6.4A THE INFLUENCE OF DRY SLOTS ON WILDLAND FIRE GROWTH DURING THE 2011 ARIZONA FIRE SEASON

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Abstract: During the May and June 2011 fire season, Arizona experienced several large wildland fires, many with erratic fire behavior causing large fire growth. From a wildland fire supervisor’s perspective, every fire examined was influenced by persistent dry slots and/or dry intrusions consistent with GOES satellite water vapor imagery (WVI). These mechanisms are responsible for rapid surface and/or near-surface drying, diminished fuel moistures, increased winds, and Haines Index 5/6. When these factors aligned, they caused erratic fire behavior on all of these 2011 Arizona fires examined.

The Alignment of Forces principle established in the Campbell Prediction System (CPS) is presented, whereby fuels, weather, and topography alignment greatly increases fire behavior. Also researched is the effect of high nighttime temperatures adversely influencing wildland fire weather and fire behavior, a factor in each of the fires examined. The increased fire behavior typically occurs on the day following the highest nighttime temperature. The principle of 'Fighting Fire by the Rules' is discussed since weather is undeniably a key component in wildland firefighting. The first Standard Firefighting Order and the Eighteen Watch Out Situations both contain weather components.

Several date-and-times stamped fire behavior photograph images of the Wallow Fire in northern Arizona in May and June 2011 are compared with GOES satellite WVI dry slots and dry intrusions at or proximate to the same time periods. The results are dramatic, strongly suggesting a powerful fire behavior cause and effect.

1. Introduction

During May and June of 2011, Arizona was plagued by several large wildland fires with very erratic fire behavior produced by dry slots (Fig. 3), many embedded within cold fronts bringing very dry air from aloft (Schroeder1964). Severe to extreme drought and low soil moistures, heavy dead-down and standing live fuel loadings, and low dead and live fuel moistures also contributed to the extreme fire behavior and large fire growth.

The organization of the paper is as follows. Dry slots, upper air influences, other fire weather indicators and methods for predicting fire behavior, and satellite water vapor imagery are described followed by a description of '*fighting fire by the rules'* for wildland fire engagement. Next will be three of the eight 2011 large wildland fires in Arizona and each fire case study examining the fuels, weather, topography, fire behavior, and drought and soil moisture; with the principal focus on the mesoscale and synoptic meteorological conditions, mainly the dry slots and dry intrusions based on NOAA satellite WVI, atmospheric soundings, and remote automated weather station (RAWS) data. Finally a summary and outlook are given.

Fig.1 reveals the 14 May 2013, Geostationary Operational Environmental Satellite (GOES) WVI depicting dry slots and dry intrusions advecting throughout the United States that day. In the northeastern United States (U.S) these mechanisms influenced at least two large wildfires in Minnesota (Green Valley Fire) and Wisconsin (Germann Road Fire). The Germann Road Fire was classified as one of the largest wildfires since 1980 (InciWeb 2013). Note the dry slot and gray-scale drying advecting through Oregon, Idaho, North Dakota, and Montana where numerous Red Flag Warnings were issued for those states and influenced locations, especially northeastern Montana (not shown). In addition, the elongated Southeastern dry slot also generated Red Flag Warnings in those states influenced by the dry slot advecting through that region (not shown).

2. Dry Slots, Dry Intrusions, Satellite WVI

Dry Slots show up as "*dark bands, filaments, or tongues*" of very dry air in satellite WVI between 600 mb to 300 mb (Weldon and Holmes 1991) (Fig.1). Dry slots tend to be associated with middle tropospheric thermal troughs (e.g. Weldon and Holmes 1991). Researching the Double Trouble State Park (DTSP) wildfire in New Jersey in June 2002, Charney discovered that the vertical structure of dry slots indicated that the genesis of this dry, high-momentum air is in the mid- to upper-troposphere and/or the lower-stratosphere (e.g. Charney 2007) (Fig. 2). These images show dry air advecting to near the surface from the troposphere. The reader is encouraged to investigate the various DTSP wildfire research papers for edification on dry slots and the complex coupling mechanism exchanges involved with upper air influences.

Likewise, the reader is encouraged to read about similar mid- to upper- air influences and the inference of dry slots on the May 1980 Mack Lake Fire as researched in Simard et al (1980), Zimet et al (2003), and Zimet et al (2007). Zimet (2007) discovered that "*organized subsidence was responsible for the downward advection of high momentum air from within the frontal zone into the fire environment*;" and utilized some vertical cross-sections, one of which employed potential temperature and RH, from a 42 hour MM5 forecast that represented "*a tongue of extremely dry RH air extending downward to ~750 hPa just northwest of the fire location*" Zimet (2007) (not shown). A dry slot can definitely be inferred down through the centerline of the RH contours (not shown) (Schoeffler 2013a).

Weldon and Holmes found that if the dark area has a well-defined definite boundary, the very dry air most likely extends to the lowest altitudes adjacent to the distinct boundary (1991). Smarsh (1994) and Wachter (2012) both maintained that dry slots can be inferred from and verified by skew-T soundings, however, they are best visible via satellite WVI where you can actually '*see*' the dry slot (Schoeffler 2013a).

The dry intrusion is often evident in the WVI almost a full day before it can be found in the infrared and visible imagery (Santurette and Georgiev 2005). A major finding of the Iaccopelli and Knox research was the extremely close concurrence between the surface reports of damaging winds and the satellite signature of the southern fork of the dry intrusion (2001) e.g. (Lagouvardos and Kotroni 2000).

The author has researched numerous wildland fires, both personally experienced and those archived in the Lessons Learned Center (LLC) Incident Reviews - where the "*humidity dropped like a rock*" and the fire behavior increased intensely (Schoeffler 2010, 2013b) and found dry slots to be both an indicator as well as a causal and coincident mechanism of extreme wildland fire weather in almost all the researched cases (e.g. LLC Incident Reviews, Schoeffler 2010, 2013a, 2013b, 2013c).

2.1 Dry Slots: Causes – Contributing Factors Precursors – Indicators – Outcomes

Dry slots are basically columns of high, fast moving, dry air that descend rapidly to or near the Earth's surface affecting surface drying and intensifying the winds (Mills 2008, 2010; Werth 2012). Generally, the darker the dry slot, the lower the humidity (e.g. Weldon and Holmes 1991) and this applies to the color-enhanced imagery as well. Surfacing dry slots almost always result in Haines 5 or 6 (Werth 2012). Different types of problem dry slots are associated with *Critical Fire Weather Patterns* discussed in the reference publication generated at the *NWS Fire Weather Forecasters Course* in Boise, ID during March 30 to April 2, 1999 (e.g. pre-frontal, and post-frontal, the breakdown of upper level ridges, foehn winds, and low-level jet entrance and exit regions) (e.g. Schroeder 1964; Mills 2006; and Werth 2012). This same publication suggested using WVI to locate dark areas (dry slots) as potentially moderate (5) to high (6) Haines Index[1] regions. It is noteworthy that it also cautioned to be on the watch for light gray areas, often referred to as 'gray shade drying' because these can truly be Haines 5/6 areas.

Dry slots most likely occur in mid-afternoon, especially on hot days (Mills 2006a). Werth (2012), Out of a total of 232 "*abrupt drying events*" Mills found that 70% occurred with troughs, dry cold front passages, and/or were co-located with jet streams and dry cool changes, with an additional 20% to 30% occurring overnight or in the early morning (Mills 2008a, Werth 2012). Dry slots always reflect a comparatively dry middle and upper troposphere (e.g. Werth 2012). Dry slots almost always indicate descending dry air and/or horizontal dry air advection (e.g. James and Clark 2003) and air parcels in the dry intrusion originate at high tropospheric, or even stratospheric, or tropopause fold levels (e.g. Charney 2007, Smarsh 1994). A relative humidity decline caused by surfacing dry slots is almost always "*surprisingly lower*" lower than the forecasted humidity (Werth 2012). They are responsible for abrupt decreases in relative humidity, dew points, and ultimately fuel moistures (e.g. Mills 2008, 2008a, 2009) and strong, gusty winds (e.g. Mills 2005b) and result in rapid, sustained increased fire behavior (e.g. Mills 2005b). Whether or not dry slots affect wildland fire behavior is solely determined by the dry air surfacing and/or near-surfacing resulting in unusually low relative humidity (e.g. Werth 2012). It is the development of a deep, statically

[1] Fire weather index based on stability and moisture content of the lower atmosphere; measures the potential for existing fires to become large (Haines 1988, Werth et al 2011). It was originally called the Lower Atmosphere Stability Index. Haines 5 is moderate and Haines 6 is high potential for large fire growth.

neutral boundary layer that contributes to the link between mid-tropospheric dry slots and the surface (e.g. Mills 2008, 2008a). Dry slots appear to "*pulse*" in the WVI as examined by Kaplan et al. (2008) when they discussed "*two separate drying pulses*" that occurred on the DTSP wildfire in New Jersey in 2002 (Fig. 2) and Kaplan et al (2005 (not shown)).

When sinking motions occur, a subsidence layer and a corresponding dry slot were found along with decreased relative humidity (Smarsh 1994, Miretzky 2009). Miretzky, focused on the Northeastern U.S. wildfires affected by subsidence and found that there are "*reservoirs*" of dry air that form just above the Planetary Boundary Layer (PBL) (2009). The '*reservoirs*' referenced in the Miretzky text may be inferred as dry slots and/or dry intrusions when examined in the archived GOES WVI. See Fig. 4 for the dry air aloft at 300 mb in the jet stream over Arizona and at 1000 mb in the lower PBL through May and June, 2011. Extremely dry air aloft also based on Skew-T sounding data suggested subsidence.

If the air immediately above the mixed layer should dry abruptly, then this transformation could be realized at the surface fairly quickly, in time-scales less than an hour (Mills 2008) and also in Kondo and Kuwagata (1991). Grumm, DeVoir, and Villani 2004), proposed that the dry slot signature may be a useful short-term forecast tool in diagnosing wind events. And Mills concluded that the potential for using WVI to monitor the movement of mid-tropospheric dry air towards an ongoing fire site should be investigated as a fire weather forecasting aid (2008, 2009).

During severe drought, red flag conditions, and severe fire weather on January 1, 2006 during a protracted Texas fire season, forecasters used *only* computer modeling and "*underestimated low-level wind speeds,*" "*overestimated the near-surface moisture*," and "*failed to depict a cold front*" (Lindley et al 2006, 2006a). There was a dynamic dry slot boldly visible in the WVI that should have made the severe fire weather potential blatantly obvious to any forecaster that viewed the WVI that day.

The known connection between mid-tropospheric dry slots and reduced atmospheric humidity may make WVI a valuable guide to areas where atmospheric instability over an active fire may be reduced, as well as their effects on lower-atmosphere drying (Mills 2005).

WVI has proved to be a valuable tool for observing the ridge developments, particularly the role of the upstream ridge where clouds are absent (Weldon and Holmes 1991). Muller and Fuelberg (1990) observed that dry slots observed in WVI are not well predicted by computer modeling and WVI is beneficial for "*providing mesoscale information that is unobtainable from conventional data*." WVI could be very useful at a later stage of the decision making process to refine forecasts and atmospheric behavior can be compared to the model output for verification (Weldon and Holmes 1991).

3. FIGHTING FIRE BY THE RULES

On the fireline, as thoroughly as possible, firefighters and specifically fireline supervisors must absolutely know, understand, and follow the Ten Standard Fire Orders, as well as accurately identify, heed, and then mitigate the Eighteen Watch Out Situations (Schoeffler 2013c). The Ten Standard Firefighting Orders, synonymous with the Fire Orders, are fundamental rules of engagement for all wildland firefighters that must be followed on every fire (NWCG 2010). The Eighteen Watch Out Situations complement the Ten Standard Orders and are observable on every fire. Firefighters cannot disobey or violate the Eighteen Watch Out Situations, however, they can fail to recognize them and/or heed their warnings and mitigate them (Wildland Fire LLC). As a generally accepted practice, wildland firefighters and fireline supervisors use clouds as weather indicators (e.g. altocumulus lenticularis in the morning usually means high winds aloft surfacing later in the day) (Schoeffler 2013c). Nowadays, we are able to utilize mobile devices for accessing satellite WVI as a means to identify and discern dry slots and dry intrusions as new fire weather indicators (Schoeffler 2013b) while still utilizing clouds. Consider now the relevant weather-related Ten Standard Fire Orders and the Eighteen Watch Out Situations in more detail.

3.1 Ten Standard Firefighting Orders

1) *Keep informed on fire weather conditions and forecasts.*

3) *Base all actions on current and expected fire behavior.*

10) *Fight fire aggressively, having provided for safety first.* (NWCG 2010)

3.2 Eighteen Watch Out Situations

4) *Unfamiliar with weather and local factors influencing fire behavior.*

5) *Uninformed on strategy, tactics, and hazards.*

14) *Weather is getting hotter and drier.*

15) *Wind increases and/or changes direction.*

(NWCG 2010)

The consequences of not knowing, recognizing, following, and heeding the Fire Orders and Watch Out Situations can be severe (Wildland Fire LLC). As a rule, all wildland fire injuries, burn-overs, fire shelter deployments, and fatalities are the result of not strictly knowing, and then following one or more of the Ten Standard Orders; and/or failing to know, recognize and heed one or more of the Eighteen Watch Out Situations (Wildland Fire LLC). Fireline supervisors base their strategy and tactics on accurate fire weather forecasting (Schoeffler 2013b). The predicted fire behavior is often underestimated and/or unheeded, most times resulting in tragic results (Wildland Fire LLC).

With few exceptions, fireline supervisors have a very basic knowledge of subsidence, upper air influences, and perhaps dry air intrusions and dry slots from their fire weather training, but usually not a working knowledge. The author suggests that fireline supervisors should regularly view WVI when they are able, to alert them to any dry slots approaching their fire and/or prescribed burn (Schoeffler 2013a, 2013b, 2013c). However, the preferred alternative according to Mills and others is for trained meteorologists to observe these signatures and events and then notify those on the firelines of the information (2006) and/or make it part of their briefings. This would allow fireline supervisors and prescribed burn managers time to anticipate the expected adverse fire weather and resultant fire behavior on a virtually real time basis, and continue fight fire and/or change tactics, disengage, secure a prescribed burn, or escape and move to safety if need be (Schoeffler 2013c). It would most definitely increase their situational awareness and enhance their management options (Mills 2006).

Interestingly, prescribed fire managers that understand the benefits of WVI and the influences of dry slots are using WVI to determine the precise time to burn chaparral, instead of relying merely on trial-and-error, instinct, or some other fire behavior predictors as they have in the past.

4. **The Alignment of Forces Principle**

The Campbell Prediction System (CPS) examines "*reading a wildland fire*" by observing and heeding the "*alignment of forces*" of wind, slope, and preheating causing variations in fire behavior. The author has included relative humidity to the list based on experience. When these forces align, the fire is going to be at its maximum intensity. With experience, one can accurately predict the fire signature that will result and take appropriate suppression and/or evasive action (Campbell 1995) Dry slots are most compatible with the alignment principle as a primary causal factor and indicator in the 2011 Arizona wildfires to be discussed.

5. 2011 Arizona Wildfires Influenced by Dry Slots and/or Dry Intrusions

- Horseshoe Two: May 8 to June 25 - 222,954 acres (3,483 sq. mi.)
- Sunflower: May 12 – 17,446 acres (272 sq. mi.)
- Gladiator: May 13 – 16,240 acres (253 sq. mi.)
- Wallow: May 29 to July 8 – 538,049 acres (8,407 sq. mi.)
- Murphy: May 30 to June 7 – 85,847 acres (1,341 sq. mi.)
- Monument: June 12 to July 8 – 32,300 acres (504 sq. mi.)

(Fig. 3).

In every case, a dry slot and/or dry air intrusion advected over the fire and/or proximate to the fire area (Figs. 6, 12, 16, 21, and 25) caused an abrupt drop in relative humidities and dew points, as well as strong, gusty winds (Figs.7, 13, 14, 18, 19, 22, 23, 26, 30, 33, and 34), to align which resulted in often extreme, and/or erratic fire behavior (Figs. 24, 27, and 29) as exhibited in photographs, and resulted in large fire growth (Table 1). The dry slots often coincided with atmospheric instability and resulted in a Haines Index of 5 or 6 in almost all cases (not shown), (Saltenberger and Barker 1993; Werth and Ochoa 1993; NWS 1999; Zimet et al. 2003 and 2007; and Prevede 2007).

Each of the fires was also influenced by severe (Horseshoe Two and Wallow) to extreme Monument) drought and very low soil moistures

(Figs. 9, 15, 20, and 35) which have an adverse effect on fire weather and behavior. The U. S. Forest Service 'Fire Weather' (1970) publication talks about how "*prolonged severe drought*" and low soil moisture can and does affect "*cessation of [plant] growth*" and can "*prove fatal*" to whole plants and shrubs, because they can lose about half of their foliar moisture making them much more flammable. It concluded the section with the significant conclusion that "*Conflagration potential is then at its peak*." ROMAN RAWS dead fuel moisture readings for all the stations were extremely low (Figs. 8, 14, 19, 23, and 34). All references to ROMAN RAWS readings are highlighted in the text in **bold red** for each wildfire and its respective date(s). These above statements are referring to live fuel moisture; however, low soil moistures affect dead fuel moisture even more so. For additional research on the subject of drought and soil moisture effects refer to Keetch and Byram (1962) and Finkele, Karla and Graham A. Mills, (2006).

The 440-hour NOAA HYSPLIT ARL (Draxler and Rolph 2013) simulation from May 28 to June 15, 2011 distinctly suggested that the dry air parcel trajectories that advected into the Southwest during the period of the wildfires, originated far to the northwest and well beyond the United States (Fig. 10). This backward trajectories simulation was performed to show the entrainment of the dry air parcels that advected specifically into Arizona, throughout the duration of each of the fires' maximum growth periods. Gallup, NM was used as the receptor site due to its proximity and alignment with could be considered as mostly mean normal mesoscale and synoptic wind flows through the respective wildland fire areas (Fig. 10).

The reader will now examine three specific Arizona wildland fires influenced by dry slots and dry intrusions during May and June 2011. Each of the fire discussions will briefly address the specific wildland fire influences of fuels, topography, fire behavior, and especially the mesoscale and synoptic weather discussions in somewhat more detail. For each fire examined, the mesoscale and synoptic weather discussions, the author paraphrased very strictly from the relevant NOAA NWS Fire Weather Outlooks in order to retain as much as possible, the forecaster's original meteorological intent and meaning.

5.1 Horseshoe Two Fire – May 8, 2011

On May 8th, the Horseshoe Two Fire started in southeastern Arizona near the town of Portal

(Fig. 3) at approximately 1100, in steep and mountainous terrain. It initially burned in grass and brush in the lower terrain, and then transitioned into timber in the higher elevations.

A May 8, 2011 NWS Fire Weather Outlook called for "*critical fire weather*" for eastern and central Arizona (NWS May 8, 2011). An upper level trough was digging its way across the western CONUS while an attendant mid-level jet was centered over southern California and into the Great Basin (Fig. 5). Along with some phasing between the trough and the subtropical jet, a confluence axis helped strengthen the mid-level westerly and southwesterly winds across New Mexico and the Southern Plains (Fig. 5) (Schroeder 1964). The strongest winds would occur across the Great Basin and into northern Arizona in advance of an approaching cold front and in close proximity to the mid-level jet (NWS May 8, 2011) (Fig.5).

GOES-11 satellite WVI for May 8th at 1745Z (1145 MDT) (Fig. 6) revealed a robust dry air intrusion throughout Arizona and the Horseshoe Two Fire area indicating drying and gusty winds (e.g. Mills 2010). The May 8th, Tucson, AZ Skew-T atmospheric soundings proximate to the fire site also indicated very dry and unstable conditions at and near the surface and aloft (Fig. 7) with anomalously low relative humidities (1% at 700 mb) and dew points (- 42.4°C at 700 mb) revealed in the listed text data (not shown).

