5.1 FIRE WEATHER AND ATMOSPHERIC CONDITION COMMONALITIES AFFECTING JUNE 2002 TO JUNE 2013 COLORADO (USA) WILDFIRES

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1. INTRODUCTION

Numerous large, destructive, sometimes deadly, wildfires plagued Colorado (USA) from 2002 to 2013. June is a critical fire weather month in the Southwest in general and for Colorado specifically. The majority of these devastating Colorado wildfires occurred during the first two weeks of June. From a wildland fire supervisor perspective, this paper highlights twelve (12) Colorado wildfires that began during the first two weeks of June 2002 to 2013 and will examine some of their atmospheric and fire weather commonalities.

The aggressive and extreme fire behavior was the result of several converging fire weather and fuel variables. Wildland fuel indices such as energy release component (ERC) were at record levels. Long-term drought had affected the areas precipitating lower atmospheric drying. Significant mid-level dry intrusions and dry slots accompanied by ridging and troughing often brought low humidity, warm overnight temperatures and high daytime temperatures, and subsidence. Turbulent mixing often led to strong, gusty winds. Cold front passages often led to drastic changes in fire spread and direction that exposed additional areas to large fire growth.

Several data sources support the June 2002 to 2013, Colorado (USA) extreme fire weather and large fire growth events, including the classic, recognized critical fire weather patterns influencing western region wildfires, skew-T soundings, satellite water vapor imagery, lower atmospheric stability (Haines) indices, Energy Release Component, fire weather forecasts and outlooks, drought-fuel indices, and HYSPLIT backward trajectory runs. The paper begins with fire background, then compares and contrasts climatology; drought, synoptic and mesoscale fire weather, and fire potential; summary and conclusions, closing with acknowledgements.

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2. BACKGROUND - FIRE HISTORY

Fig. 1 reveals the approximate locations of the June 2002 to June 2013 Colorado fires examined in this paper. Colorado elevations range from about 3,300' to 14,400' with a mean of 6,800.' The lower elevation fires, less than 6000', were primarily in southern Colorado. These fires burned in mostly grass and brush fuels with mixed pines and conifers interspersed within Pinyon-Juniper-Gambel oak woodlands. The higher elevation fires ranged from 6000' and above and were in western and northern Colorado. These fires burned in woodland and conifer timber and woodland fuels with grass and brush understory (CDFPC 2013), Table 1.

Table 1 reveals the pertinent information on each of the fires and/or fire complexes examined. A fire complex is one with multiple fires administered by the same Incident Management Team (IMT). Included are the fire names based on geographic locality, the specific county and closest identified municipal location, the dates from start to final control of each fire, and the area burned. To simplify fire weather and meteorological details, only the ignition and/or initial response date of each fire is analyzed. Structures were lost on most of the fires (Table 1) and the Black Forest Fire would gain distinction for the most structures lost in a wildland fire in Colorado. There were also several fatalities, six (6) on the Hayman Fire and one on the Missionary Ridge fire, all indirectly fire-related (RMA Annual Activity Report 2002).

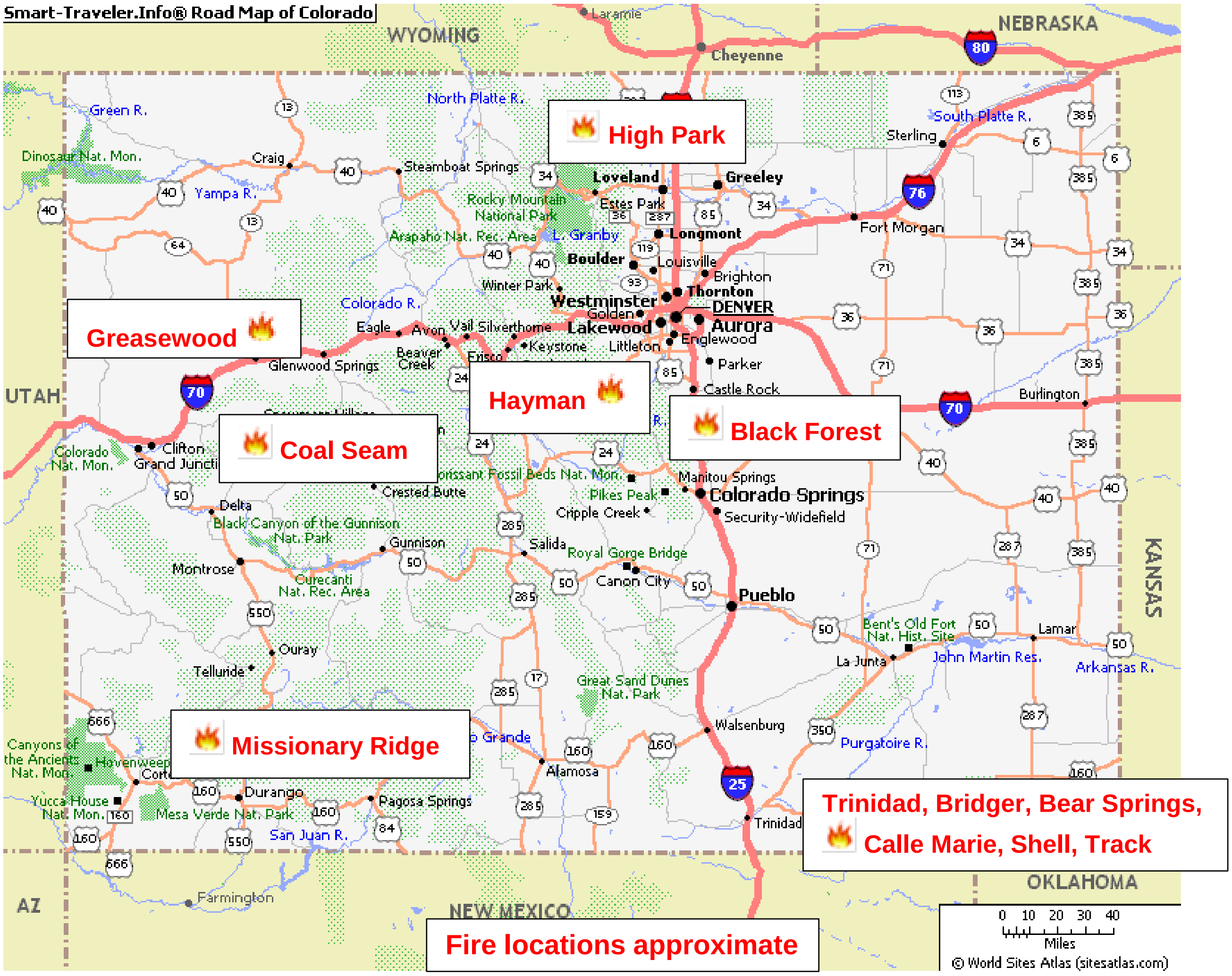


Figure 1. Map of Colorado with approximate fire locations

FIRE NAME or COMPLEX	COUNTY MUNICIPAL LOCATION	DATES	AREA BURNED	STRUCTURES DESTROYED
Trinidad Complex (3)	Las Animas Trinidad - Stonewall	2 - 14 June 2002	33,000 ac 13,354 ha 51.56 sq mi	0
Coal Seam	Garfield Glenwood Springs	7 June to 9 July 2002	12,209 ac 4,940 ha 19.07 sq mi	43
Hayman	Park Lake George	8-18 June 2002	138,114 ac 55,892 ha 215.8 sq mi	133
Missionary Ridge	La Plata Durango	9 June to July 14 2002	71,739 ac 29,031 ha 112.09 sq mi	56
Greasewood	Rio Blanco Meeker	1-24 June 2004	7,815 ac 3,162 ha 12.21 sq mi	0

Bridger	Las Animas Pinion Cyn Maneuver Site	8 June to 9 July 2008	25,800 ac 10,440 ha 40.31 sq mi	3
Bear Springs	Las Animas Pinion Cyn Maneuver Site	5-21 June 2011	35,583 ac 14,400 ha 55.59 sq mi	5 total among Bear Springs Calle Marie
Calle Marie	Las Animas Pinion Cyn Maneuver Site	5-21 June 2011	9,079 ac 3,674 ha 55.59 sq mi	5 total among Bear Springs Calle Marie
Shell Complex (3)	Las Animas Kim	7-17 June 2011	13,312 ac 5,387 ha 20.8 sq mi	7
Track	Las Animas Trinidad - Raton, NM	12-28 June 2011	7,830 ac 3,168 ha 12.23 sq mi	11
High Park	Larimer Fort Collins	9-30 June 2012	87,250 ac 35,308 ha 136.32 sq mi	259
Black Forest	El Paso Black Forest	11-20 June 2013	4,280 ac 5,778 ha 6.68 sq mi	509

Table 1. Details of fires examined (name, county/ closest municipal location, dates, area burned [acres (ac), hectares (ha), square miles (sq mi)], and structures destroyed) CDFPC (2013)

3. DISCUSSION

3.1 Climatology

Precipitation, snowpack, and water runoff are critical factors that determine the annual fire danger and likelihood of large fires within wildland fire environments. The 2002 snowpack would become an unparalleled low when compared to future snowpack readings (NRCS 2002; Fig. 2 a-d). Spring 2002 was marked the driest on record with snowpack readings of only 52% of average statewide (NRCS 2002). The 1 April 2004 (March snowpack levels reported April 1) (NRCS 2004; Fig. 2 e) Colorado snowpack report was only 65% of average while the 1 April 2008 snowpack reported 123% of average (NRCS 2008; Fig. 2 f). The 1 April 2011 Colorado snowpack was 113% (NRCS 2011; Fig. 2 g-i) with the 1 April 2012 levels at 47% to 57% of average (NRCS 2012; Fig. 2 j). The 1 April 2013 (NRCS 2013; Fig. 2 k) snowpack reading was 74 percent of median.

Adequate soil moisture during the growing seasons in El Nino years provided significant amounts of wildland fuel growth. The heavier fuel loadings carried over into leaner La Nina conditions, which helped intensify drought conditions during the drier winter and spring months, while low soil moistures desiccated the wildland fuels. The live and dead fuels would become additionally stressed leading up to the start of each wildfire due to abnormally warm and dry conditions coupled with strong mid-level dry intrusions and atmospheric ridging (Fig. 3, Tables 5-6). The high snowpack years increased the lower elevation grasses, resulting in deep and continuous fuel beds especially across the lower elevations e.g. Las Animas county, (Fig. 1, Table 1; Fig. 2 (a, f-i). In contrast, in the higher elevations, the lower snowpack years resulted in low soil and dead fuel moistures, which contributed to dry atmospheric conditions and led to several aggressive and extreme fire behavior and large growth timber fires. These were the (b) Coal Seam, (c) Hayman, (d) Missionary Ridge, (j) High Park, and (k) Black Forest Fires indicated and listed in Fig. 1, Table 1, and with aggressive fire behavior indicated in Figs. 11 and 12.

