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LARGE WILDFIRE GROWTH INFLUENCED BY TROPOSPHERIC AND STRATOSPHERIC DRY SLOTS IN THE UNITED STATES

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Abstract

Dry slots are responsible for rapid surface drying and increased gusty winds causing increased wildland fire behavior in the United States (U.S.). There are several research papers dealing with fire weather and wildland fires in the U.S. However, few of them address the actual influence of dry slots in wildland fire weather. Therefore, a reexamination and reevaluation of the previously published research regarding wildfires explicitly influenced by dry slots is approached from the perspective of a wildland fire supervisor for utilizing more water vapor satellite imagery (WVI) toward improved operational wildland fire weather meteorology in the U.S. It is generally accepted that operational wildland fire weather forecasting in the U.S. is an important facet of mesoscale and synoptic meteorology. Indeed, the very first Standard Firefighting Order deals precisely with weather – “Keep informed on fire weather conditions and forecasts.” Moreover, two of the 18 Watch Out Situations deal specifically with temperature/dryness and winds.

It is well documented in the available wildland fire weather literature that surfacing lower-stratospheric and mid- to upper-tropospheric weather is responsible for dry air intrusions and descending dry air. Most times, these dry intrusions manifest themselves as clearly visible dark bands in the satellite water vapor imagery, referred to as dry slots. These dry slots usually result in abrupt surface drying and strong, gusty winds often radically influencing wildland fire behavior and hence fire growth. These phenomena can be significant safety issues for fire managers, especially for those fireline supervisors and firefighters on or near active firelines. The same issues very well apply to active prescribed and/or controlled burns. Therefore, accurate and timely dry slot recognition and warnings clearly address the rules in the Standard Firefighting Orders and would allow for better recognition and mitigation of the 18 Watch Out Situations.

Dry slots are particularly well documented for Australian wildfires thanks to the work of Dr. Graham Mills and others. Due in large part to their research and efforts, the Australian Bureau of Meteorology (BoM) regularly utilizes dry slot forecasting and nowcasting on a regular basis during their bushfire seasons. In fact, they even utilize a 'dry slot poster' to better educate and inform their fire managers to 'beware the dry slot.' However, little is known or documented for such dry slot occurrences in the U.S. In the cases examined, taken from the existing literature, it will be shown that several wildland fires in the U.S. have in fact been influenced by these dry slots resulting in extreme and unusual fire behavior and large wildfire growth. One of the issues addressed by the author is the fact that the 'dry slot' term is not very well utilized in the U.S. and there as many as thirty synonymous expressions used in the relevant literature.

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Introduction

There are several good reasons for engaging in the review and re-examination of the mesoscale and synoptic meteorology of the United States wildand fires dealing with dry slots discussed in the literature. First of all, wildland fire weather influences wildland fire behavior, so obviously, the more extreme the weather, the more extreme the fire. Next, those authors in the literature precisely identify the upper air influences on these fires, and this is a focus area that needs attention nationally in the wildland fire weather operational meteorology realm. However, only a few actually refer to the sources and signatures as dry slots. Next, the actual verification of WVI features and signatures is good, however, the verbiage to consistently identify them as dry slots is somewhat lacking, albeit there is undeniably improvement here. There are more than 30 synonymous terms for dry slots used in the United States. Lastly, Charney (2007) and Charney and Keyser (2010) have very perceptively stated the importance of researching "*atmospheric conditions aloft*" for establishing better and "*more accurate fire weather and fire behavior predictions"* expressly for those potentially extreme and erratic fire behavior stages (2007, 2010). They accurately recognize the importance of such structures as dry slots "*predictable hours or even days in advance of the event*" (2007, 2010). In the long run, they seek 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*" (all emphasis added) (2007 and 2010). From the author's perspective, satellite water vapor imagery and dry slots align very well with their notions.

There are basically two themes to this paper: one, that dry slots are both an indicator and a source of dry air influencing wildland fire weather and fire behavior and two, that satellite WVI is a useful tool for identifying these dry slots. The structure of the paper is as follows: To begin with, the author will list over a dozen U.S. wildland fires affected by dry slots and upper air influences examined in the U.S. literature; four of them will be discussed in some detail. The following section takes into account '*fighting fire by the rules'* for wildland fire engagement. Considered next will be those wildland fires examined in the literature, concentrating primarily on the mid- and upper-air influences. Each fire case study will briefly address the fuels, topography, and fire behavior; however, the principal focus will be on the meteorological conditions, mainly dry slots and dry intrusions that influenced these wildland fires. And followed by a brief review of the 2011 Wildland Fire Weather: Multi-Agency Portfolio of Current and In-Development Capabilities to Support User Needs. Next, both positive and negative reviews and comments regarding WVI in the literature are addressed. And the final section consists of some discussion and conclusions, including potential implications of the results of this study for real-time fire-weather forecasting and future research in the areas addressed.

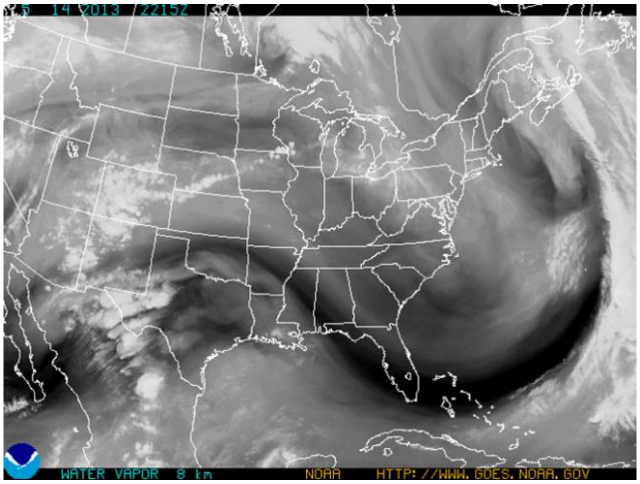

Fig. 1. National Oceanic Atmospheric Agency (NOAA) GOES Water Vapor Imagery (WVI) 14 May 2013 (2215Z) indicating several dry slots in various regions of the U.S.

Consider the dry slot signatures shown in Figure 1. Revealed are several dry slot signatures on the 14 May 2013, Geostationary Operational Environmental Satellite (GOES) WVI. Notice the wide dry slot advecting through South Dakota and into Minnesota and Wisconsin in the northern United States (U.S). This broad dry slot influenced fire weather and fire behavior on several large wildfires in several of the Great Lakes States at the time. Careful examination of the image also reveals a narrow dry slot advecting through Oregon, Idaho, Montana, and North Dakota that spawned numerous Red Flag and wind warnings in those states. In addition, notice the well-defined, elongated southern dry slot that produced Red Flag Warnings in many of those influenced states. All-in-all, this image relates a busy day for dry slots in the U.S.

Dry Slots, Dry Intrusions, and Satellite WVI

As shown in Figure 1, dry slots show up as "*dark bands, filaments, or tongues*" of very dry air in satellite WVI between 600 mb to 300 mb concluded Weldon and Holmes (1991). High-altitude moisture areas appear cold (bright - white), and areas where upper-levels are dry appear warm (dark) in Weldon and Holmes (1991). Dry slots tend to be associated with middle tropospheric thermal troughs, e.g. Weldon and Holmes (1991). The vertical - structure of dry slots indicates that the genesis of this dry, high-momentum air is in the mid- to upper-troposphere and/or the lower-stratosphere, discovered by e.g. Charney (2007) and they manifest themselves quite distinctly in the WVI, e.g. Weldon and Holmes (1991). 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 in Weldon and Holmes (1991). Commonly, the dark zones of the dry slot category are vertically deep with dry air extending downward to near the surface as documented by Weldon and Holmes (1991). Dry slots can be inferred from skew-T soundings, according to e.g. Smarsh (1994), however, they are best visible by means of satellite WVI where you can actually '*see*' the dry slot signature. Identifying dry slots can provide fire weather forecasters with beneficial nowcasting and forecasting advice for verifying National Weather Predictions (NWP) as well as Fire Weather predictions. It is recommended that the dry slots should be corroborated with sounding data to verify if they are truly the source and indicator of dry, windy, and unstable conditions concluded Watcher (2012-2013). The author has researched and experienced numerous wildland fires, both professionally and those archived in the Wildland Fire Lessons Learned Center (LLC) Incident Reviews - where the "*humidity dropped like a rock*" and the fire behavior increased as presented in Schoeffler (2010). The author found that those numerous experienced-fire-weather-events most often indicated that the fire weather and resultant fire behavior were indeed influenced by low to very low relative humidities and dewpoints, as well as gusty winds (2010). In almost all the researched cases, dry slots were found to be a causal and coincident mechanism and indicator of extreme wildland fire weather, as also determined in e.g. Kaplan et al. (2008) and Schoeffler (2010).