The Muleshoe Ranch, Real-time Observation Monitor and Analysis Network (ROMAN) Remote Automated Weather Station (RAWS) located at 5460' elevation was used for the May 8, 2011 readings (Fig 8). The data revealed critically high nighttime temperatures from midnight to 0600 MDT that ranged from 55° F to 62° F during that time (Bates 1962). The relative humidities during those hours were low but not critical. And the winds were fairly light. However, during the daylight and into the evening hours the relative humidities and dew points were extremely low (Fig. 8). There were single digit RH's from 0900 to 2100 MDT and the dew points for that same period were also very low, and ranged from 11.6° F to a – 12.6° F (Fig. 8). The afternoon and evening winds were brisk and averaged about 10 mi/h with strong gusts from 17 to 30 mi/h (Figs. 7, 8). Severe drought and low soil moisture would have also contributed (Fig.9). It burned over 9,000 acres that day

(14.1 sq. mi; 3600 ha) (InciWeb) under a Haines of 5 (not shown).

5.2 Wallow Fire - May 29, 2013

This fire was started at approximately 0130 MDT in east central Arizona in the White Mountains near Alpine (Fig. 3) in fairly heavy pine and conifer fuels under the influence of a Haines of 4 (not shown). The May 29, 2011 Fire Weather Outlook called for "*critical fire weather*" in eastern Arizona (NWS May 29, 2011). An upper-level trough located over the Pacific Coast progressed across the Great Basin (Fig. 11) (Schroeder 1964). Simultaneously, strong mid-level southwesterly winds spread across the Southwestern states and the High Plains. Farther west, a surface cold front was expected to move across Utah and Arizona during the afternoon and then into New Mexico and Colorado during the overnight hours (NWS May 29, 2011) (Fig. 11).

GOES-11 satellite WVI for May 29th at 1145Z (0545 MDT) (Fig. 12) revealed a robust dry air intrusion throughout Arizona and the Wallow Fire area indicating drying and gusty winds (e.g. Mills 2010). The Alpine, AZ Skew-T atmospheric soundings also indicated very dry and unstable conditions at and near the surface and very high aloft (Fig. 13) with very low relative humidities (4% to 6% between 600 mb and 400 mb) and dew points (- 41° C to – 65° C) between 600 mb and 400 mb) revealed in the listed text data (not shown).

The Alpine, AZ ROMAN RAWS at an elevation of 8031' (Fig. 14) recorded critically high nighttime temperatures from midnight to 0600 MDT that ranged from 51° F to 58° F (Bates 1962). There were also fairly steady, moderate to strong nighttime winds and gusts recorded.

Additionally, there were low daytime relative humidities in the teens to lower twenties, along with a dry cold front passage that caused some fairly brisk winds and gusts (Figs. 12, 13). There was even evidence of some jet stream influence at 18Z (1200 MDT) (Fig. 19) with increased winds for several hours as it passed over the fire area (Figs. 13, 14). Dry slots, dry intrusions, low RH, winds, and severe drought effects (Fig. 13, 14, 15) suggested that these factors aligned and generated 1,445 acres of fire growth that day (Table 1). Surprisingly, this resulted in fairly low acreage burned considering the growth potential based on the fire weather, but that would all change in the days to come (Table 1).

5.3 Wallow Fire - June 3, 2011

The June 3, 2011 Fire Weather Outlook (NWS June 3, 2011) called for a "*critical fire weather area*" for east central Arizona. An upper trough centered over the central Canadian provinces gradually ejected eastward with the associated jet core exiting to the southwest through the day (NWS). Amplified upper ridging persisted in advance of the low from the Gulf northwestward into the Great Lakes region (NWS). While an upper low over Nova Scotia gradually drifted southeastward and maintained dry northwesterly and northerly flow from the mid-Atlantic into New England. Farther west, a strong mid/upper jet dove southeastward along the western periphery of a closed upper low off the Pacific Northwest coast and allowed it to eject southward to the central California coast (NWS). The core of the stronger 500 mb southwesterly winds progressed northeastward, and flow from 40 to 60 mi/h remained prevalent through the bulk of the afternoon with deep vertical mixing, sustained surface winds of 20 to 25 mi/h will become common with gusts from 30 to 45 mi/h (NWS).

An antecedent dry air mass will lead to a continuation of single digit RH's across much of Arizona and New Mexico, but winds will generally be weaker than farther east, though 15 to 20 mi/h speeds will enhance the threat in areas plagued by severe to exceptional drought (NWS).

The June 3, 2011 GOES-13 WVI revealed a significant dry air intrusion throughout most of Arizona and the Wallow Fire area (Fig. 16). The Flagstaff, AZ Skew-T atmospheric soundings also indicated very dry and unstable conditions at and near the surface and aloft (Fig. 18) likewise with anomalously low relative humidities (1% at 684 mb) and dew points (- 45.4° C) revealed in the listed text data (not shown).

For June 3rd, the Wallow Fire experienced a Haines of 5 (USFS WFAS - not shown). Taken from the Alpine ROMAN RAWS (Fig. 19), critically high nighttime temperatures (Bates 1962) from midnight to 0600 MDT that ranged from 51° F to 62° F as well as very low relative humidities and dew points for the entire 24-hour period. The winds were fairly brisk and gusty both day and night (Fig. 19). Dry slots and dry intrusions revealed in the WVI (Fig.21) indicated that these factors aligned and caused the fire to grow intensely, burning 60,093 acres that day (Table 1).

5.4 Wallow Fire – June 5, 2011

The June 5, 2011 Fire Weather Outlook for 0346 AM CDT (NWS June 5, 2011) called for "*extremely critical fire weather for northern Arizona*." A potent short wave trough over central California traversed east-northeastward into the northern Intermountain West overnight (Schroeder 1964). It strengthened winds over much of the southwest which lead to an increased threat of wind-driven fires (NWS June 5, 2011) (Fig. 22, 23).

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The Alpine ROMAN RAWS indicated high nighttime temperatures from midnight to 0600 MDT ranging from 43°F to 53°F (Bates 1962) and fairly low RH's and dew points for the day with fairly steady winds day and night (Fig. 23). Dry slots and dry intrusions revealed in the WVI (Fig.21) indicated that these factors aligned and the fire burned 40,321 acres (630 sq. mi.) that day (Table 1). The Flagstaff, AZ Skew-T atmospheric soundings also indicated dry and unstable conditions at and near the surface and high aloft (Fig. 22) likewise with very low relative humidities (16% to 17% between 777 mb and 765 mb) and dew points (averaging - 10° C) revealed in the listed text data (not shown).

5.5 Wallow Fire – June 8, 2011

The June 8, 2011 Fire Weather Outlook for 1149 AM CDT (NWS June 8, 2011) called for "*critical fire weather over eastern Arizona*" A compact closed low was forecasted to slowly drift into Idaho while a separate wave over southern California progressed eastward into the Four Corners region. There was also a modest westerly flow ahead of the broad trough over the West and southerly winds in the southern and central Plains continued to support critical fire weather conditions across portions of the Southwest (NWS June 8, 2011) (Schroeder 1964).

The Alpine ROMAN RAWS revealed critically high nighttime temperatures from midnight to 0600 MDT ranging from 51°F to 55°F (Bates 1962) and very low daytime RH's, steady winds with occasionally strong gusts (Fig. 18,19) also revealed on the Flagstaff atmospheric sounding (Fig. 19). It is inferred that the dry slots and dry intrusions revealed in the WVI (Fig.16) indicated that these factors aligned and the fire burned 24,865 acres (388 sq. mi.) that day (Table 1).

The Flagstaff, AZ Skew-T atmospheric soundings also indicated very dry and unstable conditions at and near the surface and aloft (Fig. 26) likewise with anomalously low relative humidities (average 2% between 659 mb and 606 mb) and dew points (between - 37° C and 44° C at the same levels) revealed in the listed text data (not shown).

5.6 Monument Fire – June 12, 2011

The Monument Fire began June 12, 2011 at approximately 1315 MDT under the influence of a Haines Index of 5 / 6 that day (not shown). It burned most of the Coronado National Memorial in southeastern AZ near Sierra Vista (Fig. 3) in grass, chaparral, oak, and mesquite in steep mountainous terrain

A mid-level trough was positioned across portions of the western U.S. with a persistent mid-level ridge over portions of the southern Plains (NWS June 12, 2013). The ridge was expected to build and amplify while a mid-level impulse over southwestern Arizona moved northeastward to the Four Corners area (Fig.31). This pattern supported a zone of enhanced mid-level southwesterly to westerly flow over portions of the southwest deserts, central Great Basin, southern and central Rocky Mountains, and the southern and central High Plains (NWS June 12, 2013) (Fig.31). Saturday evening soundings revealed steep low-to-mid level lapse rates with dry boundary layer conditions already in place (Figs. 32, 34).

A close examination of the Noon Creek, AZ ROMAN RAWS data at 4925' elevation (Fig.34) revealed critically high nighttime temperatures from midnight to 0600 MDT, ranging from 55° F to 62° F during that time. The relative humidities during those hours were low but not critical, and the winds were very light. However, during the daylight and into the evening hours the relative humidities and dew points were extremely low. There were single digit RH's from 0900 to 2100 MDT (not shown). Likewise, the dew points for that same period were very low, ranging from 11.6° F to – 12.6° F. The afternoon and evening winds were brisk averaging about 10 mi/h with strong gusts from 17 to 30 mi/h (Figs. 30, 31). Dry slots and dry intrusions revealed in the WVI on June 12th (Fig.32) and through June 19th (not shown) indicated that these factors aligned and the fire burned 26,956 acres (42 sq. mi.) (Table 1). The Tucson, AZ Skew-T atmospheric soundings also indicated very dry and unstable conditions at and near the surface and aloft (Fig. 32) likewise with very low relative humidities (3% to 7% between 781 mb and 700 mb) and dew points (average - 25° C) revealed in the listed text data (not shown).

6. Fire Weather Commonalities

All three of these fires examined revealed some noteworthy, yet predictable, commonalities. They are enumerated as follows: (a) dry slots and/or dry intrusions were clearly evident on the satellite WVI during and/or proximate to these fire behavior events, (b) the Alignment of Forces concept of relative humidity, wind, slope, preheating added to the mix, (c) critical to blow-up high nighttime temperatures on every fire, during every night examined, (d) very low to anomalously low relative humidities, often single digit for hours on end and sometimes at night, (e) low to extremely low nighttime and/or daytime dew points that generally corresponded to the low RH's, (f) moderate to strong daytime and/or nighttime winds and gusts particularly after the onset of solar heating, (g) troughs during almost every event, (h) all of the surrounding RAWS within 50 air miles of the RAWS sites examined revealed similar readings, (i) Haines Index 5 / 6 on all but one day, (j) exceptionally dry 2010-2011 winter months with very little rain and/or snowpack, (k) very low soil moistures, very low dead and live fuel moistures along with heavy fuel loadings, (l) antecedent prolonged Southwest drought for several years, and (m) all under the influence of dry air from afar based on backward trajectories over the 4 week period May to June . All of these mechanisms directly contributed to erratic to extreme fire behavior and large fire growth!

6. Summary and Conclusions

Dry slots and other weather factors were shown to be responsible for large wildland fire growth in the 2011 Arizona wildfires examined. The original dry slot "*theory*" proposed by Australian BoM Dr. Graham Mills (retired) has been shown in the Australian and United States literature to verify that dry slots are responsible for decreased dew points and relative humidities that result in abrupt near-surface and sometimes surface drying, decreased fuel moistures, and increased and gusty winds with resultant large wildland fire growth. The movement of a dry slot in the WVI towards an existing fire, or towards an area where fire danger is already extreme might be an indicator of potentially more extreme fire behavior with some hours warning. Therefore, uniting satellite WVI monitoring into existing fire weather watch procedures may be most advantageous (Mills 2005b).

The author regards Forest Service researcher J. J. Charney as exactly right with his assertions regarding atmospheric conditions aloft: "*Atmospheric conditions aloft are becoming increasingly recognized as important factors in producing more accurate fire weather and fire behavior predictions, particularly for periods of extreme and erratic fire behavior. The atmospheric structures that contribute to these conditions are, in many cases, predictable hours or even days in advance of the event. The task is to develop and implement indices and diagnostics into the operational fire weather and fire behavior forecasting that sense these conditions and communicate to the forecasters and the operational users of fire weather prediction when and where the potential exists for extreme fire behavior*" (Charney 2007) .

7. **Future Research**

The definite connection between dry air aloft, dry slots, and dry intrusions influencing large wildland fire growth in the United States and North America warrants further research. The research also revealed and suggested that there are very strong associations to high nighttime temperatures, high Haines Index, stratospheric intrusions, subsidence, nocturnal low-level jets and jet streaks, and other influencing mechanisms which warrant further research.

8. Acknowledgements

The author thankfully acknowledges the valuable encouragement and constructive criticism supplied by those that have most assisted in this dry slot research: Dr. Graham Mills, Australian BoM (retired) initially piqued this author's interest in the subject and guided him toward U.S. wildfires affected by dry slots. John F. Saltenberger, U.S. Fish and Wildlife Service meteorologist in the Northwest Interagency Coordination Center, Predictive Services Program in Portland, Oregon has been a tremendous advocate from the beginning. J. Brent Wachter, NOAA NWS meteorologist and

Incident Meteorologist (IMET) in Albuquerque, NM has continued to educate the author in the art of research and meteorology. Paul Werth, Weather Research and Consulting Services, LLC of Battle Ground, Washington; meteorologist and researcher has been a great help with dry slot insight and information, and data, Finally, Nicole Petersen, meteorologist, Rutgers University who has given valuable advice, guidance, and encouragement.

Thanks to the NOAA/ESRL Physical Sciences Division, Boulder Colorado for the RH reanalysis cross-section http://www.esrl.noaa.gov/psd/

The author gratefully acknowledges the NOAA Air Resources Laboratory (ARL) for providing the HYSPLIT transport and dispersion model and/or website http://www.ready.noaa.gov used in this publication.

9. List of Figures

four millibars (mb).; the red and green dashed lines are 1000-500mb thickness contours. lower left panel is NARR 700 mb height and RH; the black contours are isohypse at the 700mb level, and are contoured every 3dm (the isohypse are in decameters); light brown areas are regions where 700mb RH is less than 30%, with dark brown areas less than 10%; white areas indicate regions where the RH is between 30% and 70%; and the lower right panel is 6-hour precipitation, 700 mb Omega, and 850 mb 0°C isotherm; precipitation amounts are measured in hundredths of an inch; the black solid and dashed contours on the panel display the 700mb Omega.; and the red dashed contour across the map is the 850mb 0°C isotherm..

6 NOAA GOES-13 WVI color enhanced for May 8, 2011 at 1745Z (1145 MDT).

7 University of WY skew-T atmospheric soundings at Tucson, AZ for May 8, 2011 at 12Z (above) and 0Z (below).

8 May 8, 2011 Muleshoe Ranch, AZ ROMAN RAWS – elevation 4560.'

9 CONUS Drought Severity Index archive by Division map for period ending May 7, 2011. Long Term Palmer Drought Index.

10 NOAA Air Resources Laboratory (ARL) HYSPLIT GDAS, 440-hour Relative Humidity Ensemble Backward Trajectories for May 28 to June 15, 2011, ending at 18Z June 15, 2011. Gallup, NM used as receptor site (black star).

11 Penn State University, Dept. of Meteorology, 4-Panel Archive map for May 29, 2011 at 0Z (1800 MDT). Panels as in Fig. 5.

12 NOAA GOES-13 WVI color enhanced for May 29, 2011 at 1145Z (0545 MDT).

13 University of WY skew-T atmospheric soundings for May 29, 2011 at Flagstaff at 12z (above) and 0Z (below).

14 May 29, 2011 Alpine, AZ ROMAN RAWS – elevation 8029.’

15 CONUS Drought Severity Index archive by Division map for period ending May 28, 2011. Long Term Palmer Drought Index.

16 NOAA GOES-13 WVI color enhanced for June 3, 2011 at 2045Z (1445 MDT).

17 Penn State Dept. of Meteorology 4-Panel Archive for June 3, 2011 at 0Z (1800 MDT). Panels as in Figure 5.

18 University of WY skew-T atmospheric soundings for June 3, 2011 at Flagstaff, AZ at 12z (above) and 0Z (below).

19 May 29, 2013 Weather Conditions for Alpine RAWS – 8209’ elevation. ROMAN RAWS

20 CONUS Drought Severity Index archive by Division map for period ending June 4, 2011. Long Term Palmer Drought Index.

21 NOAA GOES-13 WVI color enhanced for June 5, 2011 at 1745Z (1145 MDT).

22 University of WY skew-T atmospheric soundings for June 5, 2011 at Flagstaff, AZ at 12z (above) and 0Z (below).

23 June 3, 2011 Alpine, AZ ROMAN RAWS – elevation 4560.’

24 Wallow Fire - June 5, 2011 – Intense fire behavior at 1257 MDT - Courtesy of Jason Coil - Sedona F.D.

25 NOAA – GIBBS GOES-13 WVI color enhanced for June 8, 2011 at 1745Z (1145 MDT).

26 University of WY skew-T atmospheric soundings for June 8, 2011 at Flagstaff, AZ at 12z (above) and 0Z (below).

27 Wallow Fire - June 8, 2011 - Intense fire behavior at 1139 MDT - Courtesy of Jason Coil – Sedona F.D.

28 NOAA – GIBBS GOES-13 WVI for June 8, 2011 at 2045Z (1445 MDT).

29 Wallow Fire - June 8, 2011 - Intense fire behavior at 1355 MDT. Courtesy of Jason Coil - Sedona F.D.

30 June 8, 2011 Alpine, AZ ROMAN RAWS – elevation 8029'.

31 Penn State University Dept. of Meteorology 4-Panel Archive for June 12, 2011 at 0Z (1800 MDT). Panels as in Figure 5.

32 NOAA – GIBBS GOES-13 WVI color enhanced for June 12, 2013 at 21Z (1500 MDT).

33 University of WY skew-T atmospheric soundings for June 12, 2011 at Tucson, AZ at 12Z (above) and 0Z (below).

34 June 12, 2011 Noon Creek, AZ ROMAN RAWS – elevation 4925'.

35 CONUS Drought Severity Index archive by Division map for period ending June 11, 2011. Long Term Palmer Drought Index.

Table 1. Wallow Fire progression and fire growth dates, acreages, and square miles burned from May 30 to June10, 2013. azcentral.com

10. Figures and Tables

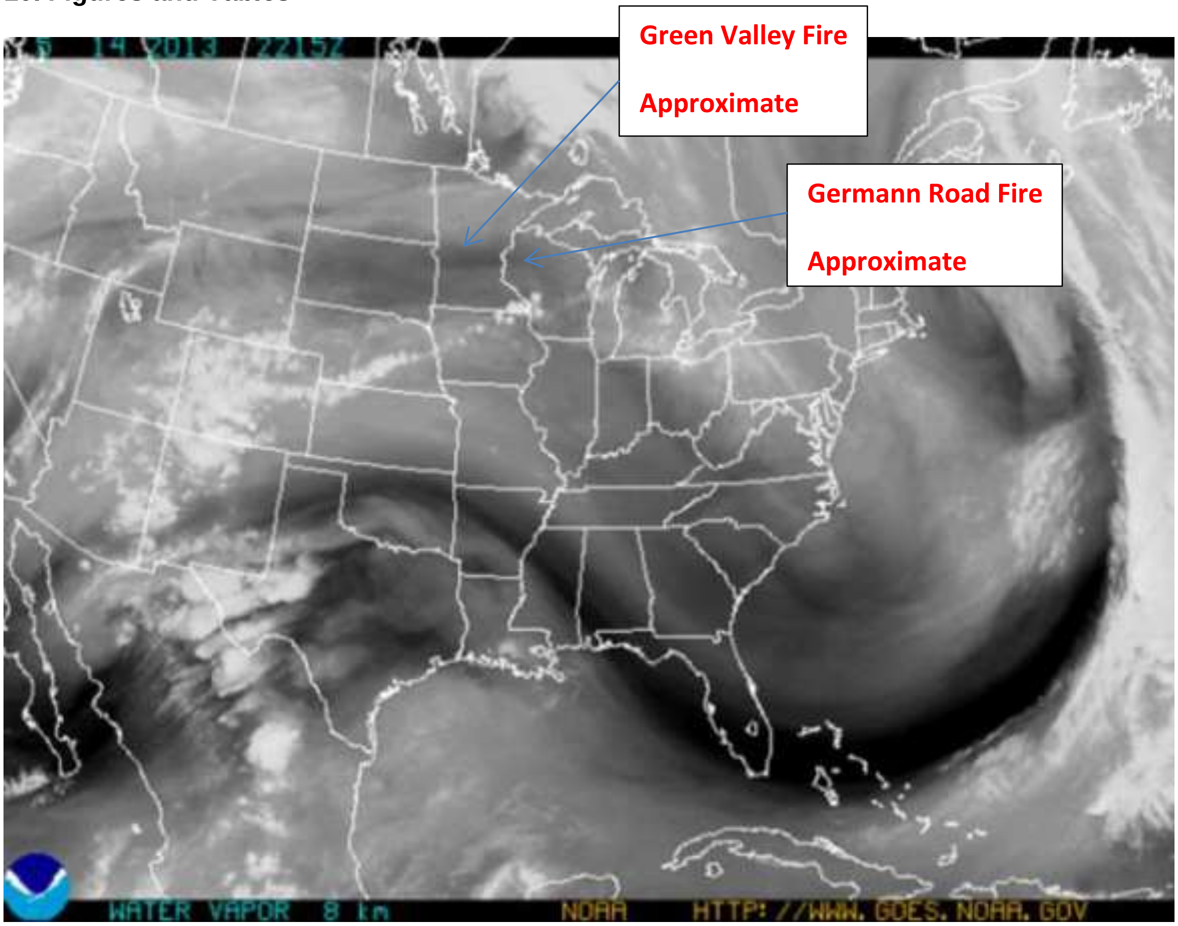


Fig.1. NOAA GOES Water Vapor Imagery (WVI) for 14 May 2013 at 2215Z.

