7.2 WEATHER AND FIRE BEHAVIOR INFLUENCING THE 11-12 JUNE 2013 BLACK FOREST COLORADO (USA) WILDFIRE

Fred J. Schoeffler[1]
Sheff LLC

ABSTRACT: The June 2013 Black Forest Fire (BF Fire) is investigated based on operational weather outlooks, satellite water vapor imagery, as well as surface and mid- to upper-air observations. From the perspective of a Wildland Fire Supervisor, this paper will focus on the fire weather preceding the fire start, and the fire weather and subsequent fire behavior from 11 to 12 June. The BF Fire, reported about 1342 MDT on 11 June 2013 in El Paso County, Colorado (USA) at an elevation of 7379', burned for 10 days before it was 100% contained and controlled on 21 June. The noteworthy fire weather and fire behavior day, occurred Wednesday, 12 June when, according to fire department personnel, the fire burned intensely in several directions and resulted in the most structures destroyed. It burned entirely within the municipal limits of Black Forest, Colorado, and the confines of El Paso County, in a predominately-mixed Ponderosa Pine, Rocky Mountain Douglas Fir, and Gambel Oak fuel type, in fairly moderate, rolling terrain. The fire was rather unremarkable in the actual 14,280 acres (22.31 mi^2; 57.8 km^2) burned, but significant in that 486 homes were destroyed, 37 others were damaged, and two people were killed. Hence, it was labeled as "*the most destructive fire in Colorado history*," as it surpassed the 2012 Waldo Canyon Fire's total homes destroyed.

Synoptic and mesoscale weather, and regional climatology for 9-12 June, are discussed to augment and support the Critical Fire Weather designations established by the National Weather Service (NWS).

[1] Corresponding Author Address: Fred J. Schoeffler, Sheff LLC
P.O. Box 446 Pine, AZ 85544 email: dougfir777@yahoo.com

1. Introduction

a. Background, Fire History, and Fire Progression, and Climatology

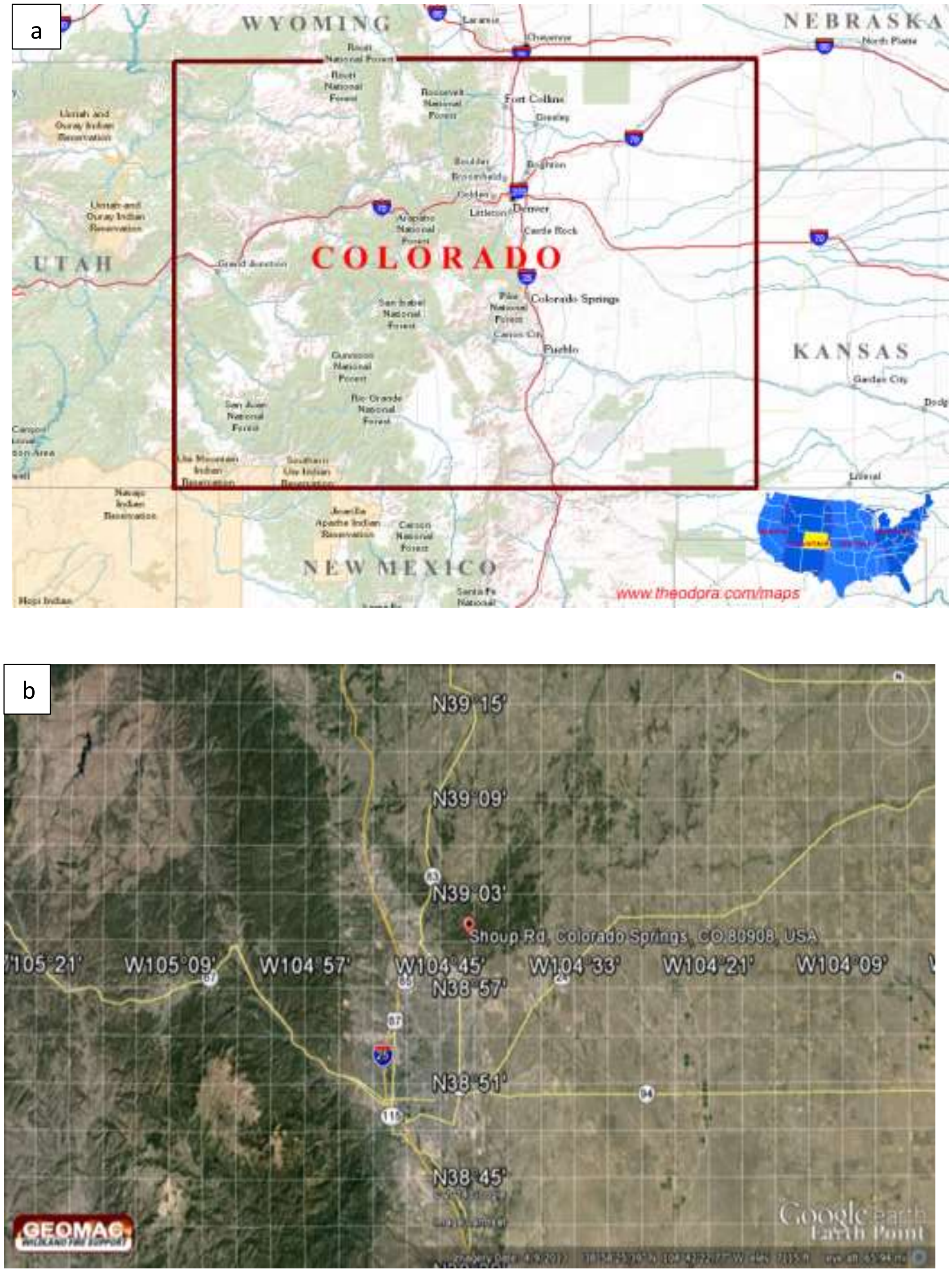

Figure 1: (a) Map of Colorado and United States (inset); (b) Google Earth image, Black Forest, CO and estimated Black Forest Fire origin near Shoup Road (red icon).

On 11 June 2013, the Black Forest Fire (BF Fire), north of Colorado Springs, Colorado (Fig. 1) started in very dense Ponderosa Pine and Gambel Oak fuels, and quickly became a major wildfire that exhibited extreme fire behavior and rapid, large fire growth. The BF Fire would eventually burn 14,280 acres, destroy 486 structures, and take the lives of two civilians. The BF Fire of 2013 was a predicted disaster, as forestry and fire officials had warned the residents of Black Forest a wildfire of this magnitude was inevitable. As is often said regarding wildland fires, it was not a matter of - if it would occur, but when it would occur, PPWPP (2014).

The initial response for the Falcon Fire (later named the Black Forest Fire) occurred at 1343 MDT on 11 June 2013. The Black Forest Fire Rescue Department, Donald Wescott Fire Department, and Colorado Springs Fire Department carried out the IA. The fuels were dense unthinned ponderosa pine ("dog hair" thickets) and Gambel oak stands. IA crew reports noted that fireline containment was within 100 yards when the winds increased and the fire aligned with a drainage in steeper, uphill terrain around 1630 MDT, Fischer (2013).

Under the influence of very strong westerly winds, the BF Fire from this point advanced eight miles to the east within the first eight-hour burning period! This equated to 640 acres per hour or approximately 10.6 acres per minute! Firefighting efforts during the entire first burn period focused on firefighter and public safety, while structural protection was secondary, PPWPP (2014). This is often the case in wildland urban interface fires. Perimeter control always becomes secondary in these situations. On 12 June, a second major large fire growth period occurred and the fire burned intensely for five miles to the north, under a southerly wind along several fire fronts. The fire laid down that evening when wind speeds dropped, PPWPP (2014).

It is essential to understand the antecedent climatological factors that led up to the 11-12 June 2013 BF Fire weather. The mountain snowpack data for January through April 2013 revealed between 50% and 70% of normal snowpack, (Fig. 2, a-d). The 2013 water year, Arkansas River Basin Snowpack Summary indicated slightly over 8" high of snow water equivalence that peaked in late April, (Fig. 3, a). Yet, the NRCS Colorado Historical Snowpack Percentages for the Arkansas Basin watershed revealed over 100% snowpack for the 2005, 2007, 2008, 2009, and 2011 seasons from January through March/April, (not shown).

Initial discussion will focus on the early stages of the BF Fire, including the climatology. The mesoscale weather and the microscale influences of the Colorado Front Range follow. Wildland fire weather and the subsequent fire behavior, and some basic wildland firefighting rules are next. Fire Weather archives are used and NWS Fire Weather products to indicate the extent of the weather influences. Archived satellite water vapor imagery, Remote Automated Weather System data, atmospheric Skew-T soundings, contoured surface maps indicating temperatures, RH, winds; meteograms, and backward trajectory runs are used for validation. This will be followed by the summary and conclusion.

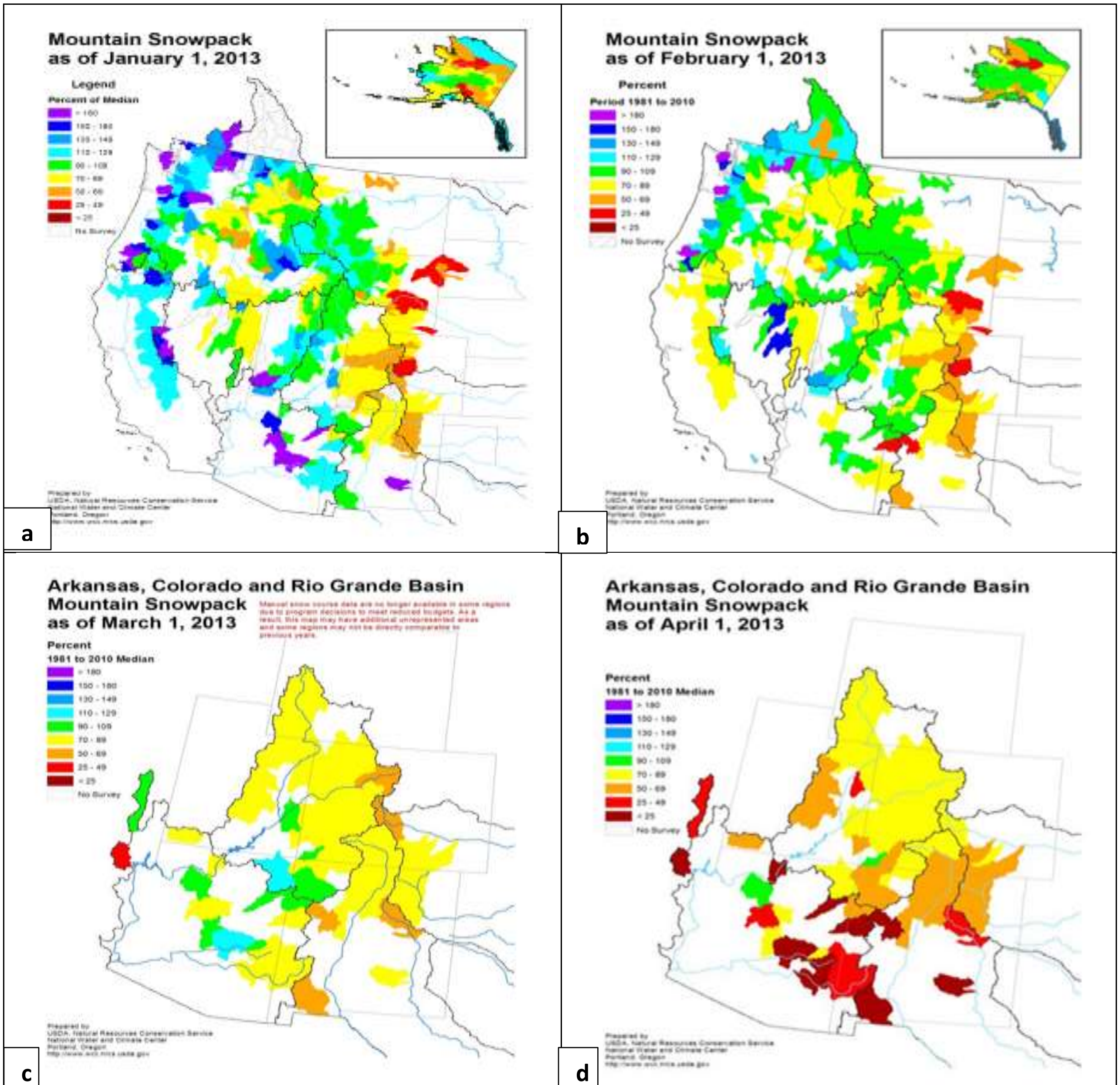

Figure 2: 1 January to 1 April 2013 (a-d) Arkansas, Colorado, and Rio Grande Basins, Colorado Mountain Snowpack images, U.S.D.A. Natural Resources Conservation ervice, National Water and Climate Center.

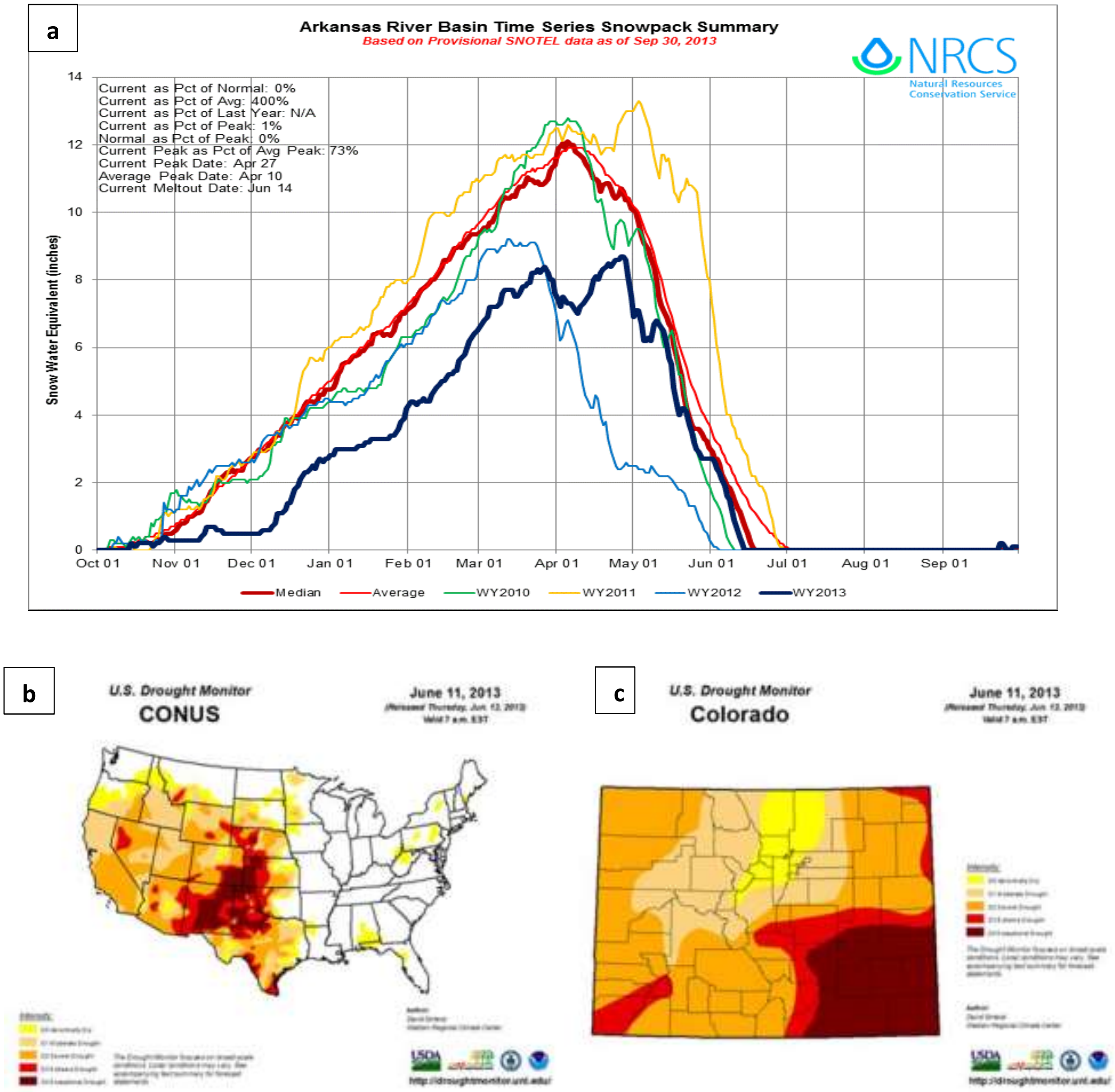

Figure 3: (a) Natural Resources Conservation Service Arkansas River Basin High/Low Snowpack Summary; Water Year 2013 is solid dark blue line; (b) United States map of National Drought Mitigation Center, U.S. Drought Monitor, June 11, 2013, University of Nebraska-Lincoln, the United States Department of Agriculture, and the National Oceanic and Atmospheric Administration, 2014; (c) and U. S. Drought Monitor map of Colorado.

El Paso County and the Black Forest, Fire area (CO) indicated a D3 value, or Extreme Drought, on the U.S. Drought Monitor map, (Fig. 3, a).

Researchers Fast and Heilman found that low soil moisture “not only influenced the surface, but the entire lower atmosphere,” (1996).