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

A brief examination of the causes, contributing factors, precursors, indicators, and outcomes of dry slots addressed by all the U.S. fire weather researchers is useful. These will be explained and detailed to some extent as they are introduced into the discussion: 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 in Mills (2010) and Werth (2012). Generally, the darker the dry slot, the lower the humidity, discerned in e.g. Weldon and Holmes (1991). A common exception to this is with the color-enhanced imagery. In one variety, the driest signatures progressed from brownish to copper, and then to black; somewhat similar in the yellowish-orange style. Weldon and Holmes (1991) recognized that each water vapor image is "*unique*" and they suggest using a sequence of previous images or images viewed in a time-lapse motion for better interpretation.

Different types of problem dry slots are associated with *Critical Fire Weather Patterns* examined in the publication generated at the *NWS Fire Weather Forecasters Course* in Boise, ID from March 30 to April 2, 1999 (e.g. pre-frontal, and post-frontal, the breakdown of upper level ridges, foehn winds, low-level jet entrance and exit regions, and in advance of tropical storms), and these were also examined by Schroeder (1969); Brotak et al. (1977); Mills (2006); Prevedel (2007); Werth (2012), and others.

This 1999 NWS publication suggested using WVI to locate dark areas (dry slots) as potentially moderate to high Haines Index regions. The Haines Index is based on the stability and moisture content of the lower atmosphere and it measures the potential for existing fires to become large (Haines 1988). Ratings are from 2 (moist, stable lower atmosphere) to 6 (dry, unstable lower atmosphere). Most fires get large during Haines Index of 5-6 (e.g. Haines 1988, Werth et al. 2011). Werth holds that surfacing dry slots almost always result in Haines of 5 or 6 (2012). Saltenberger and Barker also found similar indicators on the 1990 Awbrey Hall Fire (1993). The NWS publication also recommended to examine the WVI very carefully for totally black areas, since these black regions (dry slots) are frequently associated with a 5/6 Haines Index (1999). Prevedel (2007) also discovered this dry slot and Haines 5/6 connection. It is especially noteworthy that the NWS publication also cautioned to be on the look-out for "*light gray (i.e. moist)* zones," because these can actually be Haines 5/6 areas. Weldon and Holmes refer to these as "*grade shades*" in the "*gray shade scale*" (1991). They further added that there are multiple layers of moisture with dry layers between them likely through the troposphere (1991). Weldon and Holmes concluded that "*gray shade differences and patterns can be seen within the relatively dark region*." As a result, these gray shade scale images can range from light, to medium, to dark; and they further discovered that "*significant gray shade differences were observed … when the air is relatively dry at middle levels*" (1991) (all emphasis added).

It has been revealed that satellite imagery will reveal structures not detected by conventional data, in e.g. Muller and Fuelberg (1990). It is quite significant that dry slots and dry intrusions are often evident in WVI almost a full day before being realized in infrared or visible imagery, suggested by e.g. Muller and Fuelberg (1990). They most likely occur in mid-afternoon, especially on hot days in Mills (2006a) and Miretzky (2009). Dry slots are <u>not</u> well predicted by computer modeling as concluded by 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. In Australia, cold fronts and 'cool changes' are basically identical because they obviously break up the oppressive summertime heat waves (Smith et al. 1983), and naturally, with fire weather, the leading concern is the same as with cold fronts - dangerous wind shifts (e.g. Mills 2008).An additional 20% to 30% occurred overnight or in the early morning (2006a, 2009) and Werth (2012).

Dry slots form during tropospheric jet stream-induced gravity waves and they are influenced by topographic rather than coastal stimuli in Mills (2006a). They are influenced by mountain-wave breaking and lee trough circulations according to Mills (2006a). Dry slots always reflect comparatively dry middle and upper troposphere, as discovered by e.g. Werth (2012). Dry slots almost *always* indicate descending dry air and/or horizontal dry air advection in e.g. James and Clark (2003) and air parcels in the dry intrusion originate at high tropospheric, or even stratospheric, or tropopause fold levels in e.g. Smarsh (1994), and then descend in the region upstream of a developing cyclone in e.g. James and Clark (2010).

A relative humidity decline caused by surfacing dry slots is almost always lower than the forecasted humidity; "*surprisingly lower*" concluded Werth (2012). Dry slots are responsible for abrupt decreased in relative humidity, dewpoints, and ultimately fuel moistures as discovered by e.g. Mills (2008, 2008a, 2009) and strong, gusty winds in Mills (2005b). They can cause rapid, sustained increased fire behavior discovered in e.g. Mills (2005b) and Saltenberger and Barker (1993). 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 concluded by e.g. Werth (2012). It is the development of a deep, statically neutral boundary layer that contributes to the link between mid-tropospheric dry slots and the surface in e.g. Mills (2008, 2008a). The source of the extremely dry air associated with the abrupt surface drying is a band of mid- to upper-tropospheric dry air that could be associated with identifiable dark (dry) features in the WVI in e.g. Mills (2005, 2008a), Prevedel (2007), and Charney (2007).

Dry slots appear to "*pulse*" in the WVI. Kaplan et al. (2008) discussed "*two separate drying pulses*" that occurred on the Double Trouble State Park wildfire in New Jersey in 2002. When sinking motions occurred, a subsidence layer and a corresponding dry slot were found and relative humidity minima followed as examined in Smarsh (1994).

And lastly, Miretzky (2009) focused exclusively on the wildfires in the Northeastern U.S (NEUS) affected by subsidence, and found that there are "*reservoirs*" of dry air that form just above the Planetary Boundary Layer (PBL) (emphasis added). This author analyzed the Miretzky NEUS fires examined using WVI verification from the National Climate Data Center (NCDC), Global ISCCP B1 Browse System (GIBBS) satellite archives from 1980 to present (not shown). The '*reservoirs*' referenced in the Miretzky thesis may be inferred as dry slots and/or dry intrusions.

Fighting Fire by the Rules

On the fireline, 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 18 Watch Out Situations. The Ten Standard Firefighting Orders are essential rules of engagement for all wildland firefighters that must be followed on every fire (NWCG 2010). The first Standard Fire Order deals specifically with recognizing current weather conditions and obtaining forecasts (NWCG 2010). The third Fire Order is fully coupled to the first Order in relation to the weather, because it deals with basing your firefighting actions on the current and expected fire behavior (NWCG 2010). Fire behavior is intricately tied to fire weather. This will all be addressed further in the text.

Along with the Ten Standard Orders, wildland firefighters use the 18 Watch Out Situations. The Watch Out Situations complement the Ten Standard Orders. Firefighters cannot violate the 18 Watch Out Situations, however, they can fail to recognize them and/or heed their warnings and mitigate them, hence one needs to “watch out” (Wildland Fire LLC). As a generally accepted practice, wildland firefighters and fireline supervisors have used clouds as weather indicators (e.g. altocumulus lenticularis clouds in the morning suggest high winds aloft surfacing later in the day). Without a doubt this sustained practice will continue. At this point, the author recommends utilizing satellite WVI as another tested means to identify and discern dry slots and dry intrusions as a new fire weather tool and signature indicators.