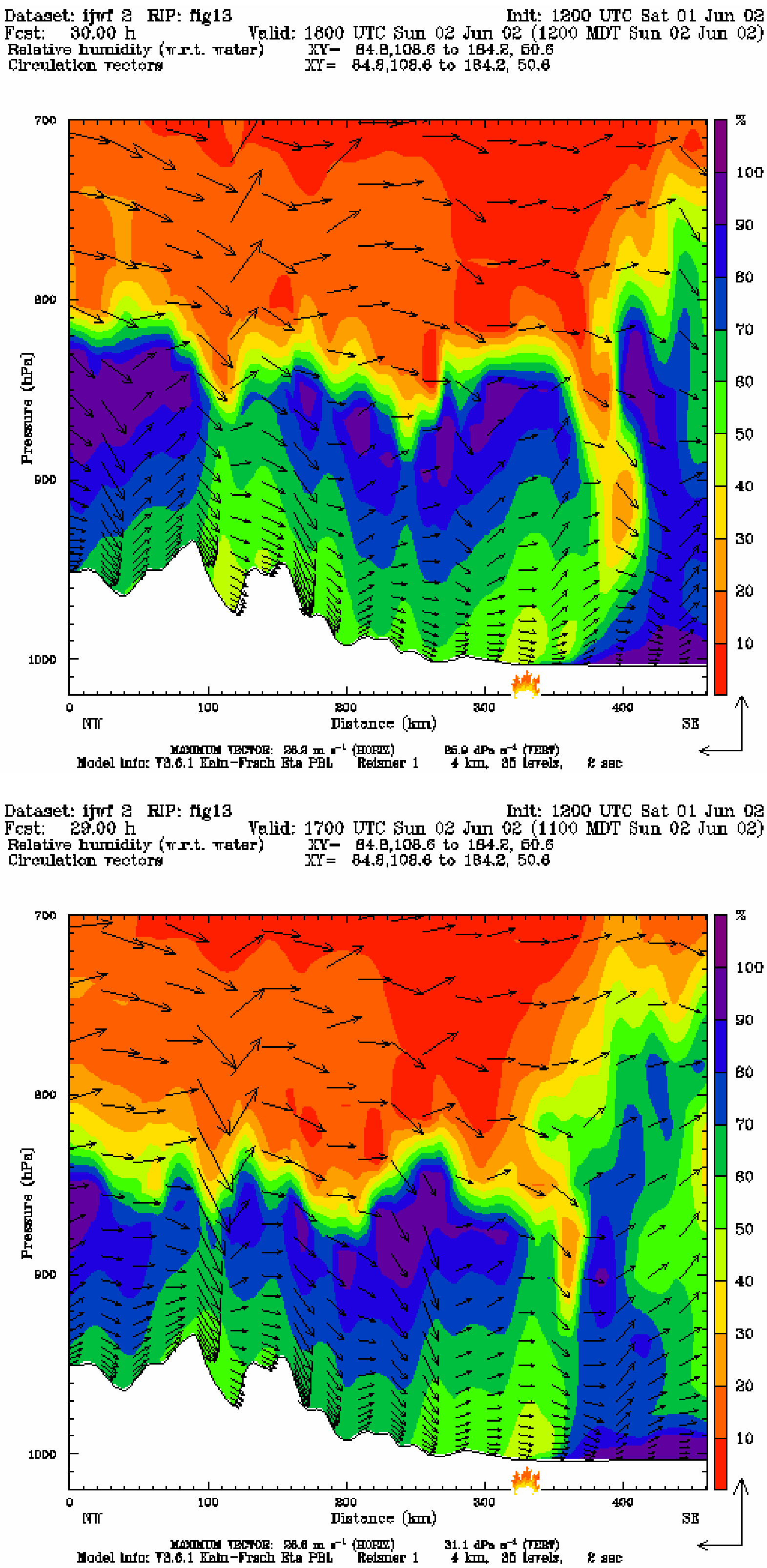
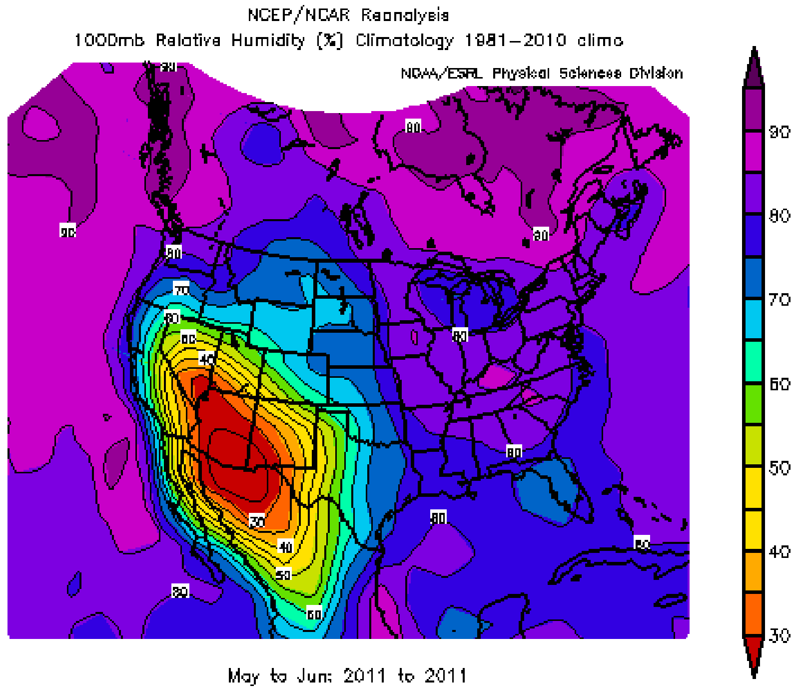


Fig.2. Northwest-southeast vertical cross section of simulated relative humidity and wind vectors for the 2 June 2002 Double Trouble State Park (DTSP) wildfire in New Jersey valid at 17Z (above) and 18Z (below) (Charney 2007).

Fig.3. Arizona map indicating approximate 2011 wildfire locations. Wikipedia online
http://en.wikipedia.org/wiki/Arizona



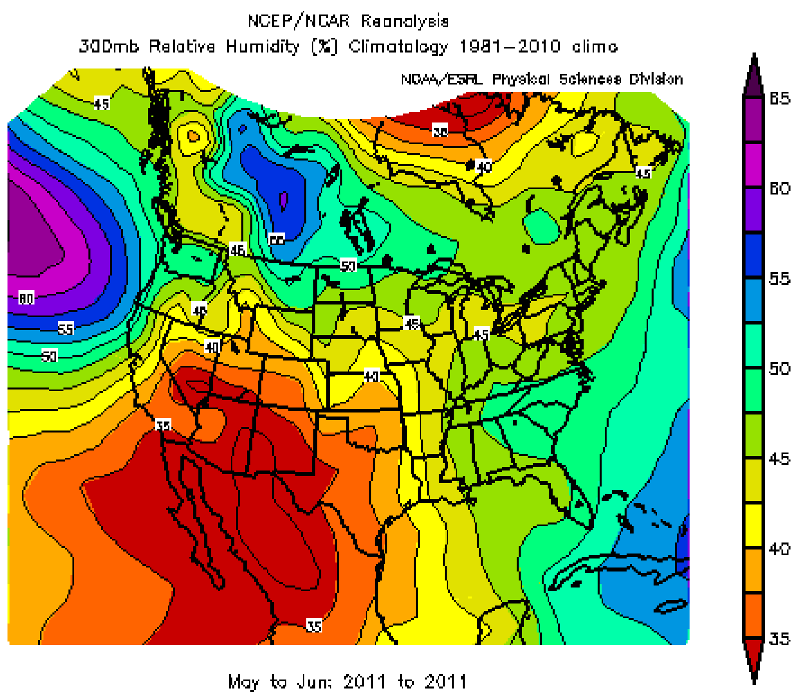


Fig. 4. NOAA NCEP/NCARR Reanalysis vertical cross-section for the United States for May 2011 to June 2011 for long term mean relative humidity at 1000 mb (above) and 300 mb (below).

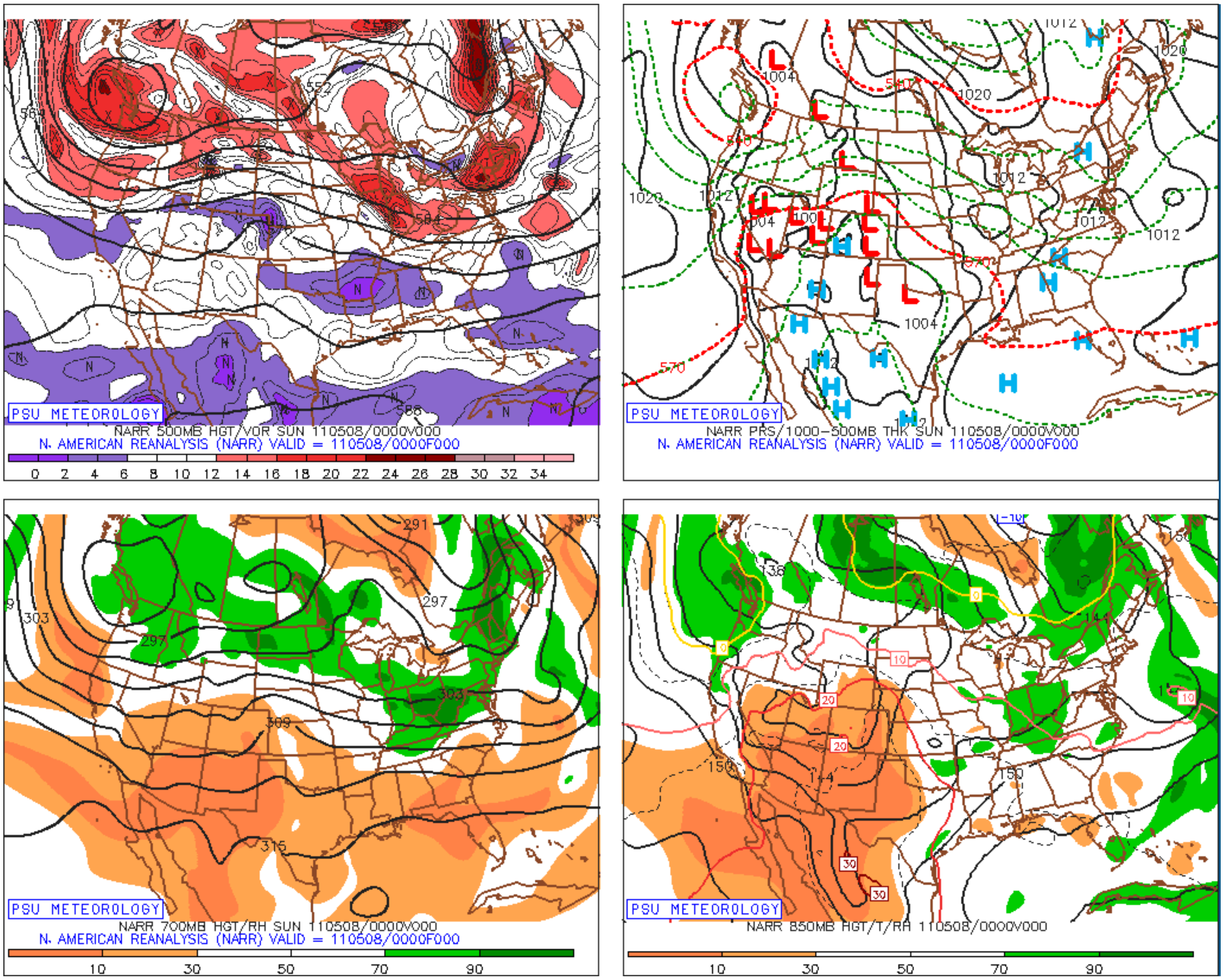


Fig.5. 5 Pennsylvania State University (PSU) 4-Panel Archive Map for May 8, 2011 at 0Z (1800 MDT) – upper left panel is 500 mb height and vorticity; the black contours are isohypse (lines of constant height), and are contoured every 6 decameters (the values on the isohypse are in decameters (dm); the red and purple shading on the map indicate areas of vorticity in the atmosphere; the upper right panel is surface pressure and 1000-500 mb thickness; the black lines on this panel are isobars, (lines of constant pressure), and are contoured every four millibars (mb).; the red and green dashed lines are 1000-500mb thickness contours. lower left panel is NARR 700 mb height and RH; the black contours are isohypse at the 700mb level, and are contoured every 3dm (the isohypse are in decameters); light brown areas are regions where 700mb RH is less than 30%, with dark brown areas less than 10%; white areas indicate regions where the RH is between 30% and 70%; and the lower right panel is 6-hour precipitation, 700 mb Omega, and 850 mb 0°C isotherm; precipitation amounts are measured in hundredths of an inch; the black solid and dashed contours on the panel display the 700mb Omega.; and the red dashed contour across the map is the 850mb 0°C isotherm.

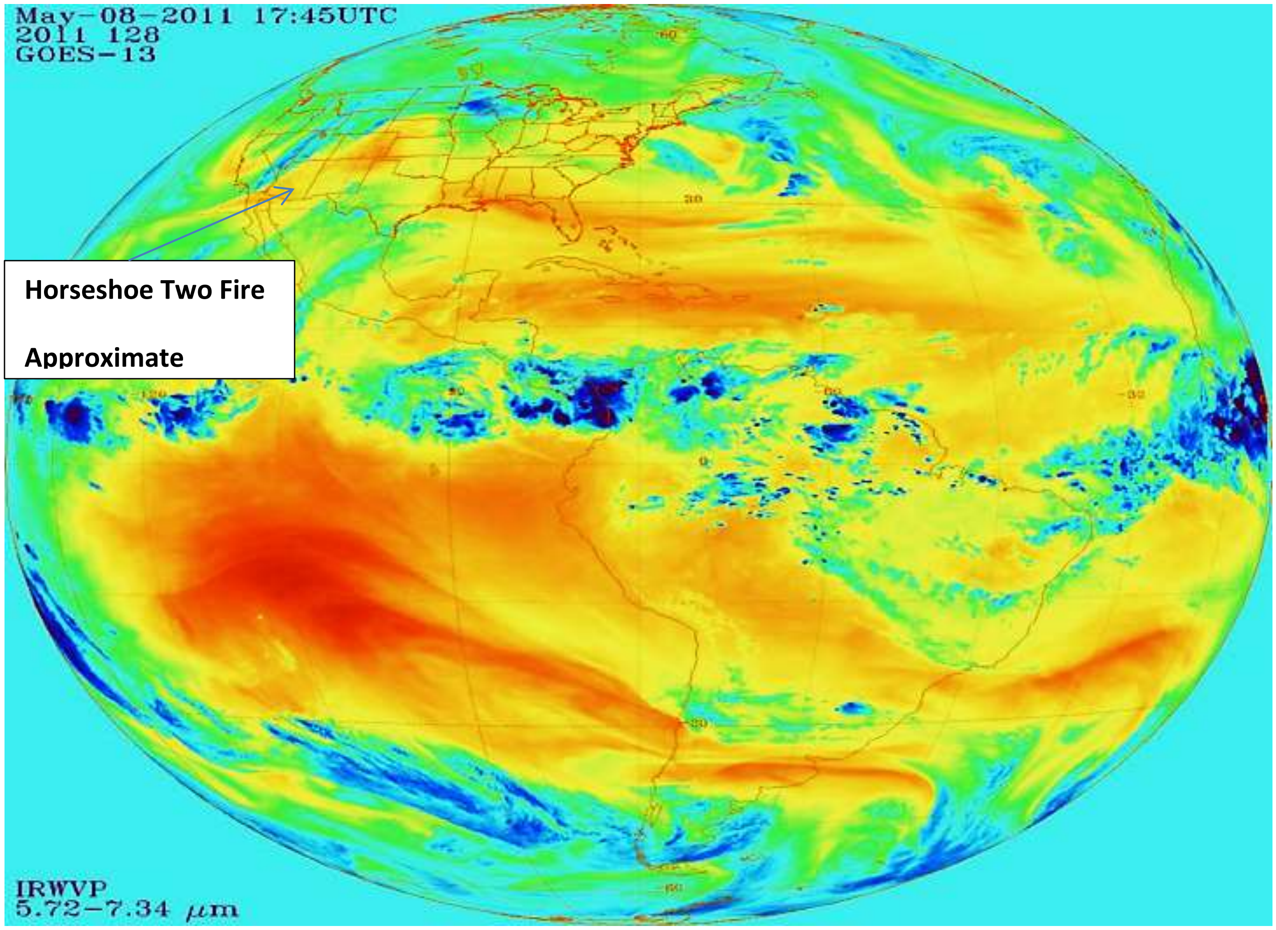
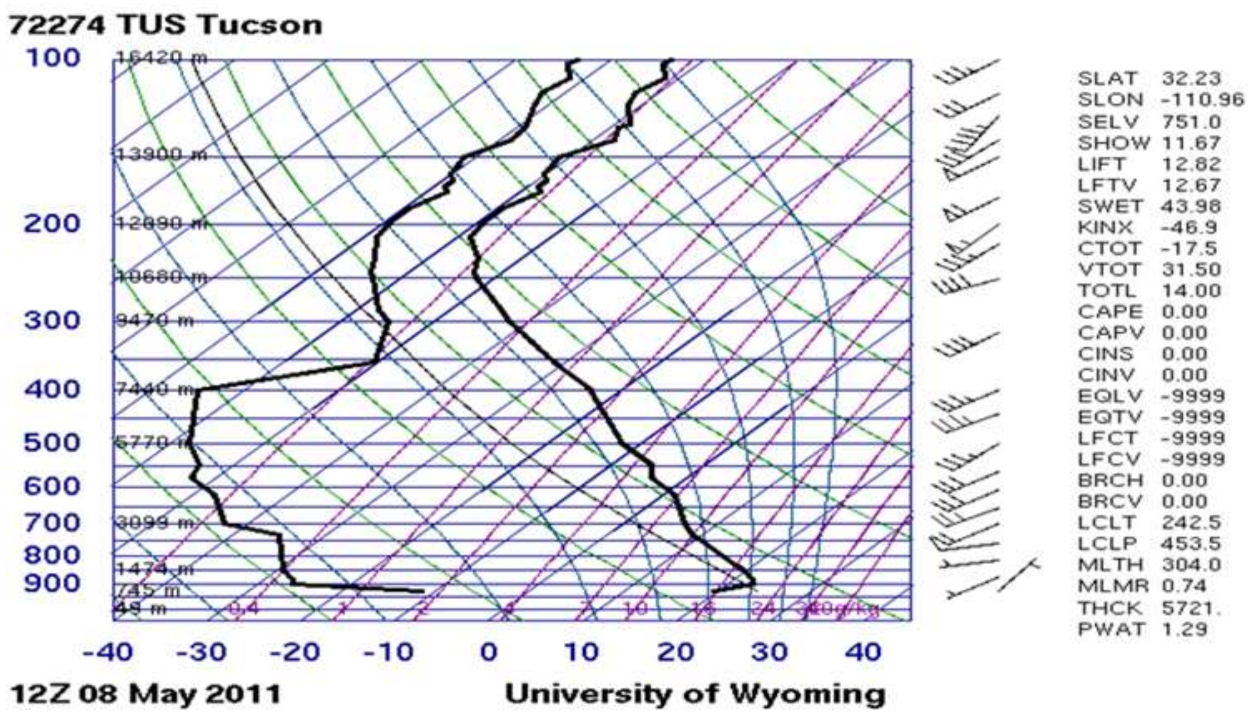


Fig.6. NOAA GOES-13 Satellite Water Vapor Imagery (WVI) color enhanced for May 8, 2011 at 1745Z (1145 MDT).