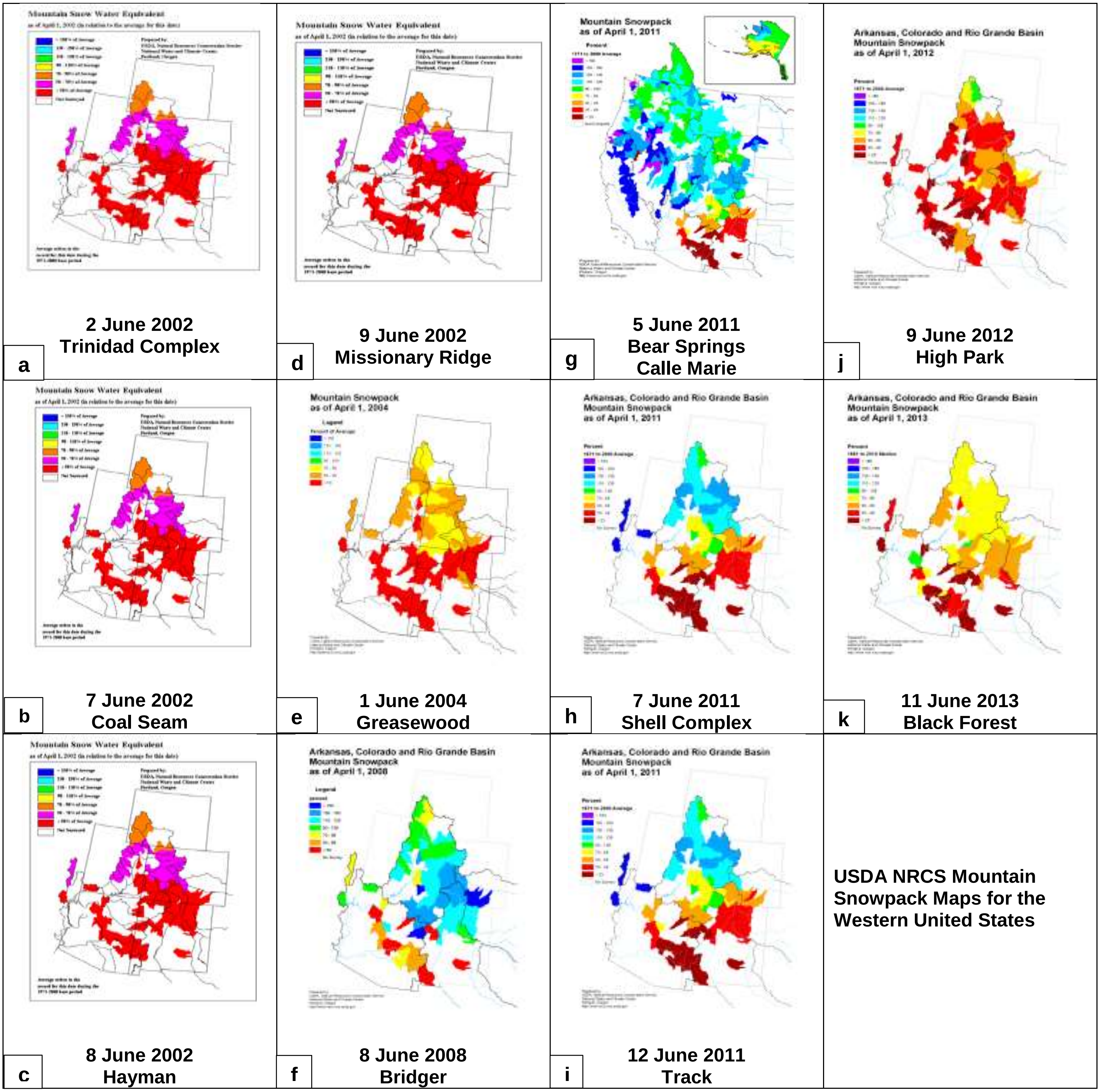


Figure 2. Western US mountain snowpack and Snow Water Equivalence (SWE) maps – (a) 2 June 2002 Trinidad Complex; (b) 7 June 2002 Coal Seam; (c) 8 June 2002 Hayman; (d) 9 June 2002 Missionary Ridge; (e) 1 June 2004 Greasewood; (f) 8 June 2008 Bridger; (g) 5 June 2011 Bear Springs – Calle Marie; (h) 7 June 2011 Shell Complex; (i) 12 June 2011 Track; (j) 9 June 2012 High Park; and (k) 11 June 2013 Black Forest Fires. Note that the Red SWE 'level' changes from < 50% to 25% to 49% in April 2011

3.2 Synoptic and mesoscale weather

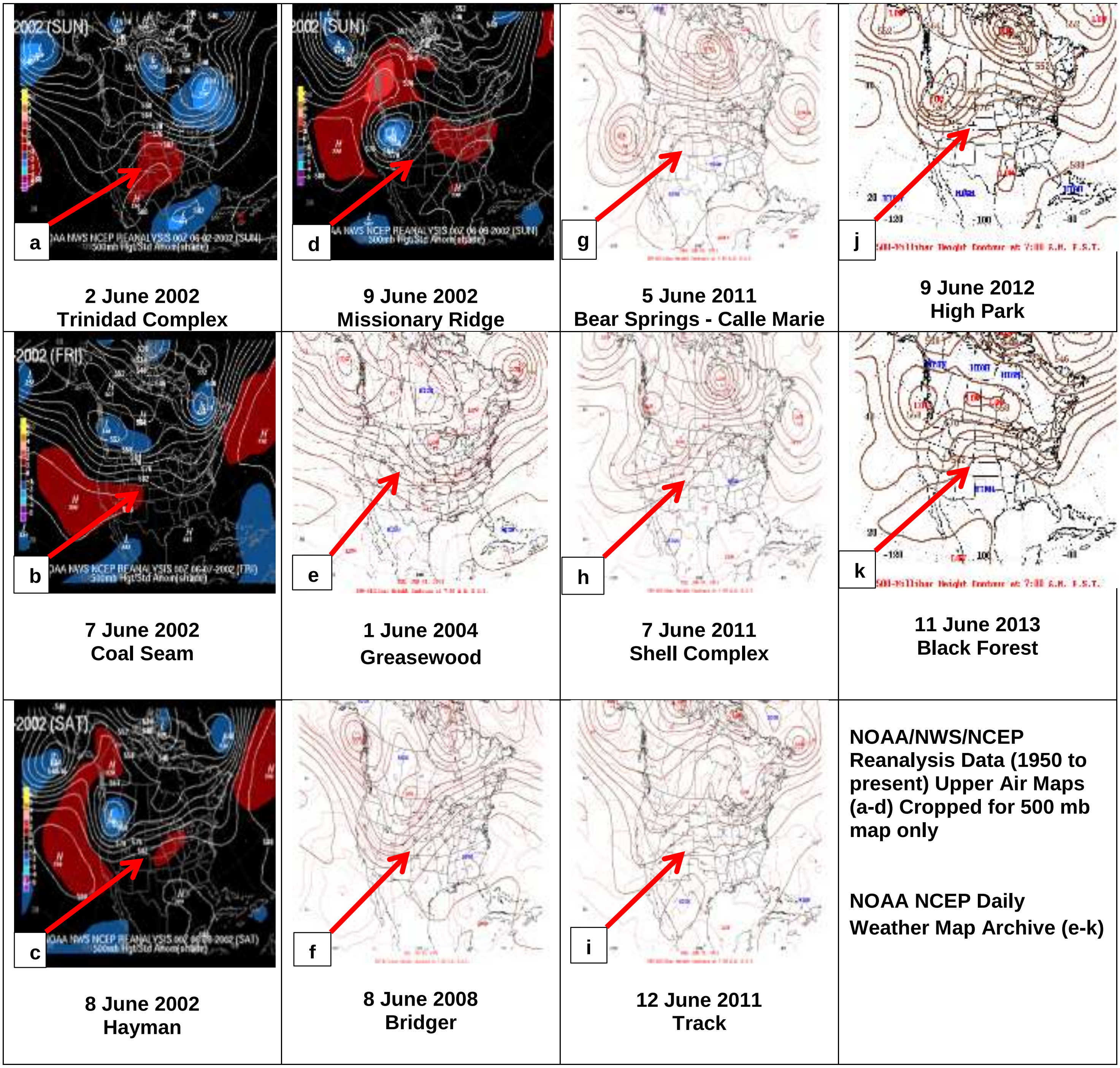


Figure 3. 00 UTC (a-i), 0700 EST (j-k) NOAA NCEP charts, and Daily Weather maps for the contiguous United States showing the 500 mb upper air pressure, red arrow indicates approximate fire location, fires and dates as in Fig. 2

Referencing historical wide-ranging fire weather research, e.g. (Syverson 1963 and others), Werth concluded that “most periods of critical fire weather occurred in transition zones between high- and low-pressure systems, both at the surface and in the upper air," (2015). According to Werth, those researchers focused on the 500 mb charts because they represent weather conditions in the mid-troposphere, and because many weather systems tend to follow the wind flow at that level (Werth 2015). Werth studied 625 large fires in the Pacific Northwest (PNW) over a 10-year period and concluded that when the 500 mb heights were plummeting - transitioning from an upper ridge to an upper trough - 72% of those fires exhibited large fire growth. He categorized them in the "falling 500 hPa heights but above normal" category (Fig. 4). These transition periods lead to unstable air masses, stronger surface winds and winds aloft, hot temperatures, low RH and dew point, moderate to high Haines Index, increased chance of thunderstorms and dry lightning, and often a thermal trough or cold front at the surface (Werth 2015). These same atmospheric conditions are evident in Figs. 3, 8. and 9.

Werth next divided the start dates of large wildland fires into four categories or phases compared to normal 500 hPa heights; 1) falling height above normal 2) falling height below normal 3) rising height below normal and 4) rising height above normal. These four categories or phases are plotted on an idealized classic sine wave to illustrate their location in relation to the overall full wavelength (Fig. 4). Fully three–fourths of the fires examined in this paper were influenced by mid- and/or upper level shortwave troughs, with some influenced by associated cold fronts that began in the Rockies and/or PNW and advected into California and/or the Great Basin (Fig. 3, Table 2).

