Analysis of an Intense Narrow Cold Frontal Rainband and the Springs Fire Burn Area Debris Flows of 12 December 2014

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1. Introduction

Southwest California occasionally receives periods of winter rainfall that result in flash flooding and debris flows. These heavy rainfall events are often associated with atmospheric rivers (ARs) and on very rare occasions, narrow cold frontal rainbands (NCFRs). Additionally, the region is subject to large wildfires due to prolonged periods with little rain, Santa Ana winds, and steep, complex terrain. These wildfires often produce soil conditions that greatly increase the threat of debris flows.

On 12 December 2014, the scenario described above resulted in several significant debris flows in the Springs Fire burn area (Fig. 1). The debris flows were the result of an intense, short-duration rainfall event with a return interval of approximately 500 years, and were produced by an NCFR and associated AR. The heavy rain event came about a year and a half following the Springs Fire, which occurred in early May 2013.

Debris flows are a type of fast-moving landslide that generally occur during intense rainfall. Their consistency ranges from watery mud to thick, rocky mud, which can carry boulders, trees, and other large debris (USGS 1995). Wildfires in the western United States can increase the threat of debris flows by reducing the infiltration capacity of soils and removing ground cover that would otherwise help to hold the soil in place. This leads to changes in hillslope hydrologic function in the form of increased runoff and erosion. Such conditions result in increased flash flooding, sedimentation and deterioration of soil conditions. In addition, dry ravel (a surface erosion process) and sediment loading of drainage channels can lead to potentially life threatening debris flows. Fire-related debris flows are most likely within the first two rainy seasons in southern California, provided that several significant rainfall events occur in those first two seasons. In general, it takes much lower rainfall rates to produce debris flows in burn areas in comparison to non-burn areas. In southern California, storms that produce rainfall intensities greater than 0.40 in hr^{-1} are capable of producing debris flows over many burn areas (USGS 2005). In contrast, the rule of thumb used to issue warnings for flash flooding and debris flows in non-burn areas by forecasters at NWS Los Angeles/Oxnard (LOX) is 1.00 in hr^{-1}.

According to Rutz et al. (2014), ARs are narrow corridors of high atmospheric moisture content that are responsible for nearly 90 percent of the poleward transport of water vapor. The two common definitions that Rutz et al. (2014) and others use to identify ARs are 1) a contiguous region of 2000 km or more in length, with vertically integrated water vapor transport (IVT) greater than or equal to 250 kg m^{-1} s^{-1}, or 2) a contiguous region of 2000 km or more in length, with vertically integrated water vapor (IWV) or precipitable water (PWAT) greater than or equal to 20 mm. It will be shown that the AR associated with the December 2014 event met both of these criteria.

Additionally, it will be shown that the December 2014 event was produced by a line of convection that had many characteristics common to NCFRs. Hobbs (1978) was one of the first to classify NCFRs into their own category. In his study of rainbands associated with extratropical cyclones, Hobbs found NCFRs to be the most intense. Jorgensen et al. (2003) described NCFRs as narrow regions of high radar reflectivity only a few kilometers wide, which have many of the same characteristics as squall lines on radar, including breaks and gaps due to bowing segments. They also found that NCFRs form close to a surface cold front, which serves as the primary source of lift in an environment with very little instability. Additional NCFR characteristics noted by Jorgensen et al. include strong, but relatively shallow updrafts on the order of 10-20 m s^{-1}, radar echo tops around 4-5 km AGL, occasional severe weather (hail, convective winds, and tornadoes), a strong low-level jet ahead of and parallel to the heavy rain band (about 1.5 km AGL), and a westerly rear inflow jet behind the heavy rain band (about 1 km AGL). Furthermore, Geerts and Hobbs (1995) made the distinction between NCFRs and squall lines by showing that NCFRs are driven primarily by frontal convergence and the cold airmass behind the front, rather than an unstable atmosphere and evaporative driven cold pool dynamics.

The next section will provide a brief geographic overview of the LOX county warning area (CWA). Following that, the Synoptic Overview, Mesoscale Analysis, and Hydrology and Impacts sections will describe the details of this significant event.

2. Geographic Overview

Fig. 1 provides an overview of the LOX CWA, which includes San Luis Obispo, Santa Barbara, Ventura, and Los Angeles (LA) counties. From Fig. 1, it can be seen that the LOX CWA is a region of complex topography. A unique aspect of the topography in the LOX CWA is that many of the mountain ranges are oriented from east to west, which results in enhanced rainfall on south facing slopes when southerly low-level flow is present ahead of an approaching low pressure system. The main geographic features that will commonly be referred to throughout this paper are labeled in white in Fig. 1, and include the Central Coast, the Santa Barbara Channel, the Oxnard Plain, the Santa Monica Mountains, and the LA Basin. The Springs Fire burn area is outlined and labeled in red, and is located on the western fringe of the Santa Monica Mountains.

3. Synoptic Overview

The synoptic pattern associated with the December 2014 heavy rain event produced a type of AR that is commonly referred to as a "Pineapple Express." Figure 2 shows the Global Forecast System (GFS) initializations of the 500 mb heights, PWAT, and mean sea level pressure (MSLP) from 0000 UTC 11 December through 1200 UTC 12 December. From Fig. 2, a deep, negatively-tilted 500 mb trough developed over the Eastern Pacific. Southwesterly flow around the base of this 500 mb trough was able to tap into a rich area of moisture that extended to the southwest towards Hawaii, with PWAT values in excess of 20 mm. This moist southwesterly flow took aim on the West Coast, producing the highest rainfall totals in northern California, where the AR remain relatively stationary for a period of time. It should also be noted that the main 500 mb low and surface low moved across Washington, well north of Southern California.