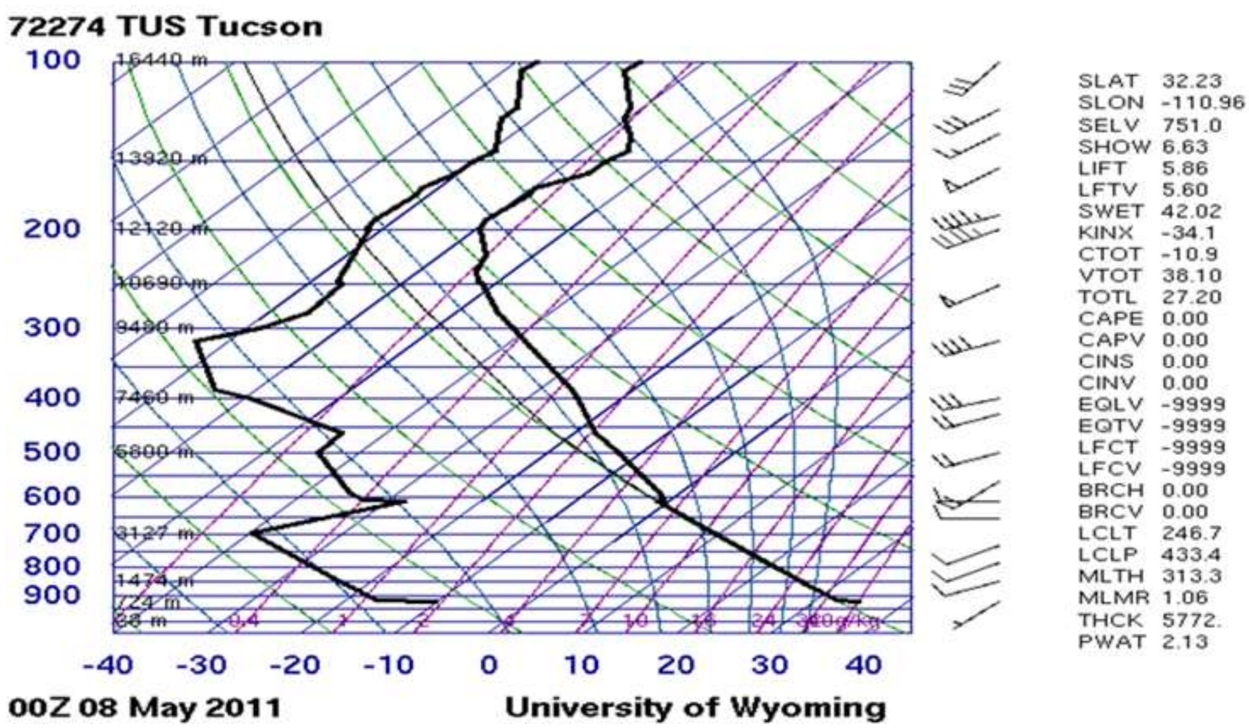


Fig.7. University of WY skew-T atmospheric soundings at Tucson, AZ for May 8, 2011 at 12Z (above) and 0Z (below).

Fig. 8. May 8, 2011 Muleshoe Ranch, AZ ROMAN RAWS – elevation 4560’

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
2:03	80.0	-7.7	3	8	23	W	OK	101.0	1.59	76.0	2
1:03	85.0	-12.6	2	9	30	WNW	OK	350.0	1.59	87.0	2
0:03	87.0	-11.3	2	12	25	W	OK	613.0	1.59	93.0	2
23:03	88.0	-10.7	2	12	26	W	OK	850.0	1.59	98.0	2
22:03	88.0	-10.7	2	12	29	W	OK	1033.0	1.59	101.0	2
21:03	89.0	-10.0	2	12	26	NW	OK	1153.0	1.59	103.0	2
20:03	88.0	3.8	4	12	24	WSW	OK	1198.0	1.59	104.0	2
19:03	86.0	-3.7	3	10	21	SW	OK	1182.0	1.59	99.0	2
18:03	85.0	-4.3	3	10	17	S	OK	1087.0	1.59	98.0	2
17:03	84.0	5.8	5	7	13	SW	OK	915.0	1.59	98.0	2
16:03	79.0	12.7	8	7	10	SE	OK	693.0	1.59	86.0	2
15:03	74.0	11.6	9	6	9	SSE	OK	439.0	1.59	77.0	2
14:03	68.0	11.5	11	5	7	SSE	OK	129.0	1.59	64.0	2
13:03	54.0	10.2	17	1	3	NW	OK	9.0	1.59	48.0	2
12:03	57.0	11.3	16	0	3	NE	OK	0.0	1.59	49.0	2
11:03	55.0	9.7	16	2	5	S	OK	0.0	1.59	49.0	2
10:03	55.0	8.2	15	0	2	WSW	OK	0.0	1.59	48.0	2
9:03	58.0	7.5	13	1	3	SSE	OK	0.0	1.59	50.0	2
8:03	58.0	7.5	13	0	3	NW	OK	0.0	1.59	51.0	2
7:03	60.0	5.4	11	2	4	ESE	OK	0.0	1.59	54.0	2
6:03	62.0	6.9	11	3	5	NE	OK	0.0	1.59	55.0	2
5:03	64.0	4.1	9	1	4	WNW	OK	0.0	1.59	57.0	2
4:03	71.0	6.7	8	3	12	E	OK	0.0	1.59	66.0	2
3:03	76.0	4.1	6	7	17	N	OK	2.0	1.59	72.0	2
2:03	79.0	2.3	5	10	19	NW	OK	95.0	1.59	76.0	2

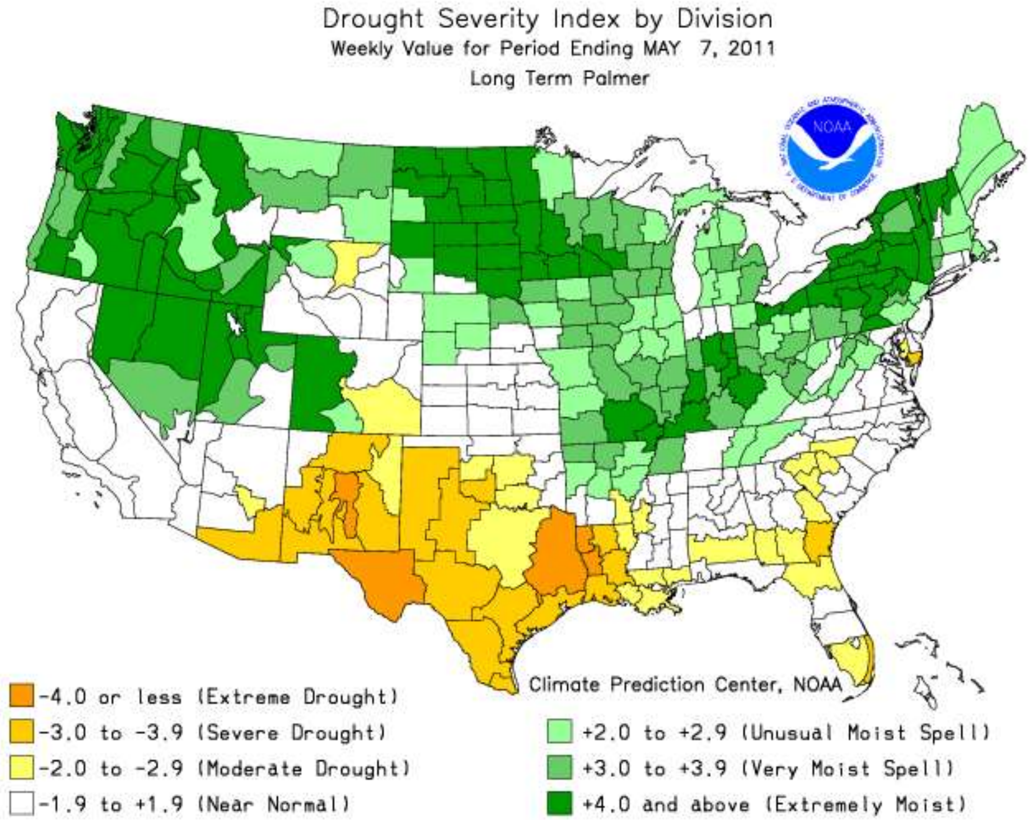


Fig. 9. CONUS Drought Severity Index archive by Division map for period ending May 7, 2011. Long Term Palmer Drought Index.

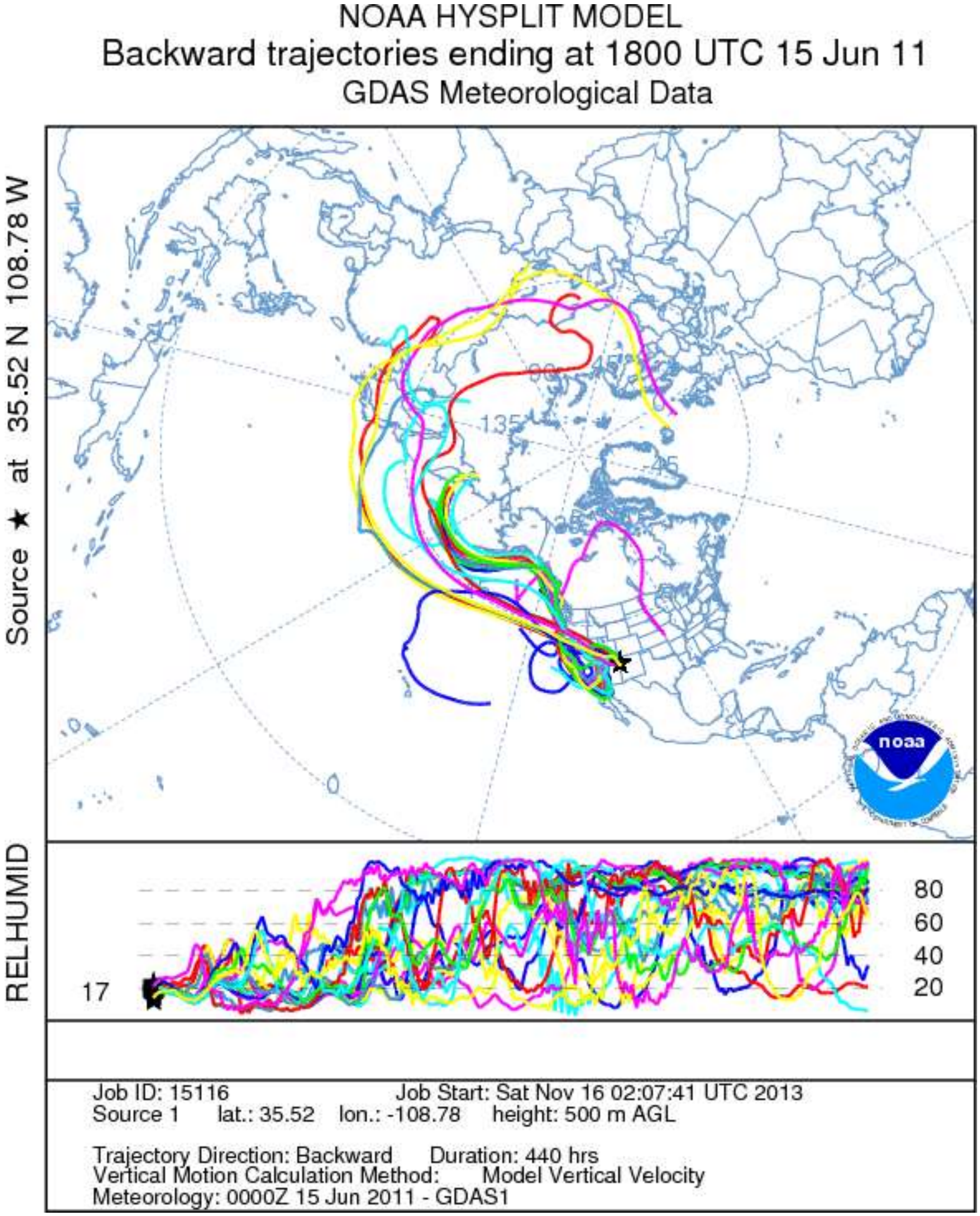


Fig. 10. NOAA Air Resources Laboratory (ARL) HYSPLIT GDAS, 440-hour Relative Humidity Ensemble Backward Trajectories for May 28 to June 15, 2011, ending at 18Z June 15, 2011. Gallup, NM used as receptor site (black star).

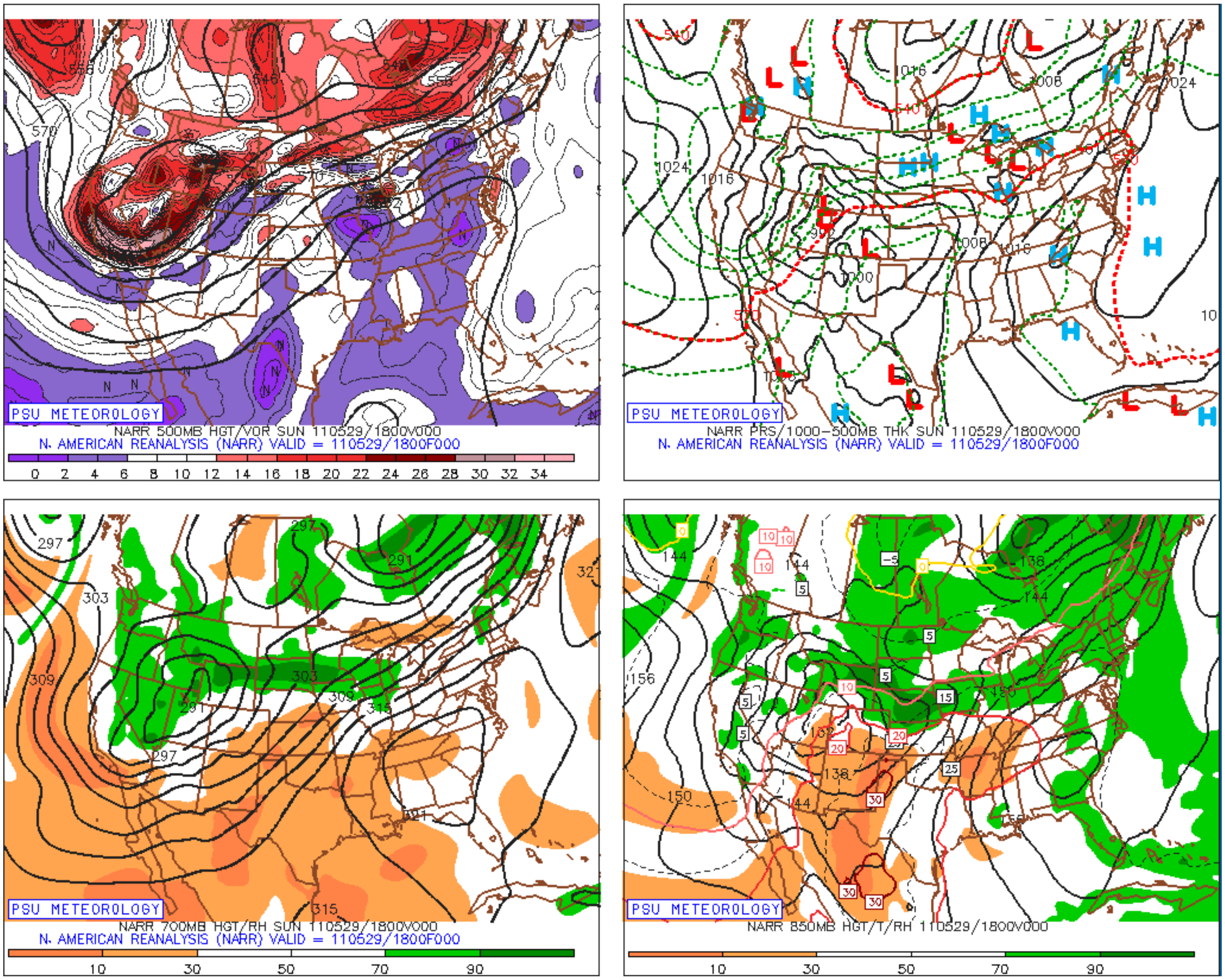


Fig.11. Penn State University, Dept. of Meteorology, 4-Panel Archive for May 29, 2011 at 0Z (1800 MDT). Panels as in Figure 5.