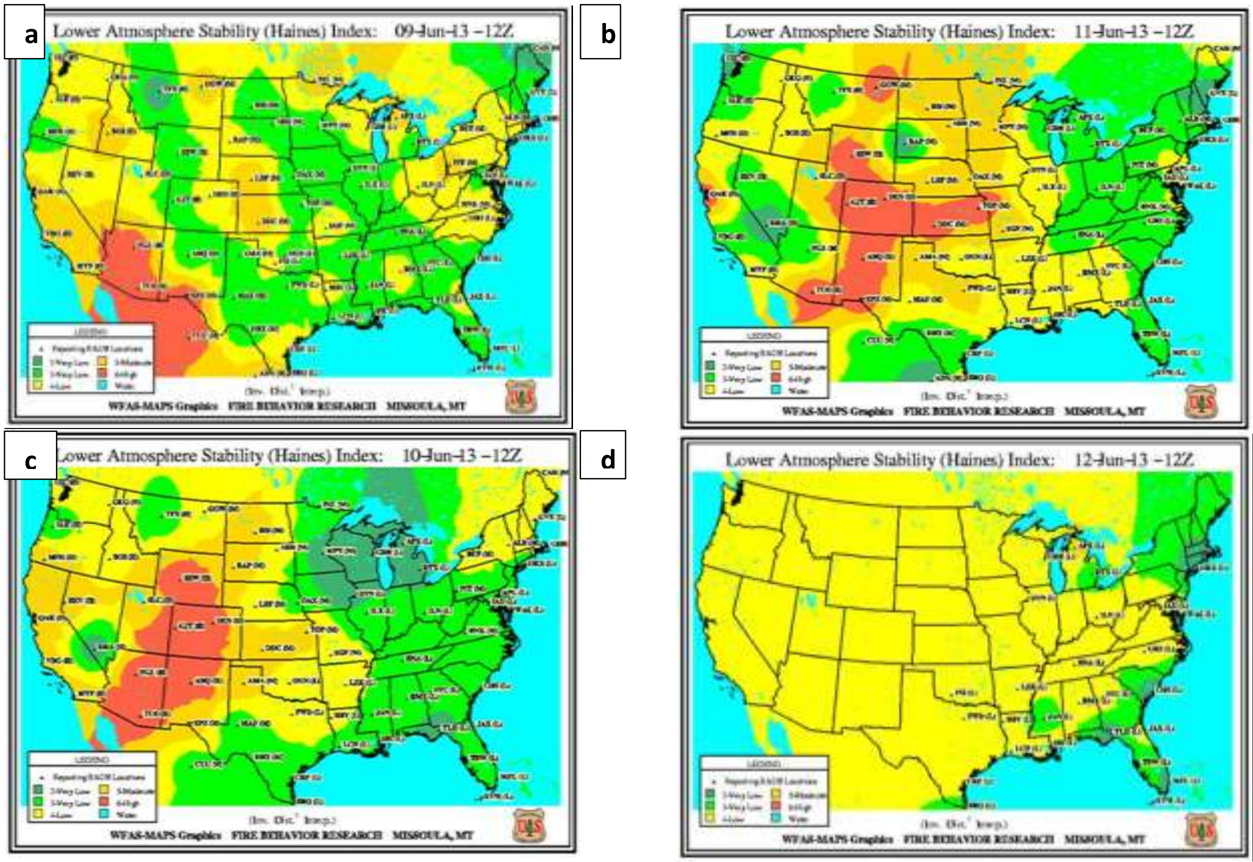

Figure 4: Lower Atmospheric Stability (Haines) Index maps for (a) 9th, (b) 10th, (c) 11th, (d),and 12th June 2013, (a-d) respectively, WFAS-MAPS

b. Lower Atmospheric Stability (Haines) Index (LASI)

Since 1988, fire weather forecasters have used the Haines Index as an indicator for potential extreme fire behavior (e.g. high rates of spread, extensive spotting, and running crown fires) associated with plume-dominated[2] fires. The Haines Index combined two atmospheric parameters - stability and dryness - that can potentially affect the growth of wildland fires. A Haines Index of 2 indicates moist, stable air with very low potential for large fire growth, while a 6 indicates dry, unstable air with an increasing potential for plume dominated fires. Other factors such as slope, fuel loading, and wind also play a crucial role in plume-dominated development and large fire growth, Haines (1988) (Fig. 4). The 9 June Haines Index was Moderate (5) (Fig. 4, a) which then became High Haines (6) during the day that preceded the BF Fire and the first large fire growth day (Fig. 4, b-c). It then dropped back to Moderate (5) (Fig. 4, d) on 12 June, the second large fire growth day.

[2] A plume-dominated fire is one where the power of the fire is more influential than the power of the wind. Conversely, a wind-driven fire spreads by the power and direction of the wind, notwithstanding terrain features, Byram (1954) and Werth et al (2011).

c. Mesoscale Weather

Winds down sloping off the Front Range typically produced very low relative humidities and abnormally warm temperatures in areas adjacent to the Front Range, regardless of the time of day; and RH values of less than ten percent were common with these katabatic (downslope) winds, Baker (2011).

The local topography of the Black Forest area, accurately described as rising and falling, with frequent changes in slope and aspect, resulted in a typical "roller coaster" appearance. In general, slopes of 3 to 12 percent predominate, with some areas possessing slightly steeper slopes, El Paso County (1987).

The mountains of the western U.S., as well as the sloping Great Plains to the east, interact with the atmosphere on a wide range of horizontal scales, Toth and Johnson (1984). The diurnal flows were consistent from month to month. During the late morning and early afternoon hours, solar heating of the ground and mountain slopes caused upslope flow to develop, Johnson and Toth (1982). In the late afternoon, flow reversal started at the top of the Continental Divide and a convergence line formed and moved down and east during the evening hours. Finally, downslope winds took over the entire region again around midnight (1982). However, along the front range of eastern Colorado, the downslope-to-upslope and upslope-to-downslope wind transitions did not occur at the same time, but rather began at the foothills of the Rocky Mountains and propagated eastward toward The Plains. The pattern was less than 3 hours for the transitions from downslope-to-upslope in the mornings and approximately 4-5 hours for upslope-to-downslope winds in the afternoons, (1984). Bell (2014) stated that typically, the downslope winds began around 1500 MDT and always between 1400 and 1800 MDT.

In addition, especially during weak synoptic conditions, air masses entrained into the westerly flow over the Continental Divide, mixed down from the free troposphere into the expanding Planetary Boundary Layer (PBL) during the following morning (1982). While researching Colorado Front Range mountain winds, Turnipseed et al, citing other sources (2004) discovered that the predominant winds were from the West, flowing downslope. BF Fire Department Captain Bell (2014) stated that the normal winds were customarily from the south-southeast and reversed to north-northwest in the evenings. Summertime meteorology produced valley–mountain airflows, with thermally induced, near-surface anabatic (upslope) winds during the days, contrary to the higher, geostrophic westerly wind, (2004). Upslope flow also occurred with large synoptic storm systems that passed to the south of the region, or upon cold front passages associated with the approach of high-pressure regions from the North (2004).

2. Discussion

a. Basic Firefighting Rules

Safe and effective wildland firefighting requires knowing and following the Ten Standard Fire Orders and knowing, recognizing, and mitigating the Eighteen Watch Out Situations. It is instructive that the very first Fire Order deals specifically with weather. Indeed, it is imperative to receive accurate and timely fire weather forecasts for safe wildland firefighting.

The Ten Standard Orders dealing with weather directly and indirectly are as follows:

1) Recognize current weather conditions and obtain forecasts

3) Base all actions on current and expected behavior of the fire

10) Fight fire aggressively having provided for safety first

The Eighteen Watch Out Situations that deal specifically with weather are:

4) Unfamiliar with weather and local factors influencing fire behavior

14) Weather is getting hotter and drier

15) Wind increases and/or changes direction, NWCG IRPG.

b. Wildland Fire Weather

Southern Great Plains (SGP) Meteorologist Lindley and others, clearly knowing well the importance of the Ten Standard Fire Orders and the Eighteen Watch Out Situations, noted that in 1956, Beebe revealed the value of meteorological composites in operational meteorology pattern-recognition tornado forecasting. The connection of synoptic-scale patterns during many tornado events was "striking", observed Beebe. Hence, composite charts provided a process for identifying large-scale atmospheric features common to specific weather situations, Lindley et al (2014). These SGP fire weather meteorologists also recognized a striking similarity of large-scale patterns associated with their Southern Great Plain Wildfire Outbreaks (SGPWO) characterized by the passage of mid-latitude cyclones and strong negative-geopotential-height and mean sea level pressure anomalies. Thus, Lindley et al (2014) engaged in several composite methodologies to measure the relative magnitude and location of common synoptic-scale atmospheric features associated with SGPWO. This same synoptic scale pattern-recognition methodology could easily be created for the Southwest as well.

Indeed, June is a very critical fire weather month in the Southwest in general and for Colorado in particular. You will readily note that many of Colorado's largest, most destructive fires have occurred during the month of June, particularly within the first two weeks. Among other factors, drought due to low rainfall and/or snowpack, low snow water equivalence, high nocturnal temperatures from midnight to 0600 LST, low humidities, strong winds, Moderate (5) to High (6) Haines Indices, and low fuel moistures have contributed to the extreme fire behavior and large fire growth. Some common fire weather highlights emerged in the Colorado wildfires listed below. They were influenced by well-recognized, historical meteorological fire weather factors. These included 'The Breakdown of the Upper Ridge', mid to upper-level troughs and shortwave troughs, surface lows, steep lapse rates, deep mixing, low level jets, and subsidence. These have been long publicized and put forward by Schroeder et al (1964), Brotak and Reinsnyder (1977), Nimchuk (1983), Hull et al (1996), Heilman et al (1996), and NWS (1999). Schroeder and others

(1964) concluded that large fire occurrences followed closely the pattern of high fire danger days and that high fire danger days allied with certain synoptic scale weather systems. They also noted that these systems appeared at times without producing any high index values. Ongoing wildfires always experienced large fire growth during these episodes.

The twelve Colorado, June 2000 to 2013 wildfires enumerated below are listed in chronological order and detailed by the fire name, location (city and county), dates, and the number of acres and structures burned.

1) **High Meadow Fire**, Bailey (Park County), June 12 to 20, 2000; 10,800 acres, 51 structures;
2) Trinidad Complex, Stonewall/Trinidad (Las Animas County); June 2 – 14, 2002; 33,000 acres;
3) **Coal Seam Fire**, Glenwood Springs (Garfield County), June 7 to July 9, 2002, 12, 209 acres; 43 structures;
4) **Hayman Fire**, Lake George (Park County); June 8 – July 18, 2002, 138,114 acres, 133 structures;
5) **Missionary Ridge Fire**, Durango (La Plata County); June 9 – July 14, 2002, 71,739 acres, 56 structures;
6) **Spring Creek Complex**, New Castle (Garfield County); June 22 to July 21, 2002, 13,490 acres;
7) **Bridger Fire**, Piñon (Las Animas County) June 8 - July 9, 2008; 45,800 acres; 3 structures;
8) **Last Chance Fire**, (Las Animas County) June 5 – 21, 2011; 44,662 acres; 11 structures;
9) **Shell Fire**, Kim (Las Animas County), June 7 to 17, 2011, 14,390 acres; 7 structures;
10) **High Park Fire**, Fort Collins (Larimer County); June 9 – 30, 2012, 87,250 acres, 259 structures;
11) **Waldo Canyon Fire**, Colorado Springs (El Paso County); June 23 - July 10, 2012; 18,247 acres, 346 structures; and
12) **Black Forest Fire**, Black Forest (El Paso County); June 11 to 21, 2013; 14,280 acres, 487 structures; Makings (2012).

c. Synoptic BF Fire Weather

The following NOAA NWS Fire Weather Outlooks for the period from 9 to 12 June 2013, preceding and during the BF Fire, accurately forecast continuous fire weather during that period that repeatedly called for “prolonged period[s] of critical fire weather conditions,” SPC (2014).

The 0142 AM CDT Sunday, June 09 2013 outlook, valid for 10 June 12Z to 11 June 12Z, forecast an upper trough in the Pacific Northwest and a closed low over California (Fig. 5, c) combined with a 30-50 knot mid-level southwest speed maximum to result in a significant wind event across the Great Basin and the Southwest. The 0121 PM CDT Monday, June 10 2013 outlook, valid for 11 June 12Z to 12 June 12Z, called for the passage of a midlevel shortwave trough over the southern Rockies (Fig. 5, c) to promote downslope westerly winds across eastern/southern Colorado and northern New Mexico. The latest model guidance showed that sustained wind speeds from 20-30 mph would be probable over Colorado with critically low relative humidity values, SPC (2014).

The 0238 AM CDT Monday, June 10 2013 outlook, valid for 11 June 12Z to 12 June 12Z, forecast an upper level shortwave trough over the Great Basin to eject northeastward and crest an upper ridge located over the Northern and Central Plains (Fig. 5, c and 7, c). Meanwhile surface cyclogenesis would occur in the lee of the southern Rockies ahead of the upper disturbance, (Fig. 7, c). A surface trough axis would extend southwest from the low in eastern New Mexico. Two separate wind regimes were forecast to develop east and west of a surface trough axis that would extend southwestward from southeastern Colorado and northern New Mexico during Tuesday afternoon (Fig. 5, 7, c). West of the surface trough, the passage of a midlevel shortwave trough over the southern Rockies would promote downslope westerly winds across eastern and southern Colorado and northern New Mexico, (Fig. 5, 7, c), SPC (2014).

The 0242 AM CDT Tuesday, June 11 2013 forecast, valid for 11 June 12Z to 12 June 12Z, called for a lee surface low to intensify across parts of eastern Colorado, (Fig. 5, 7, c). The pressure gradient would aid in strong wind development across the central Rockies with expected warm temperatures. Deep boundary layer mixing would occur with steep, low to mid-level lapse rates forecast (Fig. 21, b). Southwest winds would increase to 20-25 mph, gusts to 45 mph and relative humidity values would fall into the 5-10 percent range, SPC (2014).

The 139 AM CDT Tuesday, June 11 2013 forecast, valid for 11 June 17Z to 12 June 12Z, noted that soundings revealed a very warm airmass over the region (Figs. 19, 20) which was expected to support near-record temperature-breaking highs in the Colorado foothills, SPC (2014).

d. Mesoscale BF Fire weather, initial response, fire behavior

The NWS Fire Weather Forecast, the day preceding the BF Fire start, began to set the stage for this disastrous wildland fire. At 1433 MDT, 10 June 2013, the Pueblo NWS Office issued an urgent Fire Weather Message for a Red Flag Warning from 0900 MDT to 2100 MDT, for the Black Forest area, Fischer (2013). The NWS Fire Weather Message, Red Flag Warning called for gusty winds, low relative humidity, high Haines 6 or high potential for plume dominated fires, and dry fuels, NWS Pueblo (2013); Fischer, (2013). The NWS forecast southwest winds for 15 to 25 mph, with gusts 40 to 45 mph. The temperatures forecast were for the high 90’s and the relative humidity (RH) as low as 6%! The NWS Fire Weather Message included, “extreme fire behavior was likely” if a fire started, NWS Pueblo (2013), Fischer (2013). Without a doubt, the stage was set for extreme fire behavior.

Black Forest, CO is essentially a large peninsula-like enclave of timber on the eastern slopes of the Colorado Front Range, which projects out to the east into the Eastern High Plains (Fig. 2). The High Plains emerge gradually from the plains of Kansas and Nebraska, and lead to the high plains of Colorado, which slope gently upward for some 200 miles from the eastern border to the base of the foothills of the Rocky Mountains. The area is influenced by strong horizontal and vertical, thermal gradients which normally favor upslope winds during the day and downslope winds at night, and low RH, Colorado Climate Center (2010). The Black Forest area normally had south-southeast winds during the day and the reverse at night.

The BF Fire was first reported at approximately 1342 MST on 11 June 2012. It was originally known as the Falcon Fire, and later changed to the BF Fire, Fischer (2013). The fire's initial location based on citizen reports was somewhat ambiguous and assumed to be near Shoup Road and Highway 83, (Fig. 2). The IA resources sized up the fire as a "lazy" surface fire with very light winds, Fischer (2013).

Colorado state law (Colo. Rev. Stat. § 30-10-512) required that the County Sheriff was responsible for wildfire suppression in 'unincorporated areas' (EPCSO – ESD (2011). Therefore, the three neighboring Fire Protection Districts responded due to the unclear location and jurisdiction, and which of the Fire District(s) actually had first response responsibility Fischer (2013).

A 1355 MST, a Computer Aided Dispatch (CAD) weather report for the area reported the temperature was 95° and the RH was anomalously low at 4%! Additionally, there was a corresponding low dew point at 10° C, with 29 mph winds. The IA resources reported an approximate 15 mph west wind, with a large smoke column heading to the east. These IA resources stated the fire was contained within a bowl, somewhat sheltered from the winds. Due to the dense trees and vegetation, they estimated it to be about 50' x 50' in size. The fire progressed to the south and southeast, eventually exited the bowl via a chimney, and burned intensely with an uphill run toward a nearby house. The firefighters reported a hot moving surface fire with 2' to 4' flame lengths; and they had already experienced increased ember storms and resultant spot fires well ahead of the main fire, in size and distance, influenced by light winds, Fischer (2013).

At approximately 1400, the winds increased and turned southwest. At 1418 MDT, the fire finally escaped their tenuous containment lines and control once the winds further increased. This caused the fire to align with an uphill drainage (chimney) along Thiedaud Lane. It then rapidly transitioned into the tree crowns, and then crowned on up into and through the Brentwood Subdivision around 1630 MDT. Intense ember showers and spot fires multiplied and exacerbated safe and effective firefighting, Fischer (2013), Bell (2014). Without a doubt, the BF Fire had begun its 8-mile run episode.

e. Ember Storms Responsible for Structure Loss

Embers are responsible for a large percentage of structures lost on wildland fires, notwithstanding those structures where there has been no clearing or mitigation. The two video clips below will give the reader a very good, realistic, visual understanding of intense ember storms: (1) 'Driving through an [AU Bushfire] Ember Attack,' YouTube by Flame Sniffer WD, (http://www.youtube.com/watch?v=qvLBuDnCTPU) and (2) Australian Bush Fire Ember Attack, 2001, Hawkesbury, YouTube by John Keeble, (https://www.youtube.com/watch?v=WfIRo92DyXA). Both video clips are very instructive, however, the second clip is more representative of the ember storm(s) experienced every time during structure protection, no matter what fuel type.

Researchers studied ember storms and used a unique and novel method to measure ember attacks. They interestingly studied the burn patterns on lawn furniture and backyard trampolines for several wildland urban interface fires, and discovered how ember storms were responsible for many structure losses. The noteworthy fires in their research were the Angora Fire (CA) in 2007 and the Bastrop Fire (TX) in 2011, Foote et al (2011), Rissel and Ridenour (2013), Manzello and Foote (2014).