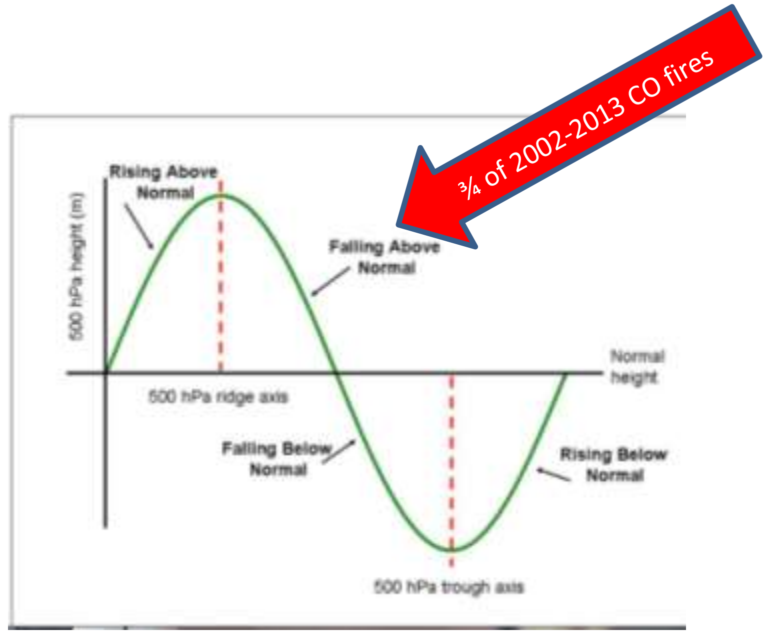


Figure 4 – Idealized sine wave with 4 phases of 500 hPa height fields compared to normal. Red arrow indicates majority of June 2002 to June 2013 Colorado wildfires in the 'Falling 500 hPa Heights But Above Normal' category

A strong upper level trough over CA, the PNW, and Intermountain West and a strong high pressure system over the Four Corners region. A weak cold front approached the PNW and developed into an occluded front as it progressed eastward. **a** **2 June 2002** **Trinidad Complex**	A strong mid-level shortwave trough ejected east-northeastward across the northern and central Rockies. A surface cold front moved east-southeastward then extended from a low pressure center over the upper Midwest south into southwestern KS and central CO, then westward to southern NV **d** **9 June 2002** **Missionary Ridge**	A potent central CA shortwave trough traversed east-northeastward into the northern Intermountain Region and triggered increased southerly and southwesterly flow. There was breakdown of the expansive upper ridge further east. **g** **5 June 2011** **Bear Springs** **Calle Marie**	The 300 mb analyses (not shown) from 1500 UTC 9 June indicated that the polar jet had moved farther south than usual and a trough moved over the Great Basin associated with a stationary front. An upper low over the Northern Rockies and the attendant trough that extended southwestward across the the Great Basin and Central Rockies progressed eastward. **j** **9 June 2012** **High Park**
A strong mid-level shortwave trough continued to dig slowly southeastward into the Great Basin and PNW. A broad surface to upper level ridge continued to dominate much of the eastern half of the United States. **b** **7 June 2002** **Coal Seam**	In the West, a building 700mb Thermal Ridge north-northwestward across the central Rockies into portions of the northern Rockies region. The eastern United States had a broad and slow moving upper low across the Great Lakes region. **e** **1 June 2004** **Greasewood**	A potent shortwave trough over the northern Intermountain Region turned east-northeastward into the northern High Plains. A weak upper low over northern CA advanced southeastward toward the eastern Great Basin and a closed low dove southwest into the PNW. **h** **7 June 2011** **Shell Complex**	A strong shortwave trough over the Great Basin lifted toward the northeast across the central Rockies. A lee surface low intensified across parts of eastern CO into western KS. **k** **11 June 2013** **Black Forest**
An upper level trough over northeastern Oregon amplified and closed off, while an upper level ridge over the eastern US held in place. A broad upper trough centered over the Great Basin shifted east-southeastward across the eastern Great Basin and northern Rockies and northeastward into the northern and central Rockies **c** **8 June 2002** **Hayman**	An upper trough dug southeastward Into the Great Basin. A surface lee-side low over the High Plains moved southeastward as a cold front moved south of the High Plains region while a dryline ranged southwestward from the surface low. **f** **8 June 2008** **Bridger**	A mid-level trough extended across portions of the western CONUS while a mid-level ridge persisted over portions of the southern Plains. A mid-level impulse over southwestern AZ turned northeastward toward the Four Corners region. **i** **12 June 2011** **Track**	**NOAA NWS - Storm Prediction Center (SPC) Archive - Fire Weather Outlooks**

Table 2. Fire Weather Outlook summaries, NOAA Storm Prediction Center – fires and dates as in Fig. 2

3.3 Drought and soil moisture

The 2002-2013 Winter and Spring snowpack and low snow water equivalence (SWE) (Fig. 2) seasons varied considerably, often resulting in low soil moisture (Fig. 5 a-k) and dead fuel moisture levels, having a significant drying effect on wildland fire weather. Fast and Heilman (1996) found that soil moisture “significantly affects” the near-surface temperature and RH fields, cloud cover, precipitation, and sometimes, wind speed. They also found that air masses advecting over a parched soil region, take on those dry regional traits, capable of entrainment a significant distance downwind, with the potential to affect the surface and the entire lower atmosphere (1996). Likewise, Tardiff (2006) found that below normal soil moisture anomalies noticeably triggered steep lapse rates at the 700mb to 500mb levels, linked to strong downwind severe weather events, mainly tornadoes. Persistent and progressive land-atmosphere exchanges between anomalously dry soils and consequent higher temperatures induced the 2003 and 2010 European heatwaves and generated their “mega-heatwaves,” (Miralles et al 2012, 2014 and Fischer et al 2014). Fischer and others concluded drought induced the tropospheric circulation by spawning a surface heat low at lower levels increasing anticyclonic ridging in the mid- to upper troposphere (Fig. 3), a clear feedback process between continental-scale soil moisture, circulations, and temperature (2007).

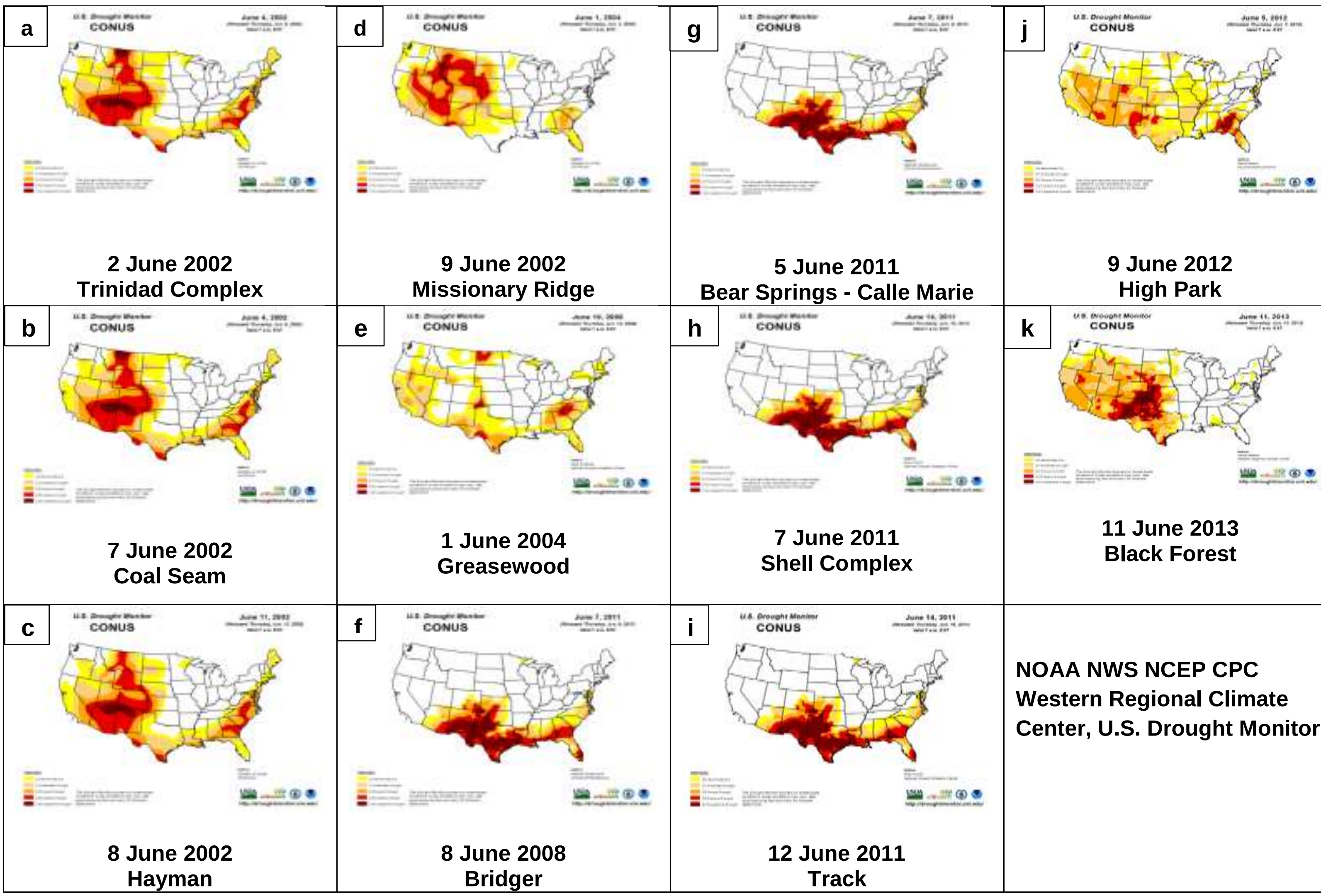
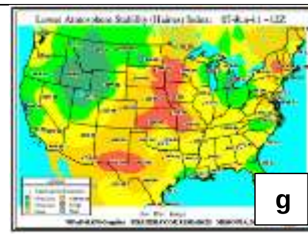


Figure 5. U.S. Drought Monitor maps - fires and dates as in Fig. 2

3.4 Fire Potential

**12 UTC 2 June 2002
Trinidad Complex**

**12 UTC 9 June 2002
Missionary Ridge**



**12 UTC 7 June 2011
(no 5 June 2011
Haines map)
Proxy for 5 June
Bear Springs
-Calle Marie**

**12 UTC 9 June 2012
High Park**

**12 UTC 7 June 2002
Coal Seam**

**12 UTC 1 June 2004
Greasewood**

**12 UTC 7 June 2011
Shell Complex**

**12 UTC 11 June 2013
Black Forest**

**12 UTC 7 June 2002
(no 8 June 2002
Haines map)
Calculated afternoon
Haines 6. Proxy for
Hayman**

**12 UTC 8 June 2008
Bridger**

**12 UTC 12 June 2011
Track**

USDA Rocky Mountain Research Station, Wildland Fire Assessment System (WFAS)

Figure 6. 12 UTC Lower Atmosphere Stability Index (LASI) maps, more commonly referred to as the Haines Index maps – fires and dates as in Fig. 2

3.5 Lower Atmosphere Stability Index (LASI) and Haines Index

The LASI or Haines Index development was due to the severe fire behaviour observed during dry and unstable conditions (Haines 1988; Werth and Ochoa 1993). The LASI, more commonly known as the Haines Index, was developed by Forest Service meteorologist Donald Haines to quantify (via index) the lapse rate (stability) and dryness (dew point depression) of lower atmosphere levels, and correlate the index with days of large fire growth, particularly in the absence of significant surface winds. An index value of 2 or 3 (moist stable lower atmosphere) indicates low potential for large fire growth, and 5 or 6 (dry unstable) indicates moderate or high potential (PNWRS 2015).