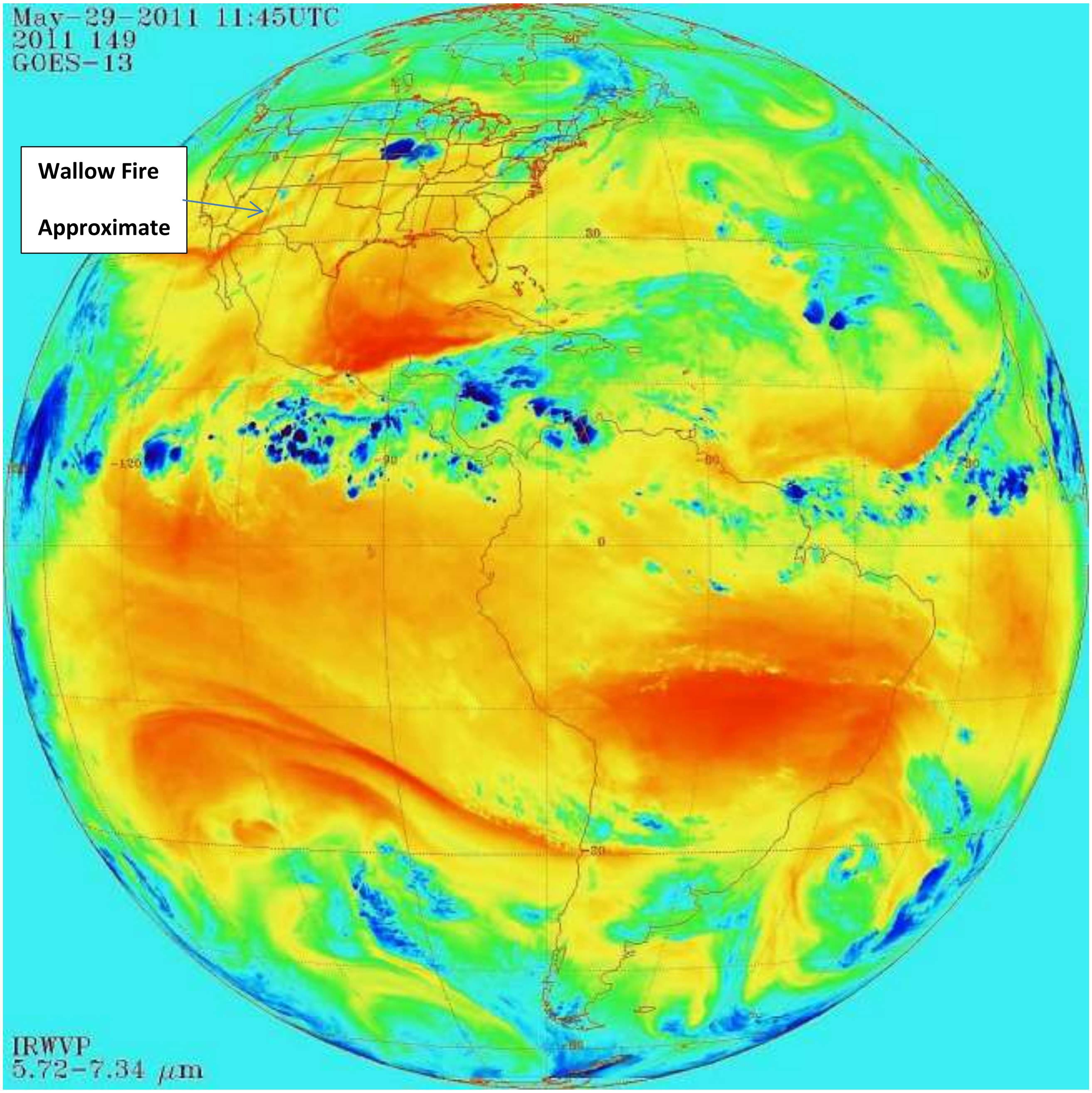
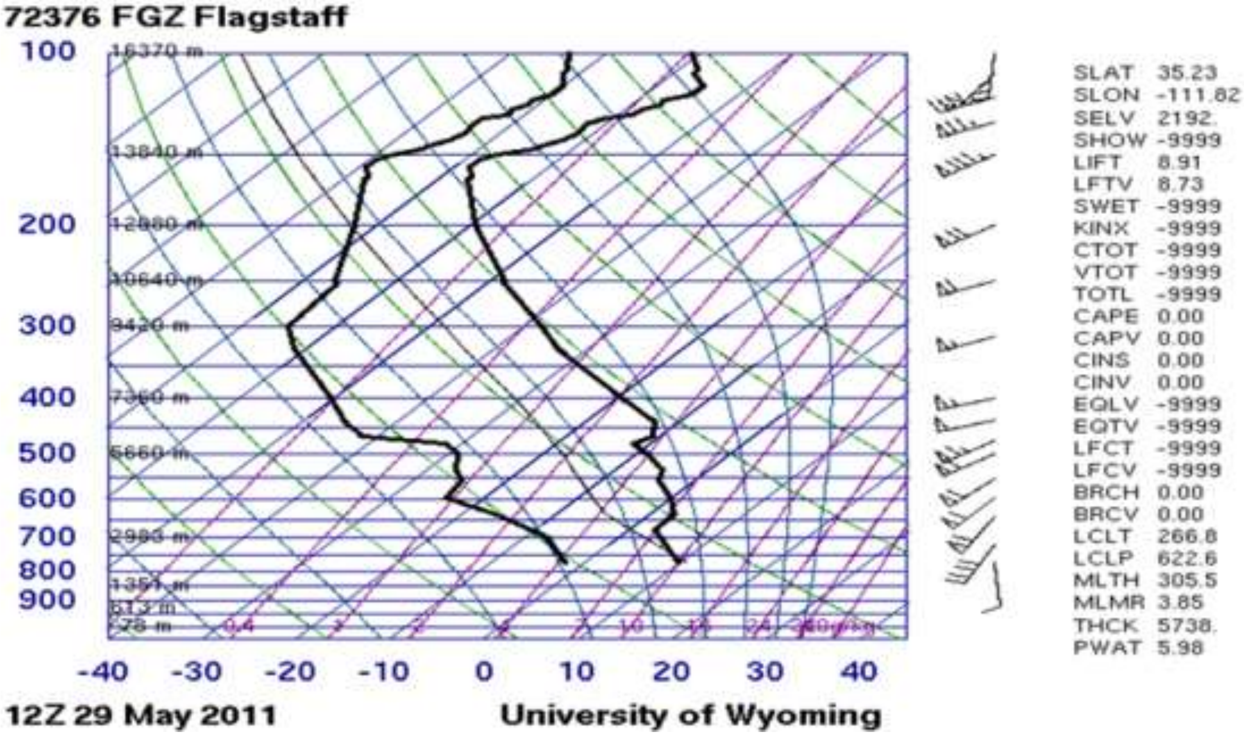


Fig.12. NOAA GOES-13 Satellite Water Vapor Imagery (WVI) color enhanced for May 29, 2011 at 1145Z (0545 MDT).



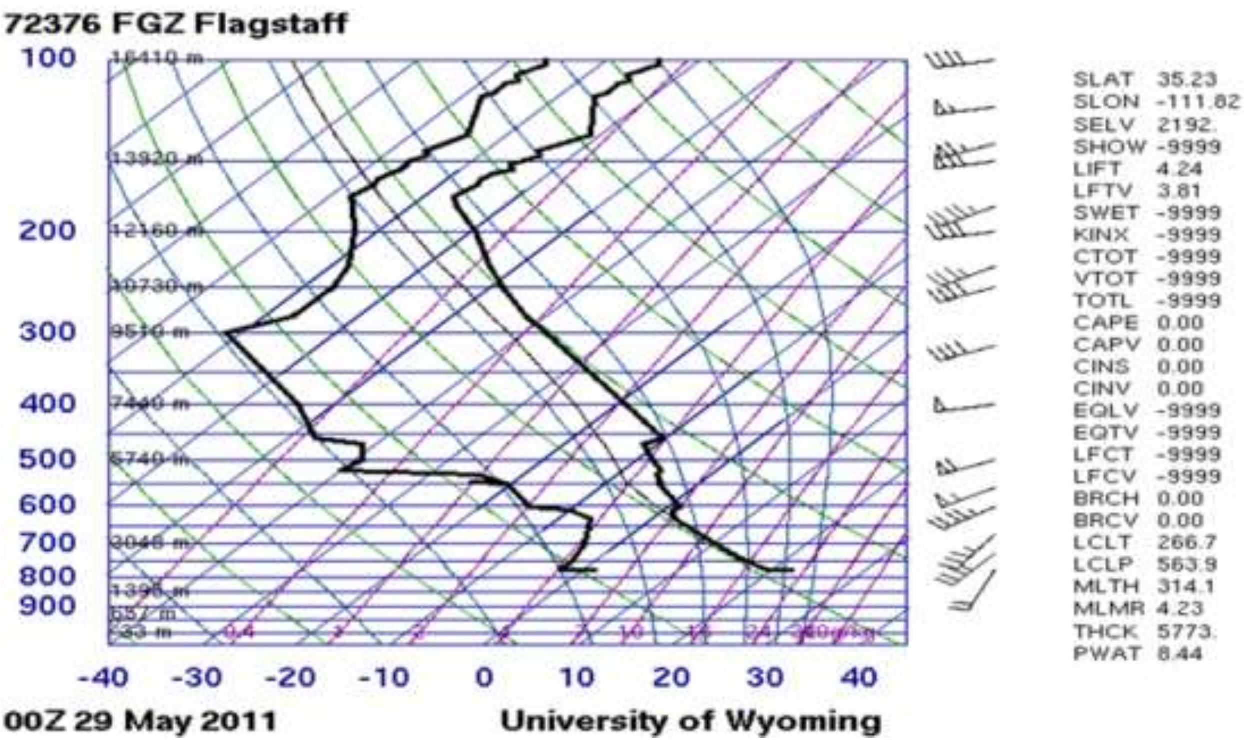


Fig.13. University of WY skew-T atmospheric soundings for May 29, 2011 at Flagstaff, AZ at 12z (above) and 0Z (below).

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	Battery voltage
	° F	° F	%	mph	mph			W/m*m	in	° F	gm	volt
14:16	57.0	28.9	34	**9**	**17**	WSW	OK	313.0	1.10	58.0	**4**	12.80
13:16	51.0	27.5	40	**4**	**17**	SW	OK	71.0	1.10	48.0	**4**	12.70
12:16	**51.0**	26.9	39	**8**	**15**	WSW	OK	3.0	1.10	47.0	**4**	12.70
11:16	**52.0**	26.5	37	**10**	**18**	WSW	OK	0.0	1.10	48.0	**4**	12.70
10:16	**52.0**	23.8	33	**8**	**25**	WSW	OK	0.0	1.10	48.0	**4**	12.70
9:16	**54.0**	24.1	31	**15**	**30**	WSW	OK	0.0	1.10	51.0	**4**	12.80
8:16	**55.0**	24.9	31	**16**	**28**	WSW	OK	0.0	1.10	52.0	**4**	12.80
7:16	**56.0**	24.2	29	**12**	**20**	WSW	OK	0.0	1.10	53.0	**4**	12.80
6:16	**58.0**	24.2	27	**11**	**19**	WSW	OK	0.0	1.10	54.0	**4**	12.80
5:16	58.0	23.3	26	**10**	**22**	WSW	OK	0.0	1.10	55.0	**4**	12.90
4:16	60.0	23.1	24	**11**	**19**	WSW	OK	0.0	1.10	56.0	**4**	12.90
3:16	61.0	21.9	22	**10**	**21**	WSW	OK	1.0	1.10	57.0	**4**	13.00
2:16	63.0	22.5	21	**12**	**25**	WSW	OK	73.0	1.10	61.0	**4**	13.20
1:16	68.0	21.6	**17**	**14**	**27**	WSW	OK	275.0	1.10	68.0	**4**	13.40
0:16	71.0	19.4	**14**	**13**	**26**	WSW	OK	493.0	1.10	75.0	**4**	13.70
23:16	72.0	20.2	**14**	**14**	**29**	WSW	OK	700.0	1.10	79.0	**4**	14.20
22:16	74.0	21.8	**14**	**15**	**26**	WSW	OK	874.0	1.10	84.0	**4**	14.30
21:16	74.0	21.8	**14**	**14**	**25**	WSW	OK	995.0	1.10	87.0	**4**	13.50
20:16	75.0	24.2	**15**	**12**	**21**	WSW	OK	1057.0	1.10	83.0	**4**	13.60
19:16	74.0	25.0	**16**	**10**	**20**	WSW	OK	1063.0	1.10	89.0	**4**	13.70
18:16	73.0	27.0	**18**	**8**	**19**	SW	OK	1017.0	1.10	87.0	**4**	13.80
17:16	71.0	27.9	20	**8**	**22**	WSW	OK	908.0	1.10	82.0	**4**	13.70
16:16	67.0	29.0	24	**8**	**19**	SW	OK	742.0	1.10	75.0	**4**	14.40
15:16	64.0	31.9	30	**5**	**15**	WSW	OK	537.0	1.10	69.0	**4**	13.60
14:16	60.0	33.0	36	**5**	**12**	WSW	OK	313.0	1.10	60.0	**4**	12.80

Fig.14. May 29, 2011 Alpine, AZ ROMAN RAWS – elevation 8029’

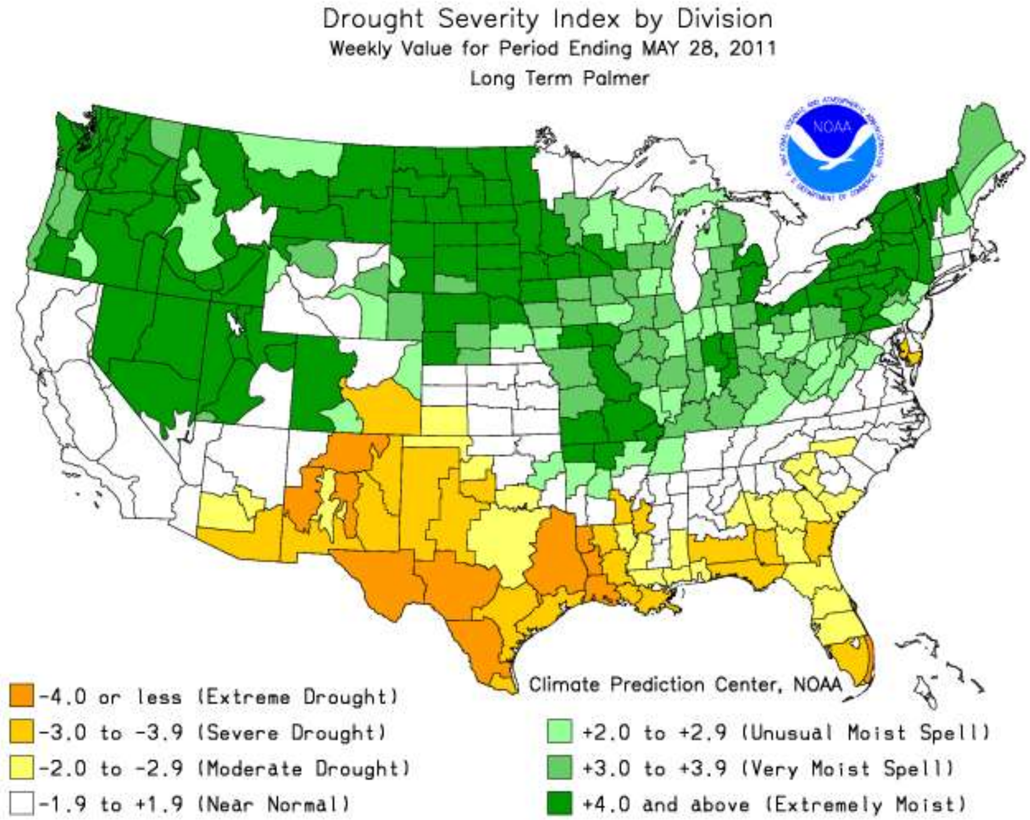


Fig.15. CONUS Drought Severity Index archive by Division map for period ending May 28, 2011. Long Term Palmer Drought Index.

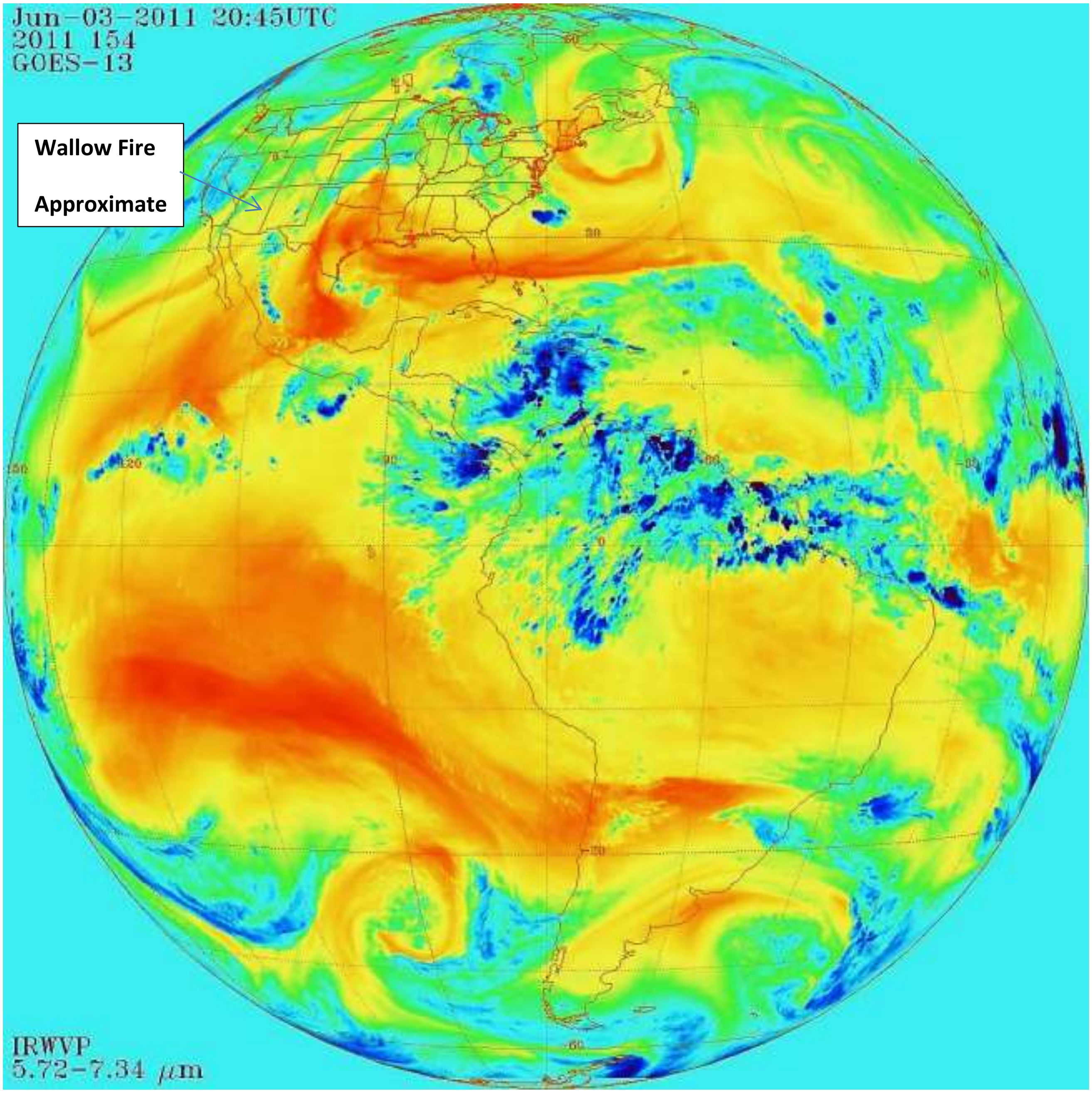


Fig.16. NOAA GOES-13 Satellite Water Vapor Imagery (WVI) color enhanced for June 3, 2011 at 2045Z (1445 MDT).