The Bastrop Fire trampolines, taken from seven sites, were generally 3 feet from the ground and roughly 12 foot in diameter. From thousands of ember burn indicators, they concluded that 91% to 99% of the measured firebrand holes were 0.5 cm in diameter, and the firebrand density ranged between 9 to 68 holes per square foot, Rissel and Ridenour (2013). In contrast, Manzello et al (2014) noted on the Angora Fire that 85% of all embers measured on that fire were less than .05 cm^2 in width. On both fires, there was evidence of intense fire behavior manifested by firebrands with vertical fire whirls and horizontal roll vortices.

f. Alignment of Forces Principle

The Alignment of Forces Principle validated by the Campbell Prediction System (CPS) noticeably influenced the BF Fire. Campbell described it as when the fire behavior speed and direction is dictated by variations of topography, it will change based on the combination of steepness of slope, wind speed and direction, and fuel preheating and flammability, i.e. alignment. Fire behavior predictions are made by observing the alignment and strength of these forces in the fire's path. Where the forces are more in alignment, the fire intensity will increase, CPS (2010). The forces of temperature, RH, dew point depression (Tdd), wind, and terrain were well aligned from 11-12 June 2013 and resulted in extreme fire behavior and large fire growth.

g. Mesoscale Weather Forecasts and Messages

At 1458 MDT, 11 June 2013, the Pueblo NWS Office issued another urgent *Fire Weather Message*[3] that called for a Red Flag Warning day, similar to the day before. Specifically, daytime temperatures were forecast to be in the 90's into the 100's, RH values as low as 6%, and a high Haines 6 or high potential for plume dominated fires. The winds would be 25 to 35 mph with gusts to 45 mph. The predicted fire behavior potential was upgraded to reflect, "extreme fire behavior was imminent" if a fire started, Fischer (2013).

A *Spot Weather Forecast* was issued at 1634 MDT, 11 June 2013 that called for sunny skies, temperatures from 89°F to 94°F, and anomalously low RH values from 2% to 7%! Southwest winds from 17 mph to 27 mph, with gusts to 35 mph in the afternoon were to continue until 2100 MDT. Mixing heights of 500 feet AGL until 0800 MDT, then

[3] The NWS uses at least these several Fire Weather monikers, e.g. Fire Weather … Forecast, Watch, Warning, Message, Notification, and Spot Weather Forecast. Red Flag Watches and Warnings would also be included.

20,000 feet AGL after 0900 MDT (very unstable air) were forecast (Fig. 21, b). Furthermore, transport winds of 25 mph were forecast with excellent smoke dispersal after 0900 MDT (very unstable air). The NWS forecast a weak cold front to turn winds northwesterly, with moderate RH recovery overnight, Fischer (2013). Mixing height is defined as the height to which a parcel of air, or a column of smoke, will rise, mix, or disperse, NOAA (2009). Transport winds are defined as the average wind over a specified time-period near the center of the mixing depth, NOAA (2009).

The 11 June nighttime forecast portion of the 11 June *Spot Weather Forecast* called for mostly clear skies, very warm temperatures from 54°F to 59°F and higher RH values from 31% to 36%. The forecast winds were southwest winds 17 mph to 25 mph, with gusts to 25 mph. After 2100 MDT, winds were forecast to shift from northwest from 10 mph to 20 mph by midnight. The mixing height was 1,500 feet AGL until 2000 MDT and then 500 feet AGL after 2200 MDT (Fig. 21, b). The transport winds were forecast northwest around 17 mph, with excellent smoke dispersal until 2200 MDT (unstable air), NWS Pueblo (2013); Fischer (2013).

The Wednesday, 12 June Fire Weather Forecast, included in the above 11 June Spot Weather Forecast, called for sunny skies, a temperature range from 83°F to 88°F with RH from 6% to 11%, and a high Haines 6 or high potential for plume dominated fires . Variable and strong winds were forecast for northwest at 9 mph until 0900 MDT, then south 12 mph to 16 mph, with gusts to 31 mph. The mixing height (Fig. 21, b) was forecast for 500 feet AGL until 0800 MDT, then 20,000 feet AGL after 0900 MDT (very unstable air) with southwest transport winds around 25 mph., NWS Pueblo (2013); Fischer (2013).

The 11 June 2013, 300 mb maps (Fig. 5, a-b) revealed a split jet stream with an embedded jet streak from the PNW eastward into Canada with increased speed as it progressed. The PNW jet maxima was westerly in the 75 to 90 knot range. To the east, in southern Canada and the Great Lakes region, the winds were stronger, in the 75 to 110 knot range. Further south, in the BF Fire area, the winds were mostly southwesterly to westerly at speeds of 45 to 70 knots in the morning hours and decreased slightly from 25 to 35 knots during the afternoon hours.

The 07 MST 11 June 2013, 500 mb height contour map (Fig. 5, c) indicated the strong low pressure trough over the PNW that extended east into Canada above the Great lakes Region. A shortwave trough on a northwest-southeast axis from the PNW, dipped down into the Great Basin and northwestern edge of the Four Corners region, (Fig. 5, c). The 11 June PNW winds were southwesterly between 35 and 45 knots. These winds turned westerly as they advected into the Rocky Mountains, The Dakotas, Minnesota, and Wisconsin in the 35 to 65 knot range. The winds were westerly to southwesterly further south in the Four Corners Region, in the 35 to 55 knot range under high pressure (Fig. 5, c).

The 12 June 2013, 300 mb maps (Fig. 7, a-b) revealed a split jet stream from the PNW eastward into Canada with increased speed as it progressed. The jet maxima was westerly in the 75 to 125 knot range. Further south, in the BF Fire area, the winds were mostly southwesterly to westerly at speeds of 25 to 70 knots throughout the day.

The 12Z (0600 MDT) and 00Z (1800 MDT) 12 June 2013, 300 mb map (Fig. 7, a-b) revealed several separate northern jet stream segments, with an embedded jet streak had advected from the PNW eastward into Canada, and increased in speed as it progressed eastward. The jet maxima winds were westerly in the 75 to 125 knot range. General winds further to the south were westerly in the 50 to 60 knot range in the BF Fire area (Fig. 7, a-c).

The 07 MST 12 June 500 mb height contour map (Fig. 7, c) revealed the strong low pressure trough over the PNW, and that the 11 June shortwave trough had advected east on a north-south axis into The Dakotas, while a high pressure dome began to build over northern Canada, effectively split the two northern low pressure systems. The winds shifted more westerly in the BF Fire area and slightly increased to 45 knots.

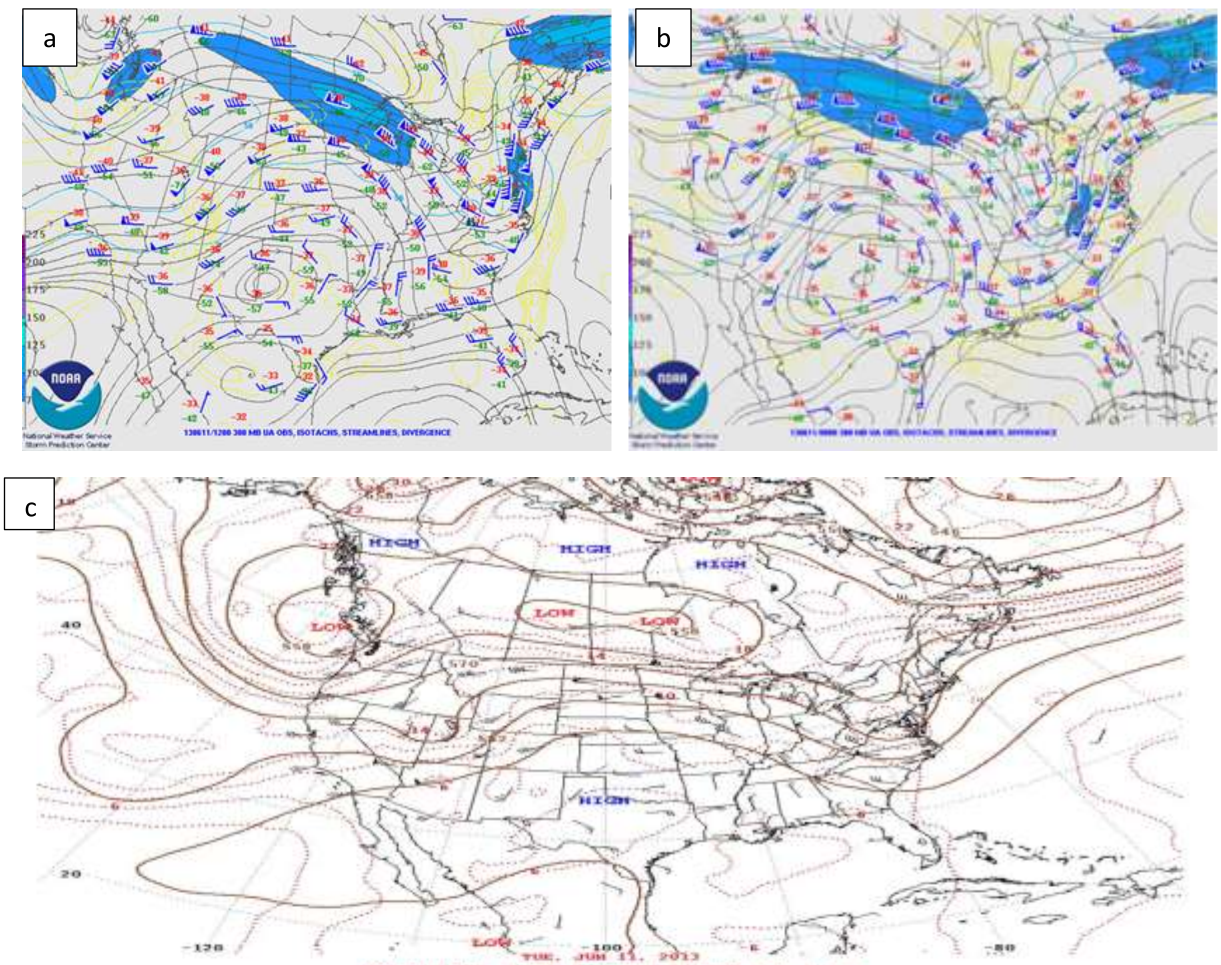

Figure 5: (a) 12Z and (b) 00Z 11 June 2013, 300 mb upper air map, NOAA SPC; (c) 0700 EST, 11 June 2013, 500mb Height Contour map, HPC, NCEP, NOAA.

h. Satellite Water Vapor Imagery, Dry Intrusions, Dry Slots, Meteograms, Remote Automated Weather System (RAWS)

Satellite water vapor imagery (WVI) is a valuable tool for locating dry air at the mid- to upper atmospheric levels, Carlson et al (1983), Mills (2008a, 2008b, 2009, 2010), and Kaplan et al (2008). According to Weldon and Holmes, these dry air signatures, are often referred to as dry tongues, dry slots, and dry intrusions (1991). These signatures indicated abrupt surface to near-surface drying, strong, gusty winds, reduced fuel moistures, and increased fire potential and/or fire behavior when they passed over a fire region and/or an ongoing fire, Kaplan et al (2008), Mills (2006, 2008a, 2008b, 2009, 2010), and Werth (2014),.

Mills (2006) concluded that dry slots were the result of troposphere ascent and descent in the upper levels due to circulations of the jet stream and upper troughs. He found that more than 70% of dry slots reached the surface by means of troughs or fronts, occurred most often during mid-afternoon, likely due to dry convective mixing. Mills noted other contributing factors included pre-frontal updrafts, self-stabilization above the mixed layer, low level jet entrance vertical circulations, post-frontal descent, breaking mountain waves, and lee trough circulations. He concluded that since these dry slots were frequently seen in satellite WVI, monitoring them would likely be a good short-range forecast tool to enhance fire weather forecasting.

Charney and others (2003) realized the significance of fire weather impacts from dry air aloft and sought to improve the prediction of these surface mixed layers. As these layers tapped into the dry, high-momentum air aloft, they felt it was useful to understand the ultimate source of the dry air, which would intensify the likelihood of large fire growth.

Zimet and others (2007) also studied upper air influence effects on wildland fires. The intense fire behavior and large fire growth of the May 1980 Mack Lake Fire in Michigan, resulted from a dry cold front passage. This particular fire was largely impacted by the influence of a tropopause fold. The fold signature showed up in the WVI as a "dark band" (dry slot) that was collocated with the most intense region of the upper front. The authors noted regions of low RH in the mid-troposphere provided an indication of strong subsidence, often collocated with the warm side of a frontal zone in the upper troposphere. They utilized a vertical cross-section view of RH through an upper-level front to illustrate the downward extent of the stratospheric air (not shown). The dynamic tropopause fold extended downward to roughly 600 mb.

The NWS held a Fire Weather Forecasters workshop in Boise Idaho in 1999 and established a paper titled 'Critical Fire Weather Patterns of the United States.' They stressed using WVI to locate 'dark areas' as potential regions of moderate to high Haines Index. They stressed that even light gray (i.e. moist) areas, would be a Haines Index of 5 or 6. Weldon and Holmes (1991) referred to this as "gray shade drying," NWS (1999).

Iacopelli and Knox (2001) examined dry intrusions during a winterseason, upper Midwest mid-latitude cyclone wind event. They maintained that the “main finding of [their] work,” was when they observed a bifurcated dry intrusion with two distinct paths near the low-pressure center, coincident to the surface reports of damaging winds, linked very closely in time and space to the location of the southern fork of the dry intrusion. Tollerud discovered that exceptionally dark filaments or dry slots can extend from short distances to hundreds of miles, and the inferred midlevel dryness within these filaments strongly indicated subsidence, (2002).

In 2009, Mills re-examined his research of the January 2003, Australian Canberra Fire weather causal factors. His analysis showed that a mid-tropospheric dry slot, clearly identifiable in the WVI, moved over Canberra at about the same time as the abrupt dewpoint decrease. He proposed that dry convective mixing through a very deep mixed layer that extended to 600 hPa, possibly allowed mid-tropospheric dry air to mix to the surface.

Werth and Ochoa (1990) studied several 1985, 1988, and 1989 wildland fires in Idaho and the Rocky Mountains. They used water vapor imagery to conclude that dry slots coincided with Haines 5-6 and large fire growth on each of these fires. The authors also found the WVI to be quite useful in locating the subtropical jet influence on several of the fires.

On 11 June 2013, the WVI (Fig. 6, a-d) revealed a dry intrusion throughout the Southwest, as well as a very distinct dry slot in southeastern Utah that advected into Colorado and the BF Fire area throughout the day. The 15Z (0900 MDT) (b), 18Z (1200 MDT) (c), and 21Z (1500 MDT) (d) WVI revealed that very dry air had advected into south central Colorado, prior to the BF Fire start and during the initial stages of the fire. This dry air advection, albeit less strong, would carry on into the following day, 12 June (Fig. 8, a-d).

This dry air advection, validated in the two RAWS meteograms from the Grand Junction (KCAG), Trinidad - Animas (KTAD), and Akron/Washington (KAKO) Colorado (ROMAN) Real-time Observation Monitor and Analysis Network RAWS sites, (Figs. 11-12) gives a good overview of the fire weather during that period. Both meteograms for the 11 and 12 June 2013 periods, 00Z (1800 MDT) to 23Z (1700 MDT) revealed the early morning temperature rise which then levelled off around early afternoon. This coincided with the lowered dewpoint values, steady winds, and strong wind gusts later in the afternoon. This was also reflected in the WVI dry intrusion and dry slot signatures (Figs. 6, 8). These were also the times of the most intense fire behavior and large fire growth, Mills (2009),Bell (2014).

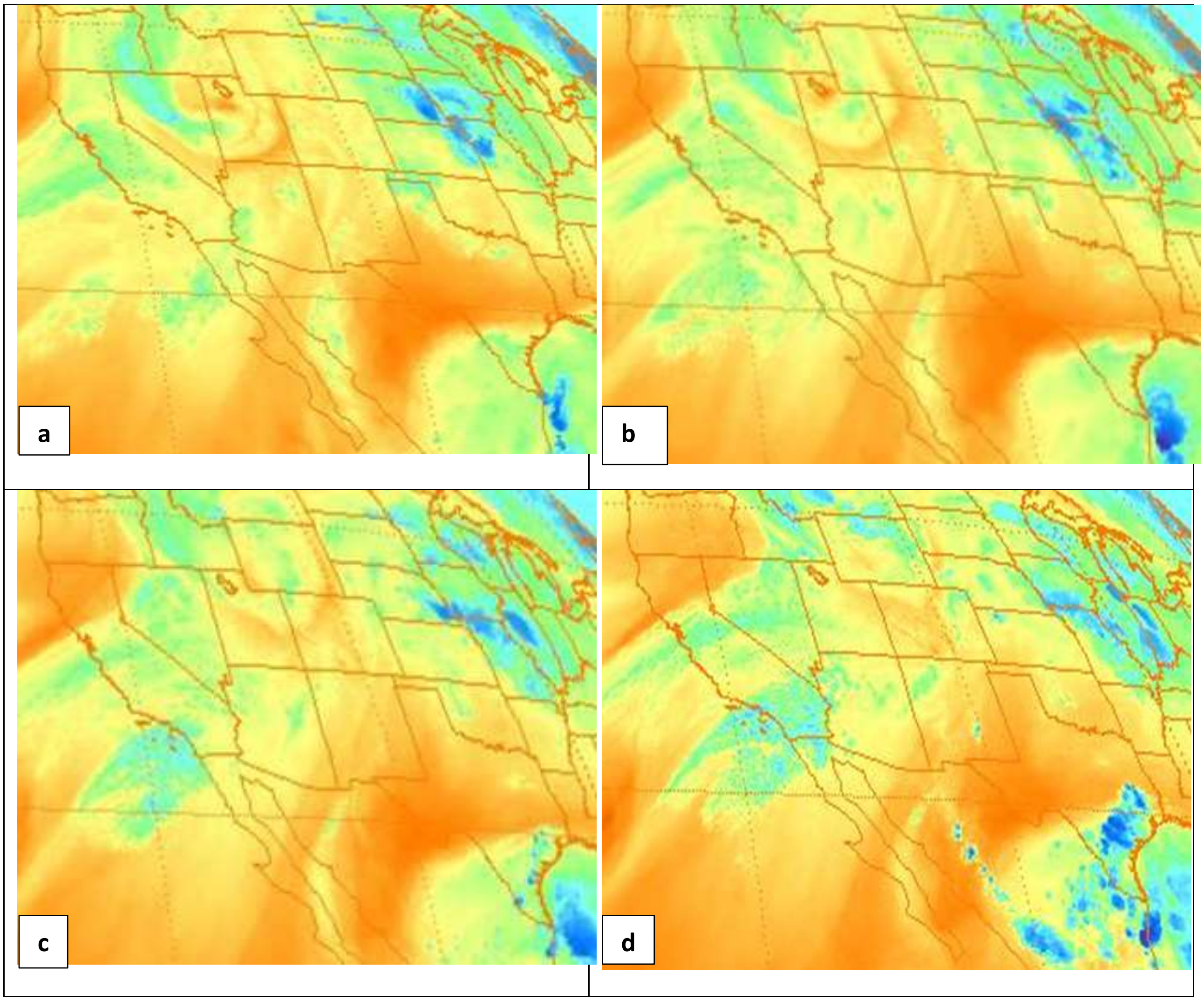

Figure 6: (a) 12Z (0600 MDT), (b) 15Z (0900 MDT), (c) 18Z (1200 MDT), and (d) 21Z (1500 MDT) 11 June 2013, NOAA GIBBS GOES-15 Water Vapor Imagery (WVI)