The Haines Index is broken into three indices throughout the CONUS based on regional elevations as follows: Low (4) in the East, Moderate (5) in the High Plains and Midwest, and High (6) in the West (Haines 1988; Werth and Werth 1998). On most of the fires studied, the upper air data revealed very dry and well-mixed atmospheres, especially in the afternoon soundings (00Z) (Fig. 9) which then calculated out to a Haines Index value of 5 or 6 (not shown) (Haines 1998; Werth and Werth 1998).

Notice that the Werth and Werth (1998) Haines 6 days and percentages for Colorado (USA) in Fig. 4 match up fairly well with the 12 UTC readings in the Haines Index images in Fig. 6. They also squared very well with the 00 UTC readings, calculated (not shown) for the June 2002 to June 2013 fires examined in this paper.

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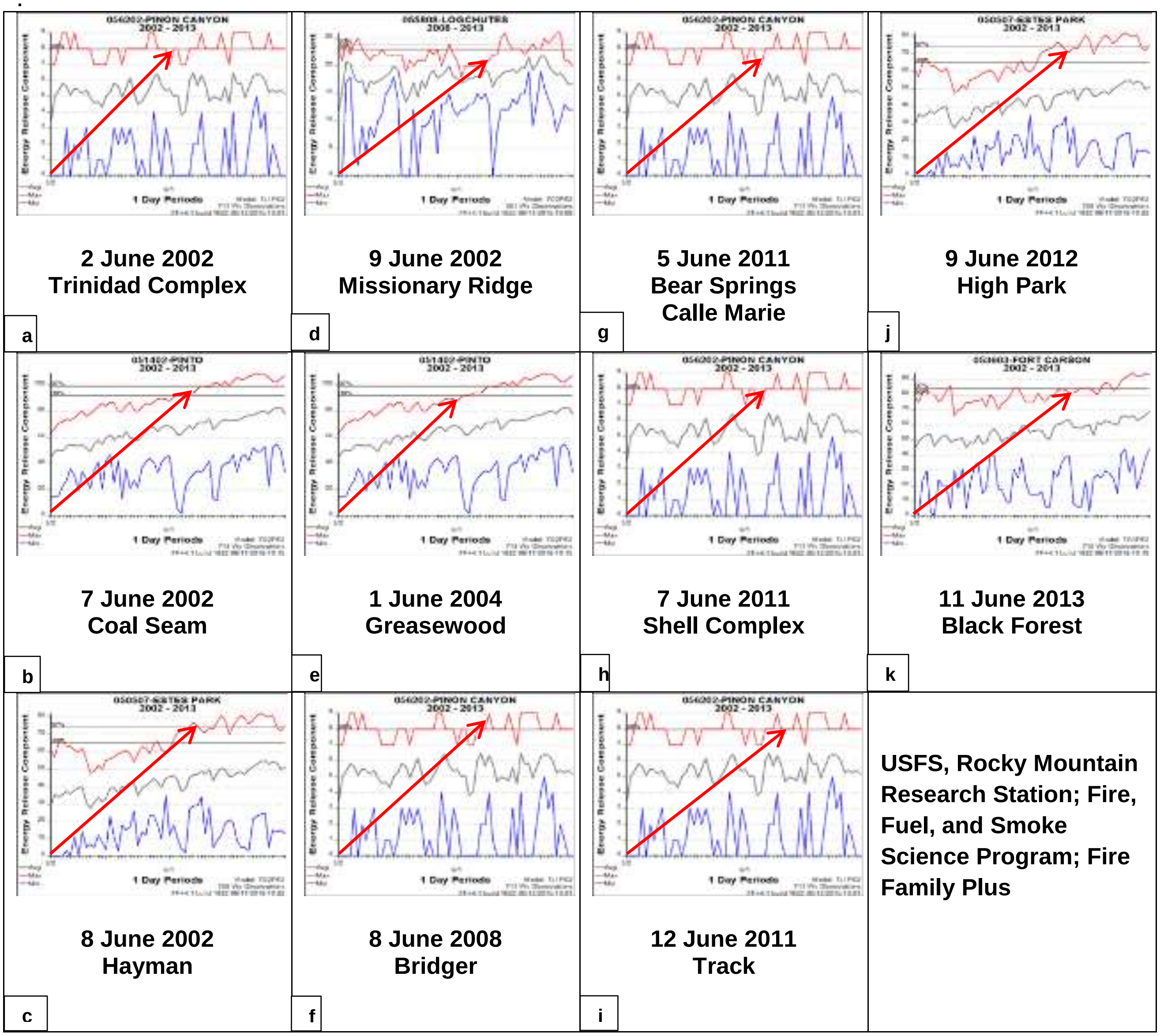


Figure 7. Energy Release Component (ERC) charts (2002- 2013, except for Missionary Ridge, Log Chutes RAWS) – fires and dates same as Fig. 2, red arrow indicates approximate fire start date and concurrent ERC index

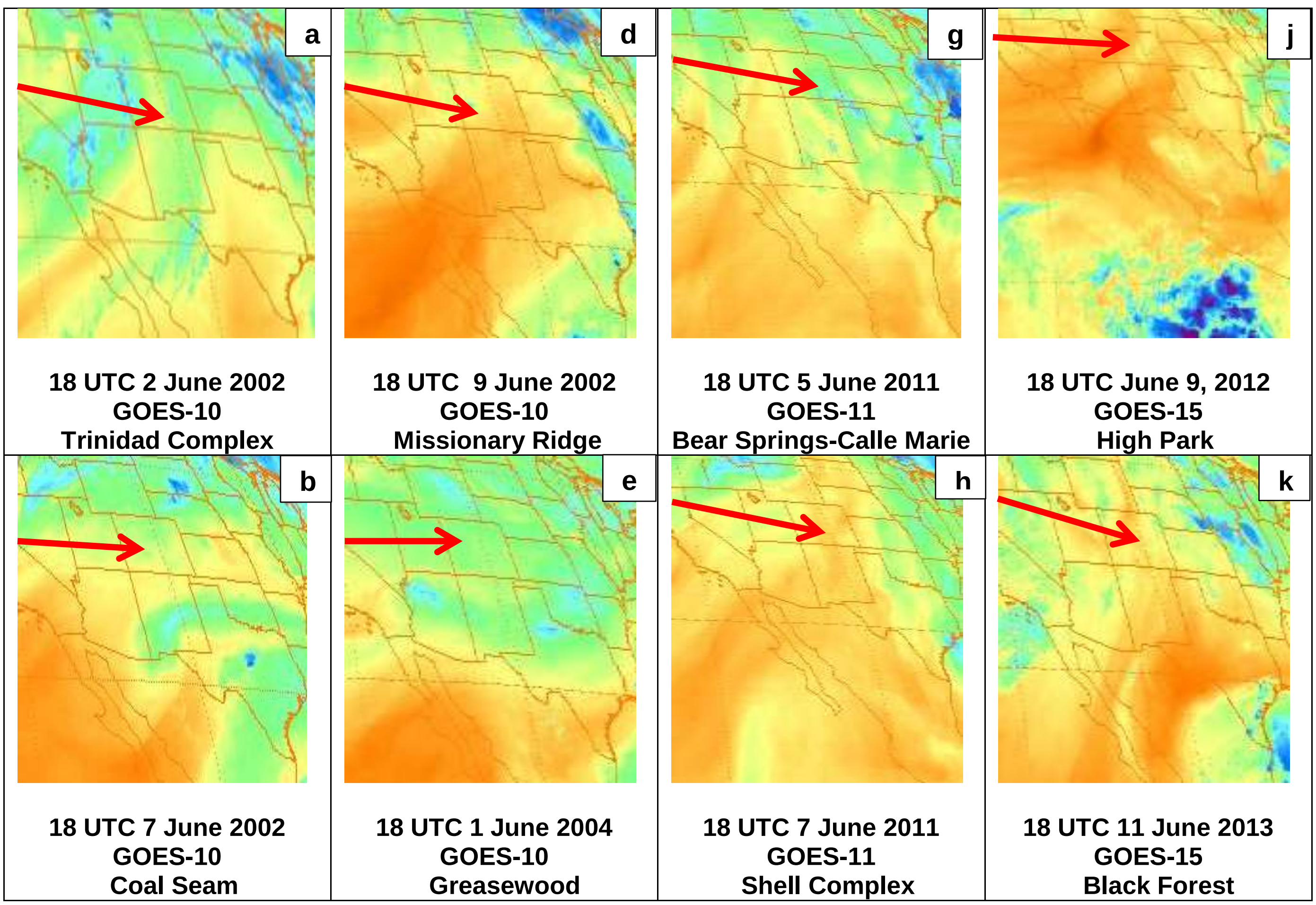
3.6 Energy Release Component (ERC)

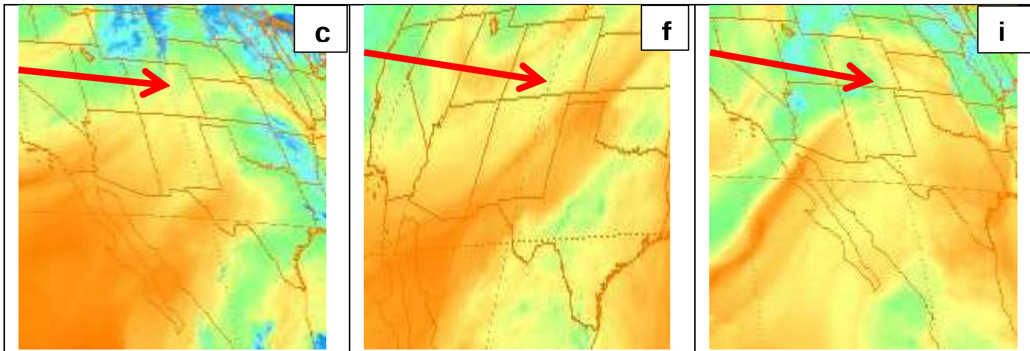
The ERC value, an output of the National Fire Danger Rating System (NFDRS), varied for each fire based on the respective RAWS locations (Fig. 7). The ERC is a number related to the available energy (BTU) per unit area (sq ft) within the flaming front at the head of a fire. Daily variations in ERC are due to changes in live and dead fuel moisture content of the various fuel classes, including the 1,000-hour timelag class (3” to 8” diameter). The ERC is derived from predictions of (1) the rate of heat release per unit area during flaming combustion and (2) the duration of flaming, (Heinsch and Andrews 2010). A fuel’s timelag is defined as the time needed for a fuel particle to lose about 63 percent of the difference between the initial moisture content and the equilibrium moisture content, when there is no net gain or loss of moisture between fuels and the surrounding air (Heinsch and Andrews 2010)

Notice in Fig. 7, that the ERC is climbing in most cases on the start dates of nine (75%) of the fires examined and that the ERC is at or approaching the 90th percentile (Very High FDR). These are visible in Fig. 7 (a) Trinidad Complex, (b) Coal Seam, (c) Hayman, (f) Bridger, (h) Shell Complex, (i) Track, (j) High Park, and (k) Black Forest Fires. Although the Haines Index images in Fig. 6 reveal several Haines 6 fire days, only the Hayman Fire was in the 97th percentile (Extreme FDR) on the start and/or initial attack days in Fig. 7(c) (Heinsch and Andrews 2010).