Fig. 3 shows atmospheric soundings taken from Oakland (OAK) and Vandenberg Air Force Base (VBG). Fig. 3a depicts the OAK sounding at 1200 UTC 11 December. At this time, the cold front was still west of OAK, but the AR was moving over the area ahead of the front. The low-level wind profile shows a veering pattern, indicative of the warm air advection ahead of the cold front. Additionally, the PWAT value of 34 mm verifies the GFS analysis shown in Fig. 2a. In Fig. 3b, two soundings from VBG are shown. The 0000 UTC 12 December VBG sounding shows the atmospheric conditions several hours prior to the cold frontal passage, distinguished by the veering of the low-level winds. On the 1200 UTC 12 December VBG sounding, the cold front had passed this location, distinguished by the backing of the mid-level winds (indicative of cold air advection) and the significantly colder temperature profile. It should be also noted that very little instability was indicated in any of the soundings.

Fig. 4 depicts the 300 mb heights and winds from the GFS initialization at 0600 UTC 12 December. Two things to note from this figure are the negatively-tilted trough over the Eastern Pacific, as well as the location of the jet streak on the eastern side of the trough. At this time, the Central Coast was in the vicinity of the right entrance region of this jet streak. The vertical lift associated with the right entrance region of the jet streak likely helped to tighten the thermal gradient at the surface and strengthen the cold front as it moved across the Central Coast.

4. Mesoscale Analysis

a. Radar Overview

Radar imagery from the Vandenberg WSR-88D radar (KVBX) indicated a strong convective line moving through the Central Coast from approximately 0400-0700 UTC 12 December (Fig. 5). As the convective line moved onshore, it had a squall line-like appearance with a long, narrow band of high reflectivity and multiple bowing segments (Fig. 5a-c).

Fig. 5c shows the convective line approaching KVBG at 0557 UTC. The meteogram for KVBG indicated strong winds ahead of the convective line around this time, with SE winds sustained at 30-40 kt and gusts as high as 50 kt from 0400-0600 UTC (Fig. 6a). In addition to the intense rainfall that was observed, the strong S to SE winds ahead of the front resulted in several significant power outages on the Central Coast during this time. Observations from KVBG also indicated a period of heavy rain with the front around 0700 UTC, followed by several hours of moderate stratiform rain (Fig. 6a). The KVBX radar shows the large area of stratiform rain behind the initial line of convection (Fig. 5).

As the main convective line moved onto the Central Coast from 0600-0700 UTC, it weakened significantly; however, redevelopment along the southern portion of the line can be seen in Figs. 5c and 5d. At 0557 UTC the southern portion of the convective line can be seen west of the Santa Barbara Channel (Fig. 5c), then moving through the Santa Barbara Channel at 0658 UTC (Fig. 5d). The southern portion of the convective line would later impact the Oxnard Plain and the Springs Fire burn area.

The southern portion of the convective line reached the Oxnard Plain around 0900 UTC. At 0914 UTC, the Sulphur Mountain WSR-88D radar (KVTX) shows the convective line as it reached its peak intensity while crossing the Oxnard Plain (Fig. 7a). At this time reflectivity values were 50-60 dBZ, with a few pixels over 60 dBZ. The convective line remained relatively strong as it approached and moved across the Springs Fire burn area from about 0945 – 1030 UTC (Fig 7b-d). Observations from the Point Mugu Naval Base (KNTD) indicated heavy rain with the convective line around 1000 UTC, followed by a period of moderate stratiform rain (Fig. 6b). The KNTD meteogram also shows that the SE winds ahead of the front remained quite strong as it moved across the Oxnard Plain, with sustained SE winds at 30-40 kt and gusts approaching 50 kt.

After 1030 UTC, the segment of the convective line that moved across the Springs Fire burn area began to weaken, but once again re-development occurred along the southern extent. At 1048 UTC, the Santa Ana WSR-88D (KSOX) showed a distinct break between the convective line that moved through the Springs Fire burn area and the new line segment that was moving towards the LA Basin (Fig 8a). The convective line moved through the LA Basin between about 1100 and 1300 UTC (Fig. 8a-c). At 1143 UTC, the KSOX radar showed the convective line approaching Long Beach airport (KLGB) as it intensified. Observations from KLGB indicated heavy rain around this time (Fig. 6c). The KLGB meteogram also shows that the SE winds ahead of the front were much weaker as it moved through LA County, with 10-15 kt SE winds and gusts of 25-30 kt (Fig. 6c).

By 1222 UTC, the convective line was approaching the Colby Fire burn area in the foothills of the San Gabriel Mountains (Fig. 8c). Leading up to this event, debris flows were a major concern for this area, much like they were for the Springs Fire burn area. While intense rainfall was observed over the Colby burn area, there were no major mud or debris flows reported.

The convective line exited LA County after 1230 UTC and approached Ontario International Airport (KONT) in San Bernardino County. Heavy rain and thunderstorms were reported as the convective line moved past KONT around 1300 UTC (Fig. 6a). The remarks section of the METAR for KONT indicated that this was in-cloud lightning. It should be noted that this was the first ASOS sensor to detect thunderstorms with the convective line. It is also interesting to note that the National Lightning Detection Network (NLDN) did not detect any cloud-to-ground lightning with the convective line as it moved through the LOX CWA, despite its intense appearance on radar.