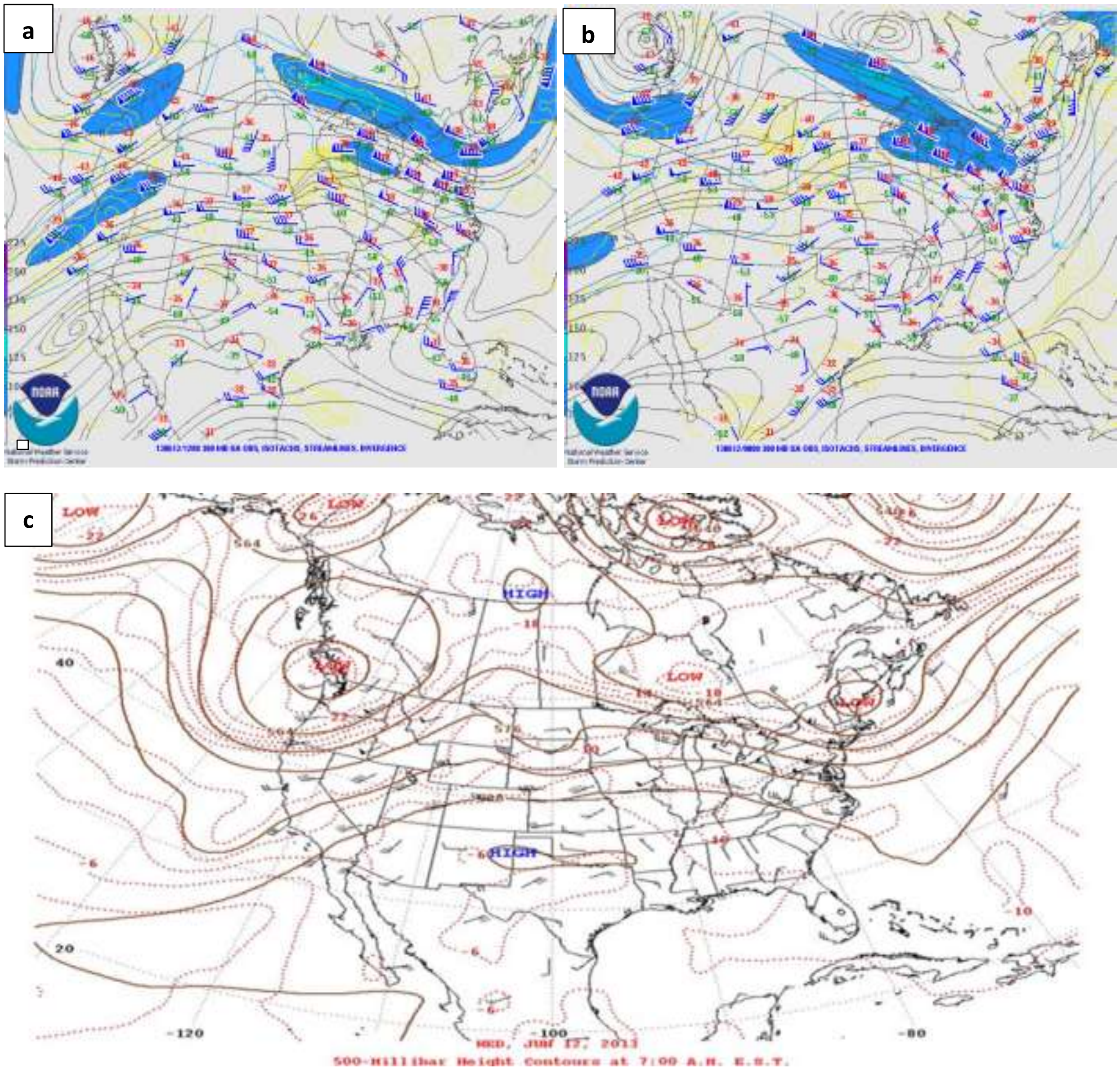

Figure 7: (a) 12Z and (b) 00Z 12 June 2013, 300 mb upper air map; (c) 0700 EST 12 June 2013, 500mb Height Contour map, HPC, NCEP, NOAA

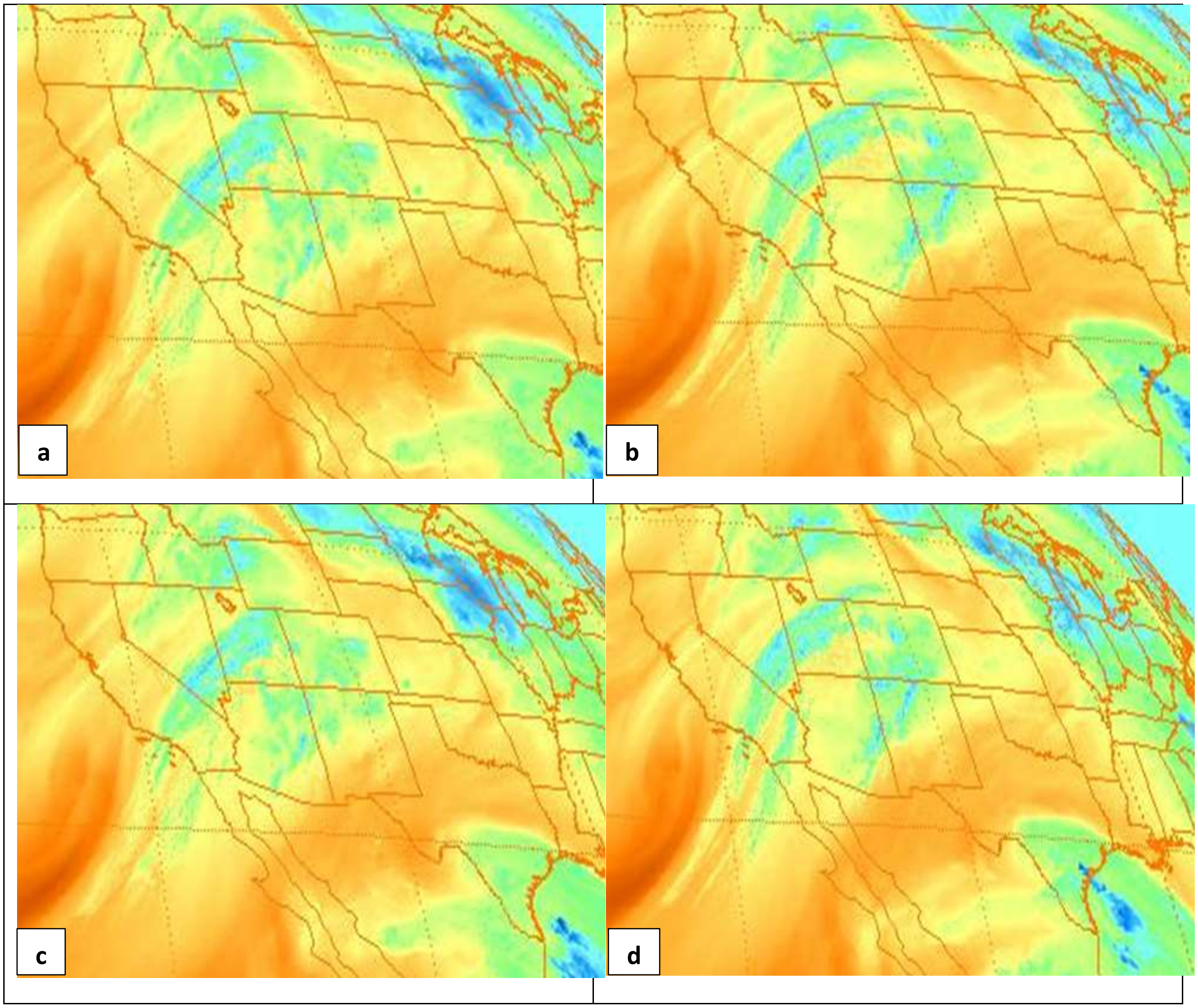

Figure 8: (a) 12Z (0600 MDT), (b) 15Z (0900 MDT), (c) 18Z (1200 MDT) and (d) 21Z (1500 MDT) 12 June 2013, NOAA GIBBS GOES-15 Water Vapor Imagery (WVI)

The (a) 11 June 2013 photo below (Fig. 9, a) revealed a darkened, increased and leaning smoke column under the influence of intense burning conditions and winds. The smoke column would unquestionably contain a heavy accumulation of burning woody materials, e.g. twigs, pine cones, etc., and would transport these aloft; they would then drop from the column to ignite spot fires below in receptive fuel beds. The intense fire behavior photo below (b) revealed the BF Fire as it crossed Black Forest Road just south of Vessey Road on 11 June 2013; the burned structure photo below (c) revealed the lack of mitigation around these structures based on the density of the standing trees. Empirically, the fire appeared to have progressed by means of surface fire as well as spot fires. In addition, either or both of these means could have ignited the structures. The same could almost be said for the 12 June 2013 photo (Figs. 13 a-b) with the twisting and bent-over smoke columns.

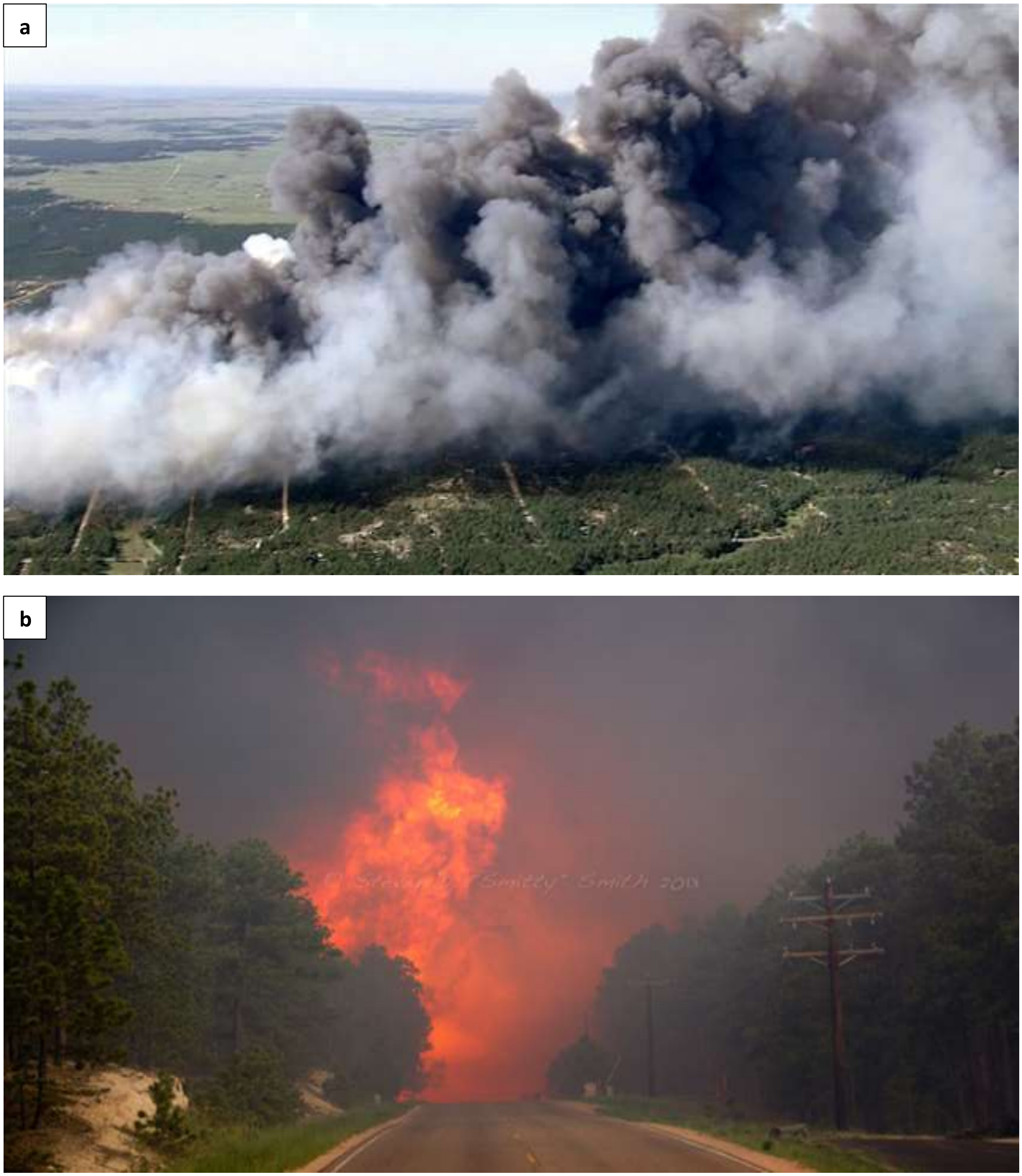

Figure 9: (a) 11 June 2013 BF Fire, Denver Channel 7 News; (b) BF Fire, 11 June 2013, Steven ‘Smitty’ Smith.

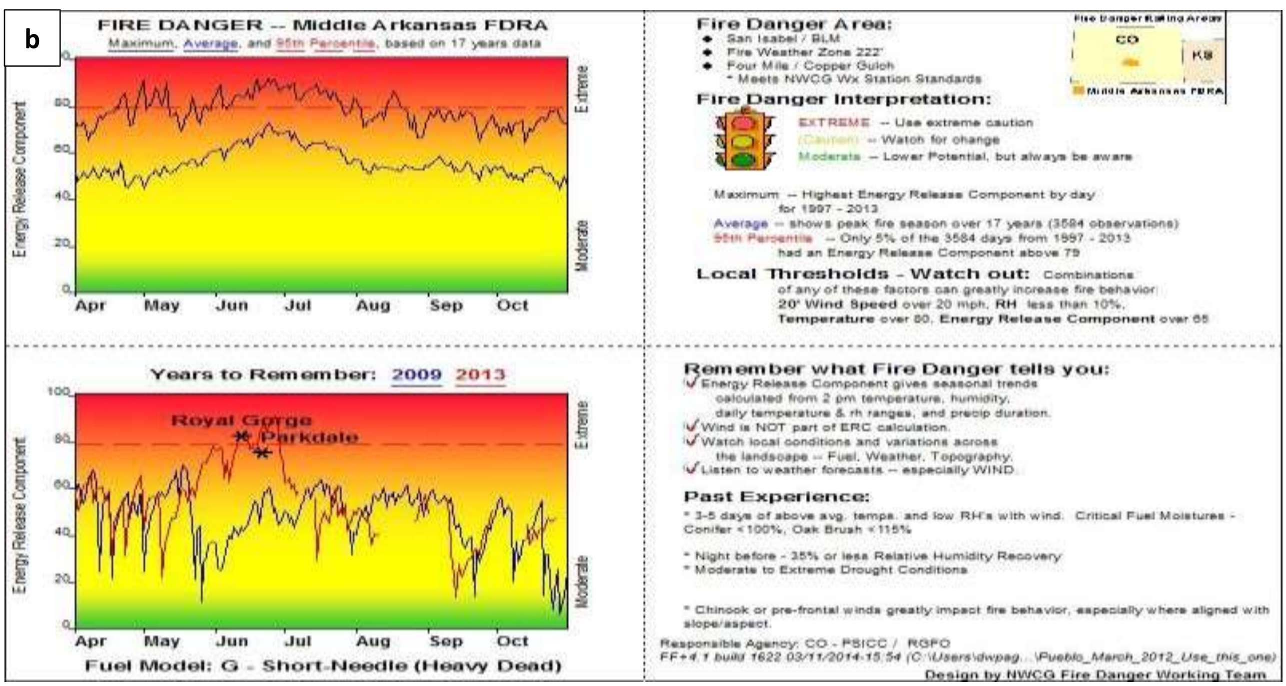

Figure 10. (a) 13 June 2013, BF Fire, John Wark, Reuters, darkroom.baltimoresun.com; (b) NWCG Fire Danger Rating Card for Middle Arkansas FDRA – FM G Timber.

