://www.unidata.ucar.edu/software/gempak/status_reports/status_Oct02.html.]

Van Speybroeck, K. M., A. R. Patrick, and M. C. Oaks, 2007: Climate variability and the Texas fire weather season of 2005–2006: An historic perspective of a statewide disaster. Preprints, *19th Conf. on Climatology Variability and Change*, San Antonio, TX, Amer. Meteor. Soc., JP2.23.

——, G. P. Murdoch, T. T. Lindley, and P. G. Witsaman, 2011: Early recognition of drought potential resulting in enhanced interagency collaboration during the 2010/11 Texas wildfire season. *9th Symp. on Fire and Forest Meteorology*, Palm Springs, CA, Amer. Meteor. Soc., 2.2.

Veblen, T. T., and T. Kitzberger, 2002: Inter-hemispheric comparison of fire history: the Colorado Front Range, U.S.A. and the northern Patagonian Andes, Argentina. *Plant Ecol.*, **163**, 187–207.

Whelan, R. J., 1995: *The Ecology of Fire.* Cambridge University Press, 346.

Wright, H. A., and Bailey, A. W. 1982: *Fire Ecology—United States and Southern Canada*. John Wiley and Sons, 501 pp.

Woodhouse, C. A., and J. T. Overpeck, 1998: 2000 years of drought variability in the central United States. *Bull. Amer. Meteor. Soc*. **79**, 2693–2714.

REVIEWER COMMENTS

[Authors' responses in *blue italics.*]

[Editor's note: This manuscript originally was submitted in two parts, and combined after the first round of reviews.]

REVIEWER A (Melissa DiSpigna):

Initial Review, Part I:

Recommendation: Accept with major revisions.

Substantive comments: I thoroughly enjoyed the paper and think it will become a must read for national fire forecasters and those located within the Southern Plains. The figures were well composed and definitely a highlight of the paper. Demonstrating the utility of pattern recognition with the relocation of firefighting resources was another strong point of the paper.

The authors would like to express their sincere appreciation to Ms. DiSpigna for her thorough review and thoughtful recommendations. Her suggested edits will certainly help result in the highest quality manuscript possible. Thank you!

However, there was a lot of repetitiveness. Many of the sections could be streamlined better to reduce redundancies, especially within the introduction that contains overly detailed information that is then repeated and broken down further into the remainder of the paper. The primary reason I am recommending the paper be accepted with major revisions is that I also believe the paper would be strengthened by combining Part I and Part II. Part I and II both discuss fuels quite extensively. When I read part I the first time I had annotated several questions for the author about drought, and seasonably wet years followed by a dry year, but received the answers in part II. Further, the 2011 case is also documented in Parts I and II, which would be cohesive if written together. Combining the papers will still keep the paper within required limits of the EJSSM, and even shorten the length by a few pages once redundancies are eliminated. As an example, 16 of the references are the same in both Parts I and II.

The previous Part I and Part II papers have now been merged into one coherent document. Hopefully our edits based on your many suggestions below have helped to eliminate much of the redundant material.

A minor issue was that the authors did not necessarily make it consistently clear throughout the paper that the fires started primarily in grasslands, but often burned into shrub and forest to the east of the I-35 corridor. The graphics the author shows to highlight the Southern Plains study area also confirms that the cases do not solely encompass grasslands.

Actually, the authors believe this is not a minor issue. Yes, individual fires during a few SGPWOs were observed to originate and burn within more forested fuel regimes east of the Interstate 35 corridor, or more notably east of the 98th meridian which is commonly referred to as the Plains "timberline". These fires largely occurred in extreme conditions which included the presence of exceptional (D4) drought. We have provided a detailed response to this issue to the Editor. In order to summarize that response here, suffice it to say that extreme rates of spread (ROS) for wind-driven wildfires in grass-dominated fuels during outbreak conditions, when compared to SGPWO-related fires in timber fuels, supports the fact that wildland fire behavior during these events presents a unique danger to life and property within Plains grasslands. This reasoning is now described in detail in Section 2 ("Outbreak definition and cases") of the revised manuscript.

The authors must also be careful about making conclusions about fire conditions being relatively "less severe" based on meteorological conditions alone. [They do] demonstrate a clear understanding that wildfires have an anthropogenic component, but the 2009 case could be strengthened significantly by examining the causes of wildfires for that particular day.