As previously noted above, the applicable wildland fire weather-related Ten Standard Orders and the 18 Watch Out Situations will be enumerated and briefly addressed

TEN STANDARD FIRE ORDERS - NWCG (2010)

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.*

18 WATCH OUT SITUATIONS - NWCG (2010)

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.*

Almost 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. This conclusion also applies to the Watch Outs. Failing to know, recognize and heed one or more of the 18 Watch Out Situations as required has been fatal. These are itemized in sometimes painful detail in the Wildland Fire LLC Incident Reviews. And on the flip-side, those that do follow and heed the Standard Orders and Watch Outs are typically safe and effective (Wildland Fire LLC and elsewhere). Based on professional experience, this has been overwhelmingly true of those firefighters and fireline supervisors that paid attention to the weather factors influencing their fire(s) at the time, changed tactics, disengaged, and then utilized their established escape route(s) to safety (Wildland Fire LLC, Schoeffler, and elsewhere).

To mitigate these and to better follow Fire Order numbers 1 and 3 respectively, the author suggests utilizing the Australian BoM dry slot fire weather nowcasting and forecasting on a regular basis. These WVI signatures occur worldwide on a continual basis and have adversely influenced wildland fire behavior. It is the *predicted* fire behavior that is most often underestimated and/or unheeded, many times resulting in tragic results as documented in the Wildland Fire LLC Incident Reviews. Fireline supervisors base their strategy and tactics on accurate fire weather forecasting; so dry slot forecasting would absolutely allow for more accurate and timely real-time fire weather predictions of abrupt surface and near-surface drying and related wind events that would adversely affect the fire behavior.

The literature reveals a full array of terms regarding dry slots, e.g. *dark bands, filaments, streamers, tongues of dry air*, and the like – at least 30 such synonyms in the U.S. literature alone. The dry slot designation and detection is applied in a limited degree in weather forecasting nationwide in the U.S. Fortunately, it is expanding. It is used quite extensively in the South and Southeast regions of the U.S. National Weather Service (NWS). Recently, the Southwestern Region and others are utilizing it more often, but nationally there is infrequent use overall. Logically, accurate and timely fire weather nowcasts and forecasts using satellite WVI are the desired outcomes of the author.

With some exceptions, fireline supervisors have a very basic knowledge of subsidence, and possibly even dry slots and dry air intrusions, from their fire weather training - but rarely a working knowledge. The author suggests that fireline supervisors regularly view WVI on the firelines when they are safely able to, in order to be aware of any dry slots approaching their fire area. This possibility is especially within their reach in this day and age due to the advent and accessibility of wireless technology; and yes, especially while on the firelines. Yet, the preferred option according to Mills would be for trained meteorologists to identify these dry slot signatures and drying events and then broadcast the vital information to the fireline over the radio (2006). This vital intelligence should allow fireline supervisors ample time to more safely practice wildland firefighting, anticipating the expected fire behavior based on the expected weather on a fairly real-time basis. Therefore, this would allow them time to either continue to fight the fire and/or to change their tactics, disengage; or escape and move to safety if need be. It would most definitely increase their situational awareness and enhance their management options as noted in Mills (2006).

The Alignment of Forces Principle

The Campbell Prediction System (CPS) talks about "*reading a wildland fire*" by heeding the "*alignment of forces*" of wind, slope, and preheating that cause variations in fire behavior. Based on professional experience, this author will also include relative humidity to the alignment list. When these forces align, the fire is going to be at its full intensity. With further experience, one can more accurately predict the fire signature that will result and take appropriate suppression and/or evasive action as determined by Campbell (1995) and Schoeffler. This author has truly gained from the CPS alignment principle extensively on fires and concluded that utilizing WVI to identify dry slots is in complete agreement with this system since dry slots are a primary causal factor and indicator in the researched fires below. As will be noted, the fire weather factors of air temperature, relative humidity, dew point, winds, and high Haines Index all aligned and resulted in intensified and often extreme fire behavior.

There are at least 16 U.S. wildland fires examined in the general literature focusing on mid- to upper-air fire weather influences, including dry slots, and they are listed below. Now consider some of these researched U.S. wildland fires, emphasizing the mid- to upper-atmospheric influences, dry slots and dry intrusions, subsidence, surface to near-surface drying, Haines Index, and ensuing winds that adversely influenced these U.S. wildland fires.

United States Wildland Fire Case Studies - Limited U.S. Dry Slot Research

- *Mann Gulch Fire - 5 August 1949 - Helena N.F. – Montana*
- *Mack Lake Fire - 5 May 1980 - Huron/Manistee N.F. - Northern Michigan*
- *Willis Gulch Fire - 26 July 1988 - Boise N.F. – Idaho*
- *Lowman Fire - 29 July 1989 - Boise N.F. - Idaho*
- *Awbrey Hall Fire - 4 August 1990 - Central Oregon*
- *Double Trouble State Park (DTSP) Fire - 2 June 2002 - East-Central New Jersey*
- *Texas and Oklahoma wildfires - 1 January 2006*
- *Lower North Fork Prescribed Burn escape - 26 March 2012 Colorado State Forestry - Conifer, Colorado*
- *Tower Lake (2 May 1999); Cottonville (5 May 2005); Cavity Lake (14 July 2006); Hamm Lake (5 May 2007); Sleeper Lake (2 August 2007); Black River Falls and Pinery (20 May 2009) Fires in the northeastern United States (NEUS)*

In every case, subsidence, a dry slot and/or dry air intrusion advected over the fire or proximate to the fire area and caused an abrupt drop in surface and/or near-surface relative humidities and dewpoints; and strong, gusty winds, to align and resulted in unusual, often erratic fire behavior and large fire growth. The subsidence and/or dry slots often coincided with atmospheric instability that resulted in a Haines Index of 5 or 6 in most cases as examined in Saltenberger and Barker (1993); Werth and Ochoa (1993); Zimet et al. (2003 and 2007); Prevedel (2007); and Bass et al. (2012). Miretzky (2009), in great detail, investigated the NEUS wildfires listed above (including the Mack Lake Fire) that were influenced by subsidence, and when analyzed by this author using archived WVI (GIBBS), the subsidence events revealed themselves in varying degrees as dry slot signatures.

Consider now the specific U.S. wildland fires studied in the literature. The following wildland fire discussions address each fire’s fuels, topography, fire behavior, and in particular the mesoscale and synoptic weather analyses. Be aware that the mesoscale and synoptic weather discussions are paraphrased very strictly from each of the fire case studies in order to retain as much as possible, each one of the author’s original meteorological intent and meaning.

Mack Lake Fire - 5 May 1980 - Huron N.F.

The Mack Lake Fire was the result of an escaped prescribed (RX) burn near Mio, Michigan in the northeast portion of the lower peninsula of Michigan, on the Huron N.F. The U.S. Forest Service *intended to burn only 27 acres that day* to prepare for replanting Jack Pine in the area, part of a wildlife project for the endangered Kirtland’s Warbler, as discovered in Simard et al. (1983). The fuels were various conifers, mainly very dense jack pine, with brush understory and the terrain was quite flat (1983). Even though rated as a "*Very High*" fire danger day, the officials ignited the RX burn at 1426 EDT on 5 May 1980 (1983).

At this point, one just has to inquire what the RX Fire Managers thinking when they ignited this burn based on the forecasted weather for that day? Consider Borie (1983) for some useful insight not included in the "official" report. Enormous modifications in the Forest Service prescribed burn policy were administratively imposed based on this judgment error. By 1615 EDT, the fire spotted across State Highway 33 and was declared a wildfire (1983). As noted by Gibson et al. (1980), in the first three and one-half hours, the "*very aggressive*" fire with "*heavy, roiling black smoke*" and "*instant changes in fire behavior due to the winds"* advanced 7.5 miles, and in Simard et al. (1983). In six hours there was an Agency tractor plow operator fatality due to a wind shift that caused a flanking fire to become an intense head fire with a "*strong, though relatively brief intense fire run to the north*," as investigated by Gibson (1980) and Simard et al. (1983). In addition, 44 homes and buildings were destroyed; and within 30 hours it burned 21,000 acres as established in Simard et al. (1983). There was a major fire run between 1230 and 1600 hours on 5 May, advanced at 6 to 8 mi/h between 1700 and 1800 EDT found in Simard et al. (1983). The Mack Lake Fire Report (1980) also noted that this fire ranked among quite a few others in the U.S. with anomalously high spread rates and fireline intensities, e.g. Badoura Fire (Minnesota) in 1959, Sundance Fire (Idaho) in 1968, and the Air Force Bomb Range Fire (North Carolina (1983). They calculated the Mack Lake Fire intensity to be 3.5 trillion BTUs or ten Hiroshima-sized atomic bombs (1983).