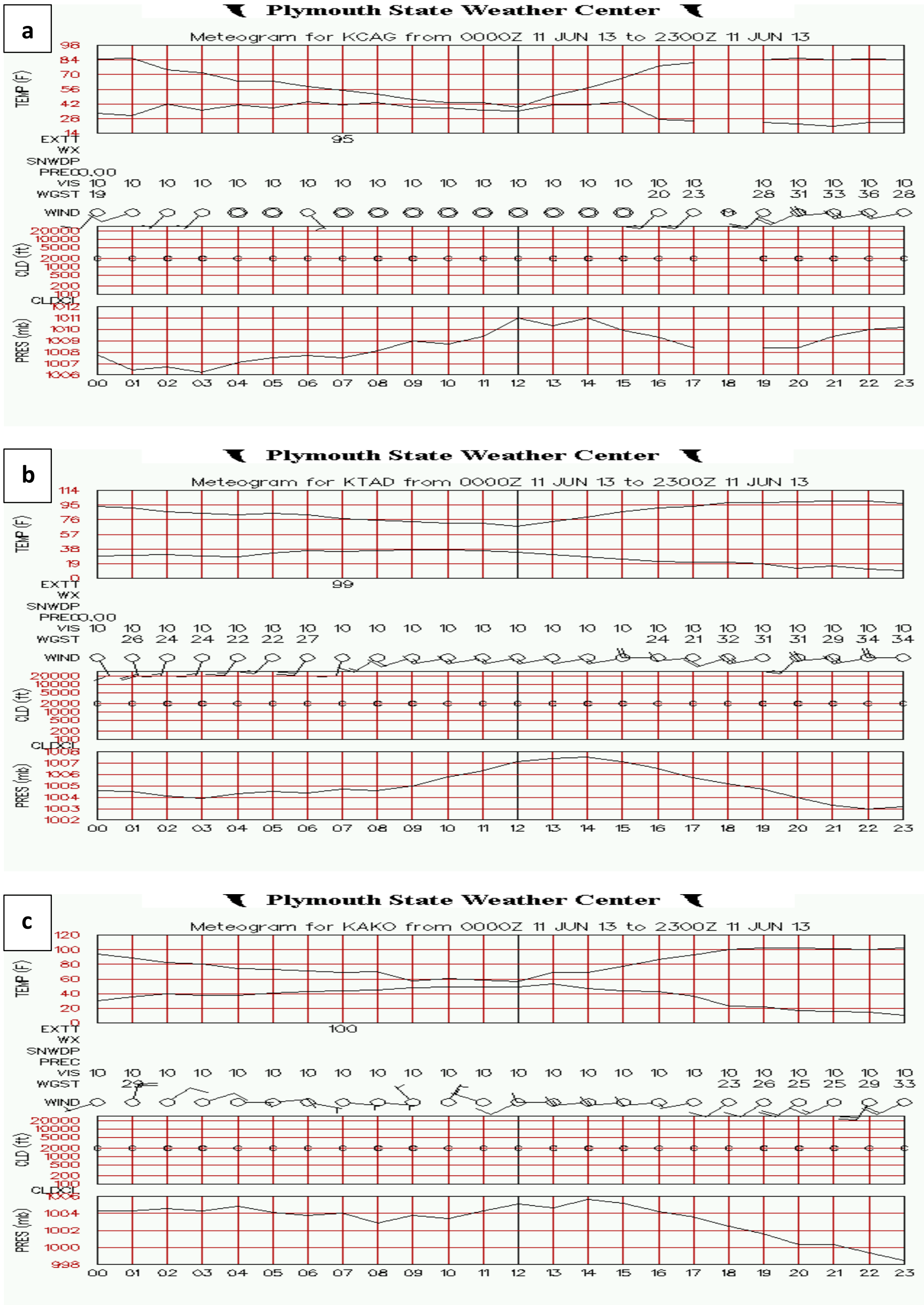

Figure 11: (a) Grand Junction (KCAG), (b) Trinidad/Animas, (KTAD), (c) Akron/Washington, CO (KAKO) Roman RAWS Meteogram for period 00Z 11 June to 23Z 11 June 2013.

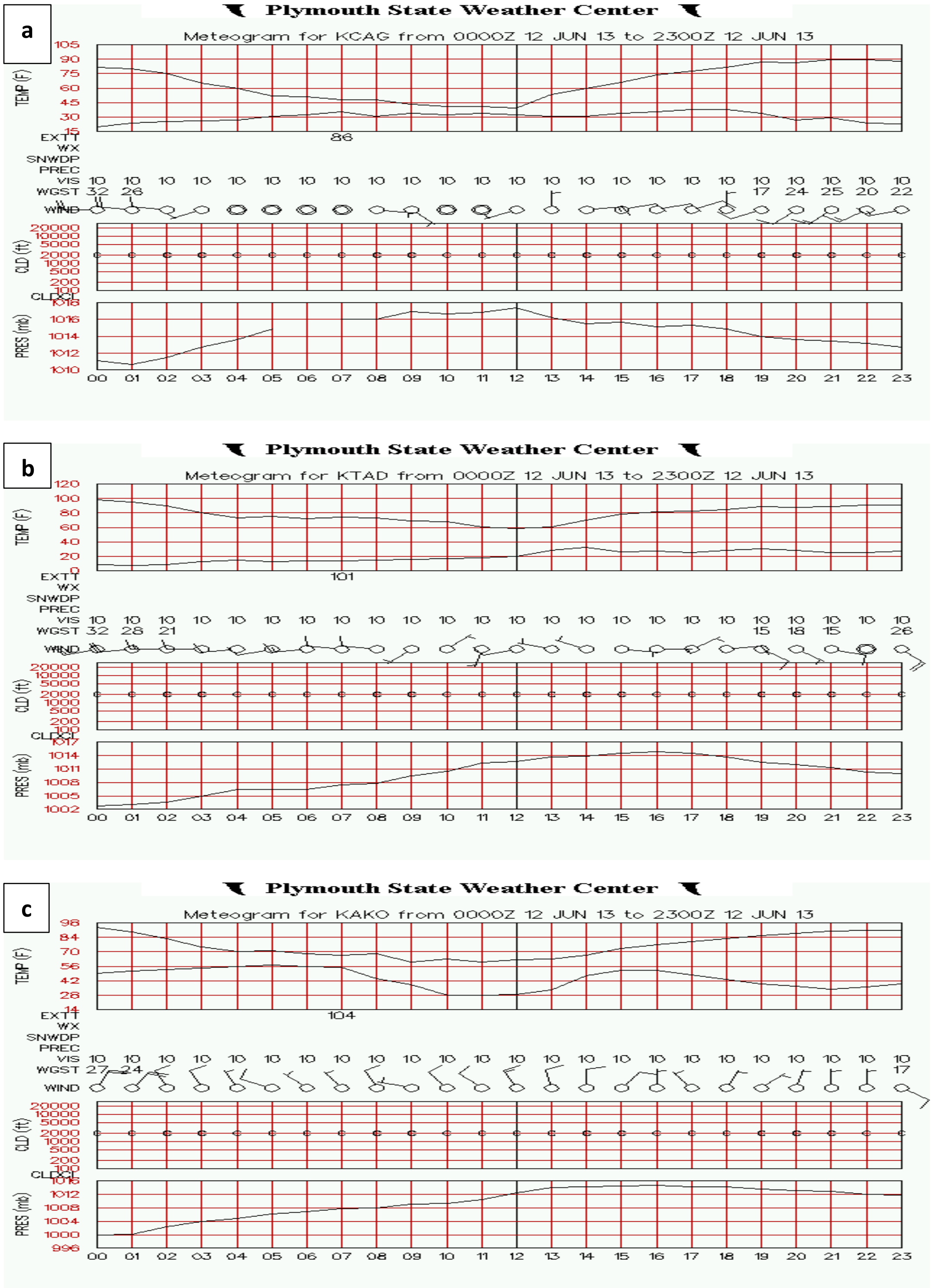

Figure 12: (a) Grand Junction (KCAG), (b) Trinidad/Animas, (KTAD), (c) Akron/Washington, CO (KAKO) Roman RAWS Meteogram for period 00Z 12 June to 23Z 12 June 2013.

Figure 13; (a) 12 June 2013 Black Forest Fire, intense fire behavior, Reuters/Rick Wilking, www.christianpost.com; (b) 12 June 2013 Black Forest Fire, John Wark, eclectic arcania 12 June 2013 Black Forest Fire, abc15, CNN, Associated Press,

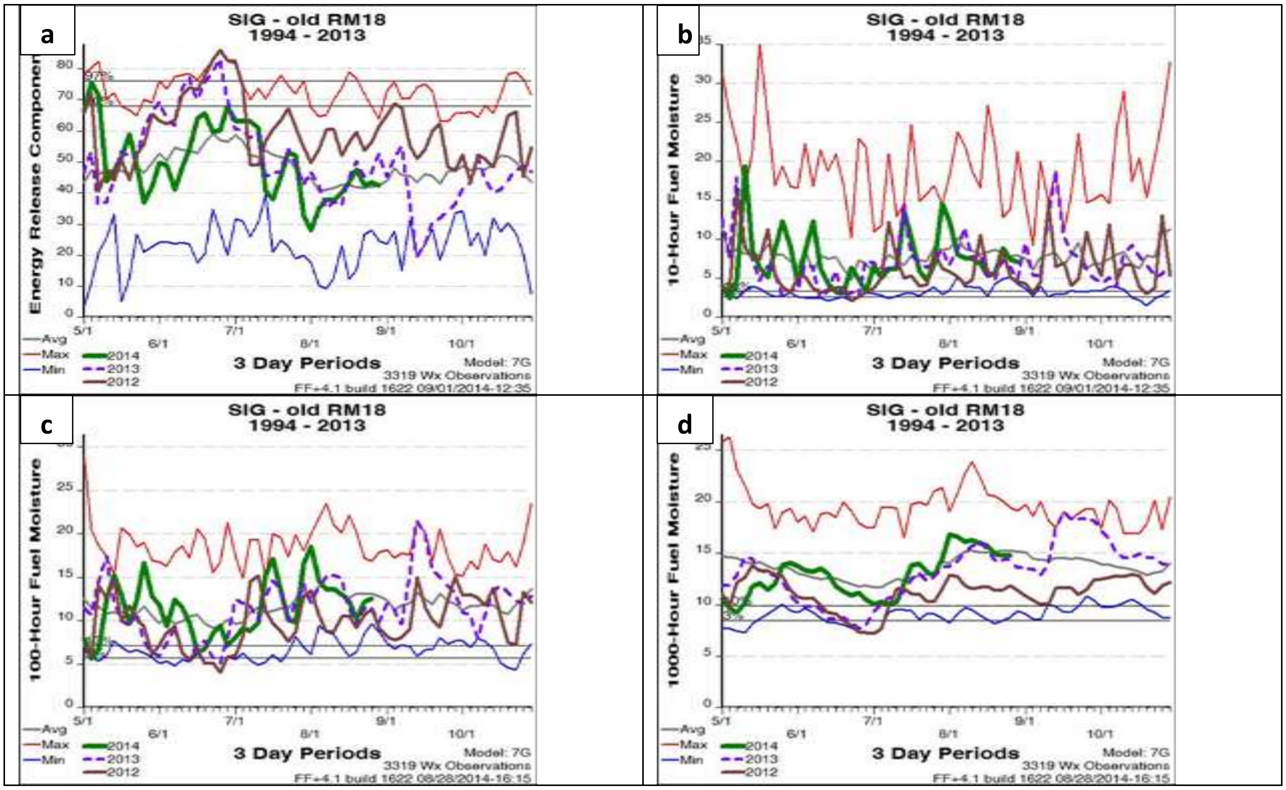

Figure 14: Fuel Model G (short-needle timber), ERC (a),10-Hour (1/4” to 1” diameter) Fuel Moisture (FM) (b), 100-Hour (1” to 3” diameter) FM (c), 1000-Hour (3” to 8” diameter) FM charts (d), 1994 to 2013, 2013 is the dashed, thick dark purple line, RM GACC (2014).

i. Energy Release Component and Extreme Fire Weather Observations and Thresholds

The Energy Release Component (ERC) is defined as the potential available energy per square foot of flaming fire at the head of the fire, i.e. ‘heat release,’ and is expressed in units of BTU’s per square foot. The day-to-day variations of the ERC are the result of changes in the moisture contents of the various fuel classes. The ERC is derived from predictions of (1) the rate of heat release per unit area during flaming combustion and (2) the duration of the flaming, NWCG S-290 (2007).

The Black Forest Fire began on 11 June at an ERC level of roughly 74; or between the 90th to 97th percentile burning index values, during the slight dip just prior to a surge to above 80 and the 97th percentile toward the middle to end of June, (Fig. 14). The percentile values are determined from historical fire weather observations and provide criteria for ranking the relative severity of the burning conditions on a given day, Andrews and Rothermel (1982). The NWCG Fire Danger Rating Card for Fuel Model G (short-needle timber type) in the Central Front Range of the Rocky Mountain Region (Fig. 10, b) indicated this was in the Extreme category.

The role of high nighttime temperatures as they relate to extreme fire behavior and large fire growth, as set forth in the 1962 research paper by Robert Bates, titled '*Blowup Conditions in the Southwest?'* is now considered. Based on ten years of data (1951-1961), Bates determined that the fire weather in the area of fires was quite warm the night before the intense fire behavior and/or fire blow-up. Bates determined that nighttime temperatures at or equal to 45°F were 'critical,' and that high nighttime temperatures at or equal to 55°F was the threshold for 'blow-up' conditions. Therefore, he set thresholds of 45°F in the high country and 81°F for the lower desert regions. The author has determined through empirical, real-world experiences and research that these nighttime temperatures and thresholds apply everywhere in the U.S. except the Southeastern region, Schoeffler (2014).

Drying is a significant contributor to fire weather and the ensued fire behavior, in that it dries out the receptive fuels and fuel beds, lowering their respective live and dead fuel moistures, making them more available for easy ignition, more susceptible to burn, and permitting a much higher amount of energy release, Davis (1959). Relative humidity, the amount of water vapor in the air, can change with both temperature and/or moisture changes. With dew point temperature, any change is strictly due to moisture change, Davis (1959). Regarding wildland fire weather, dew point effects more-or-less mirror the RH effects on fire behavior.

Consider the contoured surface temperature maps (Fig. 15 and 18) that indicated the Black Forest Fire high nighttime (0300 MDT) temperatures for 11-12 June. The author utilized both 09Z (0300 MDT) and 19Z (1300 MDT) times to best reflect the nocturnal and daytime temperatures. These high nighttime temperatures were well within Bates' 'critical' to 'blow-up' limits of 45° F and 55° F respectively. These high nocturnal temperatures led up to the intense fire behavior and large fire growth on 11 and 12 June 2013. It is significant to note that the temperatures were in the mid 60's the night before the most intense fire behavior days of 11 and 12 June! The 19Z (1300 MDT) dT was in the 40° C to 44° C range, along with the 19Z daytime, surface temperatures in the 84° F to 92° F range. The 00Z (1800 MDT) 11 June 2013, contoured surface relative humidity map (Fig. 15, c) would also reveal anomalously low relative humidity values for that time in the 5% to 8% range. The 12 June temperature values were lower in the 88° F range (Fig. 18, d) and RH was slightly higher, in the 9% to 12% range (Fig. 15, c).

Overall, the 11 and 12 June 2013 contoured surface maps below (Fig. 15, 18, a-f) clearly indicated hot, dry, and windy conditions that set the stage for and sustained the 11 to 12 June extreme fire weather and fire behavior events. These events were based on: high, early morning nighttime temperatures in the blow-up potential threshold, 19Z (1300 MDT) surface temperatures, high dew point depressions, and very low relative humidity values. To be sure, the stage had been clearly set for extreme fire behavior during that interval.

Regarding high Tdd values, several North Carolina NWS meteorologists found that Tdd as low as 10° C at 850 mb were one of the extreme fire behavior factors that contributed to a 10 February 2008 high wind and wildfire event, Smith, et al (2008). The high Tdd values were also recognized in the NOAA NWS (2005) surface, upper air, and composite charts for various levels.

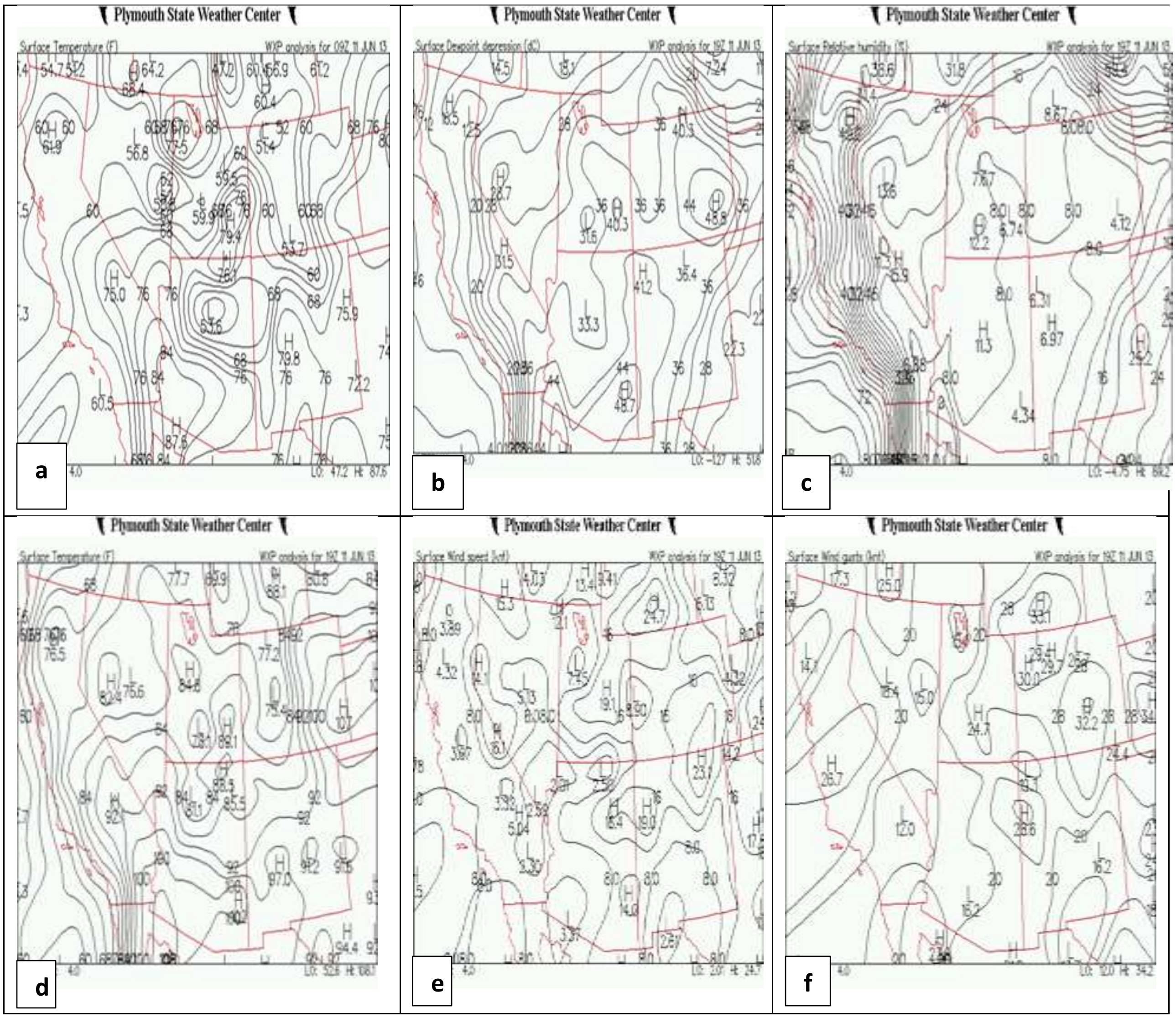

Figure 15: 11 June 2013, contoured surface measurements; (a) 09Z (0300 MDT) temperatures (F), (b) 19Z (1300 MDT) Tdd in °C, (c) 19Z (1300 MDT) RH (d) 19Z (1300 MDT) temperature (F); (e) 19Z (1300 MDT) wind speed (knts), and (f) 19Z (1300 MDT) wind gusts; interval of 4, Plymouth State Weather Center (2014).