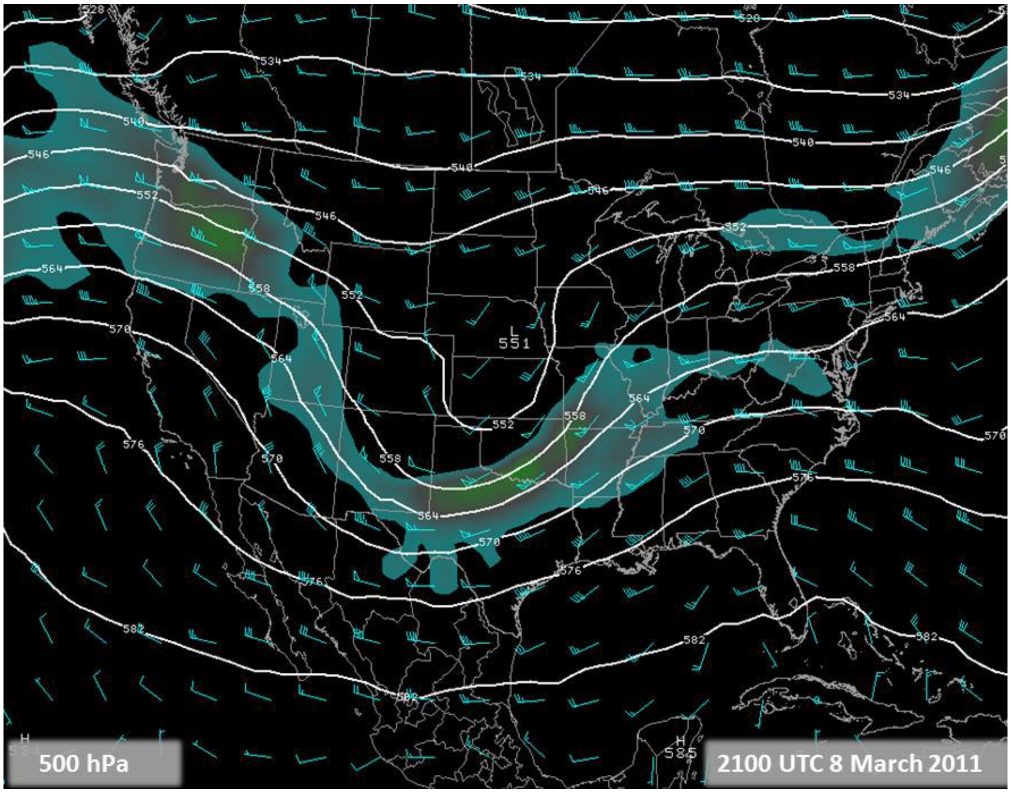
Our previous statement about relatively "less severe" conditions as related to the 9 April 2009 case actually considered combined knowledge of fuels and weather… not just weather. The authors, however, generally agree that such statements should probably be avoided, and have tried to instead include more specific descriptions of such conditions including specific RH, wind speeds, and ERC/fuel dryness versus the vague "less severe" wording.

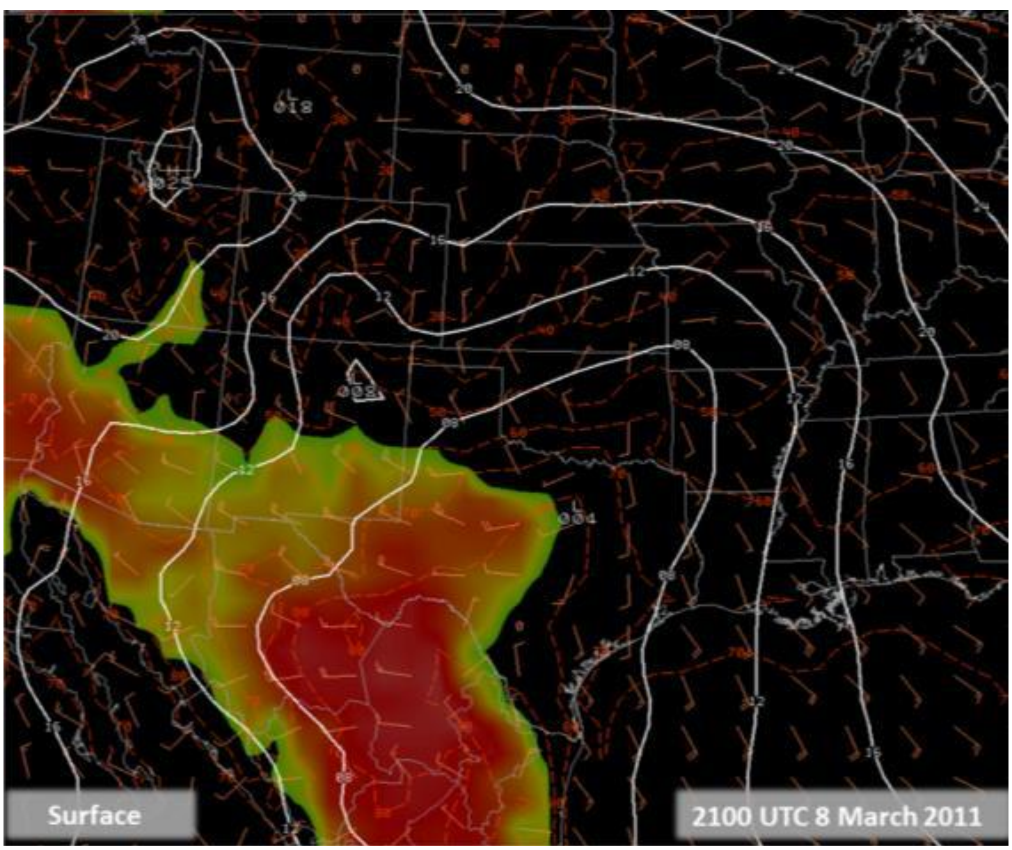
Also, the authors strongly argue that the specific ignition sources for fires on 9 April 2009 (or during any other SGPWO) are largely irrelevant. We will address this later. We do, however, understand that many readers will question what causes wildfires during these events. Therefore, we have added a brief discussion on common ignition sources during SGPWOs to the 9 April 2009 section as follows… [full text appears in manuscript].