4. Observational Weather Data

4.1 Satellite Water Vapor Imagery (WVI)





18 UTC 8 June 2002 GOES-10 Hayman	18 UTC 8 June 2008 GOES-12 Bridger	18 UTC 12 June 2011 GOES-12 Track	**NOAA NESDIS NCDC GOES Global ISCCP B1 Browse System (GIBBS)**

Figure 8. 18 UTC (1200 MDT) GOES West Satellite Water Vapor Imagery (WVI) – cropped to western US – fires and dates as in Fig. 2; red arrow indicates approximate fire location

In the WVI, a descending dry air mass appears as a distinct expanding dark or darkening region (Weldon and Holmes 1991; Charney 2007). Generally, the darker the dry slot, the lower the humidity, e.g. (Weldon and Holmes 1991); this largely applies to the color enhanced imagery as well, Fig. 8. The broad, darker orange bands in the WVI are the mid-level dry intrusions and the narrower bands or tongues are dry slots, Fig. 8 (a-k). These mid-level dry intrusions and dry slots bring significant mixing, strong gusty winds, and unusually dry air, which reduce live and dead fuel moistures resulting in rapid rates of spread with aggressive to extreme fire behavior, e.g. (Mills 2005b, 2009).

Dry intrusions are often evident in the WV imagery up to a day before detected in the IR and VIS (Browning 1997; Muller and Fuelberg 1990), thus suggesting it as a valuable short-range forecast tool to enhance fire weather forecasting (Mills (2005). Satellite WVI reveals atmospheric structures undetected by conventional means, e.g. (Muller and Fuelberg 1990) and would be a valuable means to validate models, (NWS 1999).

Dry slots usually indicate descending dry air and/or horizontal dry air advection, e.g. (Weldon and Holmes 1991; James and Clark 2003). The source of the extremely dry air associated with the abrupt surface to near surface drying originates at high tropospheric or stratospheric levels, and descends into the region upstream of a developing cyclone (James and Clark 2003). Mills discerned that dry slots are columns of high, fast moving, dry air that descend rapidly to or near the Earth's surface affecting surface drying and intensifying the winds (2005, 2006a). Associated with established Critical Fire Weather Patterns, they often occur with troughs, pre- and post-dry cold front passages, the breakdown of upper ridges, cool changes, foehn winds, and low-level jet entrance and exit regions (NWS 1999; Mills 2006a, 2009; Wachter 2012-2015; Werth 2012-2015).

The darker [black] WV areas are frequently associated with a Haines Index 5 or six, according to the NWS (1999) in the days prior to color enhanced WVI. There are dry intrusions and dry slots evident in varying degrees of darkness (dryness) in Fig. 8 (a-k) associated with each of the fires examined. According to the researchers cited above, the surface to near surface drying, strong gusty winds, and Haines 5 or 6 were indicated by, and the result of these dry intrusions and/or dry slots visible in Fig. 8, Table 6.

The dry, unstable atmospheric conditions depicted to in the Skew-T soundings section below in Fig. 9 are also evident in the dry air intrusions and dry slots in the satellite WVI advecting over the fire areas in Fig. 8. Several of the dry intrusions and slots advecting into and/or over several of the examined fires in Fig. 8 are quite apparent and quite dynamic, indicating abrupt and strong drying, gusty winds, and Haines 5 or 6, e.g. (c) Hayman, (d) Missionary Ridge, (h) Shell Complex, (j) High Park, and (k) Black Forest Fires. The (f) Bridger and (i) Track Fire images also reveal very dynamic dry slots even though outside the respective fire areas.

4.2 Skew-T Soundings and 850 mb RH

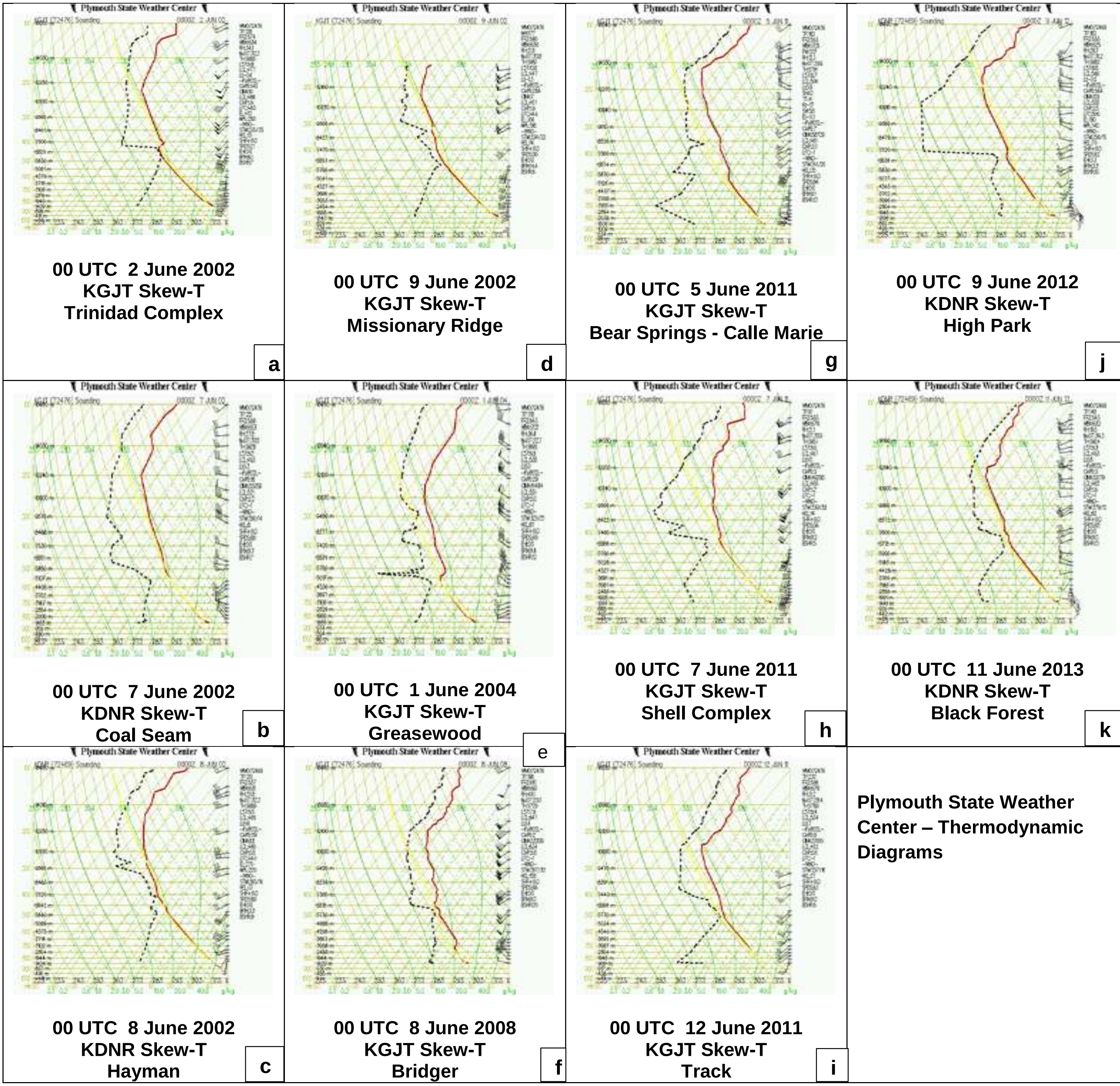


Figure 9 – 00 UTC (1800 MDT) 850 mb Skew-T soundings – fires and dates as in Figure 2

The several 00 UTC June 2002 to June 2013 upper air soundings from Denver (KDNR) and Grand Junction (KGJT) (Fig. 9), varying distances from the fire sites, provide additional details of the dry, unstable atmospheric conditions that helped generate the aggressive and extreme fire growth of each of the fires examined. The 00 UTC sounding data generally revealed very dry and well-mixed atmospheres with mid-level subsidence inversions within the 400 mb to 500 mb range (Milionis and Davies 2003). The exceptions were the (b) Coal Seam Fire with a subsidence inversion at about 200 mb and the (d) Missionary Ridge Fire with one at about 325 mb (Fig. 9). Inversions occur when the temperature of air increases with height, calculated from the mandatory and significant levels reported from morning (12 UTC) and late afternoon (00 UTC) balloon soundings. Subsidence inversions occur when air flows down from a higher location to a lower elevation. The descending, typically dry air warms as it sinks because of the compression it undergoes (Gonski 2013).

Each of the 12 UTC morning Skew-T soundings (not shown) revealed shallow to deep surface and/or near-surface radiation inversions (750 mb to 850mb) and these dissipated likely due to normal solar heating and mixing into the afternoon (Fig. 9). The 12 UTC 9 Jun 2002 Missionary Ridge radiation inversion was the shallowest (not shown). In comparison, the 850 mb RH Reanalysis vertical cross sections in Fig. 10 reveal dry to anomalously dry air aloft above the radiosonde sites and downwind of those sites, suggesting subsidence, corroborating the dry air revealed in the upper air soundings.

The forward, anticyclonic shear sides of jet streaks are associated with subsidence that can transport extremely dry air aloft down toward the surface. This air often originates with dew points near or below 0 °F (-18 °C) and often results in single digit surface to near-surface humidity as the air warms and dries during its descent (Graham et al 2003; Miretzky 2009), (Fig. 3). This subsidence condition occurred on half of the radiosonde soundings proximate to the fires in Fig. 9: (a) Trinidad Complex, (c) Hayman, (d) Missionary Ridge, (h) Shell Complex, (j) High Park, and (k) Black Forest with RH values as low as 2% to 6% from 1100 to 1900 MDT (Table 6) also revealed in the Tables 4-6 RAWS data !! These same conditions are fundamentally mirrored in the Fig. 10 850 mb, RH vertical cross sections for the same fires and dates. These atmospheric conditions occurred on separate, subsequent occasions on the Hayman, Missionary Ridge, High Park, and Black Forest Fires as well (not shown), e.g. (Graham et al 2003; Coen and Schroeder 2015). The June 2002 to June 2013 dry air intrusions and dry slots shown in the satellite WVI in Fig. 8 can be inferred in both the Denver (KDNR) and Grand Junction (KGJT) soundings in Fig. 9 indicating dry air aloft on the fires and dates discussed above.

Werth and Werth maintained that for *forecast* purposes, the Haines Index values calculated from the 1200 UTC morning soundings would be a better measure of synoptic-scale atmospheric stability and moisture conditions in the Western United States (1998). Morning soundings would most definitely benefit *forecasting* for the upcoming day; however, in this paper the afternoon (00 UTC) soundings are utilized for better characterizing the actual atmospheric conditions proximate to the respective fire areas at the time of the fires.