A noticeable, precipitous drying trend preceded the BF Fire 11 June start date and time. On 9 June, the RH was in the 15% range (not shown), then it dried by half to almost 8% on 10 June (not shown). Further drying occurred on 11 June (Fig.15) the fire start date, by half again, to less than 5%! On 12 June (Fig. 18) the RH recovered somewhat, but this was still well within the realm of serious drying at less than 10%. Mixed with the winds, these factors resulted in very active to extreme fire behavior on each of these days and nights, 11-12 June 2013

Meteorologists maintain that an 850 mb Tdd of greater than or equal to 8.0° C indicated very dry air, NWS (2005). The elevation at Black Forest was 7379' so these Tdd surface and 850 mb values should closely correspond for the BF Fire. At 700 mb, NWS (2005) and Smith et al (2008) found that a Tdd of 6° C indicated significant dry air in the mid- levels that may signal the chance of strong downdrafts. The BF Fire was situated in between these atmospheric levels.

The 00Z (1800 MDT) 11 June Tdd was in the 32° C to 36° C range and the 12 June Tdd was even higher, in the 36° C to 44° C range (Figs. 15 and 18). Both of these Tdd value ranges during the 11-12 June periods were well above the meteorological parameters established by NWS for significant drying and downdraft potential NWS (2005). Moreover, several of the SPC Outlooks forecast downslope winds for portions of Colorado and the BF Fire area during the 11-12 June periods.

Next, the 11-12 June 2013, high nighttime temperatures, RH's, winds, and fuel moistures for the BF Fire are considered and highlighted in red. The midnight to 0630 MDT, 11 June 2013 (Fig. 16), Rampart Range (RRAC2), CO RAWS data (9207'), approximately 20 miles (32 km) southwest of the Black Forest Fire, was significant. It revealed high nighttime temperatures that ranged from 59° F (17.7° C) to 65° F (19.4° C) with low RH values that ranged from 18% to 25% during those nighttime hours. The daytime, 1535 to 1635 MDT RH was anomalously low at 3%; from 0735 to 1435, the RH was still very low between 5% to 10%. The 24-hr winds were steady from a calm, 1 knot up to 13 knots, with gusts 5-26 knots, mostly westerly.

The midnight to 0630 MDT 12 June 2013 (Fig. 17), Rampart Range (RRAC2), CO RAWS data was also indicative of the fire behavior day to follow. The nighttime temperatures were warm, and within Bates' blow-up condition realm. The same period RH was low, from 17% to 20%, and the daytime RH averaged about 15%, with significant drying between 1635 and 1935 MDT. These daytime RH values were very low and ranged between 3% to 6%. The 24-hr winds were mostly westerly and ranged from 2 to 19 knots, with gusts from 4-35 knots. The gustiest wind periods were between 1200 and midnight MDT and ranged from 20 to 35 knots.

Notwithstanding the 1828' elevation difference between the BF Fire and the Rampart Range RAWS site, applying the dry adiabatic lapse rate of 5.5° F per 1,000' elevation to the 11 and 12 June 2013 readings, the high nighttime temperatures fall well within the critical (≥ 45° F) and blow-up levels (≥ 55° F).

Figure 16: 11 June 2013 Rampart Range, Colorado ROMAN RAWS (RRAC2) at 9207'.

Time(GMT)	Temperature	Dew Point	Relative Humidity	Wind Speed	Wind Gust	Wind Direction	Quality check	Solar Radiation	Precipitation accumulated	Fuel Temperature	10 hr Fuel Moisture
	° F	° F	%	mph	mph			W/m*m	in	° F	gm
23:35	75.0	19.0	12	5	13	WSW	OK	220.0	23.59	75.0	4
22:35	74.0	23.4	15	7	14	ENE	OK	227.0	23.59	77.0	4
21:35	76.0	13.1	9	9	37	WSW	OK	393.0	23.59	79.0	4
20:35	83.0	15.6	8	7	16	W	OK	921.0	23.59	100.0	4
19:35	78.0	11.9	8	7	23	WSW	OK	881.0	23.59	88.0	4
18:35	81.0	16.9	9	5	17	NW	OK	852.0	23.59	95.0	4
17:35	79.0	15.4	9	6	20	WSW	OK	922.0	23.59	93.0	5
16:35	75.0	19.0	12	10	23	WNW	OK	783.0	23.59	85.0	5
15:35	74.0	18.2	12	9	19	WNW	OK	619.0	23.59	78.0	6
14:35	71.0	19.4	14	10	18	WNW	OK	429.0	23.59	72.0	6
13:35	68.0	20.1	16	10	17	WNW	OK	208.0	23.59	66.0	6
12:35	65.0	20.5	18	7	14	W	OK	59.0	23.59	63.0	6
11:35	64.0	20.9	19	9	15	W	OK	1.0	23.59	59.0	6
10:35	63.0	23.6	22	10	16	W	OK	0.0	23.59	58.0	6
9:35	63.0	22.5	21	10	14	W	OK	0.0	23.59	59.0	6
8:35	63.0	21.3	20	7	10	W	OK	0.0	23.59	57.0	6
7:35	59.0	23.2	25	1	3	NNW	OK	0.0	23.59	53.0	6
6:35	61.0	24.0	24	0	5	NW	OK	0.0	23.59	55.0	6
5:35	62.0	24.8	24	3	11	S	OK	0.0	23.59	56.0	6
4:35	62.0	25.8	25	8	19	SSE	OK	0.0	23.59	59.0	5
3:35	63.0	25.6	24	10	22	SSE	OK	0.0	23.59	60.0	5
2:35	64.0	26.5	24	8	18	SE	OK	35.0	23.59	61.0	5
1:35	67.0	25.8	21	8	17	SE	OK	223.0	23.59	67.0	5
0:35	69.0	26.3	20	9	18	ESE	OK	410.0	23.59	72.0	5
23:35	70.0	28.3	21	10	18	SE	OK	612.0	23.59	76.0	5

Time(GMT)	Temperature	Dew Point	Relative Humidity	Wind Speed	Wind Gust	Wind Direction	Quality check	Solar Radiation	Precipitation accumulated	Fuel Temperature	10 hr Fuel Moisture
	° F	° F	%	mph	mph			W/m*m	in	° F	gm
23:35	81.0	-1.0	4	10	31	W	OK	629.0	23.59	86.0	3
22:35	80.0	-7.7	3	15	35	W	OK	810.0	23.59	88.0	3
21:35	81.0	-7.0	3	8	34	W	OK	880.0	23.59	91.0	3
20:35	78.0	1.6	5	13	36	WSW	OK	990.0	23.59	90.0	3
19:35	76.0	4.1	6	17	36	WSW	OK	1018.0	23.59	87.0	3
18:35	77.0	8.2	7	14	31	WSW	OK	970.0	23.59	89.0	4
17:35	75.0	9.7	8	20	42	WSW	OK	902.0	23.59	85.0	4
16:35	74.0	11.6	9	12	26	WSW	OK	542.0	23.59	81.0	4
15:35	71.0	11.7	10	7	16	SSW	OK	418.0	23.59	72.0	4
14:35	72.0	12.5	10	4	16	WSW	OK	429.0	23.59	75.0	5
13:35	70.0	13.1	11	6	11	S	OK	194.0	23.59	68.0	5
12:35	**67.0**	**14.5**	13	5	18	SW	OK	50.0	23.59	64.0	5
11:35	**64.0**	**16.9**	16	13	19	W	OK	1.0	23.59	60.0	5
10:35	**64.0**	**18.3**	17	10	16	W	OK	0.0	23.59	60.0	5
9:35	**65.0**	**21.7**	19	9	15	W	OK	0.0	23.59	61.0	5
8:35	**67.0**	**22.1**	18	9	15	W	OK	0.0	23.59	62.0	4
7:35	**67.0**	**20.8**	17	9	13	W	OK	0.0	23.59	62.0	4
6:35	**67.0**	**23.4**	19	7	18	W	OK	0.0	23.59	63.0	4
5:35	**68.0**	**24.2**	19	12	19	WNW	OK	0.0	23.59	65.0	4
4:35	68.0	21.6	17	7	12	W	OK	0.0	23.59	64.0	4
3:35	67.0	23.4	19	2	5	SSW	OK	0.0	23.59	62.0	4
2:35	68.0	24.2	19	1	8	ESE	OK	34.0	23.59	64.0	4
1:35	72.0	23.4	16	8	14	NW	OK	162.0	23.59	72.0	4
0:35	75.0	16.9	11	8	16	W	OK	146.0	23.59	76.0	4
23:35	75.0	19.0	12	5	13	WSW	OK	220.0	23.59	75.0	4

Figure 17: 12 June 2013 Rampart Range, Colorado ROMAN RAWS (RRAC2) at 9207'.

Next, the 10-12 June 2013 (Figs. 19, 20), 700 mb Relative Humidity (RH) and Dew Point Depression (Tdd) values for Denver, Colorado are considered, based on Skew-T sounding text data. The (12Z) 10 June RH (not shown) was 16% with a 26° C Tdd and the 00Z RH and Tdd held at 16% and 26° C respectively. The next day, the 12Z 11 June RH was lower, at 12% with a higher Tdd at 30° C, and by the afternoon the 00Z RH was lower at 10% with a higher Tdd at 32° C. The BF fire started that day about 1355 MDT and escaped about 1418 MDT - within less than 25 minutes. The following day, the 12Z 12 June RH was 19% with a Tdd of 23° C, and the (00Z) RH dropped abruptly to 5%, while the Tdd nearly doubled to 41° C!, Plymouth State.

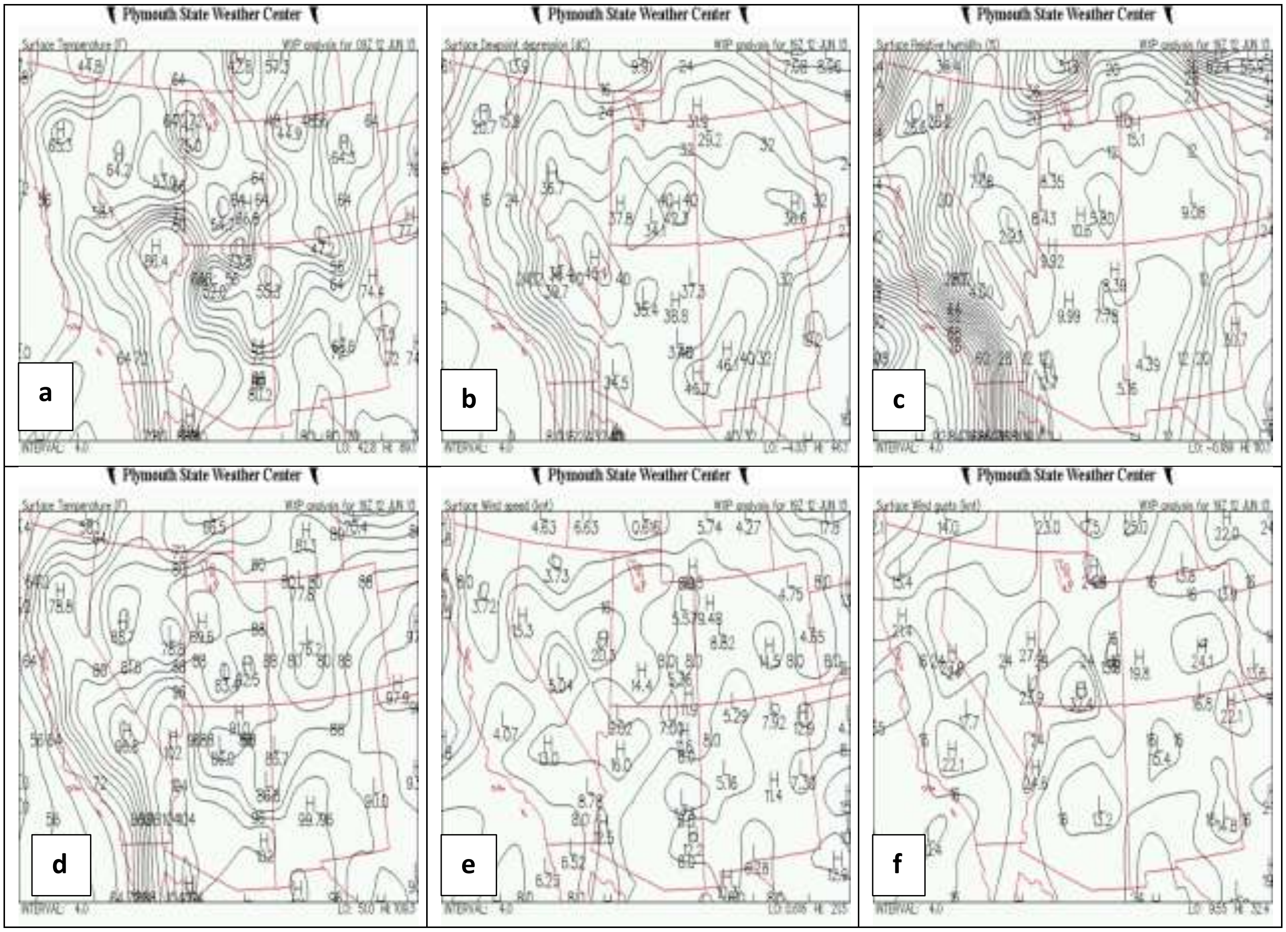

Figure 18: 12 June 2013, contoured surface measurements; (a) 09Z (0300 MDT) temperatures (°F), (b) 19Z (1300 MDT) Tdd, (c) 19Z (1300 MDT) RH (d) 19Z (1300 MDT) wind speed (knts), (e) 19Z (1300 MDT) temperature (F), (f) 19Z (1300 MDT) wind gusts; interval of 4, Plymouth State Weather Center (2014).

The 12Z (0600 MDT) 11 June 2013, Denver, CO (KDNR) atmospheric sounding, Fig. 19 (a), revealed an inversion at about 850 mb and dry air up to about 450 mb. Subsidence inversions were located at about 740 mb and 600 mb. Plymouth State atmospheric sounding text data (not shown) revealed dry air from 823 mb to 607 mb and the RH ranged from 12% to 19%. There was another band of dry air from 429 mb to 359 mb where values ranged from 15% to 19%. Dew points were also low. The 700 mb Tdd was 30° C. There were southwesterly winds from 11 to 34 knots in the mid- to lower elevations, with southwesterly winds 35 knots to 37 knots in the jet levels.

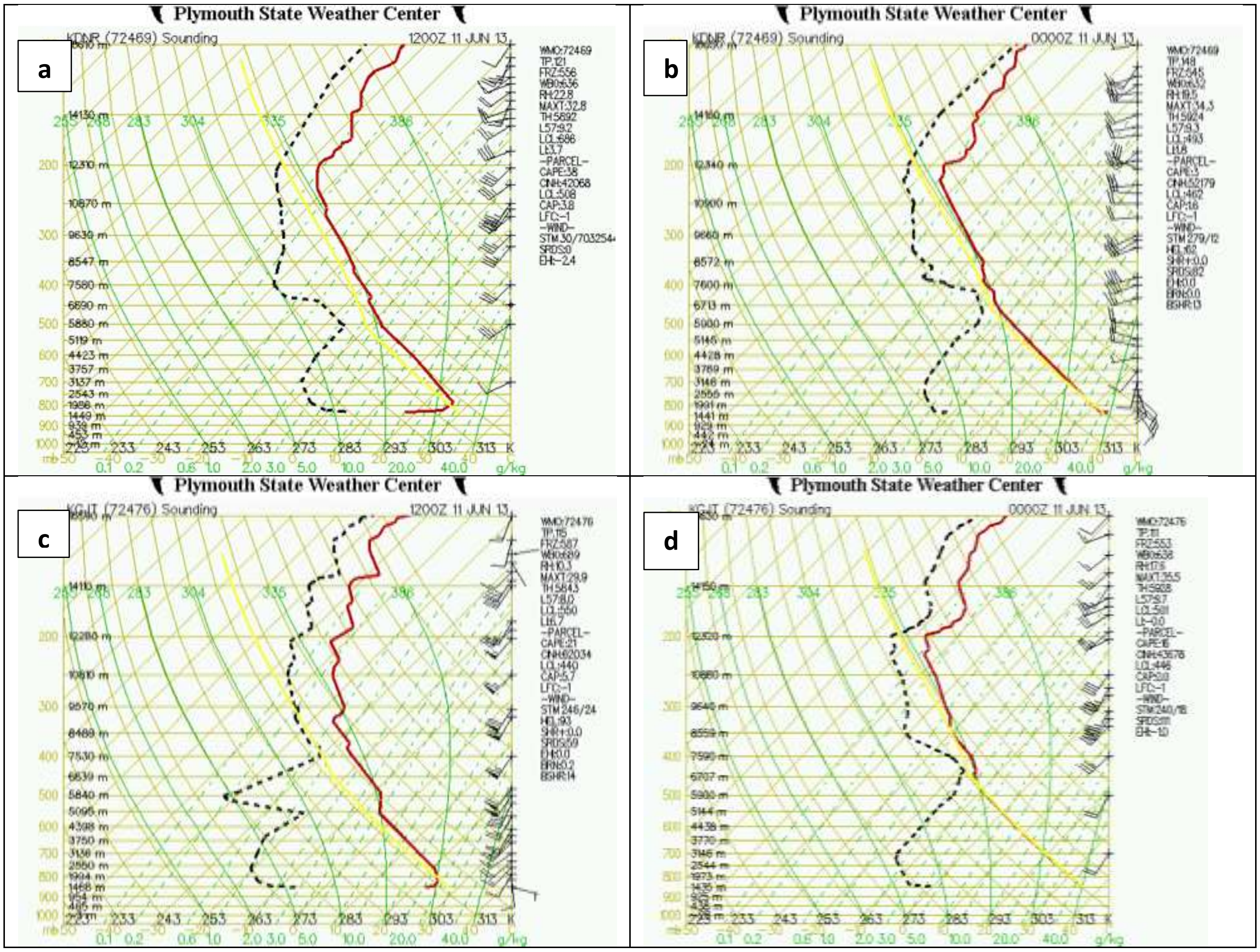

Figure 19: (a) 12Z (0600 MDT); (b) 00Z 1800 MDT) 11 June 2013, Denver, Colorado (KDNR), (c) 12Z (0600 MDT); (d) 00Z 1800 MDT) 11 June 2013, Grand Junction, Colorado (KGJT), Plymouth State Weather Center atmospheric soundings

The 00Z (1800 MDT) 11 June 2013 in Fig. 19(b), Denver, CO (KDNR), Plymouth State atmospheric sounding revealed an inversion at about 840 mb with subsidence inversions at about 520 mb and 430 mb. The atmospheric sounding data (not shown) revealed very low RH between 834 mb and 668 mb that ranged from 9% to 12%. The dew points were also low at those altitudes and ranged from – 1.4 to - 13.6 C. The 700 mb Tdd was 32° C. The lowest level winds were southeast between 9 to 19 knots. The low and mid-level winds were southeasterly from 852 mb to 735 mb between 6 to 10 knots. The jet stream level winds were west-southwest from 53 to 56 knots.