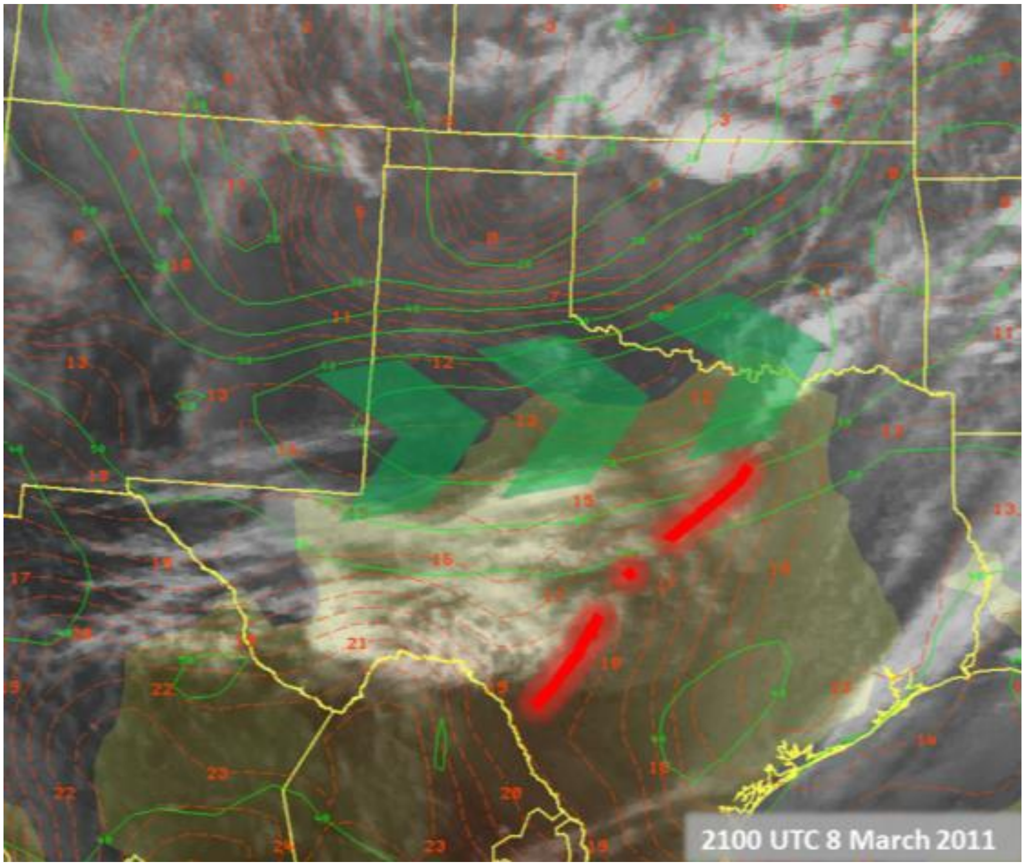
For future work, I would be interested to see the authors build upon a false alarm dataset in which the SGPWO composite weather pattern occurred, but little fire activity was recorded. While moving resources in anticipation of a significant wildfire event can be beneficial and cost-effective, certainly not overstaffing and allocating too many resources can be cost-effective as well. The authors touched upon the subject in the 2001 season discussed in Part II.