Several hours following the passage of the cold front, convection in LA County became more showery and cellular as colder air began to move in aloft and daytime heating began. This can be seen in the KSOX reflectivity image at 1717 UTC 12 December (Fig. 8d). It was at this time that a short-lived EF0 tornado was captured on video several miles southwest of downtown LA, within the white box in Figure 8d. A closer look at the convective cell that produced the weak tornado is shown in Figure 9a. Despite the video evidence of the weak tornado, the KSOX radar did not detect any rotation with this storm (Fig. 9b).

b. Environmental Instability

Although the line of heavy rain that moved through the LOX CWA was convective, environmental instability near and ahead of the front was weak as shown by the Rapid Refresh (RAP) model analysis in Fig. 10. As the convective line approached the Central Coast at 0500 UTC 12 December, the RAP analysis only indicated about 200-300 J kg^{-1} of convective available potential energy (CAPE) and lifted index (LI) values of 0 to -1 along and ahead of the front (Fig 10a). A RAP sounding taken ahead of the front at this time shows that the reason for the weak instability was a lack of steep mid-level lapse rates (Fig. 11a). In fact, the 0500 UTC RAP sounding indicated a near moist adiabatic temperature profile from about 850-500 mb (Fig. 11a), as the strong southerly winds ahead of the front advected warm moist air northward. Instability remained weak for the same reasons as the convective line approached the Springs Fire burn area at 0900 UTC (Fig. 10b and 11b) and the LA basin at 1100 UTC (Fig. 10c and 11c). The 1200 UTC 12 December sounding from KVBG (Fig. 3b) supports the weak instability shown in the RAP analysis. The absence of significant instability near and ahead of the front explains why there was very little or no lightning associated with the convective line as it moved through the LOX CWA. The near moist adiabatic lapse rates and skinny CAPE profiles from the surface to 500 mb were also indicative of an environment that was conducive for heavy rain.

Better instability developed well after the passage of the surface cold front as cold air started to move in aloft and daytime heating began. Fig. 10d shows CAPE values of 500-1000 J Kg^{-1} and LIs of -3 to -5 over the coastal waters at 1800 UTC 12 December, which was around the time that the EF0 tornado occurred near downtown LA. A RAP sounding at this time also shows steeper mid-level lapse rates with the colder air moving in aloft (Fig. 11d). It appears that there was a brief period between about 1600 and 1900 UTC when conditions became favorable for the EF0 tornado to form, as the higher CAPE values started to move into the LA basin and significant low-level shear was still present. Fig. 10d shows that there was about 35 kt of 0-3 km shear over the LA basin around the time that the tornado occurred.

c. NCFR Characteristics

As previously shown, the convective line that moved through the LOX CWA exhibited features on radar that are consistent with NCFRs. This included a long, narrow band of high reflectivity values, with multiple bowing segments that resulted in breaks in the convective line. NCFRs also tend to occur in environments with weak environmental instability, which was shown to be true in this case. Furthermore, the convective line occurred just ahead of a strong, fast-moving cold front. Additional characteristics of NCFRs outlined by Jorgensen et al. (2003) were shallow radar echo tops of 4-5 km AGL, a strong low-level jet ahead of and parallel to the line of convection around 1.5 km AGL, strong but relatively shallow updrafts of 10-20 ms^{-1}, and a westerly rear inflow jet about 1 km AGL.

The reflectivity cross-section taken as the convective line approached the Central Coast, shows echo tops (reflectivity values greater than 18 dBZ) up to about 15 kft, which is roughly 4.5 km (Fig. 12a). Also note that reflectivity values greater than 50 dBZ are mostly below about 8 kft. Additionally, the base velocity cross-section in Fig.12b shows shows the rear inflow jet behind the front, with inbound velocities (green shading) below 5 kft. The rear inflow jet is centered around 3 kft, or about 1 km AGL. The above observations are consistent with observations of NCFRs made by Jorgensen et al.

The 850 mb analysis from the RAP also indicated a strong low-level jet ahead of the convective line as it approached the Central Coast at 0500 UTC 12 December, with a large area of 40-50 kt winds along the front and a 65 kt maximum over San Luis Obispo and Santa Barbara counties (Fig. 13). An east-west cross-section of the RAP data through line A-A' in Fig. 13 provides more details on the structure of the low-level jet and the front (Fig. 14). In Fig. 14, omega values of -35 μb s^{-1} indicated a shallow region of strong ascent along the front, centered around 850 mb. The 65 kt low-level jet can also be seen in the cross-section to the east of the region of strong ascent, centered around 850 mb or about 1.5 km ASL (Fig. 14). This is also in good agreement with Jorgensen et al. (2003). Furthermore, the vertical azimuth display (VAD) wind profile from KVBX supports the RAP analysis, with 60-70 kt winds at 5 kft AGL (about 1.5 km AGL) around 0500 UTC 12 December (Fig. 15).

The observations discussed in this section support the idea that the intense convective line that produced the Springs Fire burn area debris flows and heavy rain throughout the LOX CWA, can be classified as a NCFR rather than a squall line. This point is further strengthened when one considers that the primary source of lift was a powerful, fast-moving cold front, rather than strong instability and evaporative driven cold pool dynamics.

5. Hydrology and Impacts

a. Springs Fire Burn Area Background

The Springs Fire occurred in early May 2013 in the extreme western portion of the Santa Monica Mountains and adjacent coastal foothill areas (Fig. 1). After igniting during the early morning hours on 2 May 2013 in the foothills above Camarillo Springs (Fig. 16), the fire rapidly spread to the southwest under Santa Ana conditions, reaching the coast about 8 miles away later that evening. The fire continued for several more days, burning over 24,000 acres in total. The most significant hydrologic influence of the Springs Fire was the loss of ground cover, which lead to increased runoff, along with exposed soil and loose debris. This in turn, likely lead to dry ravel (a surface erosion process) and sediment loading of drainage channels. Decreased infiltration capacity of the soil resulting from the fire may have also been a factor in the severity of the debris flows.

Fig. 16 shows the United States Geological Survey (USGS) debris flow relative hazard areas for the Springs Fire burn area prior to the December 2014 heavy rain event, but also provides a closer look at some locations of particular interest. Leading up to this event there was concern that many homes in the Camarillo Springs area (Fig. 16) were in danger of being impacted by a debris flow. As seen in Fig. 16, Camarillo Springs was located on the northern fringe of the burn area below several drainage basins that were considered to be at moderate risk for debris flows according to USGS modeling results. A closer look at the topography near Camarillo Springs shows that the community is located below Conejo Mountain, which has steep slopes and several deep canyons that drain down into the development (Fig. 17). Following the Springs Fire, the steep, rocky slopes of Conejo Mountain were covered by loose soil and talus (rock debris), which served as the source material for the subsequent mud and debris flows. San Como Lane (Fig. 17) was the area of greatest concern, where a clogged storm drain had caused less serious problems a week prior during an event that produced rainfall rates of no more than 0.33 in hr^{-1}. The same storm drain played an important role in the much more significant debris flow that occurred in this area on 12 December.