The 12Z (0600 MDT) 11 June 2013, Plymouth State atmospheric sounding in Fig. 19(c), for Grand Junction, CO (KGJT) revealed an inversion at about 850 mb with concomitant subsidence inversions at about 800 mb, 550 mb, 500 mb, and 380 mb respectively. Very dry air was evident from 850 mb to up to about 350 mb, with an obvious dry band between roughly 520 mb and 480 mb. Atmospheric sounding text data (not shown) revealed from roughly 849 mb to

494 mb the RH ranged from 4% to 25% with the 25% band at only the 555 mb level. Dew points were also low as well in those levels and ranged from - 6.4° C to - 40.5° C respectively. Winds were light and southeasterly at the lowest levels then southwesterly from 15 to 54 knots to the 500 mb level. The jet stream winds were southwesterly from 40 to 71 knots up to the 200 mb level.

The 00Z (1800 MDT) 11 June 2013, Plymouth State atmospheric sounding in Fig. 19(d), for Grand Junction, CO (KGJT) revealed dry air from approximately 850 mb, 800 mb, 550 mb, 500 mb, and 380 mb respectively. Atmospheric sounding text data (not shown) from Plymouth State revealed from 846 mb to 611 mb, the RH ranged from 7% to 16%. Dew points were also low in those levels. The 700 mb Tdd was 35° C. Winds were southwesterly from 20 to 34 knots up to 400 mb, and then southwesterly from 28 to 38 knots in the jet stream levels

The Denver, CO sounding station (KDNR) was approximately 50 miles north of Black Forest, CO. The Grand Junction, CO sounding station (KGJT) was approximately 150 miles west-southwest of Black Forest, CO. These soundings and sounding data readily indicated dry air aloft with fairly steady southwesterly winds. These fire weather influences both preceded the BF Fire start and continued during the initial stages of the first day of the fire, when it made its eight mile run to the east within the first eight-hour period.

j. Subsidence and Subsidence Inversions

The continual subsidence inversions indicated in the Skew-T soundings (Figs. 19, 20) strongly suggested the presence and influence of dry air mixing down by means of subsidence and associated with downslope winds. These downslope winds were accurately forecast in the fire Weather Outlooks and experienced on the firelines during the 11-12 June 2013 large fire growth days, Bell (2014).

Subsidence inversions are defined as an increase in temperature with increasing height produced by the slow sinking of a layer of middle or high level associated with high pressure. As the high air aloft sinks or subsides, it warms by compression, and then produces a layer of warm, dry, and very stable air. Subsidence can take several days to occur. During this time, the subsidence inversion intensifies as it lowers and becomes increasingly warmer and drier than the layer of air below it (COMET 2010).

The tops of the mountain ranges experience the warm, very dry conditions of a subsidence inversion much sooner than the lower elevations. This change is combined with a rapid increase in downslope winds and clearing skies distant from the fire. The result is increased fire spread and intensity. It is well recognized that these hot, dry and windy conditions can continue for several days and utterly exacerbate fire suppression efforts (COMET 2010).

Researchers Zimet et al (2007), Kaplan et al (2008), and Huang et al (2009) examined wildfires in the northeastern U.S. and California, and concluded that subsidence was a key causal factor when large fire growth was influenced by frontal and post-frontal circulations.

Zimet (2007) noted on the May 1980 Mack Lake Fire that subsidence advected dry air from the middle and upper-troposphere downward along sloping isentropes, as it adiabatically warmed and dried it along its path. A dynamic dry intrusion associated with these synoptic processes extended almost to the 750 mb level. They noted that this was far downstream from the actual upper-frontal zone that supplied the fire environment with dry air, originally located in the upper-troposphere and lower stratosphere (2007). This organized subsidence also caused downward advection of high momentum air from within the frontal zone into the fire environment, and thus further influenced the large fire growth. The researchers concluded that upper-frontal processes, characteristic of northwesterly synoptic-scale flows, were a probable causative factor to the prevalence of large wildfire growth under such synoptic-scale conditions (2007). Kaplan et al (2008) discovered a fire weather environment on the New Jersey DTSP Fire, where an initial drying event subsequent to a surface cold front, combined with a second drying event of very dry subsided air, under a polar jet streak right exit region, which resulted in rapid and intense fire growth.

Miretzsky (2009) extensively studied fire weather on four Northeast U.S. (NEUS) wildfires from 1980 to 2009. He discovered that 500 mb upper ridges and surface high-pressure systems were significant, common elements of a much larger three-dimensional circulation system. These two features were known to be associated with high fire danger days, large fire growth, and synoptic scale subsidence. This 3-D circulation system dried the air by means of synoptic scale subsidence and then horizontally advected the dry air from distant source regions. This led to reservoirs of dry air just above the PBL with associated surface lows. These then provided the means to advect the subsided air. Specific mesoscale and microscale PBL, smaller-scale mixing processes, forced by diabatic heating or turbulence, then caused the dry air reservoirs to mix down to the surface, and thus lower the near surface RH over the fire environment. On the May 1980 Mack Lake Fire, the dew point dropped 7.3°C in just one hour due to subsidence! This occurred four hours ahead of the surface cold front. This clearly indicated strong evidence that the dry air was able to mix down to the surface as soon as the more stable nighttime inversion weakened, and the mixed layer attained considerable enough depth, Miretzsky (2009).

Huang and others (2009) used observational data and numerical simulation to research two drying events on October 2003 southern California wildfires under the influence of strong Santa Ana winds. They found that a high-pressure ridge and an associated upper-level jet streak led to mesoscale subsidence in the jet exit region, and led to severe downslope winds. Clearly, subsidence and subsidence inversions intensified fire behavior and fire spread on the BF Fire and resulted in large fire growth from 11-12 June 2013, similar to the above referenced researchers' findings and conclusions.

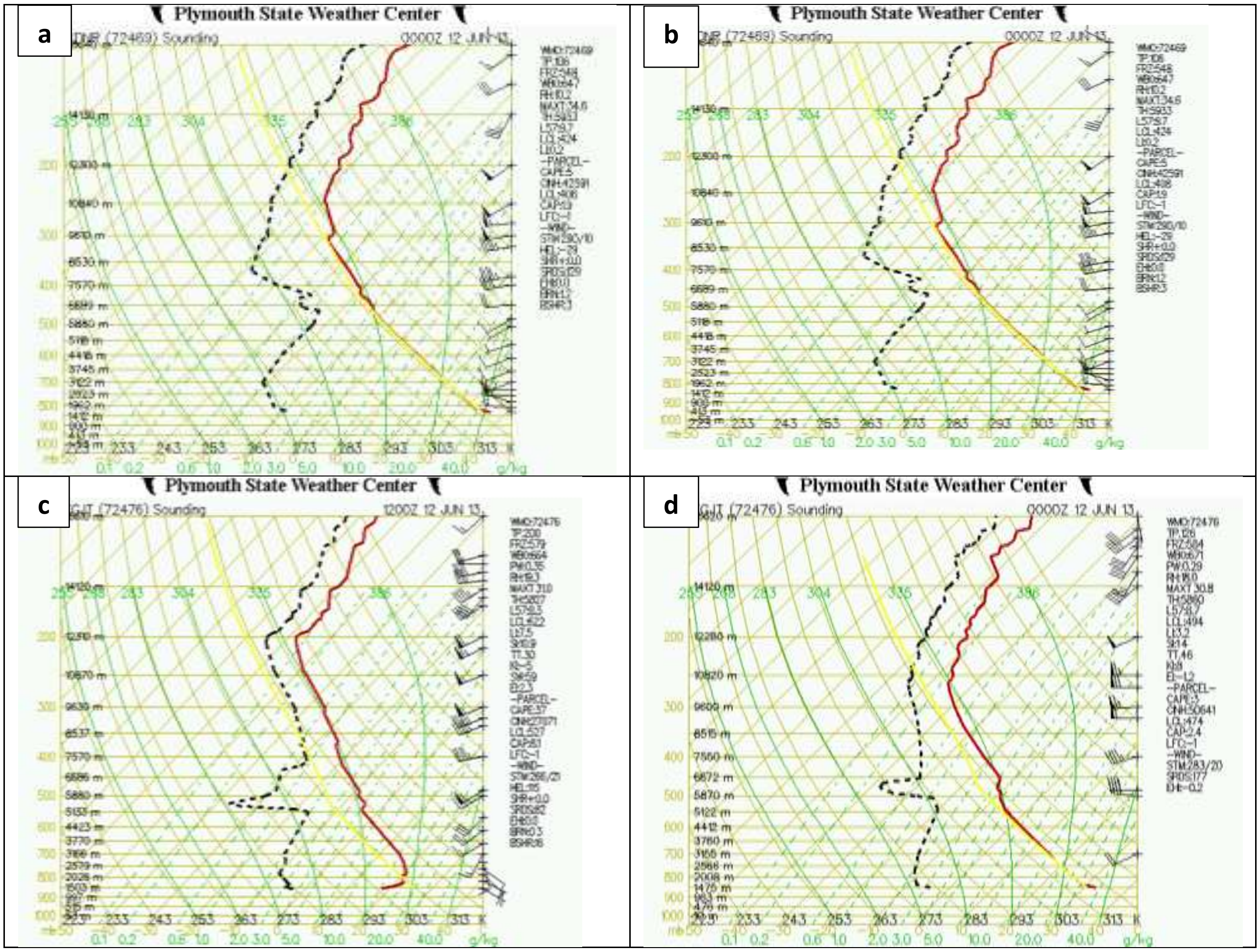

Figure 20: (a) 12Z (0600 MDT) and (b) 00Z (1800 MDT) Denver, CO; (c) 12Z (0600 MDT), (d) 00Z (1800 MDT) Grand Junction, CO atmospheric soundings 12 June 2013, Plymouth State Weather Center.

The 12Z (0600 MDT) 12 June 2013, Denver, CO (KDNR), Plymouth State atmospheric sounding in Fig. 20 (a) revealed an inversion at about 850 mb and several subsidence inversions at roughly 730 mb, 600 mb, 500mb, and 420 mb respectively. There was dry air up to about 350 mb. Atmospheric sounding text data from Plymouth State revealed two separate dry air bands from 823 mb to 489 mb with 15% to 19% RH and a band of 34% at 591 mb. The 700 mb Tdd was 23° C. Dew points were also low as well in those levels. winds were westerly from 3 to 44 knots in the lower and mid- elevations and from 59 to 67 knots in the jet levels.

The 00Z (1800 MDT) 12 June 2013, Denver, CO (KDNR), Plymouth State Weather Center atmospheric sounding in Fig. 20 (b) revealed a shallow inversion at around 860 mb with dry air on up to around 500 mb. There were subsidence inversions at roughly the 430 mb, 460 mb, and 310 mb levels.

Atmospheric sounding text data from Plymouth State revealed very dry air from the 831 mb to 597 mb levels that ranged from 5% to 10% with the 10% at only the 597 mb level. The winds were westerly 6 to 16 knots in the lower and mid-levels and increased to 52 knots in the jet stream levels.

The 12Z (0600 MDT) 12 June 2013 in Fig. 20 (c), atmospheric sounding for Grand Junction, CO (KGJT) revealed an inversion at about 850 mb and dry air from there up to about 450 mb, with a very dry pocket of air between 450 mb and 500 mb. There are subsidence inversions between about 540 mb, 500 mb, and 360 mb. Atmospheric sounding text data (not shown) from Plymouth State revealed two separate dry bands from 850mb to 700mb and another band from 532 mb to 489 mb. The RH ranged from 12% to 19% and from 6% to 18% respectively. Dew points were also low as well in those levels and ranged from - 5.2° C to - 33.5° C throughout both bands. The 700 mb Tdd was 27° C. Winds were southeasterly from 853 mb to 753 mb at 6 to 10 knots, then southwesterly from 33 to 45 knots from 700 mb to 500 mb. The jet stream winds were southwesterly from 53 to 61 knots.

The 00Z (1800 MDT) 12 June 2013, Grand Junction, CO (KGJT), Plymouth State atmospheric sounding in Fig. 20 (d) revealed a shallow inversion at about 850 mb and dry air up to about 400 mb, with a dry band at about the 475 mb level. There were subsidence inversions between about 500 mb and 530 mb. Atmospheric sounding text data revealed dry air from 850 mb to 700 mb with a second dry band from 500 mb to 452 mb. The relative humidity ranged from 8% to 12% and 9% to 21% respectively. Dew points were also low at those elevations and ranged from – 4.4° to – 28.1° C and - 28.1° C and – 31.1° C respectively. The 700 mb Tdd was 29° C. Winds were westerly in the lowest levels from 18 to 44 knots with westerly jet stream level winds from 49 to 67 knots.

The 12 June soundings and sounding data readily indicated the dry air aloft and fairly steady westerly winds. These fire weather influences continued when a second major large fire growth period occurred and the fire burned intensely for five miles to the north, under a southerly wind along several fire fronts.

The two ARL HYSPLIT, 72-hour backward trajectory runs below (Fig. 21) revealed the source(s) of the dry air. The runs indicated most of the 10-12 June 2013 dry air (a) and mixed layer, vertical velocity air (b) advected from the southwestern coast of southern California and northwestern Baja, southwestern Nevada, extreme southern Idaho, far southern Wyoming, and several of the Four Corners states. The drying event (a) occurred from around 00Z 10 June through 00Z 13 June. The mixed layer image (b) indicated deep mixing and subsidence on both days at or slightly after 12Z and on up to the 4000 meter level, Draxler and Rolph (2003), ARL HYSPLIT (2014).

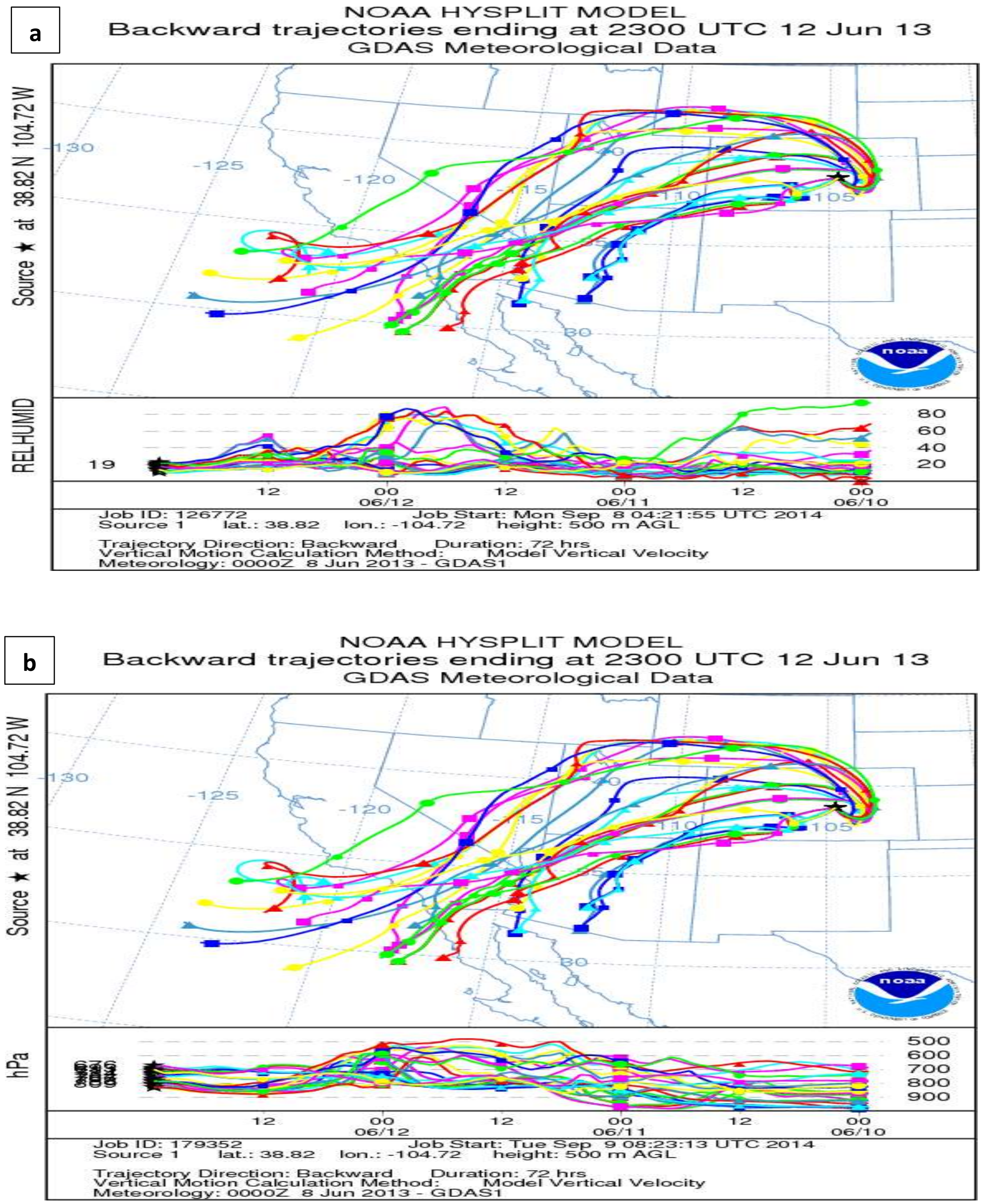

Figure 21: (a) 00Z to 00Z, 10-13 June 2013 respectively, 72-Hour Relative Humidity (%) and (b) Mixed Layer Depth, Vertical Velocity (hPa), Backward trajectory from Colorado Springs, Colorado (proxy) ending at 2300 UTC 12 June 2013. NOAA HYSPLIT Air Resource Laboratory (ARL).