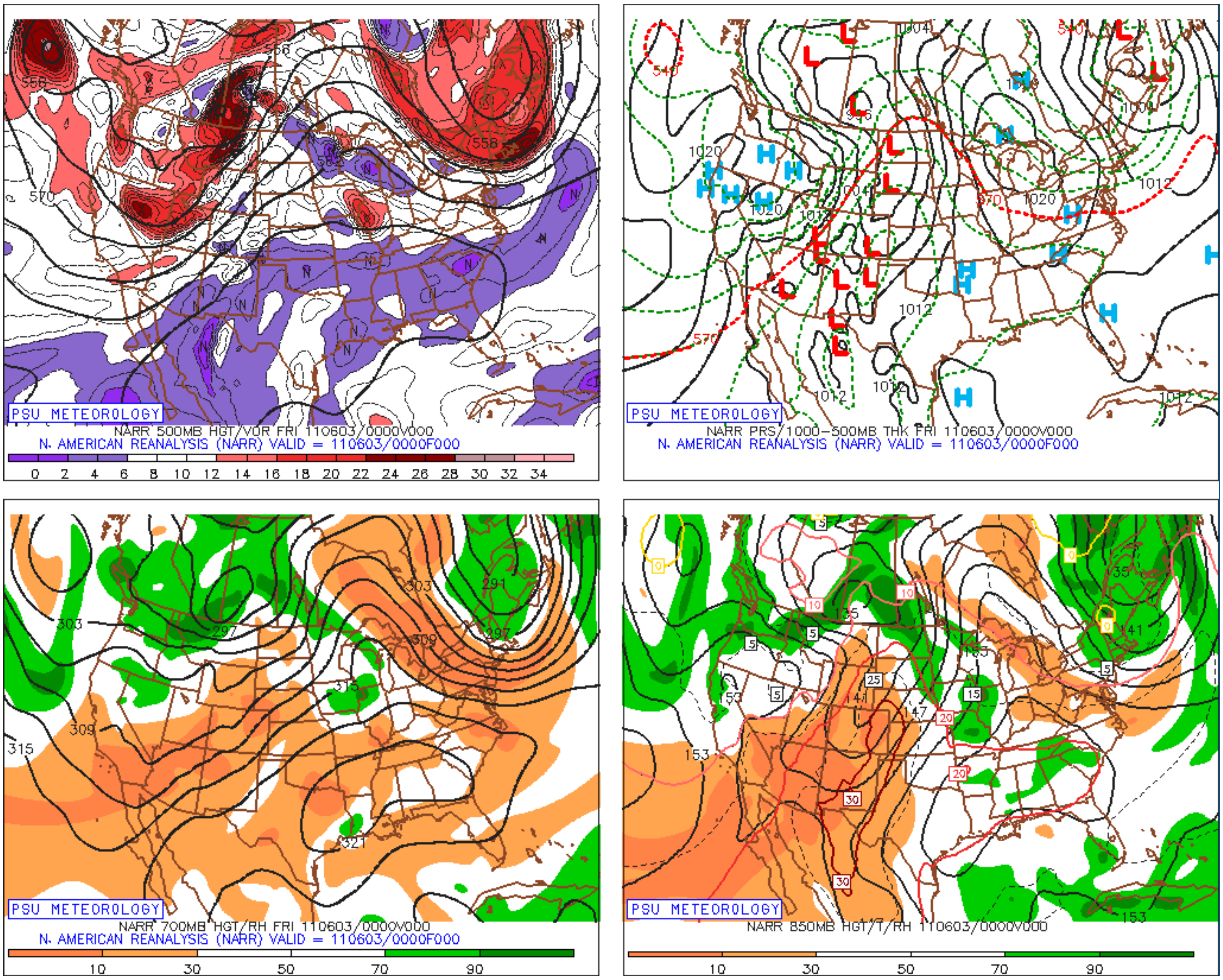
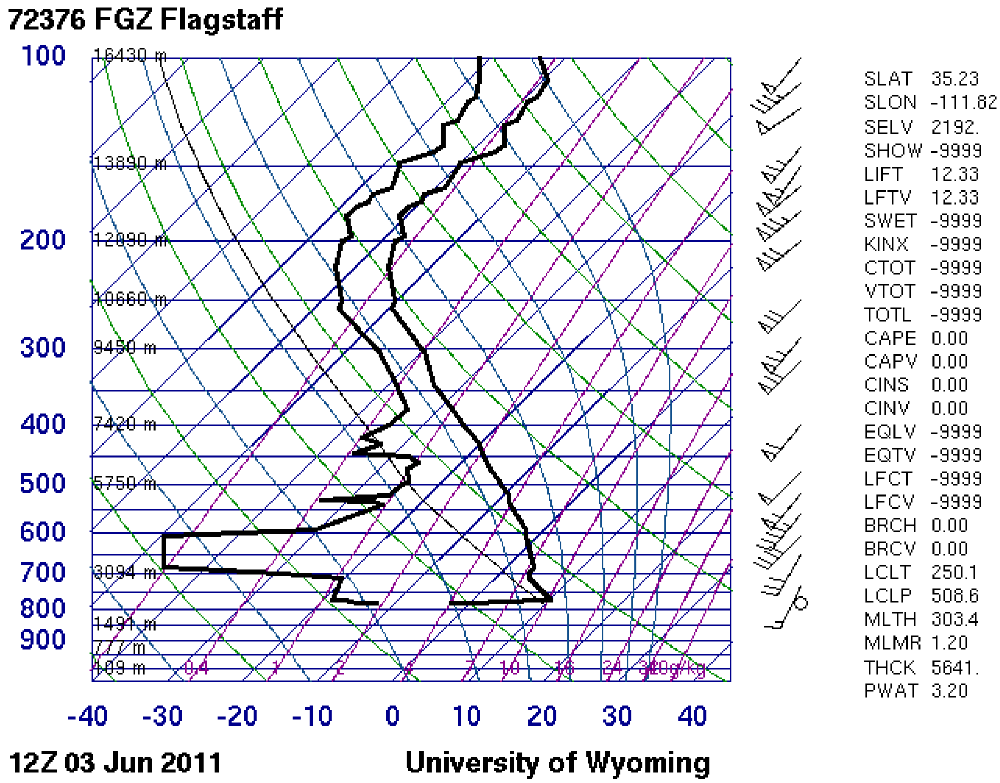


Fig.17. Penn State Dept. of Meteorology 4-Panel Archive for June 3, 2011 at 0Z (1800 MDT). Panels as in Figure 5.



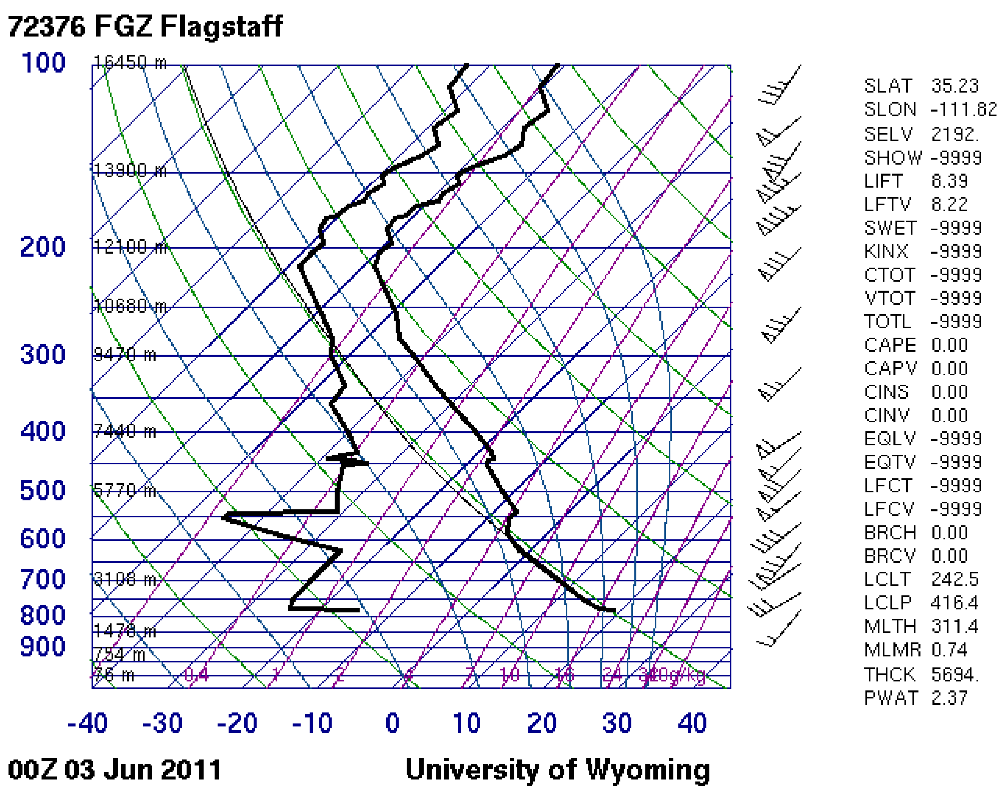


Fig.18. University of WY skew-T atmospheric soundings for June 3, 2011 at Flagstaff, AZ at 12z (above) and 0Z (below).

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
2:16	64.0	12.2	13	8	20	SSW	OK	6.0	1.10	62.0	4
1:16	65.0	11.2	12	8	27	SSW	OK	7.0	1.10	63.0	4
0:16	67.0	12.7	12	8	19	SW	OK	34.0	1.10	64.0	4
23:16	67.0	10.8	11	9	24	SW	OK	39.0	1.10	65.0	4
22:16	68.0	11.5	11	10	22	SW	OK	81.0	1.10	66.0	4
21:16	69.0	12.3	11	11	26	WSW	OK	213.0	1.10	68.0	4
20:16	72.0	12.5	10	9	22	WSW	OK	487.0	1.10	75.0	4
19:16	71.0	15.8	12	11	24	SW	OK	639.0	1.10	74.0	4
18:16	72.0	16.6	12	12	30	SW	OK	976.0	1.10	79.0	4
17:16	72.0	16.6	12	10	25	SW	OK	903.0	1.10	83.0	4
16:16	70.0	18.6	14	9	21	SW	OK	600.0	1.10	77.0	4
15:16	64.0	12.2	13	5	10	WSW	OK	302.0	1.10	65.0	4
14:16	63.0	11.4	13	6	11	SW	OK	277.0	1.10	64.0	4
13:16	57.0	11.3	16	5	11	WSW	OK	78.0	1.10	54.0	4
12:16	**53.0**	8.0	16	5	11	WSW	OK	1.0	1.10	46.0	4
11:16	**51.0**	5.0	15	3	8	W	OK	0.0	1.10	43.0	4
10:16	**54.0**	8.8	16	4	11	WSW	OK	0.0	1.10	46.0	4
9:16	**55.0**	6.7	14	6	11	WSW	OK	0.0	1.10	47.0	4
8:16	**58.0**	5.7	12	6	20	WSW	OK	0.0	1.10	50.0	4
7:16	**59.0**	6.5	12	5	11	WSW	OK	0.0	1.10	52.0	4
6:16	**62.0**	6.9	11	7	19	SW	OK	0.0	1.10	56.0	4
5:16	64.0	4.1	9	6	17	SW	OK	0.0	1.10	59.0	4
4:16	66.0	7.9	10	8	17	WSW	OK	0.0	1.10	62.0	4
3:16	66.0	10.0	11	7	15	WSW	OK	0.0	1.10	63.0	4
2:16	68.0	9.4	10	5	11	WSW	OK	7.0	1.10	64.0	4

Fig. 19.June 3, 2011 Alpine, AZ ROMAN RAWS – elevation 4560’

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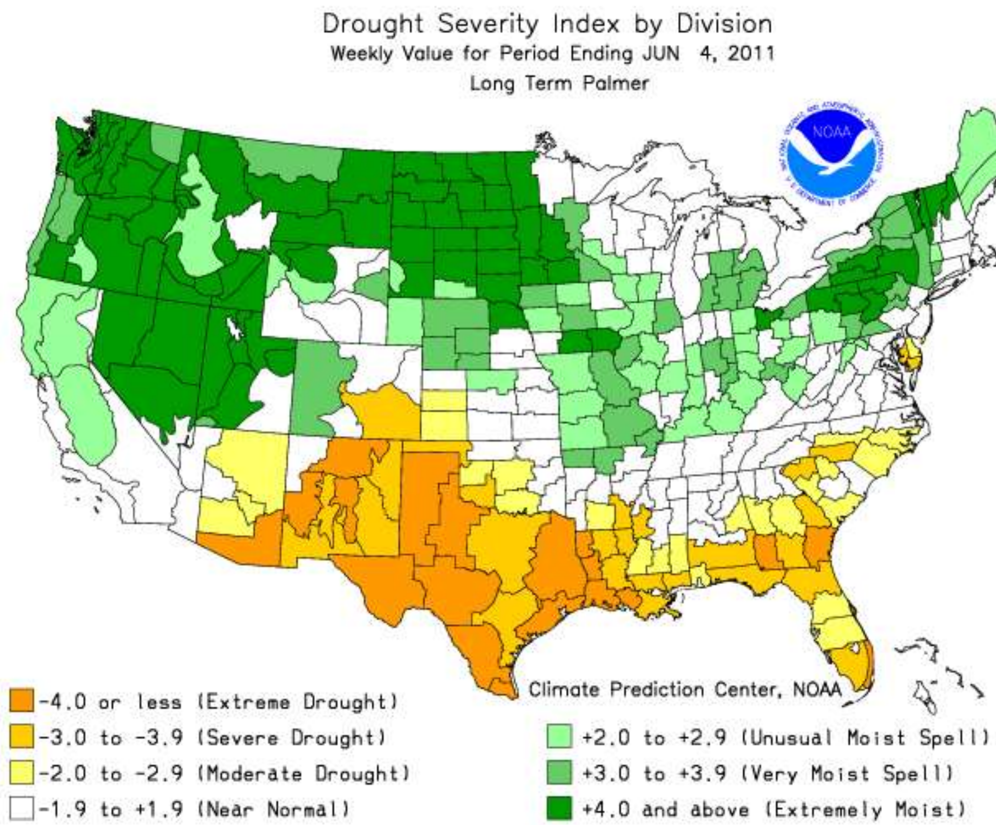


Fig. 20. CONUS Drought Severity Index archive by Division map for period ending June 4, 2011. Long Term Palmer Drought Index.

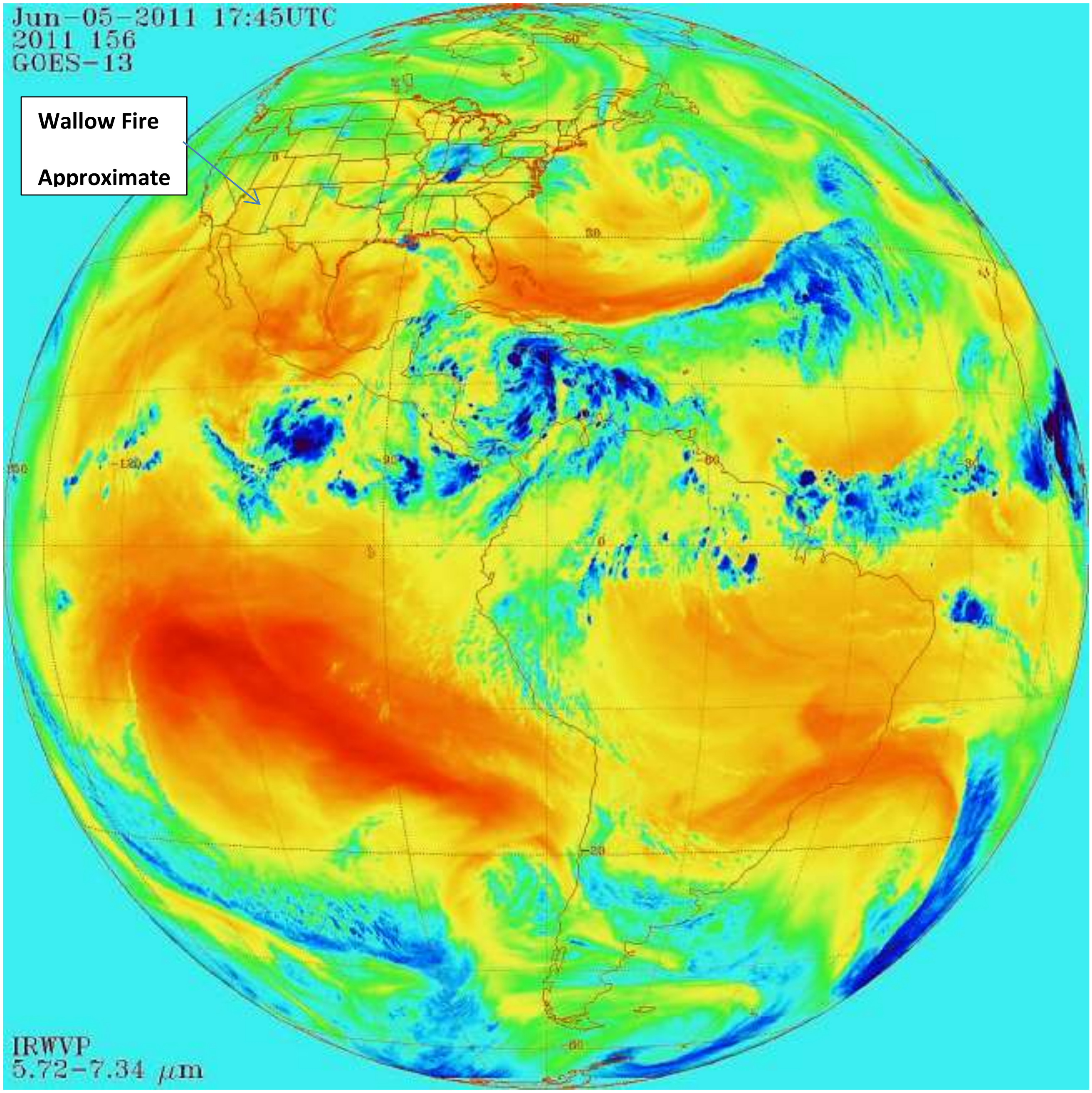
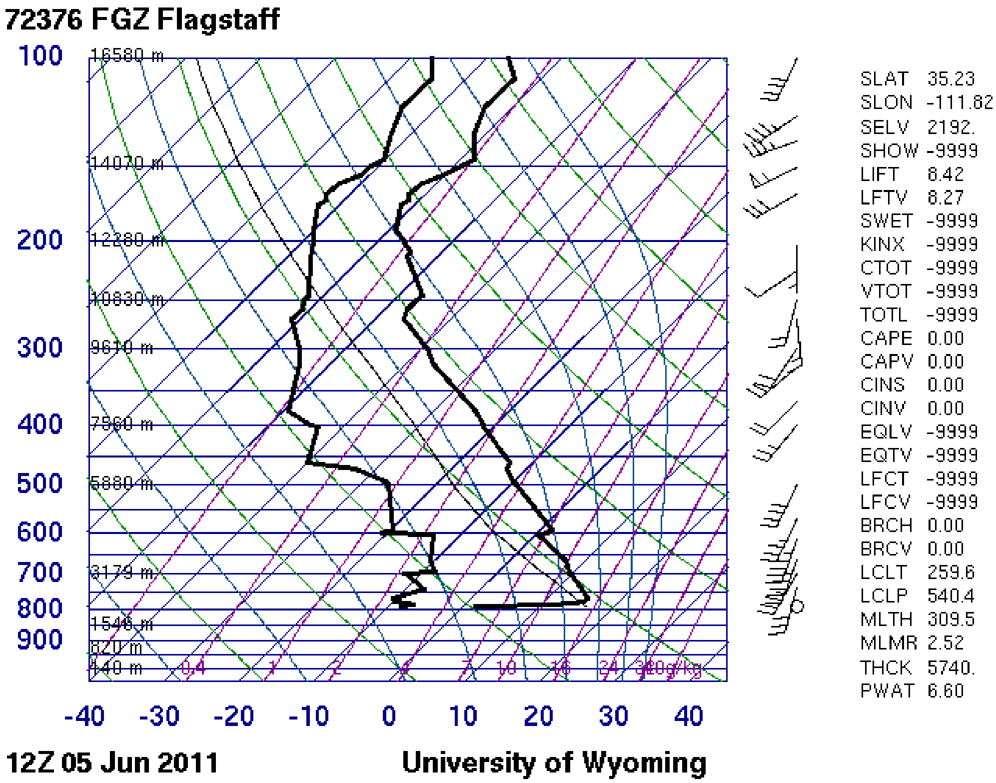


Fig. 21. NOAA GOES-13 Satellite Water Vapor Imagery (WVI) color enhanced for June 5, 2011 at 1745Z (1145 MDT).