Thank you for this comment! The authors strongly agree that it is equally important to understand why significant fire may not occur in an expected situation, and we strive to reduce the number of false alarm Red Flag Warnings. After all, significant fire occurrence is the ultimate verification, and the only true measure of whether or not combinations of fuel and weather really are "critical". Over the last several years, we have indeed collected data on several null events. These events range from 1) the passage of SGPWO composite-like systems during seasons of less fire-prone environmental fuel conditions to 2) the passage of mid latitude cyclones that approximated SGPWO composites but lack coexistence of pronounced low-level thermal ridges and overspreading mid-level wind maxima. Some of these situations have resulted in isolated significant wildland fires that did not become particularly widespread or destructive and were shy of "outbreak" criteria as defined in the text—while others resulted in no notable fire activity at all. Originally, the authors considered including a null event as part of this study, but ultimately decided not to in order to keep the manuscript from becoming overly complex. An advantage of publishing in the EJSSM is the fact that author-reviewer correspondence also is published. Your request gives us an opportunity to present data from a null event and have it published along with the article without further complicating the main article.

In the example provided by the images below, the passage of a midlatitude cyclone during the intense drought and record fire season of 2011 was associated with little to no significant wildland fire activity. The 8 March 2011 weather system that ejected over the southern Great Plains was associated with a 70-kt (36-m s^{-1}) 500-hPa wind maximum that propagated eastward over western and western north Texas. A 1004-hPa surface low developed south of the Red River in northern Texas, and contributed to a southward displacement of the system's cold front when compared to the idealized SGPWO composites as well as suppressed low-level thermal ridges displaced south and east of the overspreading wind maximum aloft. Given that the state of vegetative fuels during March 2011 was volatile, the misalignment of these key meteorological factors was considered a major factor in the reduced fire effectiveness of this particular weather system.


500 hPa
2100 UTC 8 March 2011


Surface
2100 UTC 8 March 2011



The portion on the fire weather patterns was somewhat confusing. The authors reference near-zonal flow aloft, then goes on to discuss midlatitude cyclones. It seems clear that the authors want to express that the fires occur in response to a midlatitude cyclone passage…, so perhaps rephrasing of the "zonal flow" is needed.

The pattern that the authors present here as being associated with SGPWOs is indeed characterized by the passage of midlatitude cyclones. That is not what was discussed in these particular sentences. Instead, this text was meant to provide background on previous work by Schroeder et al. (1964) which identified a critical fire weather pattern known as the "Chinook-type" pattern. [O]ur findings are actually in contrast to Schroeder's. Still, for clarification, we have re-worded this in revision to remove specific mention and elaboration of zonal flow in Schroeder's "Chinook-type" pattern.

Re: "interactions between weather and routine human activity"… I'd argue that humans interact with the dry fuels to start ignitions, and not necessarily the weather!

More times than not, it is actually the weather (namely strong winds) that interact with routine human activities and infrastructure in the presence of dry fuels that start SGPWO-related fires. A better explanation of this is now provided in the text, including examples such as ignition sources from wind-blown power lines or wind-blown sparks generated from machinery that subsequently lands in dry grass.

Since you are talking about several days in advance, would it be possible to show previous runs of a longer term model leading up to the eventual RUC analysis the day of? Perhaps GFS/Euro, though this graphic would be optional depending on the author's preference.

We could have shown data from longer-term models, but in the interest in minimizing the number of figures, we chose to stick with RUC analyses in an apples-to-apples comparison. The text referred to here has been changed to better reflect this emphasis.

[Former] Figure 17: Can you show the observational data instead?

Again, we could, but we wanted to compare apples-to-apples, i.e. RUC composites to RUC analysis. Recall, the figures do utilize initial RUC analyses, so they are heavily based on observational data.

For the particular event mentioned, many of the wildfires occurred closer to large populations, so many of the starts were likely due to anthropogenic and power infrastructure causes, especially given strong gusts. The news reports that day concluded at least a few were due to downed power lines. You may want to consider mentioning the gusts that day. Have you looked into the causes for the ignitions on April 9th? Unfortunately, as I'm sure the authors realize, even though the more "favorable" fire conditions were farther west, due to a much smaller population, it's likely that there were less sources for ignition.

The cause of individual fires during SGPWO episodes is always of interest to the authors. We strongly contend, however, that the source of individual ignitions is largely irrelevant. The authors' anecdotal observations and experience suggest that downed or arcing power lines are likely the single most common ignition source during all SGPWOs. The location of wildfires on 9 April 2009 was not determined by population density. This issue was addressed in detail by co-author Mr. Smith in his preliminary report on the event [available online at: http://ticc.tamu.edu/Documents/PredictiveServices/Outlooks/outbreak09.pdf].