In addition to the Camarillo Springs debris flow, several other debris flows occurred along the Pacific Coast Highway (PCH) between Point Mugu Rock and Deer Creek Road, where the USGS modeling results indicated a low to moderate risk (Fig. 16). The most significant debris flow on the PCH occurred just north of Deer Creek Road, below a drainage basin that was considered to be at moderate risk. The area thought to be at high risk for debris flows (red area in Figure 16) covered a low impact, rural area.

Table 1 below provides a summary of the flash flood and debris flow thresholds that were in place for Springs Fire burn area prior to the December 2014 event.

USGS Debris Flow Thresholds for the Springs Fire Burn Area	
Rainfall Duration	**Debris Flow Threshold**
15 min	0.20 in
30 min	0.30 in
1 hr	0.50 in
3 hr	1.00 in
6 hr	1.40 in
12 hr	2.20 in

Table 1. USGS flash flood and debris flow thresholds for the Springs Fire burn area prior to the 11-12 December 2014 heavy rain event.

These are the thresholds that were used by forecasters at LOX in their decisions to issue Flash Flood Warnings. The rainfall thresholds were developed by the USGS following many years of extensive research on burn areas in southern California. The USGS and staff at LOX have used the results of this research to evaluate debris flow potential for burn areas in southwest California, including Ventura County, since 2005. It should be noted that these flash flood and debris flow thresholds are significantly lower than rainfall thresholds typically used in areas outside of burn areas. For example, in non-burn areas it typically requires 1.00 in hr^{-1} or greater for flash flooding in southern California, but the threshold was set at 0.50 in hr^{-1} for the Springs Fire burn area. However, due to the intensity and short duration of the rainfall associated with the NCFR in the December 2014 event, it turned out that the threshold of 0.20 inches in 15 min was the most critical.

b. Precipitation Analysis

Fig. 18 provides an overall quantitative precipitation estimate (QPE) summary for the entire event from 1800 UTC 10 December through 1200 UTC 13 December. The most impressive rainfall totals for this event occurred in northern California where the AR remained relatively stationary for a period of time, resulting in some rainfall amounts in excess of 10 inches (Fig. 18a). Lighter amounts were observed in southern California, as the cold front and associated AR and NCFR quickly moved through the region. A closer look at rainfall totals for the LOX CWA shows 3-5 inch amounts in the mountains and along some of the coastal slopes (Fig. 18b). According to the QPE analysis, rainfall totals across the Oxnard Plain and the Springs Fire burn area were about 1.50 – 2.50 inches. Slightly lighter rainfall totals were observed in the eastern portion of the LA basin, where 1.00 – 1.50 inches fell (Fig. 18b).

The legacy Storm Total Precipitation (STP) estimate from KVTX is shown in Fig. 19. The STP estimate ends at 1100 UTC 12 December, which is shortly after the time when the convective line cleared the Springs Fire burn area. As Fig. 19 shows, the radar only estimated about 0.50 inches of rain with the main convective line across the Oxnard Plain, with some 1.00 inch amounts on the eastern side of the burn area. In reality, rain gage data in this area showed about 1.00 – 1.50 inches ending around 1100 UTC 12 December. The low bias in the radar estimate in this case was likely due to the shallow nature of the convection, with the radar beam overshooting some of the higher reflectivities at low elevations.

While the storm total rainfall amounts in this event were not overly impressive for a winter storm in southern California, the short duration rainfall amounts were historic. Fig. 20 presents the rainfall graphs for the four ALERT rain gage sensors indicated in Fig. 19. From Fig. 20, it can be seen that measurable rain across the Oxnard Plain and the Springs Fire burn area occurred between about 0600 – 1800 UTC 12 December, with the bulk of this rain coming during a 1-hr period associated with the NCFR. The 0600 – 1800 UTC 12 December rainfall totals ranged from about 1.70 inches at the Camarillo Adohr sensor (CDHC1), to about 2.50 inches at the NWS forecast office in Oxnard (LOXC1). Furthermore, the 1-hr rainfall totals ending at 1000 UTC were around 1.00 inch at Port Hueneme (OXTC1) and LOXC1 (Fig. 20a-b). The 1-hr rainfall totals ending at 1100 UTC for Circle X Ranch (CRXC1) and CDHC1 were also around 1.00 inch (Fig. 20c-d).

The 10-15 minute rainfall totals associated with the convective line were the most impressive. Table 2 below summarizes the 10-15 minute rainfall amounts for the four rain gages in Fig. 20.

Site	**Time (UTC)**	**Duration (min)**	**Amount (in)**	**Precipitation Frequency (yr)**	**Annual Probability**
Port Hueneme (OXTC1)	0922 – 0931	11	0.64	1000	0.1%
	0922 – 0938	16	0.74	500 – 1000	0.1 – 0.2%
NWS Oxnard (LOXC1)	0930 – 0945	15	0.93	> 1000	<0.1%
Camarillo Adohr (CDHC1)	1000 – 1010	10	0.60	500	0.2%
Circle X Ranch (CRXC1)	1026 – 1036	10	0.67	100 – 200	0.5 – 1.0%
	1026 – 1040	14	0.79	50 – 100	1.0 – 2.0%

Table 2. Summary of short duration rainfall amounts during specified time ranges on 12 December 2014 for four rain gages near the Springs Fire burn area (locations shown in Figure 19). Also shown are the precipitation frequency (return interval) and the probability of occurrence in any given year. Rainfall data comes from ALERT rain gages that are maintained by the Ventura County Watershed Protection District. Precipitation frequency and annual probability numbers are based on NOAA Atlas 14 estimates (http://hdsc.nws.noaa.gov/hdsc/pfds/).