Mesoscale and Synoptic Weather

On May 5th, the 1300 *relative humidity over Mio dropped an anomalous 61%* from 80% to its lowest point (19%) between 0900-1100 EDT[1] and the 500-millibar chart displayed a high pressure ridge over the Northern Rockies (not shown) as examined in Simard et al. (1983) and Gibson (1980). The investigators noted that a single weather reading at the fire site would not have detected this humidity trend as concluded by Gibson et al. (1980). A closed low enveloped eastern Canada with divergent centers over Newfoundland and Hudson Bay (not shown) (1983). It was during this time of lowest humidities, highest temperatures, and highest wind speeds that the Mack Lake Fire made its significant run examined in Simard, et al. (1983). It is noteworthy that the four days followed the very same cold front passage that impacted the Mack Lake Fire, to the north, an Alberta, Canada wildland fire increased significantly from 20,000 acres to 150,000 acres in size as discussed in Alexander et al. (1983).

The Mack Lake fire was influenced by a developing upper-level front deep within a shortwave trough in the fire area as noted by Zimet at al. (2007). Subsidence, in the form of a fully developed dry air intrusion, injected dry air from the middle and upper-troposphere descended along sloping isentropes and adiabatically warmed and dried it along its path as examined by Zimet et al. (2003 and 2007). The organized subsidence was also the mechanism for downwind advection of high momentum air from within the frontal zone downward into the fire environment (2003 and 2007). The authors concluded that upper-frontal processes, characteristic of

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northwesterly synoptic-scale flow, were most likely a causal factor in the 5 May wildfire spread (2003 and 2007). Consider Fig. 4 - a logical permissible inference is a dry slot advecting straight down through the middle of the 10% to 50% relative humidity contours. This also would very likely have shown up as a dry slot on the WVI[2]. Regrettably, only infrared and visible satellite imagery was available in the NOAA, GIBBS archive for 5 May 1980. Moreover, the angle and quality of the infrared image was so poor as to render a good image for publication unfeasible.

Unusually Intense Fire Behavior Phenomenon

There was also distinct residual evidence of intense fire behavior in the form of Horizontal Roll Vortices (HRV) determined after the fire passed through areas where "*crown streets*" of scorched canopies, remained as evidence of the very intense phenomenon examined in Simard et al. (1983); Haines (1988a); Haines and Lyon (1990); and HRV occurrence in great detail in Werth et al. (2011).

Horizontal Roll Vortices, an indication of very intense fire behavior, occur in moderate terrain under light winds initially as vertical vortices, i.e. firewhirls as examined in Werth et al. (2011) and this author's professional experiences (Schoeffler). Haines (1982) also demonstrated that the existence of HRV is consistent with existing heat transfer and fluid dynamics theories.

Forthofer and Goodrick in Werth et al. (2011) precisely described HRV occurrences when they observed that these atmospheric horizontal convective rolls are ordinary features of the PBL (2011). They noted that adding a fire brings a complicating aspect into the mix in the form of a horizontal temperature gradient that can locally alter the convective organization of the PBL environment (2011). The causal factors, in series are, transient ambient vorticity from the surface wind shear altered by the fire, slanted into the vertical, followed by longitudinal reorientation, unmistakable as a bifurcated, horizontally rolling pair of smoke columns (2011).

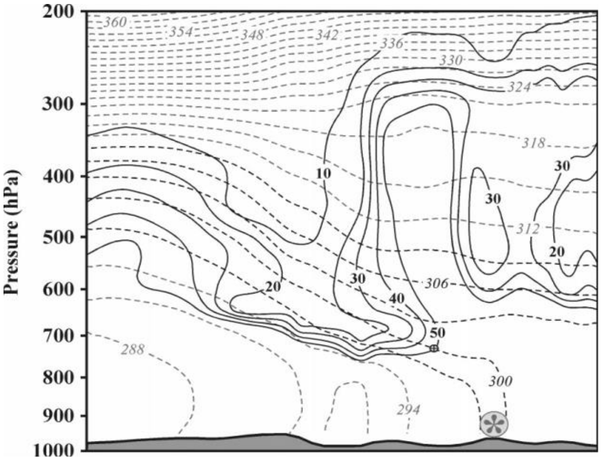

Fig. 2. Vertical cross-section of the Mack Lake Fire relative humidity valid at 18Z, 5 May 1980. RH (solid black lines) labeled in percent and contoured every 10% between 10% and 50%. Small gray circle with a + represents the location of the 750 hPa air parcel mentioned in the Zimet text. Asterisk within the circle denotes the approximate location of the Mack Lake Fire. A dry slot may be logically inferred advecting down through the centerline of the 10% to 50% RH contours (Courtesy of Zimet et al. 2007).

Lowman Fire - Boise N.F. 29 July 1989 - Idaho

Mesoscale and Synoptic Weather

The 29 July weather at the lightning-ignited Lowman Fire site was hot and dry throughout the day. It began initially as four lightning fires that burned together and resulted from an intense 26 July lightning bust where 1000 strikes p/h resulted in 300-400 new starts in central ID (Werth and Ochoa 1993). The fuels consisted of various conifers, brush understory, and slash in fairly steep, mountainous topography near Lowman, ID. Maximum temperatures ranged from 90°F to 95°F, and an anomalously low relative humidity of 8% as discovered in Werth and Ochoa (1993). An inversion that kept the fire quiet finally broke around 1100 LST, and this caused the air to rapidly warm and dry, and this event radically increased fire behavior according to Werth and Ochoa (1993). There was a Haines 6 throughout Idaho as noted in Figure 4 (Werth Figure 6). The satellite WVI indicated a dry intrusion that extended from southern California, through Nevada, and into Idaho and Montana over the Lowman Fire area at 15Z (Figure 4) (Werth and Ochoa Figure 7) in Werth and Ochoa (1993). On this day, the Lowman Fire experienced a fire behavior blow-up described as a “*fire storm*” while the fire moved at 1500 meters per hour (.93 mi/h) as concluded by Werth and Ochoa (1993). A fire storm is distinguished by violent convection caused by a large, continuous area of intense fire that is often characterized by destructively violent surface indrafts, near and beyond the fire perimeter, and sometimes by tornado-like firewhirls (NWCG 2012).

At the time of the Lowman Fire intense fire behavior, Werth and Ochoa (1993) discovered that the weather pattern at the fire site was dominated by: (1) a low pressure ‘*thermal trough*’ in the valleys of California (1993), (2) a Pacific Northwest coast upper-low moved into the area (1993), (3) the thermal trough shifted eastward across Idaho and Nevada (1993), (4) in response, an area of surface low pressure moved into the Oregon-Washington border area (1993), (5) the northern range of the thermal trough ‘*linking up’* with the warm front accompanied by the surface low that also approached the area (1993), and that (6) the Intermountain region low pressure area had thermal trough characteristics, with the warmest temperatures in the trough’s center and the highest thickness values directly over the fire area (not shown) (1993). According to Werth and Ochoa (1993) research, the Lowman Fire area was further influenced by: (1) very dry low-level air further south in the thermal trough (1993), (2) a band of air with average relative humidity below 20% stretched across Idaho and then southwest toward central California (1993), (3) satellite WVI indicated a relatively dark band across Idaho (1993), and (4) dry air over California and Nevada continued to slowly flow into Idaho during the day (not shown) (1993). On 29 July 1999, the Lowman Fire experienced erratic fire behavior due to high temperatures, low relative humidity, Haines 6, persistent drought, and coincident alignment of a dry slot/dry air intrusion as the causal factors. Consider the high Haines aligned with the dry slot in the WVI in Figure 4 (both Werth and Ochoa Figs.6 and 7).