3. Summary and Conclusions

The BF Fire began on 11 June 2013, north of Colorado Springs, Colorado. It very quickly became a major wildfire that exhibited extreme fire behavior and rapid, large fire growth. The BF Fire eventually burned 14,280 acres, destroyed 486 structures, and two civilians were killed. Forestry and fire officials had warned the residents of Black Forest for years that a wildfire of this magnitude was inevitable. The fuels were very dense, unthinned ponderosa pine, commonly referred to as "dog hair" thickets, and Gambel oak stands. The initial attack resources lost control of the fire within just a few hours when it aligned with a steep drainage in uphill terrain.

On 11 June 2013, under the influence of very strong westerly winds, the BF Fire ran eight miles to the east within the first eight-hour burning period! On 12 June, a second major large fire growth period occurred and the fire burned intensely for five miles to the north, under a southerly wind along several fire fronts. The fire weather that influenced the BF Fire was accurately forecast days in advance by the Pueblo, CO NWS Office. They accurately forecast Red Flag and extreme fire weather conditions for 11-12 June 2013, for strong, gusty winds, high daytime and nighttime temperatures, and low relative humidities and dew points, and Haines Indices of 5 and 6.

Satellite water vapor imagery revealed dry intrusions and dry slots throughout the Southwest and particularly in Colorado and the BF Fire area. This was validated with ARL HYSPLIT backward trajectory runs. These dry intrusions and dry slots were causal factors responsible for surface to near-surface drying, high Haines indices, and strong, gusty winds. Nearby RAWS data substantiated high nighttime temperature values from midnight to 0600 LST were very likely a major precursor and hypothesized cause of extreme fire behavior and large fire growth each of the days and nights following these 11 and 12 June 2013 readings.

Atmospheric conditions aloft are responsible for lower-stratospheric and mid- to upper-tropospheric origin fire weather and often results in descending dry air and subsidence, mechanisms that lead to extreme fire weather due to their ensuing surface to near-surface drying. The dry-air-aloft structures are predictable and visible in satellite imagery hours to days in advance of extreme fire weather events. Satellite WVI is long recognized among many operational forecasters as a valuable tool in wildland fire weather forecasting. To enhance firefighter and public safety, WVI should be considered and utilized to gather real-time and near real-time mid- to upper-air observations, and to verify models when there is high to extreme fire potential and/or ongoing wildland fires.

4. A*cknowledgements*

The author wishes to thank the following individuals for their steadfast support with this paper. Graham Mills (retired) of the Australian Bureau of Meteorology for initially piquing my interest in satellite water vapor imagery and dry slots as they relate to wildland fires; Makoto Moore of the Pueblo, CO

NWS for assistance with the paper and specifics regarding the BF Fire weather; John Saltenberger of the USFWS, Portland, OR Predictive Services, for unceasing support and assistance in my research; Brent Wachter of the Albuquerque, NM NWS for his continued encouragement and insight into fire weather forecasting and water vapor imagery; and Paul Werth of Weather Consulting Services from Battleground, WA for his unyielding advice, assistance, and encouragement in the areas of wildland fire weather and dry slots.

5. References

Air Services Laboratory (ARL), NOAA, 2014: HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT), http://ready.arl.noaa.gov/HYSPLIT_traj.php

Andrews, Patricia L. and Richard C. Rothermel, 1982: Charts for Interpreting Wildland Fire Behavior Characteristics, USDA, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, Utah; General Technical Report – INT-131, 24 pp. http://www.nwccweb.us/content/products/fwx/publications/Charts%20for%20Interpreting%20Wildland%20Fire%20Behavior%20Characteristics_int_gtr131.pdf

Baker, Mike, 2011: A Look Ahead to April, May and June 2011 For the Front Range and the Rest of Colorado, Boulder, CO NWS, 41 pp.

Bates, R., 1962: Blowup Conditions in the Southwest?, Fire Control Notes, 95-99. http://www.fireleadership.gov/toolbox/staffride/downloads/lsr11/lsr11_blowup.pdf

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

Bell, Larry, Captain, Black Forest Fire Department, 2014: Personal communications

Brotak, E. A. and W. E. Reifsnyder, 1977: An Investigation of the Synoptic Situations Associated With Major Wildland Fires. J. of Appl. Meteor., 867-870.

Byram, G. M., 1954: Atmospheric conditions related to blowup fires. U. S. Forest Service, Southeastern Forest Experimental Station, SE-SP 35, 34 pp.

Campbell, Doug (2010) Campbell Prediction System, http://www.dougsfire.com/

Charney, J.J., Xindi Bian, Brian E. Potter, Warren E. Heilman 2003: The Role of a Stratospheric Intrusion in the Evolution of the Double Trouble State Park Wildfire, P5.3, 5th Symposium of Fire and Forest Meteorology Joint with 2nd International Wildland Fire Ecology and Fire Management Congress, 2003, November 16-20; Orlando, FL, American Meteorological Society, 5 pp. http://www.nrs.fs.fed.us/pubs/jrnl/2003/nc_2003_charney_002.pdf

COMET program, 2010: Atmospheric Stability, Unit 6, S-290 Intermediate Fire Behavior, MetEd, University Corporation for Atmospheric Research (UCAR) http://www.meted.ucar.edu/fire/s290/unit6/print_3.htm

Draxler, R. R. and G. D. Rolph, 2003: “HYSPLIT—Hybrid Single-Particle Lagrangian Integrated Trajectory Model,” NOAA Air Resources Laboratory, Silver Spring, MD. http://www.arl.noaa.gov/ready/hysplit4.html

El Paso County Sheriff’s Office - Emergency Services Division (EPCSO-ESD), 2011: Community Wildfire Protection Plan for Unincorporated El Paso County, 57 pp. http://csfs.colostate.edu/pdfs/El-Paso-County-CWPP.pdf

Davis, Kenneth P., 1959: Forest Fire Control and Use, McGraw-Hill Book Company, 584 pp

El Paso County, Colorado, 1987: Black Forest Preservation Plan Update http://adm.elpasoco.com/Development%20Services/Documents/Comprehensive%20Plans/Black%20Forest%20Preservation%20Plan.pdf

Fast, J. D., and W. E. Heilman, 1996: The effect of regional-scale soil-moisture deficits on the mesoscale dynamics that influence fire severity. Symposium on Fire and Forest Meteorology, 28 January – 2 February 1996, Atlanta, GA. American Meteorological Society, Boston, MA. 280-283.

Flame Sniffer WD, 2010: Driving through an [Australian] ember attack, YouTube http://www.youtube.com/watch?v=qvLBuDnCTPU

Foote, E. I., Liu, J., Manzello, S. I., 2011: Characterizing firebrand exposure during wildland-urban interface fires. In: Proceedings of Fire and Materials 2011 Conference, 12th International Conference and Exhibition, London, Interscience Communications, 479-491.

Google Earth, 2014: https://earth.google.com/

Haines, Donald A., 1988: A Lower Atmosphere Severity Index For Wild[land] Fires. National Weather Dig., 13, 23-27.

Heilman, Warren, Hom, John; Birdsey, Richard; O'Brian, Kelly, eds., 1996: Overview of Current Research on Atmospheric Interactions with Wildland Fires; In Proceedings 1995 meeting of the northern global change program; Gen. Tech. Rep. NE-214. Radnor, PA: Forest Service, Northeastern Region Research Station, 192-195. http://www.nrs.fs.fed.us/pubs/gtr/gtr_ne214/gtr_ne214_192.pdf

Hull, M. K., O'Dell, C. A., and Schroeder, M. J., 1966: Critical fire weather patterns—their frequency and levels of fire danger. Pacific SW. Forest & Range Exp. Sta., U.S. Forest Serv., Berkeley, Calif. illus., 43 pp.

Hydrometeorological Prediction Center (HPC), National Centers for Environmental Prediction (NCEP), NOAA Daily Weather Maps, http://www.hpc.ncep.noaa.gov/dailywxmap

Iacopelli, A.J., and J. A. Knox. 2001: Mesoscale dynamics of the record-breaking 10 November 1998 mid-latitude cyclone: A satellite-based case study. Natl. Wea. Dig. **25,** 33-42.

Johnson, Richard H. and James J. Toth, 1982; A climatology of the July 1981 surface flow over northeast Colorado. Atmos. Sci. Paper No. 342, Colorado State University, Fort Collins, CO, 80523, 52 pp.

Kaplan, Michael L., Huang C., Yin Y. L., and Charney J.J., 2008: The development of extremely dry surface air due to vertical exchanges under the exit region of a jet streak. Meteorol. Atmos. Phys., 1-23, http://mesolab.ncat.edu/publications%20%28web%29/2008_Kaplan_etal%28MAP_Jet_Streak_and_Fire%29.pdf

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, http://www.ejssm.org/ojs/index.php/ejssm/article/viewFile/132/98

Makings, Vickie, Denver Post Research Library, The Denver Post, 2012: Colorado's largest wildfires (burn area), citing the National Interagency Fire Center; Rocky Mountain Insurance Information Association; U.S. Forest Service; Colorado State Forest Service; Colorado Division Emergency Management; Jeff Mitton, University of Colorado, Department of Ecology and Evolutionary Biology, http://blogs.denverpost.com/library/2012/06/11/colorados-largest-wildfires-ranked-acres-burned/1760/

Manzello, Samuel L. and Foote, Ethan I. D., 2014: Characterizing Firebrand Exposure From Wildland-Urban Interface (WUI) Fires: Results From the 2007 Angora Fire. Fire Technology, 50, 105-124. http://phdtree.org/pdf/29461020-characterizing-firebrand-exposure-from-wildlandurban-interface-wui-fires-results-from-the-2007-angora-fire/

MesoWest, University of Utah, ongoing: ROMAN (Real-time Observation Monitor and Analysis Network) RAWS http://raws.wrh.noaa.gov/roman/

Mills, Graham, 2006: Upper Level Dry Air and Reduced Surface Humidity, bushfire CRC, poster. http://www.bushfirecrc.com/managed/resource/posterproga-mills.pdf

Mills, Graham, 2008a: Abrupt surface drying and fire weather Part 1: overview and case study of the South Australian fires of 11 January 2005 http://www.highfirerisk.com.au/obs/mills08pt1.pdf

Mills, Graham, 2008b: Extreme surface drying and fire weather Part 2: a preliminary synoptic climatology in the forested areas of southern Australia, Aust. Met. Mag. 57, 311-328. http://www.researchgate.net/publication/242773578_Abrupt_surface_drying_and_fire_weather_Part_2_a_preliminary_synoptic_climatology_in_the_forested_areas_of_southern_Australia

Mills, Graham, 2009: Meteorological drivers of extreme bushfire events in southern Australia, http://www.cawcr.gov.au/events/modelling_workshops/workshop_2009/papers/MILLS.pdf

Mills, Graham, 2010: Dry Slots Fan The Flames. Bushfire CRC, 1 pp, http://www.bushfirecrc.com/news/news-item/dry-slots-fan-flames-research-links-high-altitude-air-bushfires-ground

Miretzky, Brian J., 2009: Model Based Analysis of the Synoptic and Mesoscale Processes Associated with Subsidence into Western Great Lakes Wildfire Environments, Univ. of Michigan, Master's Thesis, 979 pp. http://www.aos.wisc.edu/uwaosjournal/Volume11/Miretzky_MS_Thesis_2009.pdf

National Resources Conservation Service (NRCS), National Weather and Climate Center (NWCC), Portland, OR, ongoing website, http://www.wcc.nrcs.usda.gov/snowcourse/snow_map.html

National Wildfire Coordinating Group (NWCG), 2014: Incident Response Pocket Guide (IRPG), PMS 461, NFES 001077, 128 pp, http://www.nwcg.gov/pms/pubs/pms461/pms461.pdf

NWCG, 2007: S-290 Intermediate Fire Behavior, Unit 7, Wind Systems, 74. http://training.nwcg.gov/sect_course_updates_suppression_s290.htm

Nimchuk, N., 1983: Wildfire Behavior Associated with the Upper Ridge Breakdown. Alberta Forest Service, ENR Report No. T/50, 1-53.

NOAA, NESDIS, NCDC, GIBBS (Global ISCCP B-1 Browse System) - Water Vapor Imagery GOES-15, http://www.ncdc.noaa.gov/gibbs/

NOAA NWS Critical Fire Weather Patterns of the U.S., 1999: Fire Weather Forecasters Course, Boise, ID, 66 pp. http://www.nwccweb.us/content/products/fwx/publications/CRITICAL_FWX_PATTERNS_US.pdf

NOAA NWS,2005: Surface, Upper Air, and Composite Charts. Central Region Headquarters, 2 pp, http://www.crh.noaa.gov/crh/?n=tsp10-charts

NOAA, NWS, Pueblo, CO Weather Forecast Office, fire weather forecasts, 9-12 June 2013.

NWCG, 2014: Geographic Area Pocket Cards – Rocky Mountain Region http://fam.nwcg.gov/fam-web/pocketcards/pocketcards.htm#
Pikes Peak Wildfire Prevention Partners (PPWPP), Black Forest Fire Rescue Department and Falcon Fire Department, 2014: Black Forest Fire Assessment Team Report to the Governor of Colorado, 100 pp.

Plymouth State Weather Center, http://vortex.plymouth.edu/

Rissel, Sean and Karen Ridenour, 2013: Ember Production During the Bastrop Complex Fire, Fire Management Today 72, 7-13. http://www.fs.fed.us/fire/fmt/fmt_pdfs/FMT72-4.pdf

Rocky Mountain Geographic Area Coordination Center (RM GACC), 2014: Predictive Services, Fuels and Fire

Danger, NFDRS, RM 18, Central Front Range RAWS, http://gacc.nifc.gov/rmcc/predictive/erc_10_100_1000_18.htm

Rolph, G. D., 2003: Real-Time Environmental Applications and Display System (READY) Website, NOAA Air Resources Laboratory, Silver Spring, http://www.arl.noaa.gov/ready/hysplit4.html

Schoeffler, Fred J., 2014: Fire Weather Associated With the New Mexico (USA) June 2012 Little Bear Fire, Lincoln National Forest, New Mexico (6.8), 21st Conference on Applied Climatology/17th Symposium on Meteorological Observation and Instrumentation, Westminster, Colorado, 34 pp. C:\Users\Owner\AppData\Local\temp\Little Bear Fire - AMS extended-1.pdf

Schoeffler, Fred J., 2010: Dr. Graham Mills' Dry Slot Theory, International Association of Wildland Fire (IAWF), Beyond Fire Behavior and Fuels: Learning From the Past to Help Guide Us In the Future, Spokane, WA, 19 pp.

Schroeder, M. J., Glovinsky, M., Hendricks, V. F., Hood, F. C., Hull, M. K., Jacobson H. L., Kirkpatrick, R., Krueger, D. W., Mallory, L. P., Oertel, A. G., Reese, R. H., Sergius, L. A., Cyverson, C. E., 1964: Synoptic Weather Types Associated With Critical Fire Weather. 1-492. Pacific SW. Forest & Range Exp. Sta., U.S. Forest Serv., Berkeley, Calif. 1-492.

Smart Traveler maps, 2002-2011: www.smart-traveler.com/

Storm Prediction Center (SPC) – Archive Fire Weather Outlooks, NOAA NWS, 2014. http://www.spc.noaa.gov/products/fire_wx/

Smith, Barrett, Phil Badgett, and Jonathon Blaes, 2008: February 10, 2008 High Wind and Fire Weather Event. NWS Raleigh, North Carolina, website, http://www4.ncsu.edu/~nwsfo/storage/cases/20080210/

Theodora.com maps, Colorado, USA http://geographic.org/maps/us_states/colorado_state_maps.html

Tollerud, Edward I., Fernando Caracena, Adrian Marroquin, and Steven E. Koch, J. L. Moody, and Anthony Wimmers, 2002: Relation Between Dry Filaments and Convective Systems, FSL Forum, 10 pp.

Toth, James J. and Richard H. Johnson, 1984: Summer Surface Flow Characteristics over Northeast Colorado. Mon. Wea. Rev. 113, 1458-1469. http://journals.ametsoc.org/doi/pdf/10.1175/1520-0493%281985%29113%3C1458%3ASSFCON%3E2.0.CO%3B2

Turnipseed, Andrew A., Dean E. Anderson, Sean Burns, Peter D. Blanken, Russel K. Monson, Airflows and turbulent flux measurements in mountainous terrain, Part 2: Mesoscale effects. Agriculture and Forest Meteorology, 125, 187-205. http://pubs.er.usgs.gov/publication/70026544

University of Colorado, Department of Atmospheric Science, Colorado Climate Center, 2010. http://climate.atmos.colostate.edu/climateofcolorado.php

USDA, Natural Resources Conservation Service, National Water and Climate Center, http://www.wcc.nrcs.usda.gov

U. S. Drought Monitor Center, 2014: U.S.D.A., Department of Commerce, NOAA, and the National Drought Mitigation Center. http://droughtmonitor.unl.edu/

USFS-WFAS Wildland Fire Assessment System, 2014, http://www.wfas.net/

Weldon, Roger and Holmes S. J. 1991: Water Vapor Imagery: Interpretation and Applications to Weather Analysis and Forecasting. NOAA Tech. Report NESDIS 57, 1-213.

Werth Paul., Brian E. Potter, Craig B. Clements, Mark A. Finney, Scott L. Goodrick, Martin E. Alexander, Miguel G. Cruz, Jason A. Forthofer, and Sara S. McAllister, 2011: Synthesis of Knowledge of Extreme Fire Behavior: Volume I for Fire Managers, United States Department of Agriculture, Forest Service, Pacific Northwest Research Station General Technical Report PNW-GTR-854, 158 pp. http://www.fs.fed.us/pnw/pubs/pnw_gtr854.pdf

Werth, Paul, 2012-2014: meteorologist, personal communication. Weather Research and Consulting Services, LLC, Battle Ground, WA.

Werth, Paul and Richard Ochoa,1990: Evaluation of Idaho Wildfire Growth Using the Haines Index and Water Vapor Imagery, In: Proceedings, fifth conference on mountain meteorology; 1990 June 25-29, Boulder, Colorado, Boston, MA; American Meteorological Society, 187-193.

Wildland Fire Lessons Learned Center (LLC), 2014: Incident Reviews, Investigative Reports, Facilitated Learning Analyses, etc. http://www.wildfirelessons.net/home

Zimet, Tarisa, Jonathan E. Martin, and Brian E. Potter, 2007: The influence of an upper-level frontal zone on the Mack Lake Wildfire environment, Meteorol. Appl. 14, 131–147, Published online in Wiley InterScience (www.interscience.wiley.com) DOI: 10.1002/met.14.