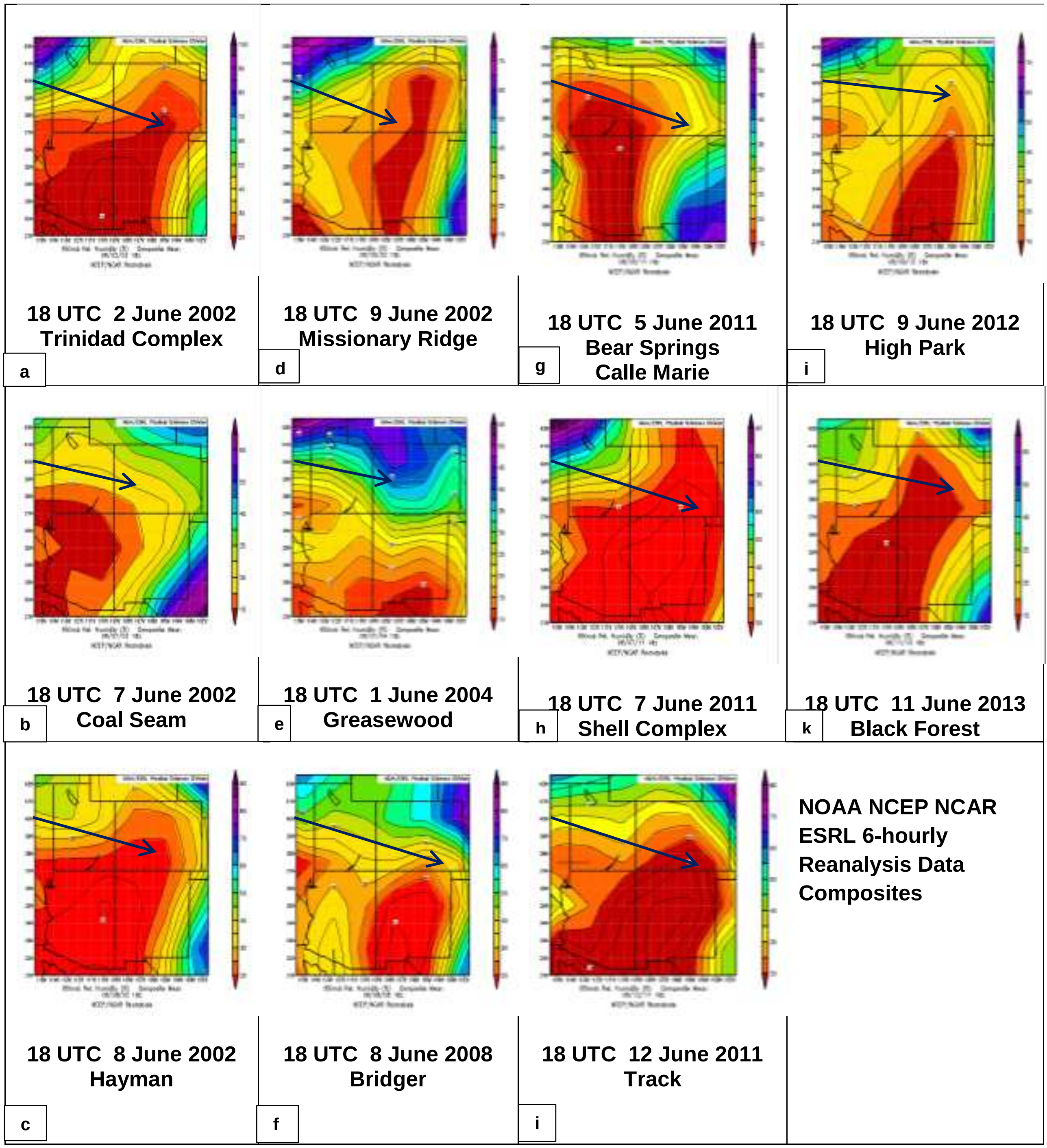


Figure 10. 18 UTC (1200 MDT) 850 mb (≈5000') Relative Humidity vertical cross sections – fires and dates as in Fig. 2, blue arrow indicates approximate fire location

4.3 Higher Elevation Timber Fire Weather

The higher elevation timber fires experienced much higher daytime temperatures, lower RH, and stronger winds (Table 6, Figs. 3, 7-10). The 24-hour meteograms (not shown) for the higher elevation timber fires, i.e. Hayman, Missionary Ridge, High Park, and Black Forest Fires revealed the alignment of the diurnal variabilities in daytime and nighttime temperatures, low to anomalously low dew points and RH, wind speeds and gusts, and wind directions that resulted in aggressive to extreme fire behavior and large fire growth (Campbell 2015). The 8 June 2002 Hayman Fire meteogram (KAKO – Akron-Washington) indicated high daytime and nighttime temperatures from midnight to 0800 MDT (96° F at 07 UTC), then rising rapidly coincident with lowering dew points and RH during the afternoon. The winds were northerly and steady at 10-15 knots through the night and early morning hours. There was obvious wind shear with the strongest southerly wind speeds and gusts (21-30 knots) from 19 UTC to 23 UTC proximate to the fire start (Peace and Mills 2012).

Beginning 8 June and continuing through 10 June 2002, the Hayman Fire had the most severe fire weather and fire spread (Graham 2003). On 8 June, due to strong southwest winds, the fire travelled 19 miles to the northeast in ten hours, burning 61,000 acres. The 8 June winds were southerly from about 00 UTC until 08 UTC at 10-20 knots with gusts 21-28 knots, then abrupt wind shear to northerly winds from 10 UTC to 19 UTC at 15-20 knots, with gusts ranging from 20-31 knots (Graham 2003). The Hayman Fire was also strongly affected by an "unseasonal downslope windstorm" on 9 June 2002, whereby the large-scale weather environment resembled the ideal conditions unique to wintertime Front Range windstorms (Coen and Schroeder 2015).

The 9 June 2002 Missionary Ridge Fire meteogram (KGJT - Grand Junction) indicated high daytime and very warm nighttime temperatures (98° F at 07 UTC) in the blow-up levels throughout the night beginning to rise shortly after 12 UTC. Winds were southerly for the 24-hour period, at 10-25 knots with gusts from 24-36 knots. Wind gusts were particularly strong from 13 UTC to 03 UTC at 23-36 knots. These particularly strong early morning winds may have been one of the mechanisms shaping the shallow 12 UTC inversion, Fig. 9 (d).

The 9 June 2012, the High Park Fire meteogram (KAKO – Akron-Washington) revealed high day and nighttime temperatures (98° F at 07 UTC) well within the blow-up condition range. Winds were southerly throughout the day at 10-20 knots, with gusts from 18-29 knots. The strongest gusts occurred midday between 18 UTC and 22 UTC and then again in the afternoon and persisting into the nighttime from 00 UTC to 07 UTC.

The 11 June 2013 Black Forest Fire meteogram (KAKO – Akron-Washington) revealed high day and nighttime temperatures (100° F at 07 UTC) also well within the blow-up range. Winds averaged 5-20 knots and variable throughout the period, north and easterly from 01 UTC to 10 UTC, westerly from 12 UTC to 17 UTC, and southwesterly 18 UTC to 00 UTC. The gusts were strongest from 18 UTC to 01 UTC in the 23-33 knots range.

These four higher elevation timber fires (three in the Front Range) illustrated the remarkable power of wildland fire events that can occur under the influence of dry atmospheric environments caused by historic drought conditions, and exacerbated by low snowpack levels and low snow water equivalence. These causal factors resulted in anomalously high nighttime temperatures, low dew points and RH, and steady, strong winds - often times downslope - which further reduced soil moisture and rapidly reduced dead fuel moistures. These fires also exhibited phenomenal fire behavior and rates of spread as they burned into and through wildland urban interface communities burning hundreds of acres and scores of structures (Graham et al 2003; Gollnick-Waid et al 2012; Peace and Mills 2012; Coen 2015).

4.4 High Nighttime Temperatures

In 1962, Tonto National Forest, District Ranger Robert Bates published "Key to Blowup Conditions in the Southwest?', a most important, although little known, study of several large wildland fires from 1951 to 1961 based on nighttime temperatures as a primary cause of extreme fire behavior and large fire growth. Bates theorized that by graphing the 8:00 am readings of the previous night's temperature, it might be possible to spot the beginning of potential blowup conditions. Bates noted that there was usually a sharp rise from relatively cool nights to hot nights during only 2 or 3 days prior to the critical and/or blow-up conditions.

He concluded that the day following the highest nighttime temperatures, followed by a warm/hot day, underwent the most active fire potential and/or active fires and produced the most aggressive and/or extreme fire behavior.

Bates determined two thresholds: (1) above or equal to 45° F was critical and (2) above or equal to 55° F was blow-up potential. He further noted that temperatures on the nights preceding the start or blow-up of these fires varied from a high of 81° F in the semi-desert to 52° F at higher elevations. From practical experience, this accurately applies elsewhere in the U.S., except much less in the Southeastern Region because of higher relative humidity and dew point values.

Consistently high nighttime temperature at the critical (≥ 45°F) and blow-up (≥ 55° F) levels preceded aggressive to extreme fire behavior the following day on each of the researched June 2002 to June 2013 Colorado Fire nights, from both midnight to 0600 MDT (Table 4) and at 0800 MDT as proposed by Bates (1962).

The questionable high RH values as high as 100% at the Dead Horse RAWS on 7 June 2002 and 83% at the Lake George RAWS on 8 June 2002 (Table 5) seemed suspect initially, however, both corroborated within reasonable limits to similar readings at nearby surrounding RAWS sites and/or RAWS networks for the same dates and times.

The 1 June 2004 Greasewood Fire, Dead Horse RAWS had no RH readings, so it would be conjecture to determine its RH values. Once the RH dropped to threshold level(s) below 35% in most cases, and below 25% in all cases, along with high nighttime temperatures, the fire behavior became aggressive to extreme the following day on each of the influenced fires.

Table 5 shows the RAWS data (midnight to 0600 MDT) for the individual fires with specific high nighttime temperatures, RH, wind speeds, gusts, and wind direction. The Dead Horse RAWS for the 1 June 2004 Greasewood Fire only revealed temperature. No other weather information was available from that particular RAWS on that night from two separate archive RAWS sources.

5.5 Dew Point Depression (Tdd) and 500 mb to 700 mb Temperature spread (Lapse Rates)

Consider now the 700 mb Tdd and the 500 mb to 700 mb temperature lapse rate of the fires examined based on Skew-T soundings (Fig.6). Dew point depression is the difference between the temperature and dew point taken at various levels and 700 mb is used in this study. It is one of the legs of the Haines Index (1988). First, critical thresholds are identified based on the high-elevation Haines Index (Werth and Werth 1998). The larger the temperature and dew point difference, the drier the air. The critical 700 mb Tdd threshold is greater than or equal to 21°C. The majority of the 12 UTC and 00 UTC Tdd of the fires examined fall within this critical threshold (Fig. 9; Table 3). Second, the critical threshold of the 500mb to 700mb temperature (C) spread is a value greater than 22° C and those values are both for the 12 UTC and 00 UTC periods. The majority of the 12 UTC and 00 UTC 500 mb to 700 mb spread of the June 2002 to June 2013 fires examined also falls within this critical threshold (Fig. 9; Table 3).