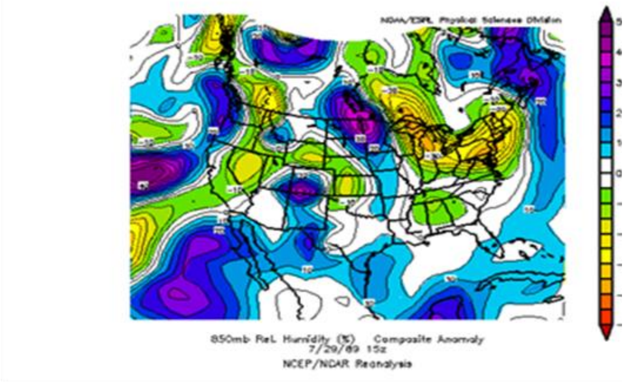

Fig. 3. NCEP/NCAR Relative Humidity Composite Anomaly Reanalysis of July 2, 1989 15Z (0900 MDT) indicating a very narrow band of exceptionally low relative humidity in the central Idaho and Lowman Fire area coincided and aligned with the dry slot and the high Haines images in Fig. 4.

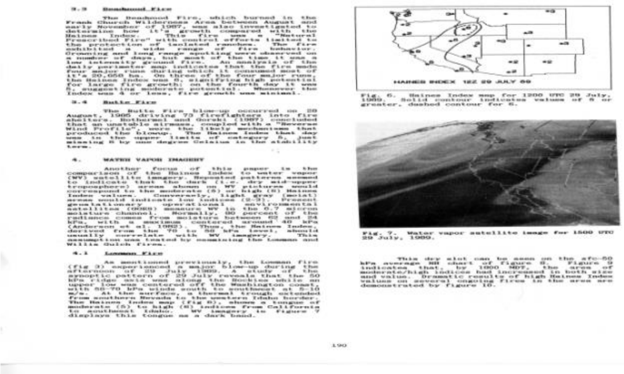

Fig. 4. Lower right WVI indicating a dry slot advecting into Idaho from the southwest and through the Lowman Fire area at 15Z. In the upper right a western U.S. map indicating a Haines Index of 6 for the Lowman Fire area. Note that the high Haines aligns with the dry slot in the WVI above in Werth Fig. 7. Courtesy of Werth and Ochoa (1993), Figures 6 and 7.

Awbrey Hall Fire – August 4, 1990 – Central OR

Mesoscale and Synoptic Weather

At the time of the 1990 Awbrey Hall Fire, Saltenberger and Barker found that the weather pattern at the fire site was dominated by: (1) the first week of August 1990, an intense long-wave ridge developed over western North America (1993), (2) warming and drying peaked on 4 August as the upper ridge axis passed over central Oregon (1993), (3) nearly every upper air station in the region reported extremely low humidity aloft (Fig. 5) (1993), (4) subsidence from high pressure east of the Cascades (not shown) (1993), and (5) a weak surface thermal trough to the west (not shown) (1993). The authors also noted that Oregon was classified as severe to extreme drought after experiencing four years of drought (1993).

RAWS observations taken from near Bend the afternoon of 4 August reported a temperature of 95°F and a relative humidity of 15% (not shown) (1993). Northerly afternoon surface winds at this site remained less than 8 mi/h during the night of 4-5 August as found in Saltenberger and Barker (1993). The fire was caused by an abandoned campfire and burned in various conifers, brush understory, and slash in fairly flat terrain (1993).

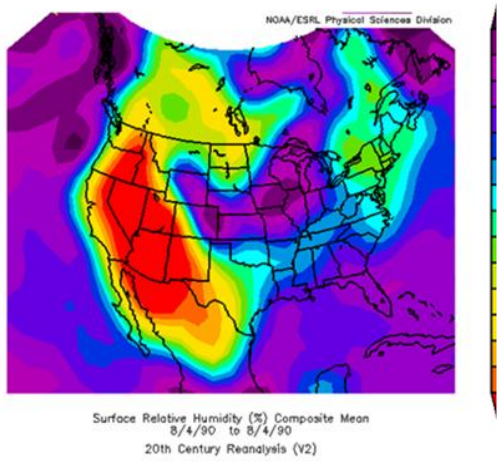

Fig. 5. 20th Century Reanalysis image for 4 August 1990 indicating low surface relative humidity throughout the West and in the Awbrey Hall Fire area of central Oregon.

Now consider Figure 6 indicating where GOES WVI revealed a dry intrusion throughout the West and the Awbrey Hall fire area on 5 August 1990 at 0301Z (1993). The authors also noted a fast-moving high-level shortwave impulse that pushed northeast along the Oregon coast at 45 knots during the evening of 4 August that affected the fire weather (1993). According to Weldon and Holmes (1991), darkening in the dry slot behind the shortwave implies increasing subsidence behind it as noted by Saltenberger and Barker (1993).

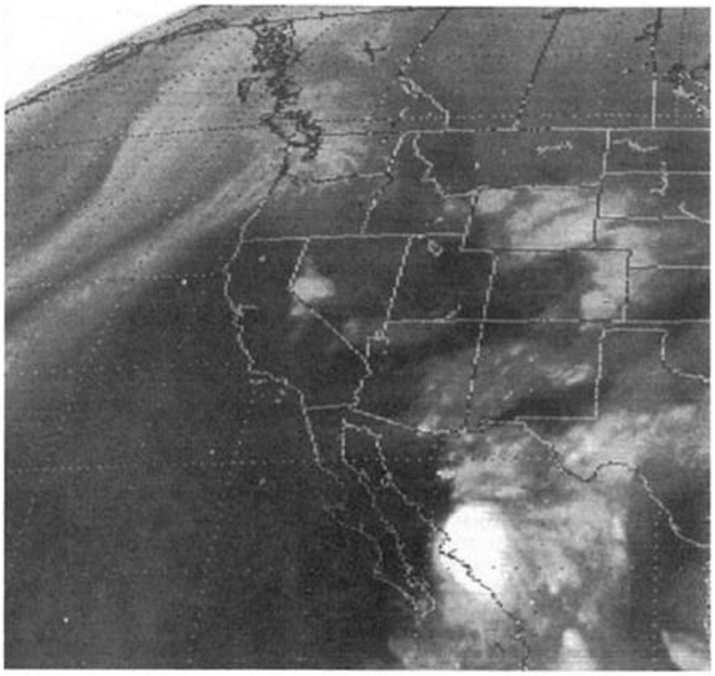

Figure 6. GOES water vapor imagery for 0301 UTC 5 August 1990.

Fig. 6. GOES WVI indicating a dry slot and dry intrusion throughout the West and the Awbrey Hall Fire area (Courtesy of Saltenberger and Barker 1993).

The fire behavior was almost immediately intense surface fire, the fire crowned and spotted, and resulted in "*a pulsating fire growth pattern*" (1993). It is noteworthy that the Awbrey Hall Fire exhibited "*unusually intense nocturnal fire behavior*," that resulted in *plume domination*[3], with very unusual peak fire intensity between 2100-2400 PDT, "*contrary to normal fire behavior*" as noted in Saltenberger and Barker (1993). Plume domination, highly unusual at night, occurs when the fire growth and intensity are powered by the convection column's strength, i.e. the power of the fire is more than the power of the wind (1993) and also addressed in Werth et al. (2011). Overall, Oregon had endured atmospheric instability with a Haines of 5 and 6 (not shown) (1993). The WVI indicated a dry slot 3-6 hours after

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erratic and unusual fire behavior examined by Saltenberger and Barker (1993) (Fig. 6). The authors inferred that erratic and unusual fire behavior was due to very low relative humidity, high nighttime temperatures as examined in Bates (1962), light surface winds, increased upper dynamic forcing, and a moderate/ high Haines Index all in alignment as a dry intrusion (in the signature of a large dry slot according to the authors) passed over fire area (1993).