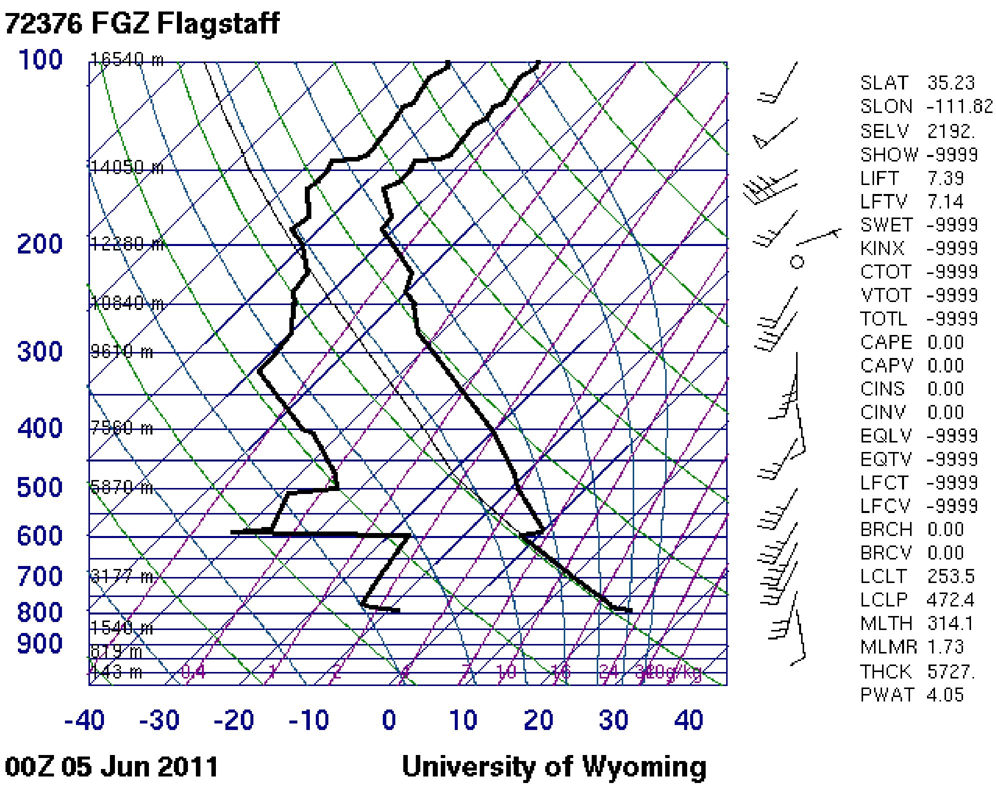


Fig. 22. University of WY skew-T atmospheric soundings for June 5, 2011 at Flagstaff, AZ at 12z (above) and 0Z (below).

Fig. 23. June 5, 2011 Alpine, AZ ROMAN RAWS – elevation 8029'.

Time(GMT)	Temperature ° F	Dew Point ° F	Relative Humidity %	Wind Speed mph	Wind Gust mph	Wind Direction	Quality check	Solar Radiation W/m*m	Precipitation accumulated in	Fuel Temperature ° F	10 hr Fuel Moisture gm
2:16	65.0	11.2	**12**	2	**11**	SSE	OK	25.0	1.10	58.0	**4**
1:16	70.0	13.1	**11**	2	**13**	SW	OK	60.0	1.10	65.0	**4**
0:16	69.0	12.3	**11**	4	**14**	S	OK	39.0	1.10	66.0	**4**
23:16	69.0	12.3	**11**	4	**16**	SW	OK	31.0	1.10	66.0	**4**
22:16	70.0	13.1	**11**	4	**17**	SW	OK	97.0	1.10	67.0	**4**
21:16	75.0	12.4	**9**	10	**21**	SSW	OK	642.0	1.10	80.0	**4**
20:16	76.0	13.1	**9**	8	**23**	SSW	OK	756.0	1.10	81.0	**4**
19:16	74.0	14.0	**10**	10	**24**	S	OK	709.0	1.10	80.0	**4**
18:16	74.0	16.2	**11**	10	**22**	S	OK	931.0	1.10	82.0	**4**
17:16	72.0	16.6	**12**	10	**23**	SSE	OK	759.0	1.10	79.0	**4**
16:16	70.0	15.1	**12**	8	**17**	S	OK	669.0	1.10	74.0	**4**
15:16	68.0	17.0	**14**	5	**12**	SSW	OK	512.0	1.10	72.0	**4**
14:16	60.0	15.1	**17**	4	8	SW	OK	292.0	1.10	60.0	**4**
13:16	52.0	19.1	27	2	3	ENE	OK	76.0	1.10	48.0	**4**
12:16	**43.0**	12.9	29	1	4	SE	OK	2.0	1.10	36.0	**4**
11:16	**43.0**	12.9	29	2	4	ESE	OK	0.0	1.10	37.0	**4**
10:16	**44.0**	13.8	29	1	4	W	OK	0.0	1.10	37.0	**4**
9:16	**44.0**	12.2	27	3	5	ESE	OK	0.0	1.10	37.0	**4**
8:16	**47.0**	11.1	23	1	3	ENE	OK	0.0	1.10	40.0	**4**
7:16	**49.0**	8.6	**19**	2	4	E	OK	0.0	1.10	42.0	**4**
6:16	**53.0**	13.0	20	4	7	ENE	OK	0.0	1.10	46.0	**4**
5:16	57.0	12.6	**17**	5	7	W	OK	0.0	1.10	50.0	**4**
4:16	59.0	11.4	**15**	4	**10**	W	OK	0.0	1.10	52.0	**4**
3:16	61.0	15.9	**17**	4	6	W	OK	1.0	1.10	53.0	**4**
2:16	63.0	14.6	**15**	3	**13**	SSW	OK	26.0	1.10	56.0	**4**

Fig.24. Wallow Fire - June 5, 2011 – Intense fire behavior at 1257 MDT - Courtesy of Jason Coil - Sedona F.D.

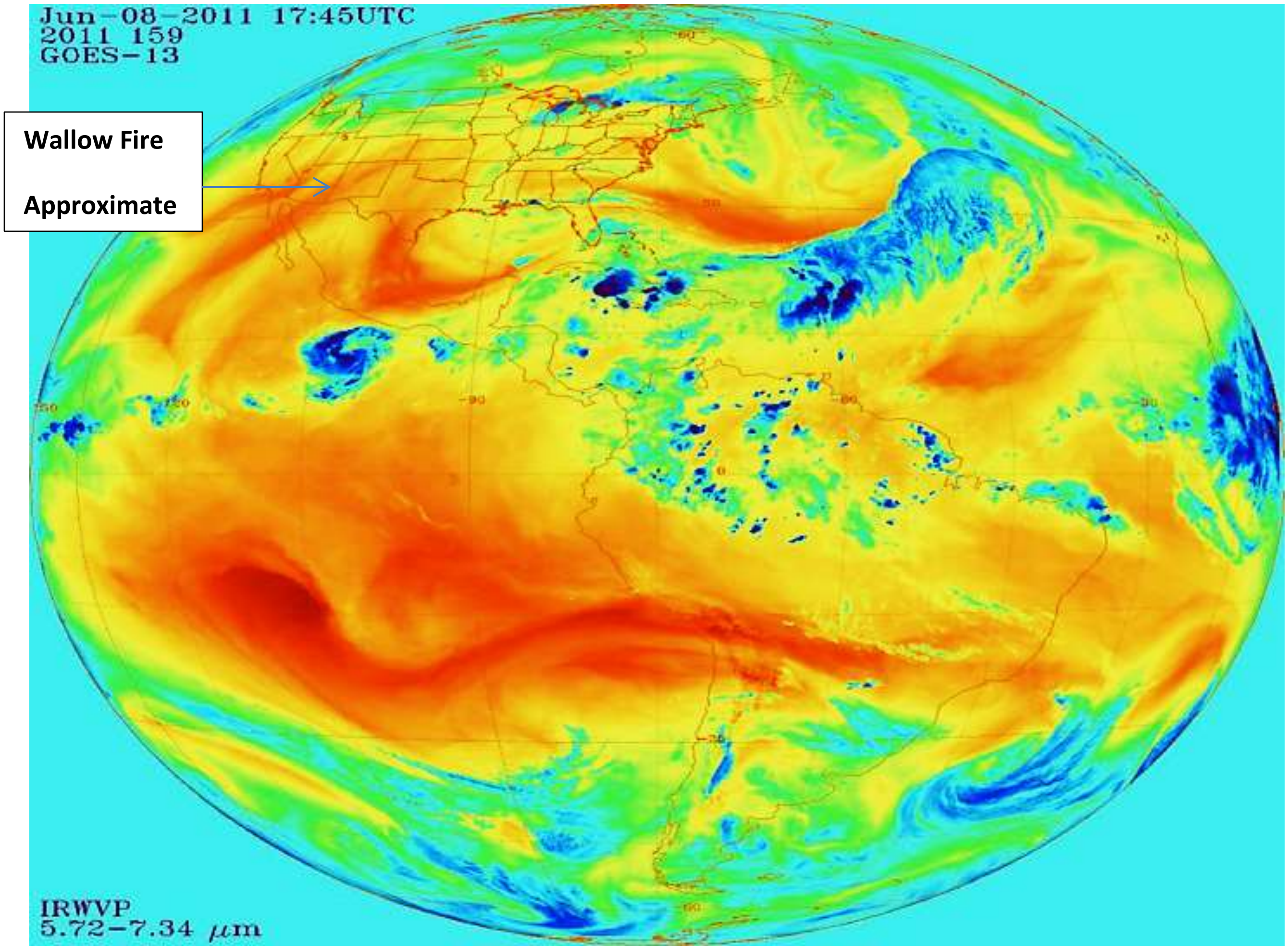


Fig.25. NOAA – GIBBS GOES-13 WVI color enhanced for June 8, 2011 at 1745Z (1145 MDT).

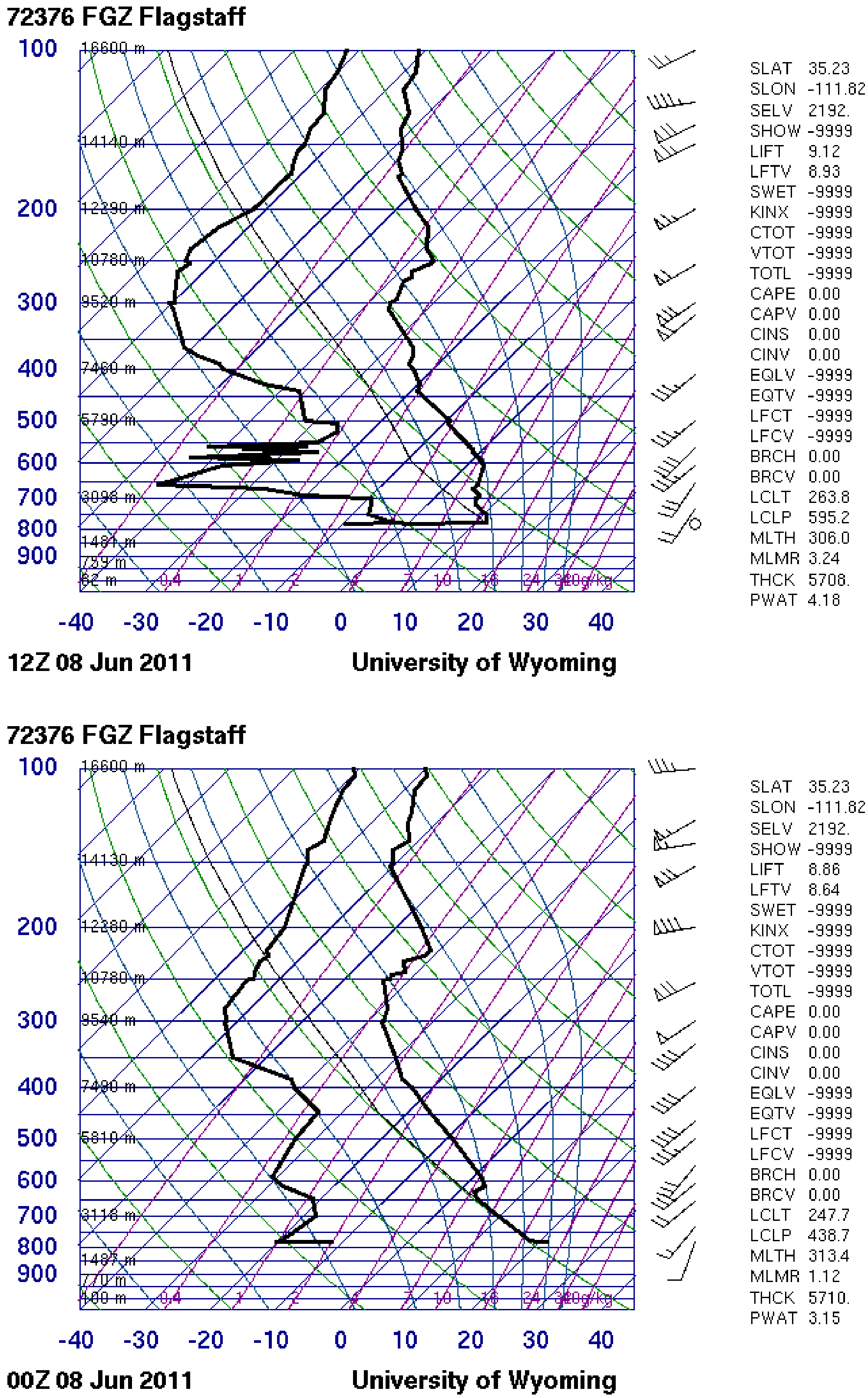


Fig. 26 University of WY skew-T atmospheric soundings for June 8, 2011 at Flagstaff, AZ at 12z (above) and 0Z (below).

Fig.27. Wallow Fire - June 8, 2011 - Intense fire behavior at 1139 MDT - Courtesy of Jason Coil – Sedona F.D.

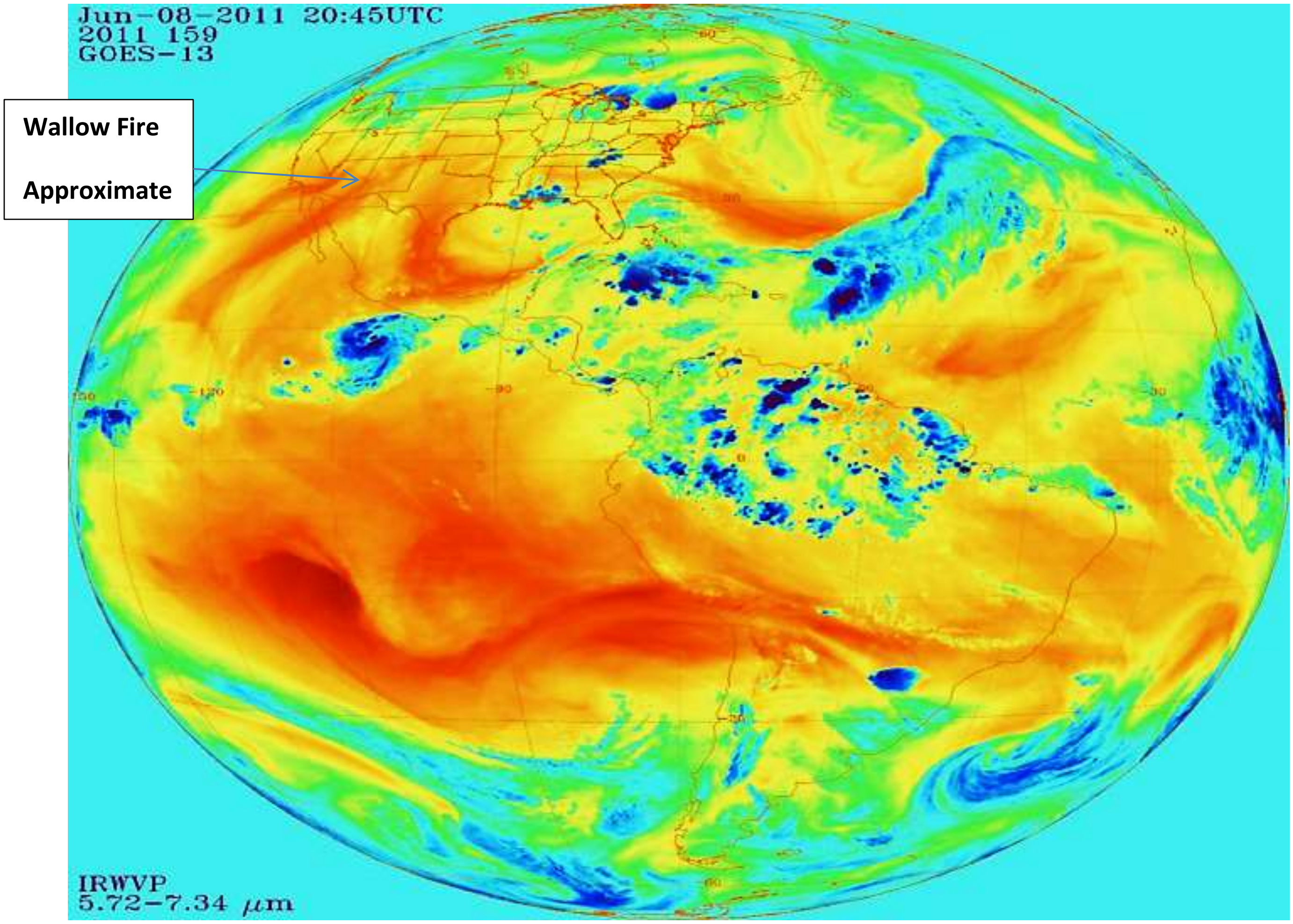


Fig.28. NOAA – GIBBS GOES-13 WVI for June 8, 2011 at 2045Z (1445 MDT).

Fig.29. Wallow Fire - June 8, 2011 - Intense fire behavior at 1355 MDT. Courtesy of Jason Coil - Sedona F.D.

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
3:16	60.0	10.7	**14**	3	**11**	W	OK	4.0	1.10	51.0	**4**
2:16	66.0	10.0	**11**	6	**15**	SW	OK	85.0	1.10	61.0	**4**
1:16	70.0	8.6	**9**	9	**19**	WSW	OK	256.0	1.10	70.0	**4**
0:16	72.0	10.1	**9**	**11**	**19**	WSW	OK	416.0	1.10	75.0	**4**
23:16	74.0	9.0	**8**	**10**	**24**	WSW	OK	589.0	1.10	80.0	**4**
22:16	76.0	10.5	**8**	9	**23**	SW	OK	756.0	1.10	84.0	**4**
21:16	75.0	6.8	**7**	**14**	**26**	WSW	OK	860.0	1.10	83.0	**4**
20:16	75.0	12.4	**9**	**12**	**24**	WSW	OK	956.0	1.10	83.0	**4**
19:16	74.0	14.0	**10**	**11**	**21**	WSW	OK	940.0	1.10	86.0	**4**
18:16	73.0	15.4	**11**	**10**	**24**	WSW	OK	895.0	1.10	85.0	**4**
17:16	70.0	18.6	**14**	**11**	**19**	WSW	OK	732.0	1.10	79.0	**4**
16:16	66.0	18.5	**16**	**10**	**19**	WSW	OK	568.0	1.10	71.0	**4**
15:16	63.0	22.5	21	5	**12**	SW	OK	438.0	1.10	66.0	**4**
14:16	59.0	24.2	26	3	9	WSW	OK	251.0	1.10	58.0	**4**
13:16	52.0	22.3	31	2	6	NNW	OK	60.0	1.10	47.0	**4**
12:16	**48.0**	21.0	34	3	7	N	OK	2.0	1.10	40.0	**4**
11:16	**48.0**	23.0	37	3	6	NNW	OK	0.0	1.10	40.0	**4**
10:16	**48.0**	21.0	34	3	5	NNE	OK	0.0	1.10	40.0	**4**
9:16	**51.0**	20.7	30	2	7	WNW	OK	0.0	1.10	43.0	**4**
8:16	**52.0**	19.1	27	2	14	WSW	OK	0.0	1.10	45.0	**4**
7:16	**56.0**	19.7	24	9	22	WSW	OK	0.0	1.10	52.0	**4**
6:16	**57.0**	17.5	21	**11**	**20**	WSW	OK	0.0	1.10	53.0	**4**
5:16	58.0	13.5	**17**	**11**	**19**	WSW	OK	0.0	1.10	54.0	**4**
4:16	60.0	10.7	**14**	9	**19**	WSW	OK	0.0	1.10	55.0	**4**
3:16	63.0	13.1	**14**	8	**21**	WSW	OK	2.0	1.10	58.0	**4**

Fig. 30. June 8, 2011 Alpine, AZ ROMAN RAWS – elevation 8029’.