The various examined time period 700mb Tdd ranged from 15° C to 46° C at 12 UTC and 11° C to 48° C at 00 UTC, respectively (Fig. 9, and Table 3), most within the critical threshold range. Additionally, the 500 to 700 mb temperature spreads ranged from 17.1° C to 27.5° C at 12 UTC and 18.3° C at 00 UTC 27° C, respectively (Fig. 9, Table 3).

4.5 Critical Thresholds

(a) 12 UTC and 00 UTC 700 mb Tdd (C) (b) 12 UTC and 00 UTC 500 mb to 700 mb temperature difference (C) Fire name/date Sounding site	(a) 12 UTC and 00 UTC 700 mb Tdd (C) (b) 12 UTC and 00 UTC 500 mb to 700 mb temperature difference (C) Fire name/date Sounding site	(a) 12 UTC and 00 UTC 700 mb Tdd (C) (b) 12 UTC and 00 UTC 500 mb to 700 mb temperature difference (C) Fire name/date Sounding site	(a) 12 UTC and 00 UTC 700 mb Tdd (C) (b) 12 UTC and 00 UTC 500 mb to 700 mb temperature difference (C) Fire name/date Sounding site
(a) 23° C/23° C (b) 23.5° C/26.7° C Trinidad Complex 2 June 2002 KGJT sounding	(a) 19°C/29°C (b) 19.1° C/27.5°C 9 June 2002 Missionary Ridge KGJT sounding	(a) 33°C/48°C (b) 17.1°C/23.5°C 5 June 2011 Bear Springs Calle Marie KGJT sounding	(a) 46°C/18°C (b) 22.5°C/24.1°C 9 June 2012 High Park KDNR sounding
(a) 15° C/14.2° C (b) 25.7° C/24.9° C Coal Seam 7 June 2002 KGJT sounding	(a) 17°C/16°C (b) 21.7°C/18.3°C 1 June 2004 Greasewood KGJT sounding	(a) 24°C/35°C (b) 14.1°C/26.1°C 7 June 2011 Shell Complex KGJT sounding	(a) 30C°/32°C (b) 25.0°C/25.7°C 11 June 2013 Black Forest KDNR sounding
(a) 27°C/25°C (b) 28.2°C/26.1°C 8 June 2002 Hayman KDNR sounding	(a) 15°C/11°C (b) 19.7°C/21.1°C 8 June 2008 Bridger KGJT sounding	(a) 28°C/27°C (b) 22.1°C/25.1°C 12 June 2011 Track KGJT sounding	Plymouth State Weather Center – Thermodynamic Diagrams

Table 3. Both (a) 12 UTC and 00 UTC (above) , 700 mb dew point depression (Tdd) (C) and (b) 12 UTC and 00 UTC (below), 500 mb to 700 mb environmental lapse rate or change in temperature with height (C) calculations – based on nearest radiosonde sounding site and Skew-T data – data meeting threshold is in red and not meeting threshold is in black – fires and dates as in Fig. 2,

Time ≈14 UTC temperature (F), dew point (F), RH (%), winds, gusts (mph), direction, RAWS, elevation, date, fire name	**Time ≈14Z UTC temperature (F) dew point (F) RH (%), winds, gusts (mph), direction, RAWS, elevation, date, fire name**	**Time ≈14 UTC temperature *F) dew point (F), RH (%), winds, gusts (MPH) direction, RAWS, elevation, date, fire name**	**Time ≈14Z UTC) temperature (F) dew point (F), RH (%), winds, gusts (mph), direction, RAWS, elevation, date, fire name**
1350 UTC **a** 79.0° F 29.0° F 16% 8 mph 16 mph Southwest **Pinion Cyn. - 6422'** **2 June 2002** **Trinidad Complex**	1410 UTC **d** 69.0° F 28.6° F 22% 5 mph 10 mph Southeast **Mesa Mtn. - 7380'** **9 June 2002** **Missionary Ridge**	1423 UTC **g** 65.0° F 43.1° F 45% 6 mph 8 mph North-northwest **Pinion Cyn. - 6422'** **5 June 2011** **Bear Springs** **Calle Marie**	1351 UTC **j** 57.0° F 18.5° F 22% 10 mph 18 mph South-southwest **Willow Creek -8760'** **9 June 2012** **High Park**
1355 UTC **b** 69.0° F 58.4° F 69% 0 mph 6 mph West **Dead Horse - 8685'** **7 June 2002** **Coal Seam**	1355 UTC **e** 53.0° F No dew point data No RH data No wind data No gusts data No direction data **Dead Horse - 8685'** **1 June 2004** **Greasewood**	1423 UTC **h** 80.0° F 34.0° F 19% 6 mph 8 mph West **Pinion Cyn. - 6422'** **7 June 2011** **Shell Complex**	1358 UTC **k** 83.0° F 23.1° F 11% 11 mph 15 mph Southwest **Fort Carson - 6450'** **11 June 2013** **Black Forest**
1355 UTC **c** 55.0° F 37.7° F 52% 2 mph 6 mph Southeast **Lake George - 7485'** **8 June 2002** **Hayman**	1350 UTC **f** 55.0° F 39.6° F 56% 7 mph 10 mph North **Pinion Cyn. - 6422'** **8 June 2008** **Bridger**	1623 UTC **i** 72.0 ° F 51.2° F 48% 6 mph 12 mph Southeast **Pinion Cyn. - 6422'** **12 June 2002** **Track**	**Plymouth Weather Center RAWS archive**

Table 4. Approximately **1**4 UTC (≈0800 MDT) time, temperature (F), dew point (F), RH (%), winds (mph), gusts (mph), wind direction, RAWS, elevation, date, fire name – fires and dates as in Fig. 2.

Time – Temperature – RH Wind speed/Gusts - Direct	**Time – Temperature – RH Wind speed/Gusts - Direct**	**Time – Temperature – RH Wind speed/Gusts - Direct**	**Time – Temperature – RH Wind speed/Gusts - Direct**
2355 76°F 5% 9/14 WSW 0055 73°F 24% 13/22 SW 0155 74°F 23% 14/24 SW 0255 69°F 27% 9/24 S 0355 73°F 22% 11/21 SW 0455 72°F 23% 12/18 SW 0555 74°F 21% 6/19 SW **Pinion Cyn. RAWS 5422’ 2 June 2002 Trinidad**	0010 68°F 17% 14/32 W 0110 64°F 19% 7/12 WSW 0210 63°F 20% 8/13 WSW 0310 61°F 23% 6/12 SW 0410 62°F 23% 1/ 8 SSE 0510 60°F 26% 6/ 9 SSW 0610 60°F 27% 5/11 S **Mesa Mtn. RAWS – 7380’ 9 June 2002 Missionary Ridge**	0023 66°F 38% 4/ 7 S 0123 67°F 32% 12/16 SW 0223 66°F 37% 11/18 SW 0323 66°F 6% 9/15 SSW 0423 67°F 35% 8/16 SW 0523 67°F 35% 8/ 5 WSW 0623 67°F 34% 4/10 SW **Pinion Mtn. RAWS 5422’ 5 June 2011 Bear Springs Calle Marie**	2351 55°F 19% 5/16 N 0051 54°F 20% 9/16 SSW 0151 54°F 20% 10/18 S 0251 54°F 20% 9/21 S 0351 54°F 20% 10/18 S 0451 53°F 21% 11/19 S 0551 52°F 23% 6/15 S **Willow Crk. RAWS 9750’ 9 June 2012 High Park**
2355 63°F 100% 8/16 S 0055 51°F 33% 0/ 4 NE 0155 53°F 34% 0/ 3 ESE 0255 55°F 19% 0/ 5 WNW 0355 56°F 13% 0/ 4 N 0455 55°F 46% 0/ 3 N 0555 57°F 37% 0/16 WNW **Dead Horse RAWS 8685’ 7 June 2002 Coal Seam**	2355 56° F N/R 3/ 8 WSW 0055 55°F N/R 0/ 3 SSW 0155 51°F N/R 0/ 3 WSW 0255 48°F N/R 0/ 4 N 0355 48°F N/R 0/ 5 NNE 0455 47°F N/R 0/ 3 NNE 0555 45°F N/R 0/ 3 NE **Dead Horse RAWS 8685’ 1 June 2004 Greasewood (*N/R = no reading*)**	0023 71°F 26% 6/ 8 WSW 0123 72°F 23% 7/11 SSW 0223 68°F 26% 7/ 9 SSW 0323 66°F 27% 9/12 SSW 0423 68°F 21% 9/11 SSW 0523 67°F 17% 8/16 SSW 0623 73°F 11% 9/13 SW **Pinion Cyn. RAWS 5422’ 7 June 2011 Shell Complex**	2358 81°F 13% 4/11 NNW 0058 76°F 15% 5/ 8 W 0158 72°F 17% 7/11 W 0258 76°F 15% 5/11 S 0358 72°F 17% 9/12 WNW 0458 72°F 16% 5/11 WNW 0558 70°F 17% 6/10 WSW **Ft. Carson RAWS 6450’ 11 June 2013 Black Forest**
2355 69°F 14% 8/16 SSE 0055 44°F 43% 3/ 6 SE 0155 41°F 57% 3/ 7 SE 0255 39°F 70% 3/ 5 SE 0355 36°F 78% 3/ 5 SE 0455 36°F 83% 1/ 6 SE 0555 37°F 83% 0/ 6 SE **Lake George RAWS 7485’ June 8, 2002 Hayman**	2350 62°F 52% 3/16 WNW 0050 59°F 62% 8/15 NW 0150 58°F 65% 11/21 NNW 0250 56°F 58% 9/16 NNW 0350 55°F 53% 7/16 N 0450 54°F 56% 6/13 N 0550 53°F 61% 7 / 8 N **Pinion Canyon RAWS 5422’ June 8, 2008 Bridger**	2323 73°F 9% 2/ 4 S 0023 63°F 17% 2/ 7 S 0123 61°F 7% 4/ 7 WNW 0223 55°F 25% 4/ 7 NNW 0323 53°F 39% 7/10 NNW 0423 54°F 75% 6/ 9 NNW 0523 54°F 83% 4/ 8 NW **Pinion Canyon RAWS 5422’ June 12, 2011 Track**	**Real-time Observation Monitor and Analysis Network (ROMAN) RAWS USA Climate Archive**

Table 5. Approximately 2400 MDT to approximately 0600 MDT, temperature (F), RH (%), winds (mph), gusts (mph), direction (cardinal), RAWS, elevation, fire date, fire name - fires and dates as in Fig. 2.