In the Southwestern Region, Tonto N. F. District Ranger Bates put forward in 1962 that "*high nighttime temperatures"* were responsible for extreme fire behavior the *day after the highest nighttime temperature*; 52°F "in the pines" and 81°F "in the semi-desert." High nighttime temperatures and extreme fire behavior are completely in agreement with the alignment principle as researched and professionally experienced by this author on numerous wildland fires with intense fire behavior (Schoeffler).

Double Trouble Fire, 2 June 2002 – Double Trouble State Park (DTSP), New Jersey

Mesoscale and synoptic weather

This human-caused wildland fire occurred in fairly flat terrain and burned in various pine type, scattered brush understory. The DTSP wildfire exhibited some rather complicated weather influences,[4] according to Kaplan et al. (2008) and Charney and Keyser (2010). Consider the Kaplan et al. (2008) and Charney and Keyser (2010) separate links below for further detailed explanations and images and the respective authors' complex fire weather research papers on the DTSP Wildfire. The DTSP wildfire was influenced by pronounced surface ridging and drying beneath an upper-level jet exit region, which led to two separate anomalous drying events as discovered by Kaplan et al. (2008) and corroborated by Charney and Keyser (2010).

At the time of the DTSP Fire the weather pattern at the fire site was dominated by: (1) deep upper tropospheric subsidence under the right exit region of a jet streak dried out the atmospheric column (Figures 7 and 8) (2008 and 2010), (2) mid-level sinking behind a second lower-level and accelerated a jet streak entrance region and further transported dry air surface-wards, (Figures 7 and 8) (2008 and 2010), (3) the development of a convective boundary layer (2008 and 2010), (4) rightward directed ageostrophic flow was directed toward eastern Pennsylvania (PA) and northern New Jersey (NJ) at 15Z (not shown) (2008 and 2010), (5) directly under the right exit region was a second jet streak at ~850 – 750 hPa whose entrance region was parallel to the leading edge of a mid-level warm pool just to the southwest (not shown) and crossed eastern PA under the right exit region of the mid-level jet (Figure 7 (2008 and 2010), and (6) this elevated warm band was transported eastward from the western High Plains over the previous 24- 36 hour period (not shown) (2008 and 2010). Charney and Keyser maintained that the likely inferences were that a cluster of circulations delivered favorable atmospheric conditions for intense fire weather over central NJ (2008 and 2010). The Palmer Drought Severity Index for the week prior to the fire indicated a severe long-term drought in central and southern NJ (not shown) (2010). Local forestry officials reported anomalous freezing temperatures (2010), thus "*freeze-drying*" any moisture from the live/dead fuels, a process known as *sublimation*.

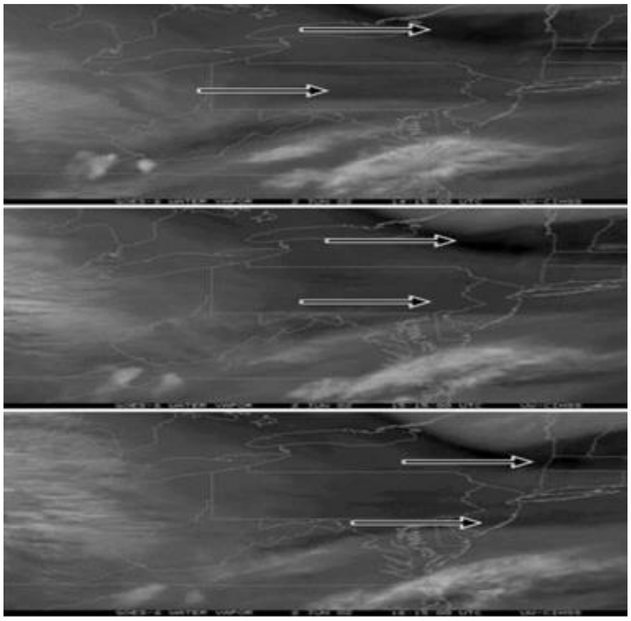

Fig. 7. GOES satellite WVI valid at (a) 1415Z (b) 1515Z, and (c) 1615Z, 2 June 2002. The arrows indicate the changing location of the *dry tongues* mentioned in the text (Courtesy of Kaplan et al. 2008).

Here is a succinct excerpt from Charney and Keyser (2010) suggested that this fire weather was the result of a dry slot phenomenon: "GOES WVI for 1215 UTC 2 June 2002 and 0015 UTC 3 June 2002 delineates a *ribbon of dry air* advecting south-eastward during this time. *This ribbon of dry air* coincided closely with the axis of the jet streak at 1200 UTC 2 June 2002 and 0000 UTC 3 June 2002" (emphasis added). The ribbons and dry tongues referenced in the text are very noticeably dry slots.

At 1915Z the temperature was 75°F with a 62% relative humidity; and at 21Z the temperature rose 20° F (2008 and 2010). The authors further discovered that by 1800 (22Z) the relative humidity fell abruptly to less than 10% - *An anomalously precipitous drop of over 50% in 4 hours!* From 21Z to 02Z, the temperature stayed unusually high at around 80° F while the winds shifted from the northwest to west-northwest, gusted and strengthened as investigated by Kaplan et al. (2008).

Charney and Keyser (2010) explained that during the late morning and early afternoon hours of 2 June, the DTSP weather observations indicated an anomalous surface relative humidity drop and an increased wind speed in the wildfire vicinity. The intensified fire weather was theorized to be the result of descended dry, high-momentum air of middle troposphere origin that occurred coincident with a deepened mixed layer (2010).

For a more comprehensive account of the complicated DTSP wildfire mesoscale and synoptic weather events and images consider Kaplan, Michael L., C. Huang, Y.L. Yin, and J.J. Charney (2008) http://mesolab.ncat.edu/publications%20(web)/2008_Kaplan_etal(MAP_Jet_Streak_and_Fire).pdf

See also: Charney, Joseph and Daniel Keyser (2010) http://www.publish.csiro.au/paper/WF08191.htm

Therefore, the GOES WVI signature that the authors refer to is a dry slot - clearly visible on GOES satellite WVI - coincided and aligned with rapidly lowered relative humidity and strong surface winds, appeared about 1600 and lasted throughout the fire's maximum intensities as researched by Charney and Keyser 2010) (Figs.7 and 8).

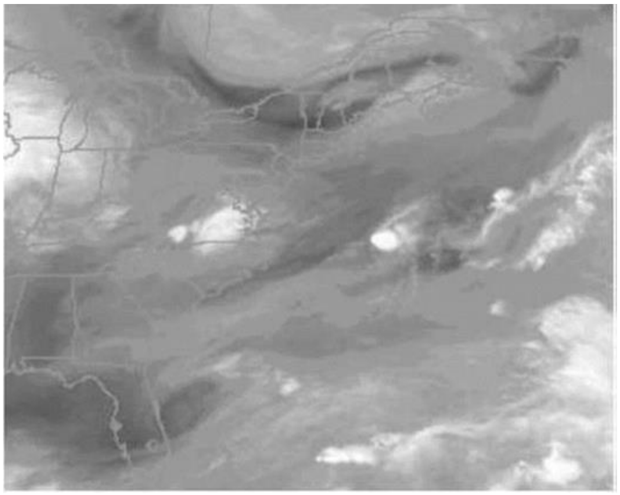

Fig. 8. GOES WVI valid at 1215Z, 2 June 2002 with a dark dry slot approaching the DTSP fire area - Courtesy of Charney and Keyser (2010).