Table 2 shows that the NCFR produced roughly 0.50 – 1.00 inches of rain in approximately 10-15 minutes as it cross the Oxnard Plain and the Springs Fire burn area. The Camarillo Adohr (CDHC1) sensor is likely the most representative of rainfall rates in Camarillo Springs, as it is the closest to the site of the debris flow in that area (Fig. 19). This sensor measured 0.60 inches in the 10 minutes ending at 1010 UTC 12 December, with the debris flow occurring several minutes later. According to the NOAA Atlas 14 point precipitation frequency estimates (http://hdsc.nws.noaa.gov/hdsc/pfds/), this equates to a rainfall rate with a 500-yr return interval at this specific location. In other words, there is a 0.2 percent chance of this rainfall rate being observed at this specific location in any given year. Also from Table 2, the 10-15 minute rainfall rates at Port Hueneme were estimated to have a 500 – 1000 year return interval. The most impressive short-duration rainfall occurred at the NWS Los Angeles/Oxnard office, where 0.93 inches was measured in 15 minutes. This was greater than a 1,000-yr event at this location. The 10-15 minute rainfall rates at Circle X Ranch near the east side of the burn area were similar to the sites further east, but the precipitation frequencies were not quite as extreme.

It should be noted that although the Camarillo Springs debris flow occurred several minutes after 1010 UTC, a Flash Flood Warning for the Springs Fire burn area was issued by LOX at 0856 UTC, well before the convective line reached the Springs Fire burn area (Fig. 7a). This provided emergency responders with well over an hour of lead time to allow for evacuations.

c. Impacts

The result of these intense, short-duration rainfall rates near the Springs Fire burn area were several significant debris flows. As previously mentioned, multiple homes along San Como Lane in Camarillo Springs were severely damaged. Fig. 21 provides an aerial view the morning after the debris flow and shows at least 5 homes that had rocks, mud, and other debris piled up against their backside. The faulty storm drain that exasperated the debris flow problem can also be seen on the hillside behind the homes that were damaged. In total, 16 homes were damaged in the Camarillo Springs debris flow. Ten of those homes were red-tagged, meaning that they were severely damaged and deemed unsafe to occupy.

There were also multiple debris flows that occurred along the PCH between Point Mugu Rock and Deer Park Road (Fig. 16). Fig. 22 shows an aerial view of the most severe debris flow on the PCH, just north of Deer Park Road. This debris flow and several others along the PCH, resulted in a 9 mi closure of the highway from Las Posas Road to Yerba Buena Road (Fig. 16). The PCH closure lasted through late February 2015, which was a period of about 2.5 months.

Other mudslide issues were also observed within the Springs Fire burn area in Point Mugu State Park. On the morning of 12 December, Conejo Creek had an observed peak flow of just over 7,000 cfs, resulting in flooding of the adjacent agricultural fields. Additionally, multiple rescues had to be made in the Camarillo Springs and PCH debris flows, but no fatalities were reported.

6. Predictability

While high-resolution models such as the High Resolution Rapid Refresh (HRRR) may be useful in predicting the timing of convective events such as the December 2014 NCFR, it seems unlikely that current operational high-resolution models can consistently and accurately predict the magnitude of such events on timescales of 10-15 minutes. However, the use of ensemble forecast systems can keep forecasters situationally aware of extremely rare events such as this one. The North American Ensemble Forecast System (NAEFS) provided an example of this situational awareness with the December 2014 event. As seen in Fig. 23a-b, the NAEFS 30-hr forecast valid at 0600 UTC 12 December indicated mean IVT values exceeding 750 kg m^{-1} s^{-1}. This ranked above the 99.5 percentile of the Climate Forecast System Reanalysis (CFSR) climatology for 1-22 December, and was also the maximum IVT value at 0600 UTC. Furthermore, the NAEFS indicated a large area of mean IVT values with a return interval exceeding 10 years, as well as mean IVT values that were outside of the 0600 UTC CFSR climatology (Fig. 23b). The NAEFS mean PWAT values were impressive as well, with 1.00-1.25 inches of precipitable water associated with the AR (Fig. 23c-d), but were not quite as extreme as the IVT values. The NAEFS mean PWAT values were at the 99^{th} percentile (Fig. 23c), with a return interval of 5-10 years (Fig. 23d). The IVT values predicted by the NAEFS were likely more extreme than the PWAT values due to the exceptionally strong low-level jet that accompanied the NCFR.

7. Summary and Conclusions

On 11-12 December 2014 an intense line of convection moved through the LOX CWA that resulted in several major debris flows in the Springs Fire burn area. This event was associated with a type of AR that is often referred to as a “Pineapple Express”. The intense line of convection that moved through the LOX CWA can be classified as a NCFR because it exhibited the following:

- A strong surface cold front that served as the primary source of lift
- Weak environmental instability (CAPE < 300 J kg^{-1} and LI values of 0 to -1)
- A long and narrow region of high radar reflectivity, with a squall line-like appearance
- Breaks and gaps in the convective line due to multiple bowing segments
- A strong low-level jet (60-70 kt) ahead of and parallel to the convective line, centered around the 850 mb level (about 5 kft or 1.5 km AGL)
- Strong, shallow updrafts also centered around 850 mb
- Shallow radar echo tops around 15 kft or about 4.5 km AGL
- A rear inflow jet centered around 3 kft or about 1 km AGL

As the line of convection moved across the Springs Fire burn area, various rain gages reported about 0.50-1.00 inches of rain in 10-15 minutes. The 10-15 minute return intervals at some of these rain gages near the burn area were estimated to be 500-1000 years. The observed 10-15 minute rainfall rates were also 3-5 times greater than USGS thresholds for debris flows in the Springs Fire burn area. While individual thunderstorms over a single location can produce similar rainfall rates on a relatively frequent basis, this was a historic event for southwest California because the extreme rainfall rates associated with the NCFR occurred over nearly the entire LOX CWA.