There, Mr. Smith states:

> *"Some initial speculation suggested that the fire occurrence was related to the proximity of the population centers of the Dallas-Ft. Worth metroplex...but population in the counties where the fires occurred was not that high. The highest county population {impacted by fire} was Wichita at 127,300. The lowest {impacted by fire} was Jack County at 8,800. Montague County has 19,700, Young County 17,500, and Clay County 10,900. In comparison, Taylor County has 126,800 and Midland County has 129,500 {neither of which were impacted by fire under similar conditions}."*

If population were the determining factor, how could we ever account for other west Texas-centric SGPWOs which have occurred almost entirely in low population areas of the Great Plains? One such event, 12 March 2006, burned more than one million acres. A determination of ignition sources for the largest fires during that particular outbreak also was attributed to utility lines. The authors' argument is this, ignition sources are ever-present, but large significant wildland fires only occur when these ignition sources are exploited by the presence of favorable fuel and weather combinations. Instead, the authors can say with a high degree of certainty that the thermodynamic structure of the low-level atmosphere influenced the location of fires on 9 April 2009 more so than population density, with the most severe fire activity occurring where temperatures were abnormally warm.

The reviewer may be correct that gusts play an important role, especially since they may account for damage to the utility infrastructure. The authors, however, have tried to keep discussions in this manuscript centered on operationally useful information derived from numerical weather guidance. Sustained wind speeds are the most readily available wind values used in numerical weather prediction, so we would like to maintain our discussion of sustained speeds.

Also, if you are talking grass fires then perhaps it's misleading to discuss 100-h fuel moisture (FM) values and a 1- or 10-h [FM] would be more appropriate.

Actually the 100-h FM when combined with ERC provides a more comprehensive representation of the background fire environment that excludes wide variations that occur due to daily weather, even in grass-dominated regimes. This includes live fuel moisture and all of the time lag dead fuels. As a build-up index (7-day memory), ERC provides representation of fire environment drying trends. The use of 100-h FM tempers ERC outputs based on short-term daily conditions, such as increased atmospheric moisture, that otherwise has little effect on ERC. The 100-hr component provides a daily adjustment to fuel dryness for fire potential.

We know that the lack of memory in Adjective Fire Danger (comprised of 1-hr FM and wind speed) leads to many false alarms for fire potential on the Plains grasslands. Combining ERC and 100-h, known as either fuel dryness or dryness level, instead provides a good representation of the underlying fuel conditions. Whereas 1-hr FM, 10-hr FM, adjective fire danger, and burning index are calculated NFDRS outputs that better represent the perceived effect of daily weather conditions on fine fuels, but at the expense of ignoring background influences from recent and seasonal moisture events. Therefore, gauging true fire potential requires combining both underlying fuel conditions and daily weather.

You may also want to mention that grasses would have been dormant at this time.

The fact that SGPWOs occur during the cool season when herbaceous vegetative fuels are "dormant" is now mentioned explicitly on six occasions throughout the paper.

What made the [Part I, section 5] outbreak violent? Perhaps the word historic would be better suited? Since you discuss the 2011 case in Part II, it also seems as though it could be folded into that discussion.

The authors argue that the term "violent" is a very appropriate and accurate description of many SGPWOs, and particularly the 27 February 2011 fire outbreak. We know that Texas officials would agree, and as quoted in the text, they have referred to SGPWOs as "a perfect storm for extreme fire". Although no adjective classification exists for fire events as for tornadoes, (i.e., weak, strong, and violent), we should consider both the areal extent of devastation as well as the magnitude of property damage caused by SGPWO-related fires. Specifically, the 27 February 2011 outbreak was comprised of 39 fires that burned a total of 284 911 acres (115 299 ha) across portions of three states, destroyed 210 structures, claimed one life and injured four people. Unlike the spectrum of damage caused by tornadoes, where weak tornadoes may cause mostly light damage to a home and violent tornadoes leave only the foundation and a pile of debris, structural damage caused by wildfires during SGPWOs tend toward total destruction- equivalent to a violent tornado.

[Minor comments omitted…]

Initial Review, Part II:

Recommendation: Accept with minor revisions.

Substantive comments: I thoroughly enjoyed the paper and think it will become a must read for national fire forecasters and those located within the southern Plains. The figures were well-composed and definitely a highlight of the paper. Demonstrating the utility of pattern recognition with the relocation of firefighting resources was another strong point of the paper.

Agree. Mention of the limited dataset is now included in the Introduction.

Again, the strength of the paper was the overview of the applicability of using overall trends in fuel dryness and climate signals to prepare fire officials for a rough fire season. For a forecaster who is new to fire forecasting, the paper will serve as a great overview of the complexities that influence fire severity beyond weather. However, similar to my recommendation for Part I, I would like to see the paper combined with Part II with a focus on eliminating redundancies and providing a cohesive discussion.