The Australian Dry Slot Forecasting Is No Longer A Theory

Consider now Australian dry slot forecasting, since they ostensibly are the ones that came up with the idea for utilizing it in their wildland (bush) fire weather forecasting. The genesis of BoM Dr. Graham Mills' dry slot "*theory*" emerged while analyzing two mid-tropospheric "*drying events*" during Australia's large, catastrophic bush fires in 2003 (Canberra) and 2005 (Eyre Peninsula) as well as a number of "*water vapour drying events*" from four weather stations over four years (emphasis added) researched by Mills (2005). Mills utilized the seminal works of American researchers Werth and Ochoa (1993) with the 1988 Willis Gulch and the 1989 Lowman wildfires in Idaho; and Charney, Potter, and Heilman (2003) as well with their examination of the 2002 New Jersey, DTSP wildfire. Mills focused on their research on the associated surface drying and enhanced fire activity from mid-tropospheric induced low relative humidity. From their research and his own, Mills hypothesized that the Australian 2003 Canberra and 2005 Eyre Peninsula bush fires were subject to "*abrupt surface drying and strong, gusty winds*" (emphasis added) (2005). He later observed satellite WVI and noted that "*dark bands or dry slots*" coincided with decreased humidities and dewpoints, "*troughs and dry cold frontal passages*," and gusty winds ("drying events") as they passed over the bushfire area (Fig.9) (emphasis added) (2005b).

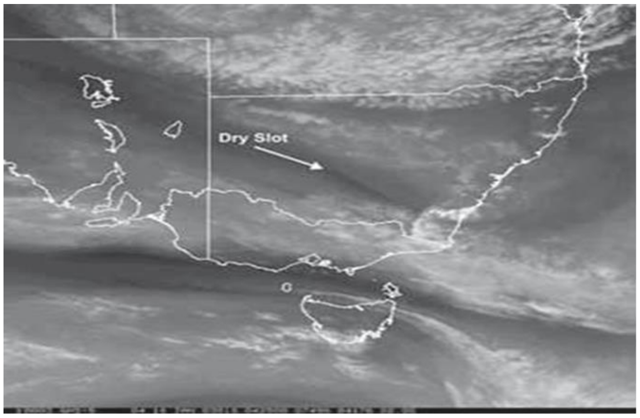

Fig. 9. Dry slot extending across New South Wales. WVI -18 January 2003 at 18Z. Courtesy of Japan Meteorological Agency and Australia BoM.

Mills cautioned that when there is a going fire, "*the dry slot is potentially one of the triggers to set the fire going uncontrollably. Suddenly, the fuel is drying out more quickly, the wind is stronger and gustier, and the fire can take off explosively*" (emphasis added) according to Mills (2006).

Mills stated that one has several hours of warning if you can see one of these dry slots moving toward an ongoing fire (Fig. 9) (2006). When a dry slot moves closer to the fire area, then the fire agencies will be given some notice that the fire behavior may soon become more explosive concluded Mills (2006). "Watch out for the dry air aloft" has long been the refrain of experienced fire managers, but little was understood about its behavior and where it originated. They didn't really know where the dry air aloft was except that it was "*up there* *somewhere*" (emphasis added) discovered by Mills (2006). Now they know precisely where the dry air originates and what sort of explosive impact it can have on a bushfire said Mills (2006). There is an expectation that fire weather forecasters will monitor WVI for dry slots of various forms according to Mills (2005b). There is, however, an obligation on Fire Managers to seek such information, or at least notify the BoM of on-going fire activity, even if they are not of sufficient intensity to require special fire weather forecasts concluded Mills (2005b). The Australians also advise that skill and care are needed when interpreting water vapor images and only qualified staff should be using them to make fire weather forecasts (2005b).

Wildland Fire Weather: Multi-Agency Portfolio of Current and In-Development Capabilities to Support User Needs

A thought-provoking publication in the literature was the above 2011 inclusive treatise by the *Office of the Federal Coordinator for Meteorological Services and Supporting Research* in Silver Springs, Maryland. It focused on the eleven Federal Departments overseeing twenty Federal Agencies that utilize wildland fire weather data, products, services, needs, and the like. Based on their findings that resulted from an extensive "*Needs Assessment Questionnaire*," several topics of interest will be discussed relative to WVI and dry slots. The author will list a few, germane to this paper.

Not surprisingly, the overarching *Fire weather* research topic was designated as important by 100% of users, with a strong requisite for better wind direction and speed predictions for better wildland fire and land management practices.

As discussed above in the text, satellite WVI has been shown to do a commendable job revealing strong, gusty, and damaging winds. The reader is directed to Iaccopelli and Knox (2001) and Grumm, DeVoir, and Villani (2004) among others' research discussed elsewhere in the text. The users also had concerns about complex terrain. Consider Meyers and Steenburg (2010) and Sharples (2007) research discussed elsewhere in the text.

Lamentably, only 54% of users indicated that dry slots and their impact on fire weather were of "*moderate*" importance. Only 38% felt that there was enough available "sufficient quality" dry slot information, while only 24% felt there was a "*sufficient quantity*" of information (emphasis added). The author would suggest that these users are perhaps unfamiliar with and/or unaware of the many benefits of using satellite WVI to identify dry slots. The reader will recall that a 1999 NWS publication, *Critical Fire Weather Patterns of the United States*, approvingly advocated the use of WVI to locate "*dark areas*" (dry slots) and warned to be on guard for obscure Haines 5/6 areas of light gray (i.e. moist), also known as gray-scale or gray-shade drying in Weldon and Holmes (1991). Another good method suggested was to scrutinize the WVI carefully for totally black areas, since these black regions (dry slots) are regularly associated with a 5/6 Haines (1999). Consider that these were all in agreement with Weldon and Holmes (1991) and their "gray shade scale" assessments.

The questionnaire also referenced the use of forecast upper-level atmospheric parameters and stability conditions. Once again, WVI can provide this. Consider now the research on the DTSP wildfire in New Jersey by Kaplan et al. (2008) and Charney and Keyser (2010) elsewhere in the text. Even though there was no WVI to verify upper-level signatures for the 1980 Mack Lake Fire, research by Zimet and Martin in 2003 and again in 2007 with Zimet, Martin, and Potter found that upper-level fronts and stratospheric intrusions highly influenced this fire dramatically. One is able to clearly infer a dry slot right down the center of the relative humidity contours in both of the two relative humidity vertical cross-section images.

Also considered in the treatise were the Fire Weather Planning Forecasts, a zone-type product intended largely as input to land management decision makers involving firefighter safety, protection of the public and property, or wildland firefighting resource allocation. WVI can be very useful for these forecasts. Clearly, Charney and Charney and Keyser aptly discussed this elsewhere in the text (2007 and 2010) when they advised to "*develop and implement indices and diagnostics into the operational fire weather and fire behavior forecasting that sense these conditions*" (emphasis added).

Regarding the need for identifying mesoscale boundaries that impact fire environments and identifying atmospheric precursors of fire weather events in the *Great Lakes region*, and developing and implementing atmospheric based predictive indices for anticipating extreme fire behavior, the following research is valid. Miretzky (2009) authored "*A Model Based Analysis of the Synoptic and Mesoscale Processes Associated with Subsidence into the Western Great Lakes Wildfire Environment*" where he analyzed nine NEUS wildfires, plus the 1980 Mack Lake Fire, and determined that subsidence was a major causal factor on each of the wildfires. And once again consider Kaplan et al. (2008) and Charney and Keyser (2010) where they examined NEUS atmospheric weather event precursors on the 2002, New Jersey DTSP Wildfire. And Zimet et al. (2003 and 2007) examined the same on the 1980 Mack Lake Fire, also a NEUS wildfire elsewhere in the text.

Several very good publications on the following mesoscale and synoptic occurrences readily come to mind, e.g. Schroeder et al. (1964) Synoptic weather types associated with critical fire weather; Brotak and Reifsnyder (1977): An investigation of the synoptic situations associated with major wildland fires; The Critical Fire Weather Patterns of the United States, 1999 NWS Fire Weather Forecasters Course; and more recently Prevedel (2007) Linking Intense Western Wildfires with Weather Patterns and Conditions.