In the days leading up to the December 2014 NCFR, forecasters at LOX correctly anticipated rainfall rates that were capable of producing flash flooding and debris flows in the Springs Fire burn area. As was shown in this case, ensemble forecasting systems can help build confidence in predicting these types of extreme events well in advance. In events such as the December 2014 NCFR that are forced by a well-defined synoptic-scale feature, high-resolution models like the HRRR may be able to provide additional information such as the approximate arrival time of the convective line several hours in advance. However, it seems unlikely that current operational high-resolution models can accurately predict extreme rainfall amounts on time scales of 10-15 minutes. Therefore, one area of future research may be to examine what additional information high-resolution models can provide for NCFRs along the west coast.

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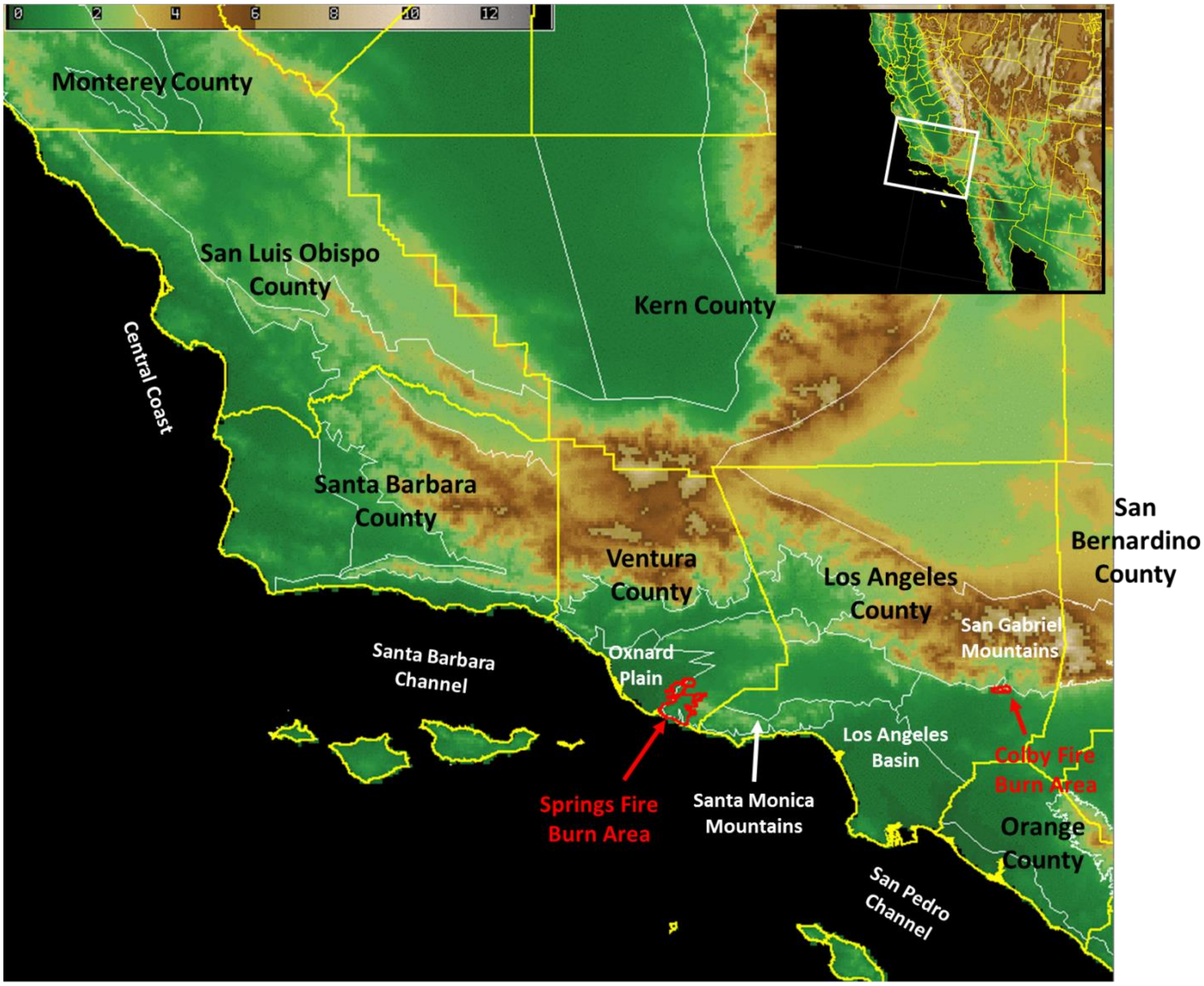

Fig. 1. Geographic overview of the NWS Los Angeles/Oxnard county warning area, which includes San Luis Obispo County, Santa Barbara County, Ventura County, and Los Angeles County. County borders are outlined in yellow and labeled in black. Thin white lines indicate the forecast zone boundaries. The Springs Fire and Colby Fire burn areas are outlined and labeled in red. Additional geographic features are labeled in white.