Time – Temperature – RH Wind speed/Gusts - Direct	Time – Temperature – RH Wind speed/Gusts - Direct	Time – Temperature – RH Wind speed/Gusts - Direct	Time – Temperature – RH Wind speed/Gusts - Direct
1100 – no data available 1200 95°F 5% 18/29 SW 1300 97°F 4% 18/37 SW 1400 95°F 5% 17/32 WSW 1500 94°F 5% 17/35 WSW 1600 90°F 5% 14/29 WSW 1700 91°F 4% 11/24 WSW 1800 87°F 4% 10/21 WSW 1900 87°F 4% 11/24 W **Pinion Cyn. RAWS 5422'** **2 June 2002** **Trinidad**	1100 78°F 14% 17/33 WSW 1200 80°F 13% 18/32 SW 1300 83°F 11% 19/39 SW 1400 82°F 10% 23/35 SW 1500 82°F 10% 20/36 SW 1600 83°F 10% 15/38 SW 1700 82°F 10% 15/33 WSW 1800 81°F 8% 18/32 WSW 1900 75°F 11% 15/32 WSW **Mesa Mtn. RAWS 7380'** **9 June 2002** **Missionary Ridge**	1100 91°F 16% 4/10 NNE 1200 90°F 15% 4/ 9 N 1300 89°F 16% 4/11 N 1400 81°F 18% 9/19 SW 1500 83°F 17% 6/18 SSW 1600 82°F 17% 3/ 8 SSE 1700 79°F 21% 11/18 SE 1800 77°F 21% 8/15 ESE 1900 73°F 23% 4/ 9 SSE **Pinion Cyn RAWS 5422'** **5 June 2011** **Bear Springs** **Calle Marie**	1100 93°F 4% 5/11 NE 1200 94°F 4% 5/11 NNE 1300 96°F 4% 6/ 9 NNE 1400 97°F 4% 5/ 9 WNW 1500 98°F 4% 6/11 NE 1600 98°F 4% 3/11 SW 1700 95°F 4% 6/12 ESE 1800 92°F 4% 7/11 NE 1900 86°F 4% 7/11 NE **Willow Creek RAWS 9750'** **9 June 2012** **High Park**
1100 73°F 19% 15/32 WNW 1200 68°F 18% 14/48 NE 1300 74°F 15% 18/36 SSE 1400 74°F 16% 18/36 SE 1500 77°F 13% 14/36 W 1600 74°F 13% 18/37 ENE 1700 77°F 12% 16/33 N 1800 76°F 12% 13/32 SSW 1900 68°F 12% 11/25 WNW **Dead Horse RAWS 8685'** **7 June 2002** **Coal Seam**	1100 60°F No RH 11/19 NW 1200 68°F No RH 15/24 ENE 1300 59°F No RH 16/32 SSE 1400 61°F No RH 17/33 SSW 1500 61°F No RH 6/31 WSW 1600 60°F No RH 14/29 S 1700 61°F No RH 7/22 SE 1800 60°F No RH 9/25 WSW 1900 54°F No RH 6/12 NE **Dead Horse RAWS 8685'** **1 June 2004** **Greasewood**	1100 90°F 6% 6/11 SW 1200 91°F 6% 5/12 WSW 1300 92°F 6% 6/13 NW 1400 94°F 6% 5/12 SW 1500 94°F 6% 6/12 WSW 1600 92°F 6% 7/12 WSW 1700 92°F 5% 8/12 WSW 1800 88°F 5% 9/13 WSW 1900 79°F 6% 5/11 WSW **Pinion Cyn RAWS 5422'** **7 June 2011** **Shell Complex**	1100 91°F 6% 17/32 WSW 1200 91°F 5% 20/36 SW 1300 92°F 4% 21/43 SSW 1400 92°F 2% 17/37 WSW 1500 93°F 2% 18 /38 SW 1600 92°F 3% 20/34 SW 1700 92°F 4%18/37 SSW 1800 91°F 4% 13/29 WSW 1900 86°F 5% 10/26 W **Fort Carson RAWS 6450'** **11 June 2013** **Black Forest**
1100 81°F 9% 16/36 SSW 1200 81°F 10% 3/32 SW 1300 83°F 10% 16/32 S 1400 82°F 10% 14/33 SSW 1500 84°F 9% 18/36 SSE 1600 84°F 8% 17/36 S 1700 83°F 8% 15/33 SE 1800 81°F 9% 18/33 SE 1900 78°F 9% 15/31 SE **Lake George RAWS 7485'** **8 June 2002** **Hayman**	1100 68°F 38% 7/18 ENE 1200 71°F 32% 7/21 ENE 1300 74°F 29% 7/20 ESE 1400 76°F 27% 8/18 ESE 1500 78°F 26% 9/19 ESE 1600 76°F 28% 6/19 ENE 1700 75°F 30% 11/16 NNE 1800 70°F 34% 12/20 NE 1900 60°F 52% 12/26 NNE **Pinion Canyon RAWS 5422'** **8 June 2008** **Bridger**	1100 83°F 22% 4/ 7 NNE 1200 86°F 16% 5/ 9 E 1300 89°F 12% 6/ 9 SE 1400 89°F 11% 6/ 9 SSE 1500 87°F 19% 8/13 ESE 1600 88°F 15% 6/16 SE 1700 89°F 7% 6/14 WSW 1800 84°F 9% 4/10 NW 1900 88°F 8% 3/ 6 NNW **Pinion Cyn RAWS 5422'** **12 June 2011** **Track**	**Real-time Observation Monitor and Analysis Network (ROMAN)** **RAWS USA Climate Archive**

Table 6 – 1100 MDT to 1900 MDT, temperature (F), RH (%), winds (mph), gusts (mph), direction (cardinal), RAWS, elevation, fire date, fire name - fires and dates as in Fig. 2.

Figure 11. 9 June 2002 Hayman Fire

Figure 12. 11 June 2012 High Park Fire

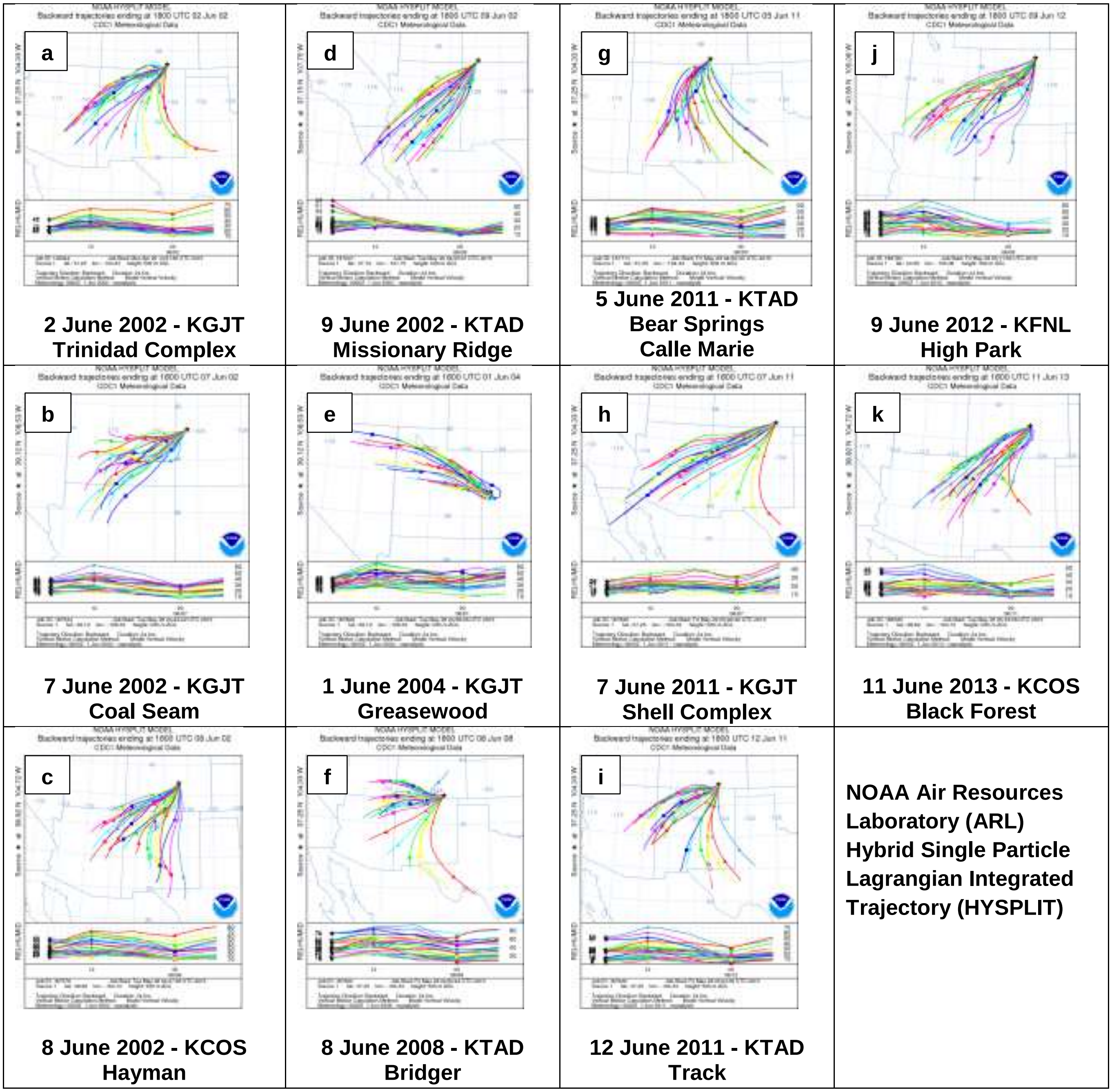


Figure 13.- HYSPLIT, 24-hour Backward Trajectory runs ending at 18 UTC (1200 MDT) from respective nearby proxy locations - fires and dates as in Fig. 2

4.5 HYSPLIT Backward Trajectory Runs

These HYSPLIT images (Draxler and Rolph 2003) generally indicate the dry air entrainment into each fire region was westerly, primarily from the southwest over desiccated, low soil moisture regions. These runs almost mirror the WVI dry intrusions and dry slots shown in Fig. 8. Proxy sites closest to the fire areas were: Denver (KDNR), Grand Junction (KGJT), Colorado Springs (KCOS), and Fort Collins-Loveland (KFNL), thus depicted on the images.

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6. SUMMARY and CONCLUSIONS

A dozen June 2002 to June 2013, Colorado wildland fires were examined to determine the common meteorological, weather, upper atmosphere, and climatological traits. Considering the fires in the aggregate, there was no indication of a single weather parameter that led to large fire growth. The respective large fire growth likely resulted from a combination of low snowpack and SWE, low soil moistures, the alignment of dry atmospheric intrusions that brought high day and nighttime temperatures, low relative humidity and dew point values, and steady to strong winds. Heavy fuel loading and dry fuel conditions led to moderate spread even on days with less severe weather conditions. Observing dry slots in the WVI advecting toward an existing fire, or toward an area where fire danger rating (FDR) is already extreme, is a strong indicator of potentially more extreme fire conditions, and with some lead-time. Therefore, incorporating WVI monitoring into existing fire weather protocols may well be beneficial. Further research in other Colorado wildfires should reveal similar results and be useful to fire weather forecasters and Incident Meteorologists in the future.

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