Part I and Part II are now merged into a single manuscript.

Thank you for stating that La Niña is not a prerequisite for high-end fire events.

You're welcome! Actually, we are always worried about an outlier ENSO neutral outbreak. We haven't seen one yet, but we are sure such future occurrences are possible.

[Former] Figure 2: It would also be interesting to see a graph with the number of acres burned.

The authors would like to thank the reviewer for this suggestion. It turns out that the La Niña-fire activity is much more pronounced when the number of acres burned is considered. A staggering 98% of the acreage burned during the study period occurred in fire seasons when La Niña conditions existed. This is obviously a very telling statistic. A graph was added to depict this.

[Former] Section 2: I thought this was an excellent discussion on ERC, but felt like it could have been stated much earlier in the paper. Combining the two papers will give the author opportunity to explain the ERC before it is mentioned as frequently in the remainder of the paper.

This issue, clearly, was resolved via the condensed manuscript.

Could you give a range of values that the long-termed averaged 70th percentile is for your sites?

Good recommendation. We chose to explicitly define the averaged 20-y 70th, 90th, and 95th percentile values in the text.

[Former] Section 4: A few issues here…I'm not sure that with such a limited dataset you can refer to a pattern as anomalous. Do you mean the pattern is anomalous compared to the conceptual model that you present? Otherwise, there have been plenty of fires that have occurred in a post frontal environment, especially across lower latitudes. Across the southern Plains, the postfrontal winds can often become downslope, slowing RH recovery while winds simultaneously strengthen. Additionally, the 2011 section could be merged with Part I's overview on the same season.

We removed the word "anomalous" from this discussion, and instead referred to the fuel conditions as "historically volatile" and said the protracted outbreak episodes "deviated temporally from the large-scale atmospheric SGPWO composites".

I believe our response to one of the reviewer's previous points addresses the issue with frontal passages. To summarize here, SGPWO conditions seem most severe in the warm/dry sector of a passing mid latitude cyclone. Typically, falling temperatures result in rising RH values and winds gradually diminish in wake of the cold front as depicted in the composites. For the 15 April 2011 case, however, the number of fires increased in the post frontal environment during the second diurnal burn cycle. This was a deviation from conceptual models based on the 2005–2009 SGPWO cases. The authors contend that the "historic volatility" of vegetative fuels during April 2011 likely contributed to these prolonged outbreak/extreme conditions.

Conclusions: The author states "it is unknown". I'm not sure if it's unknown if fires occurred in the past. Early explorers documented smoke, granted outside of human starts most would have likely been ignited by lightning. Fires have always been a part of nature, but the question is whether humans cause more starts and buildup of fuels, particularly near the WUI.

The authors did not intend to imply that "it is unknown" if fires occurred in pre-historic and/or frontier times. We instead noted that it is unknown if wildfire outbreaks occurred on the scale and scope of those seen today during SGPWOs. It would seem unlikely that they did given the anthropogenic nature of fire ignitions associated with SGPWOs. Pre-settlement and before the establishment of modern infrastructure, it is unlikely that sufficient ignition sources existed to support the widespread and numerous nature of fire starts associated with SGPWO, especially given that they occur in weather regimes absent of lightning. Without any doubt fire is, and always has been, a natural part of the southern Great Plains ecosystem. In fact, evidence suggests that wildland fire was probably more frequent on the Plains prior to the mid twentieth century. In an early draft of this paper, an entire section was devoted to the topic of long-term environmental changes on the southern Great Plains that have contributed to SGPWOs. That section, however, was removed prior to submission due to uncertainties in historic TA&MFS wildland fire reports prior to 2000. Instead, the authors submitted that particular section of the paper to the AMS 10th Symposium on Fire & Forest Meteorology, and we encourage interested readers to view the extended abstract available online: https://ams.confex.com/ams/10Fire/webprogram/Paper229314.html.

The concluding point that the authors wish to maintain is that a better understanding of how human activity has increased the likelihood of widespread and destructive SGPWO-type events can help improve long-term risk management. Thus the text in question has been restated.

[Minor comments omitted...]

Second Review:

Recommendation: Accept with minor revision.

General comment: The second revision was a substantial and impressive improvement over the first submission. The authors did an excellent job incorporating suggestions into the text and even elaborating further to clear up confusion and to educate the readers, especially those [who] may not be as familiar with fire weather forecasting. It's clear that a lot of effort was made to improve upon the original document. At this point I'd recommend accepting the paper as is, minus two extremely minor changes.

[Minor comments omitted...]

REVIEWER B (John Saltenberger):

Initial Review, Part I:

Recommendation: Accept with minor revisions.