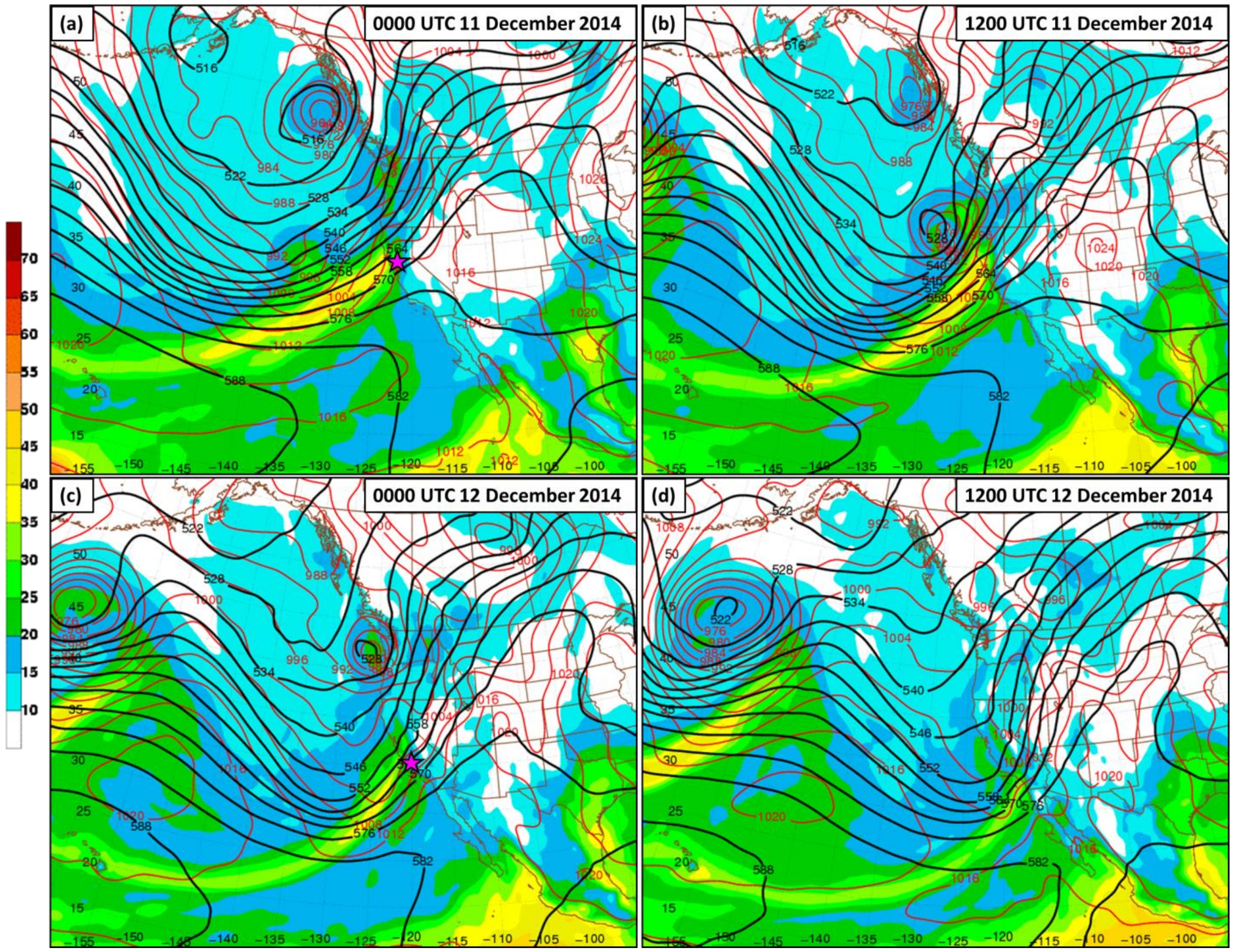

Fig. 2. 500 mb heights (dam, black contours), mean sea level pressure (mb, red contours), and precipitable water (mm, shaded) for (a) 0000 UTC 11 December 2014, (b) 1200 UTC 11 December 2014, (c) 0000 UTC 12 December 2014, and (d) 1200 UTC 12 December 2014. Data source is the GFS initialization. The pink stars in (a) and (c) indicate the upper-air sites for Oakland (OAK) and Vandenberg Air Force Base (VBG), respectively.