Also referenced in the Fire Weather treatise was their concern over Red Flag Warnings and Fire Weather Watches. These are issued by WFOs when the combination of dry fuels and weather conditions support an assessment of extreme fire danger and/or fire behavior. Mills (2005b and 2010) and Werth (2012) delve into this elsewhere in the text. Muller and Fuelberg (1990), Werth (2012), Mills (2005, 2008a), and the 1999 Fire Weather publication regarding dark areas, black regions, and the like - basically dry slots - are focused on elsewhere in the text.

As Operational Meteorologists, remember and return to some of the very basic analyses and forecasting methods vigorously encouraged in former education, research, and training venues and the literature. To become less reliant upon computer modeling and such was highly advocated by Bosart (2003) in Whither the Weather Analysis and Forecasting Process?

Given what was presented in this wide-ranging *Wildland Fire Weather: Multi-Agency Portfolio* and the readily-available references cited and applied in the literature; it is most remarkable that the author(s), editors, and users would even make such statements and/or hold some of their viewpoints. This author can only hope that many of those same users would further research these subjects. Maybe then will they change their minds and possibly others'. And finally, they will hopefully begin to acknowledge and '*see*' dry slots for what they are - a causal fire weather structure and a readily detectable signature - through the use of satellite WVI. This author considers that this would allow for much more accurate and thorough operational wildland fire weather forecasting and model verifications. And it would be "*going back to the basics*," always supported as a good idea.

Positive WVI forecasting reviews, commentary, and summarization of introductory text

In operational meteorology, satellite WVI analysis can be very beneficial concluded the USW (2008). Satellites can reveal structures not identified by conventional data as discovered by Muller and Fuelberg (1990). The dry intrusion is often evident in the WVI almost a full day before it can be found in the infrared and visible imagery examined by Santurette and Georgiev (2005). One of the most obvious interpretation scenarios occurs when the middle and upper troposphere are very dry according to Muller and Fuelberg (1990). The dark areas always reflect a comparatively dry middle and upper troposphere (1990). A dry band denotes convective instability if it moves over low level moisture and it can also be linked with the upper level disturbance that may trigger the instability discovered by Muller and Fuelberg (1990). A major finding of their research paper was the extremely close concurrence between the surface reports of damaging winds and the satellite signature of the southern fork of the dry intrusion in Iaccopelli and Knox (2001).

By combining satellite imagery and potential vorticity analyses, authors Lagouvardos and Kotroni showed that dry air originated in the lower-stratospheric and higher-tropospheric layers (2000). Grumm, DeVoir, and Villani discovered that the strongest wind gusts were confined to the region of the dry slot (2004). They also noted that the strong low-level wind gusts progressed eastward along with the dry slot (2004). Moreover, a secondary dry slot to the west was also associated with gusty winds and influenced by the dry slot (2004). They also noted that the growing dry slot and the expanding area of strong gusty winds were coincident as the cyclone moved northward and the surface front advanced eastward (2004). Therefore, the researchers proposed that the dry slot signature and WVI, over a region of anomalously high winds may be a useful short-term forecast tool in diagnosing similar wind events (2004).

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 suggested Mills (2005). Satellite data provides a significant benefit over complex terrain for the mountain meteorologist and therefore WVI is an excellent tool for diagnosing mountain wave signatures as proposed in Meyers (2010) and also Sharples (2007). The literature reveals that mountain waves often indicate extreme upper air turbulence, so this is an aviation concern for aerial firefighting resources as well as for fire weather and fire behavior concerns.

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 discovered Mills (2008). The potential for using WVI to monitor the movement of mid-tropospheric dry air towards the fire site should be investigated as a fire weather forecasting aid suggested Mills (2008). WVI has proved to be a valuable tool for observing the ridge developments, particularly the role of the upstream ridge where clouds are absent in Weldon and Holmes (1991). In addition, operational forecasters equipped with both numerical model fields and satellite WVI are in a better position to follow the synoptic situations as determined by Santurette and Georgiev (2005). According to the Cohesive Strategy, there is always a need for improved fire weather prediction and a general understanding of the weather (2011). According to Weldon and Holmes, WVI could be very useful at a later stage of the decision making process to refine forecasts and then atmospheric behavior can be compared to the model output for verification (1991). Therefore, forecasts can then be confirmed, modified, or significantly changed to reflect the observations suggested Weldon and Holmes (1991).

Model Forecasting Limitations

Each WV image is unique, and it is often difficult to interpret a single water vapor image discovered Weldon and Holmes (1991). The WVI features are transient, short-lived, and constantly in motion (1991). The task is much easier and more accurately accomplished when using a sequence of previous images, or when images are viewed in a time-lapse motion concluded Weldon and Holmes (1991). During the unfortunate 2012 Lower North Fork escaped RX Burn in Colorado, the weather forecasts made by computer models or human intuition did not accurately predict actual conditions according to Team Leader Bass (2012). During several Texas and Oklahoma, January 1, 2006 fire events, very poor weather forecast modeling "*grossly*" overestimated the relative humidity values and underestimated the winds as discovered by Lindley at al. (2006 and 2006a). Incredibly, the modeling completely missed an approaching cold front that accounted for dangerous wind shifts, according to Texas NOAA/NWS meteorologists Lindley, Conder, and Murdoch (2006 and 2006a). Grenci reasoned that high cloud tops frequently tend to contaminate water vapor images (2013). It appears that Grenci's assertion squares with the findings of Ralph et al. (1998) studying deep tropospheric gravity waves created by leeside cold fronts. They found that interleaving moist layers and clouds can degrade the satellite water vapor interpretation (1998).

Meyers and Steenburg suggested that inexperienced forecasters tend to rely too much on computer models and thus tend to be reactive with forecasts, whereas more experienced forecasters tend to be more flexible with their forecasting tools and procedures (2010). Bosart stated that "forecasters who grow accustomed to letting MOS [Model Output Statistics] and the models do their thinking for them on a regular basis during the course of their daily forecasting activities are at high risk of '*going down in flames*' when the atmosphere is in an outlier [atypical or infrequent] mode" (emphasis added) (2003). Bosart promoted the use of WVI for mesoscale analysis to hone one's skills and asserted that forecasters are losing their satellite and radar interpretation and analysis skills (2003).

Final Summary and Conclusions

This review and re-examination of United States wildland fires clearly suggests that dry slots are in fact responsible for large wildland fire growth in the United States and as reflected in the literature, despite a myriad of synonyms used for the signatures. The 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 dewpoints and relative humidities resulting in abrupt near-surface and sometimes surface drying, decreased fuel moistures, and increased and gusty winds resulting in large wildland fire growth (e.g. 2005b). 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, and 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 (2007 and 2010) as spot-on with his statements regarding atmospheric conditions aloft and utilizing new indices and diagnostics for operation wildland fire forecasting. It has been shown as an acceptable inference that dry slots and dry slot forecasting are included in the atmospheric conditions, indices, and diagnostics mentioned by Charney (2007 and 2010) are also referenced in this text. Even though addressed in the introduction, Charney is quoted here in total to make the point.

"*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*" (emphasis added) (Charney 2007 and Charney and Keyser 2010).

Future Research

The definite connection between dry air aloft and dry slots influencing large wildland fire growth in the U.S. and North America is valid and warrants further research. The research also suggests that there are very strong dry-slot-associations to high Haines Index, high potential vorticity (PV), high ozone events, inversions, thermal belts, stratospheric intrusions, subsidence, nocturnal low-level jets and jet streaks, , Red Flag Warnings and Fire Weather Watches, and other influencing mechanisms which also warrant further research.

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There were many researchers that assisted in the preparation of this paper. With gratitude, the author acknowledges the valuable encouragement and constructive criticism supplied by those that have most assisted in my dry slot research: Dr. Graham Mills, Australian BoM (retired) initially piqued this author's interest in the subject and guiding 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 huge 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, data, and images from the Mann Gulch Fire assisting with NOAA Reanalysis searches. Nicole Petersen, meteorologist, Rutgers University who has given valuable advice, guidance, and encouragement.

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