Substantive comments: [Mentioning lack of fire-outbreak standardization] is good. I like the emphasis. Attempts are underway by the National Wildfire Coordinating Group to create a standard glossary of wildfire terms, including fire weather terms.

We are glad you agree, and we are especially glad to hear that efforts are underway to standardize wildfire terms. The authors suggest that when/if terms are standardized in the future, that there should be some consideration for events in the Plains' grasslands. It often seems that much of the work that has been done in the wildland fire community is very western U.S.-centric, and more appropriately relates to the forest/desert fire regimes versus the wind-driven grassfires that are very problematic on the Plains. Hopefully the widespread and destructive events documented here can serve as useful examples in defining "outbreaks" and/or "firestorms".

Although not published in peer-review journals, NWCC Predictive Services in Portland uses a composite surface and upper air methodology to objectively rate the potential for large, costly fires in the Pacific Northwest.

The authors are encouraged to learn that composite-based methods are indeed being used in operational fire meteorology elsewhere. We contend that this is a very valid and useful means for identifying critical fire patterns, as long as details concerning the ambient state of fuels and mesoscale considerations are additionally included in decision making processes. Personally, I'd like to encourage Mr. Saltenberger to also pursue publication of the composite methods used in the Pacific Northwest. Additional resources in the formal literature detailing such work would have helped our efforts tremendously. Maybe the work we have done here can now serve to help NWCC Predictive Services formalize their study.

The dryness index of Marsha consists of more than an adjective description. As used in Oregon and Washington, the dryness index (known as Dryness Level) also includes objective probability of large, costly wildfires based on a comprehensive fire history.

Thanks for helping to clarify this. We have adjusted the wording.

These conditions may, in effect, create ignitions and become self-fulfilling prophecies. A daily climatology of fire ignitions is a valuable addition to the forecaster's toolkit. We do this at NWCC in Portland.

Ultimately this particular sentence was removed from the text during the streamlining/merging process. Multiple references to Lindley et al. (2011a), however, remain in the manuscript. That EJSSM-published paper [http://www.ejssm.org/ojs/index.php/ejssm/issue/view/26] used proximity observations from a locally dense mesonet to study conditions associated with significant fire (≥300 acres) ignitions on the Plains. Not only did the combinations of RH/wind observed on 9 April 2009 correspond to "high occurrence" conditions per that study, but the fact fires that day occurred within a zone of unusually warm temperatures also supports findings from that study—and that is what we chose to focus on in the revisions.

I suspect the ignition sources are downed power lines or escaped backyard debris burns but it would be interesting to know what typical ignition sources are during a SGPWO. Ignition sources vary by geographic area. In the Pacific Northwest, great trouble is taken to separate out ignition sources because some can be forecasted (lightning) while others are more difficult to anticipate (arson, escaped backyard burns, etc).

You are correct. Wind-damaged and/or arcing powerlines are the most common fire ignition source during SGPWOs. Of course, there also are a variety of other sources for ignition such as vehicles (either operating in off-road grassy areas or sparks from malfunctions such as blown tires), trains, welding and/or construction activities as well as many others. We have seen retained heat and embers from previously controlled burns re-ignite during SGPWOs, some of which would have been considered 1- to 3-day carryovers. Local, county, and state policies, however, have typically resulted in burn bans before the onset of most outbreaks—and this is effective in eliminating most intentional burns. Fortunately, we typically do not experience many instances of arson. Some curiously noted examples of ignition during SGPWOs have included, a pickup truck/trailer dragging a chain which sparked a half dozen fires along Interstate 27 between Amarillo and Lubbock on 12 January 2006, a blown light bulb at a Little League baseball field that started a destructive fire during the 25 February 2008 outbreak, and a man cutting irrigation pipe in order to steal copper [who] ignited a 27 000 acre fire that destroyed fifteen homes during the 27 February 2011 "firestorm".

Unlike the western U.S., lightning-started fires account for a very small number of significant wildfires on the southern Great Plains. In fact, Lindley et al. (2011a) noted that none of the ~100 fires that occurred between 2005 and 2010 resulted from lightning. Although many relatively small and brief grassfires result from lightning in the Plains' grasslands, and dry lightning occasionally occurs here, a vast majority of thunderstorm activity on the southern Great Plains is associated with sufficiently moist weather and fuel conditions to preclude extreme fire behavior and spread. Instead, the region's largest and most destructive fires tend to occur during SGPWO-type regimes when unusually dry/warm and windy conditions are present. These conditions do not support deep moist and electrified convection.