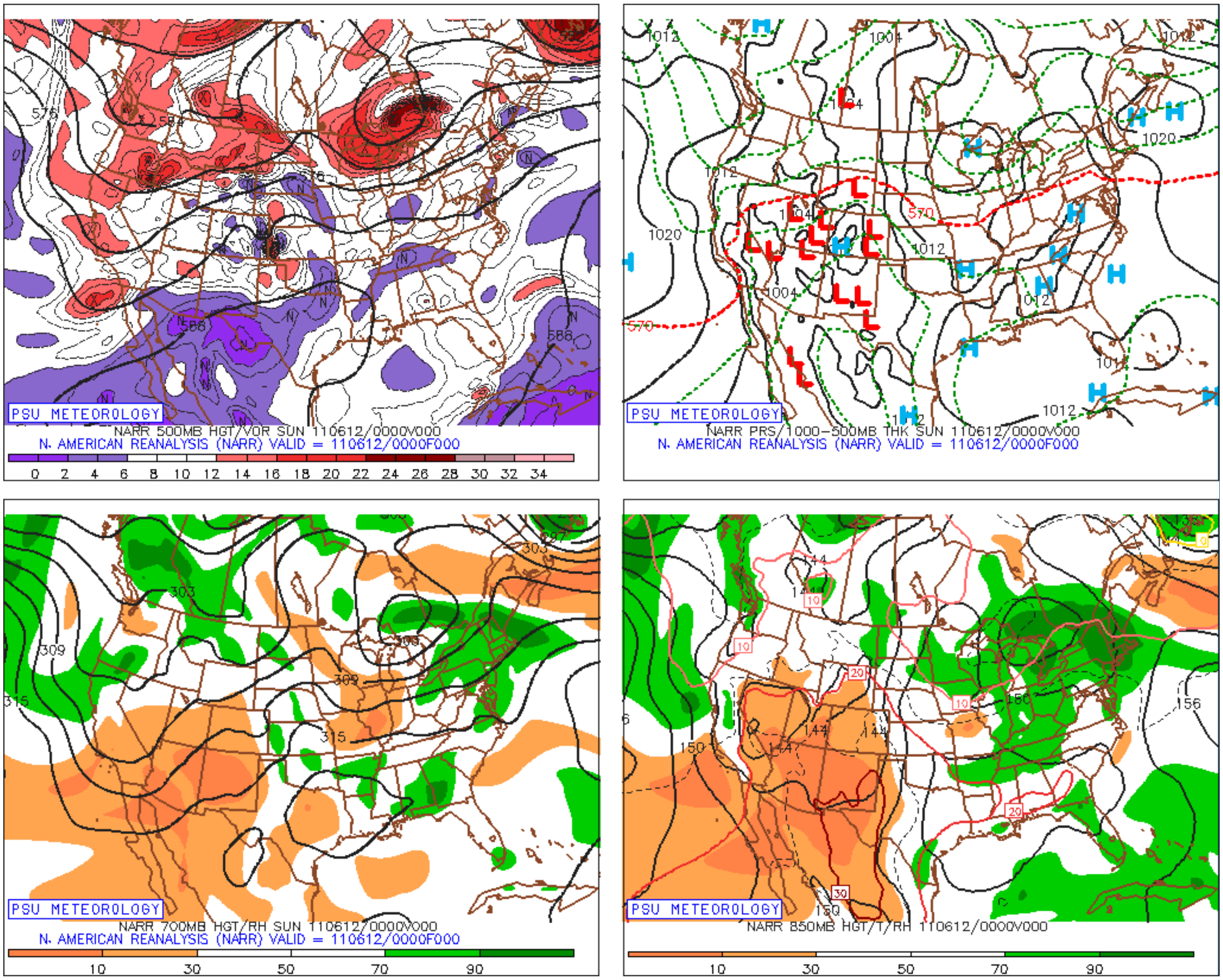


Fig.31. Penn State University Dept. of Meteorology 4-Panel Archive for June 12, 2011 at 0Z (1800 MDT). Panels as in Figure 5.

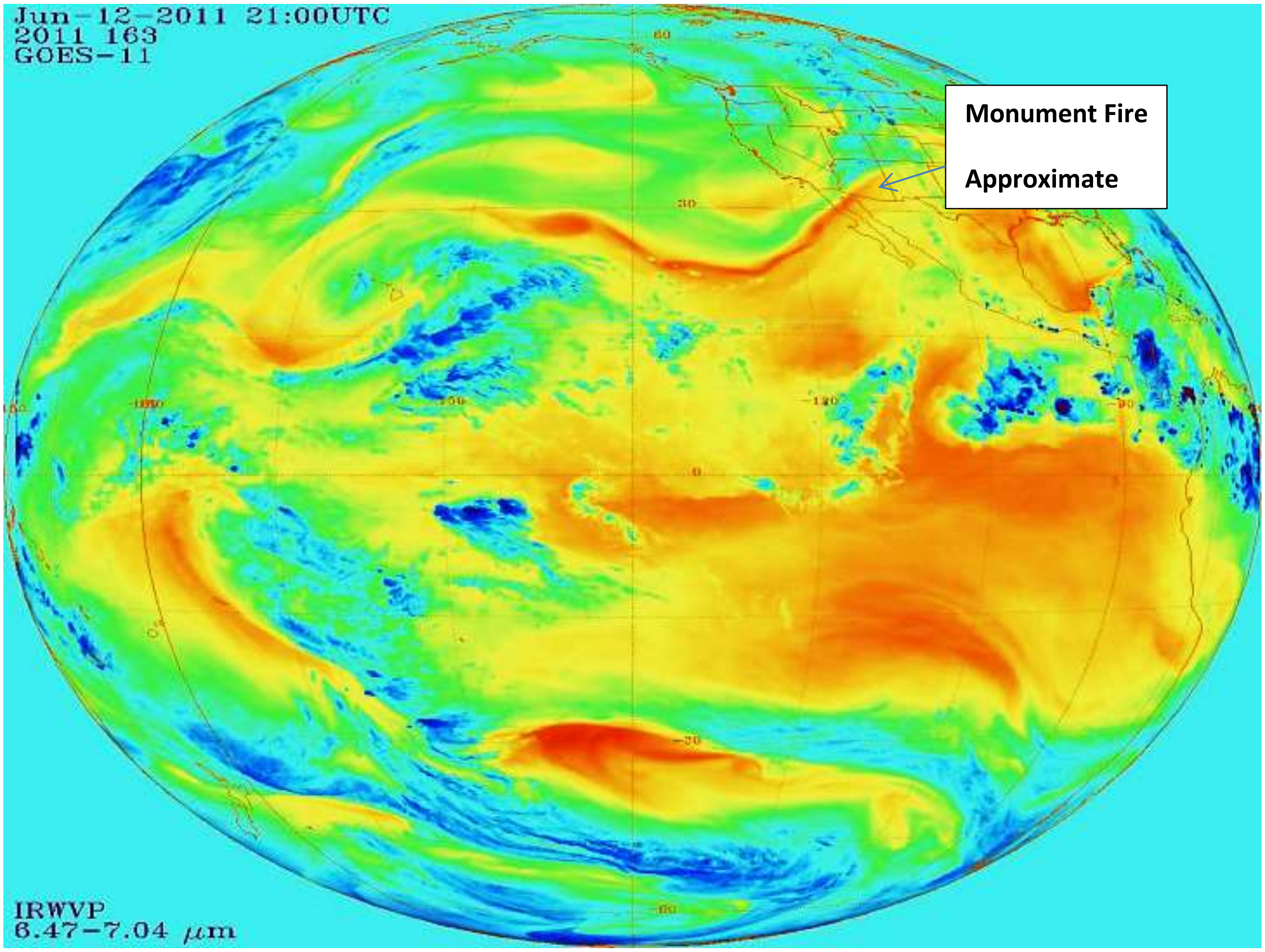
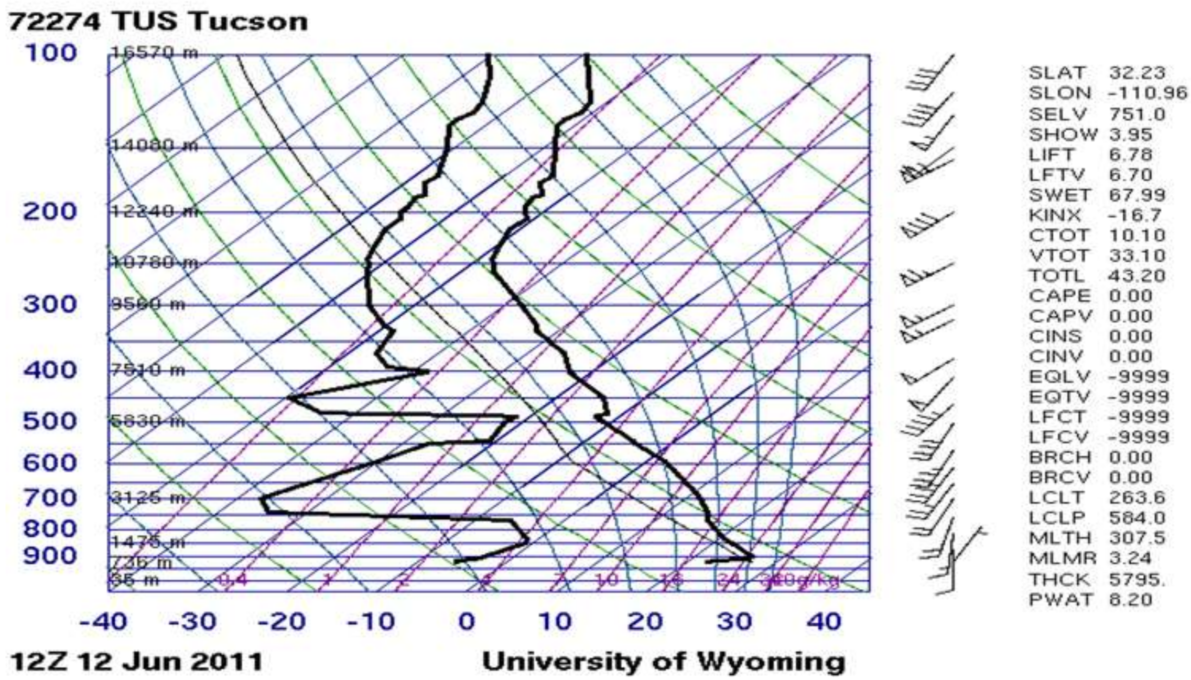


Fig.32. NOAA – GIBBS GOES-13 WVI color enhanced for June 12, 2013 at 21Z (1500 MDT).



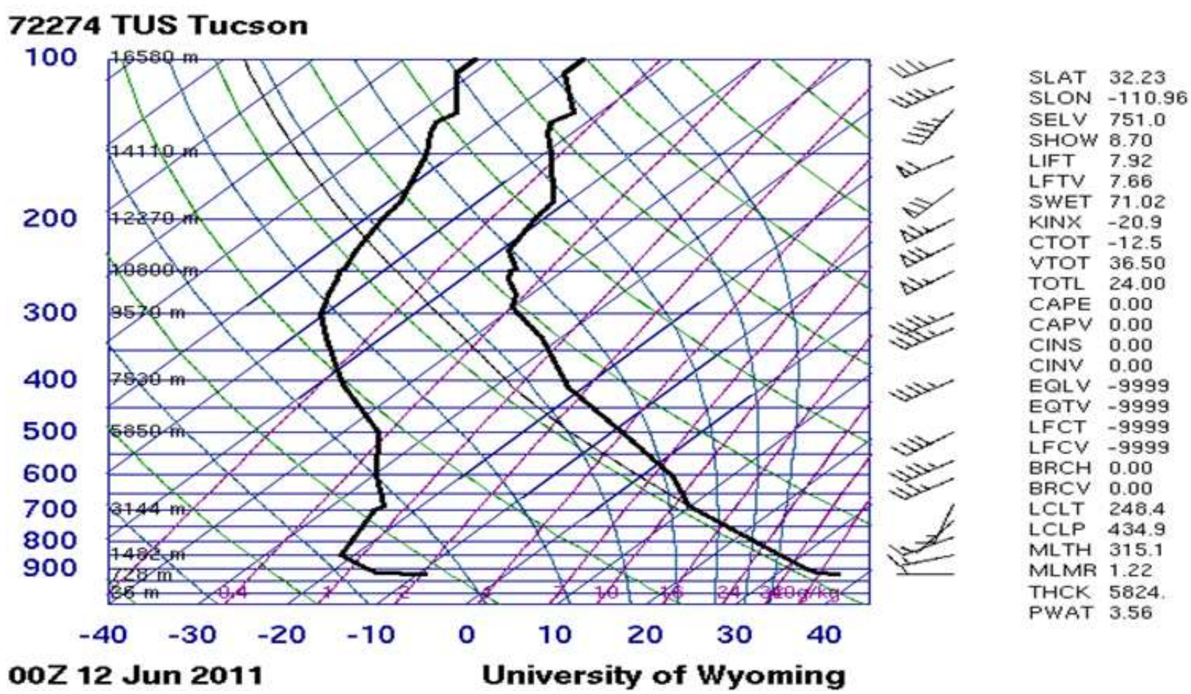


Fig. 33 University of WY skew-T atmospheric soundings for June 12, 2011 at Tucson, AZ at 12Z (above) and 0Z (below).

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
3:37	73.0	5.3	7	8	12	SW	OK	0.0	55.15	69.0	1
2:37	81.0	-1.0	4	7	15	SW	OK	10.0	55.15	75.0	1
1:37	83.0	0.3	4	5	20	W	OK	98.0	55.15	78.0	1
0:37	89.0	-1.7	3	7	25	WSW	OK	487.0	55.15	91.0	1
23:37	90.0	-1.0	3	9	16	SSW	OK	717.0	55.15	96.0	1
22:37	92.0	0.3	3	7	16	SW	OK	911.0	55.15	102.0	2
21:37	91.0	-0.4	3	6	16	SW	OK	1053.0	55.15	104.0	2
20:37	91.0	5.8	4	6	17	SSW	OK	1128.0	55.15	107.0	2
19:37	89.0	4.4	4	5	15	NW	OK	1134.0	55.15	106.0	2
18:37	88.0	16.2	7	6	14	ENE	OK	1100.0	55.15	105.0	2
17:37	84.0	23.8	11	7	14	NE	OK	986.0	55.15	99.0	2
16:37	82.0	26.3	13	5	12	ENE	OK	824.0	55.15	94.0	2
15:37	80.0	26.5	14	6	12	NE	OK	621.0	55.15	88.0	2
14:37	78.0	28.2	16	5	8	NE	OK	391.0	55.15	81.0	2
13:37	72.0	23.4	16	3	10	SW	OK	161.0	55.15	69.0	2
12:37	63.0	14.6	15	8	13	SW	OK	9.0	55.15	60.0	2
11:37	62.0	12.3	14	9	12	SW	OK	0.0	55.15	59.0	2
10:37	64.0	12.2	13	8	11	SW	OK	0.0	55.15	60.0	2
9:37	66.0	13.8	13	3	6	WSW	OK	0.0	55.15	57.0	1
8:37	66.0	13.8	13	2	7	WSW	OK	0.0	55.15	57.0	1
7:37	69.0	16.1	13	2	11	SW	OK	0.0	55.15	60.0	1
6:37	71.0	13.9	11	3	10	S	OK	0.0	55.15	64.0	1
5:37	77.0	8.2	7	11	17	SW	OK	0.0	55.15	73.0	1
4:37	75.0	12.4	9	7	14	SW	OK	0.0	55.15	70.0	1
3:37	77.0	11.2	8	7	17	SW	OK	0.0	55.15	71.0	1

Fig. 34. June 12, 2011 Noon Creek, AZ ROMAN RAWS – elevation 4925’.

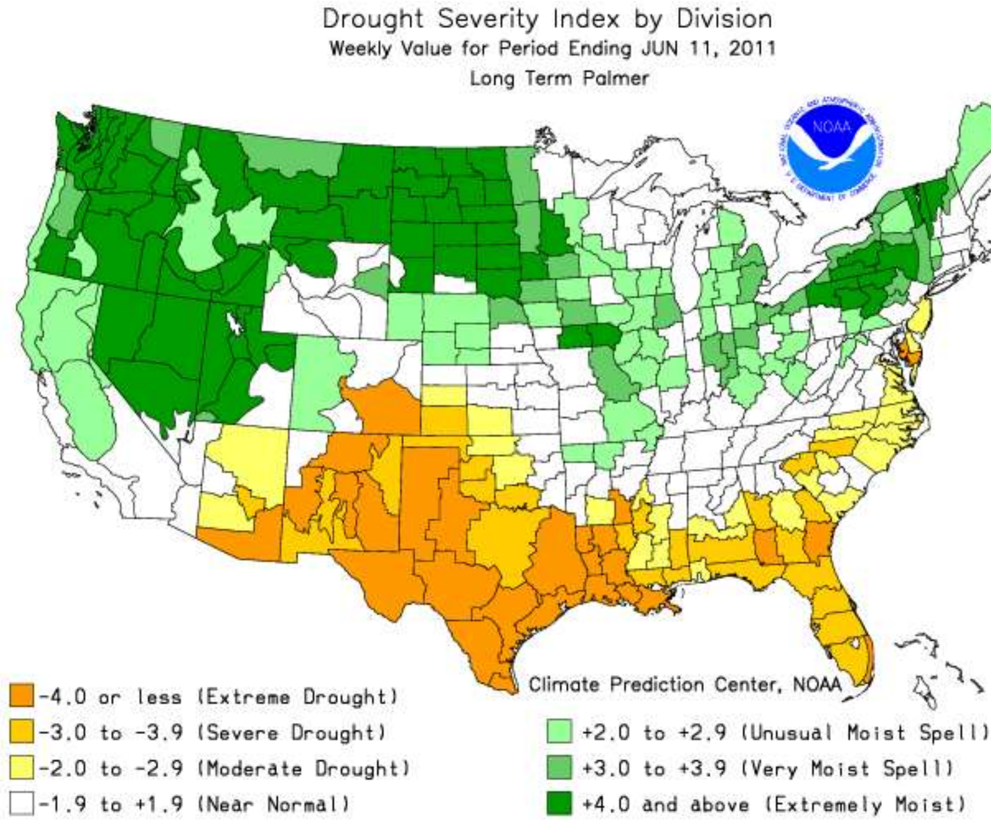


Fig.35. CONUS Drought Severity Index archive by Division map for period ending June 11, 2011. Long Term Palmer Drought Index.

Date	Acres Burned	Square Miles	Hectares (ha)
May 30	1,445 acres	22 sq. mi.	584 ha.
June 2	33,810 acres	528 sq. mi.	13,682 ha.
June 3	60,093 acres	939 sq. mi.	24,318 ha.
June 4	43,111 acres	673 sq. mi.	17,446 ha.
June 5	40,321 acres	630 sq. mi.	16,317 ha.
June 6	49,518 acres	773 sq. mi.	20,039 ha.
June 7	77,760 acres	1215 sq. mi.	31,468 ha.
June 8	24,865 acres	388 sq. mi.	10,062 ha.
June 9	50,110 acres	783 sq. mi.	20,278 ha.
June 10	22,579 acres	352 sq. mi.	9,137 ha.

Table 1. Progression of Wallow Fire indicating acres, square miles, and hectares burned from May 30 to June 10, 2011. AZ Central at http://www.azcentral.com/news/wildfires/wallow/wallow-fire-timeline.php

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