As such, the authors have placed little emphasis on ignition sources. The sources of ignition that cause SGPWO-related wildfires are ever-present but largely unpredictable on the scale of a specific fire. Thus, we have instead focused on the spatial and temporal existence of combined fuel and weather conditions that are most likely to support significant wildfire activity. If these conditions do not exist, then significant fires will not occur. We do, however, see the benefit in briefly discussing ignition sources as a way to illustrate the complexities of purely meteorological and/or ingredient-based forecast methods for wildland fire on the southern Great Plains. Therefore, the following statements have been included in the early portions of Section 5: "...interactions between weather and routine human activity or man-made infrastructure result in wildland fire ignitions. Common ignition sources during SGPWOs include wind damaged utility lines arcing into dry vegetation and wind-blown sparks generated from machinery and other human activities."

Initial Review, Part II:

Recommendation: Accept with minor revisions.

Substantive comments: Good emphasis on needed alignment of fuel and weather. Be cautious with the term 'significant fires' because there is an official definition of 'significant fire' in the National Wildfire Coordinating Group glossary that is different from the one quoted here.

As referenced in the text, the definition we have based our studies on has been NWS Directive 10-1605 which defines a significant wildfire in grasslands as ≥300 acres. That said, the National Wildfire Coordinating Group definition also describes exactly the type of events we are most concerned with. Therefore, we have tried to incorporate that definition by re-wording.

[Former] Figure 5 and Fig. 6 graphs [are] difficult to decipher. Main point doesn't jump out.

The authors acknowledge that the former Figs. 5 and 6 (now Figs. 6 and 7) are complex graphics that contain a large amount of data. These graphics have already been simplified by using 30-day averages (Fig. 6) and removing lower percentile rankings, as well as maxima and minima values. Yet, we believe that after careful study of these graphics, the main points become clear—in that SGPWOs occur when regionally averaged values of ERC are above the 70th to 90th percentiles. This is important because of the widespread nature of SGPWOs. These graphs convey that concept but also provide event-specific ERC values and their relevance to climatology, while presenting this information in the format used operationally by Texas A&M Forest Service's Predictive Services. Unless the reviewers and the editor have strong opinions and ideas on how to further improve these graphics, the authors would prefer to leave them as they are.

I'd be interested to know if there are any objective measurements of what constitutes "enhanced vegetative growth" in grass-type fuels. Or does year-to-year evaluation of fuel loading remain a subjective interpretation (as it does here in the Pacific Northwest)? How is fuel loading information transmitted to NWS and other meteorologists?

The authors agree that the current process of evaluating regional fine-fuel loading across the southern Great Plains, particularly in Texas, is a subjective process based on anecdotal information from fire managers, observations from wildland fire analysts and fire meteorologists (see pictures), and analysis of satellite rainfall estimates during the growing seasons.

Co-author and TA&MFS Wildland Fire Analyst Brad Smith surveying and documenting fuel loading in the eastern Texas Panhandle - December 2012.

Example of a fuel loading photographic catalog created by co-author and NWS meteorologist Greg Murdoch. Greg adds a photo taken of fuels at the same location to this catalog monthly.

The goal is to characterize regional loading as either below normal, normal, or above normal. These levels could be equated with fine fuel loadings in SFBFM's Gr1, Gr2, and Gr3 respectively. Reports detailing these analyses are disseminated to the meteorological and wildland fire community (examples provided per the following links). In recent years, 2011 was advertised as above normal fine fuel loading based on the subjective process…
http://ticc.tamu.edu/Documents/PredictiveServices/Outlooks/Winter2011Outlook092410.pdf.

2012 and 2013 were advertised as below normal. In 2014 TA&MFS is advertising normal fine fuel loading on the Great Plains of Texas.
http://ticc.tamu.edu/Documents/PredictiveServices/Outlooks/texas_fire_potential_update.pdf.

I am excited about this paper because of its usefulness to southern Great Plains forecasters who are tasked with warn/no warn decisions in fire weather. Further, I am glad to see research being conducted in a geographic area that hasn't (in my opinion) been adequately represented in publication of severe fire weather events.

My center uses a compositing technique to objectively identify upper air patterns that are conductive to fire events in Oregon and Washington. I suspect our techniques would prove useful in the southern Great Plains. I'd enjoy conversing with the authors on how our techniques might be adapted. I'd also like to ask their permission to use the paper as a resource at a national training course for fire behavior analysts in 2014.

[From e-mail]: I think the parts from the 2nd section can be effectively condensed into the 1st section without needlessly complicating the paper.

The authors would like to express their sincere appreciation to Mr. Saltenberger for his review of this paper. We look forward to working with him in the future, especially in adapting some of the included material for use national training course.

[Minor comments omitted...]

Second Review:

Recommendation: Accept.

General comment: No further comments on the review. Great paper for operationally oriented forecasters. Thanks for the opportunity to contribute.