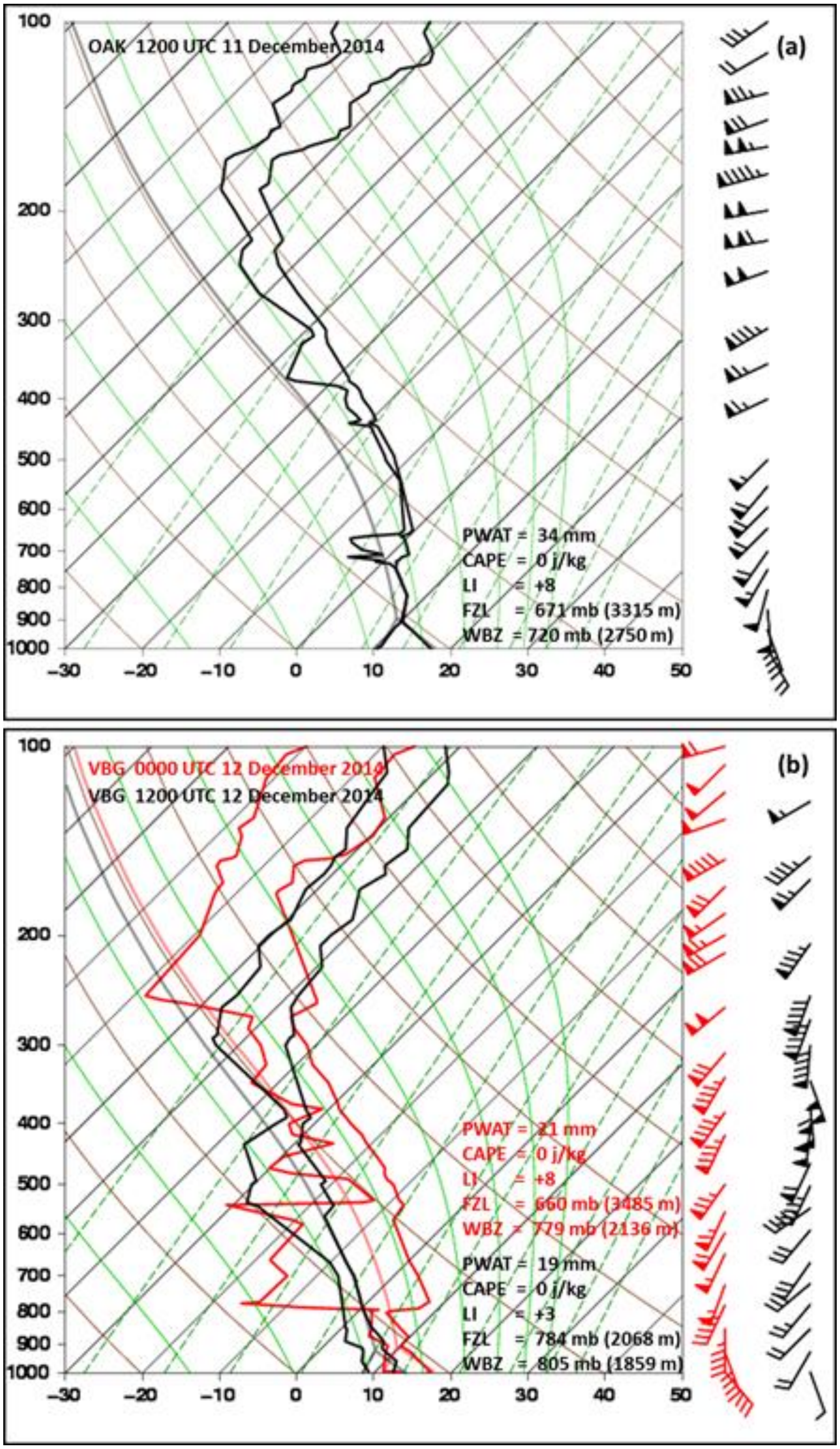

Fig. 3. Soundings for (a) OAK at 1200 UTC 11 December 2014 and (b) VBG at 0000 UTC 12 December 2014 (red) and 1200 UTC 12 December 2014 (black). The locations of these upper-air sites are shown in Figure 2.

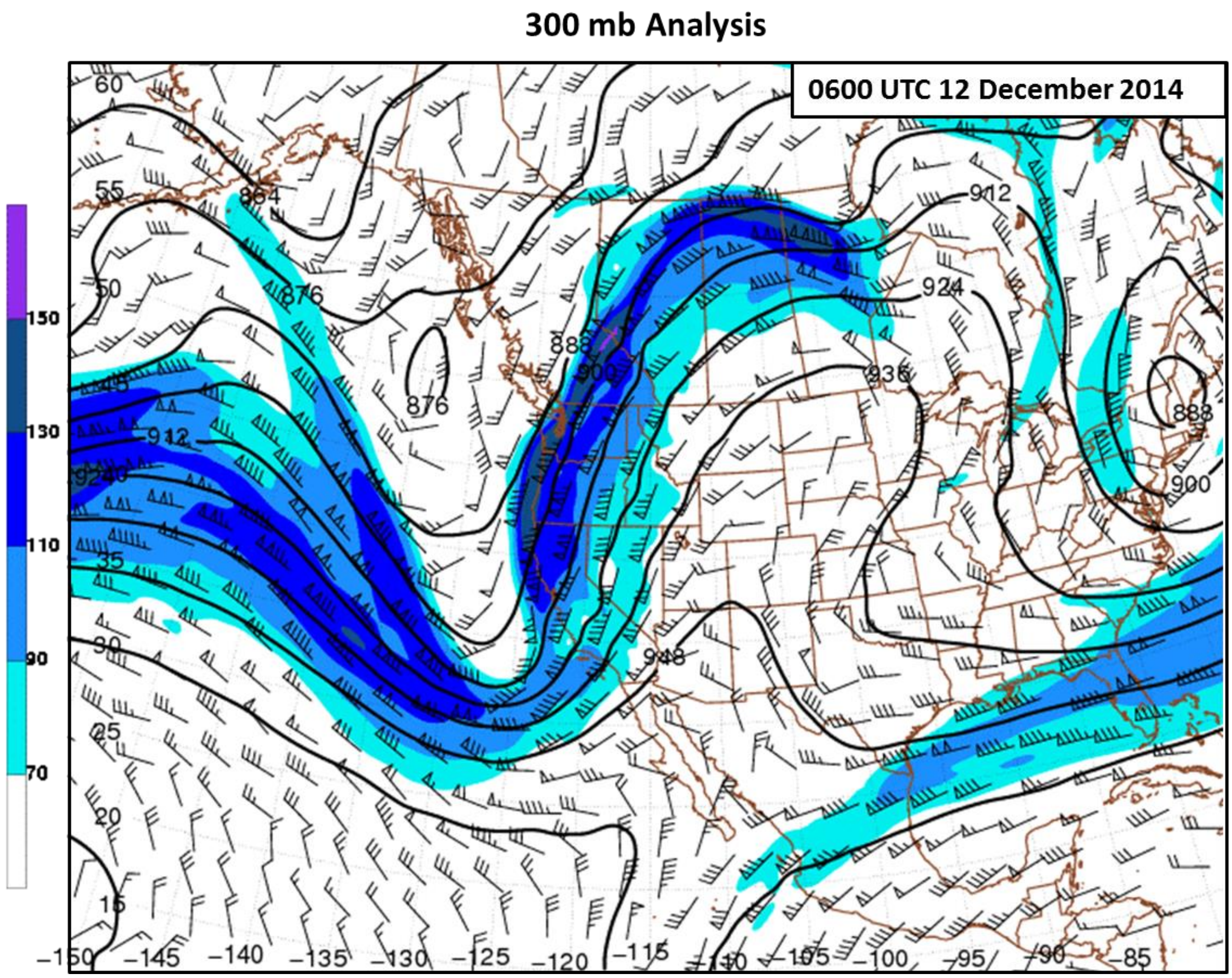

Fig. 4. 300 mb heights (dam, black contours), wind speeds (kt, shaded), and winds (kt, wind barbs) at 0600 UTC 12 December 2014. Data source is the GFS initialization.

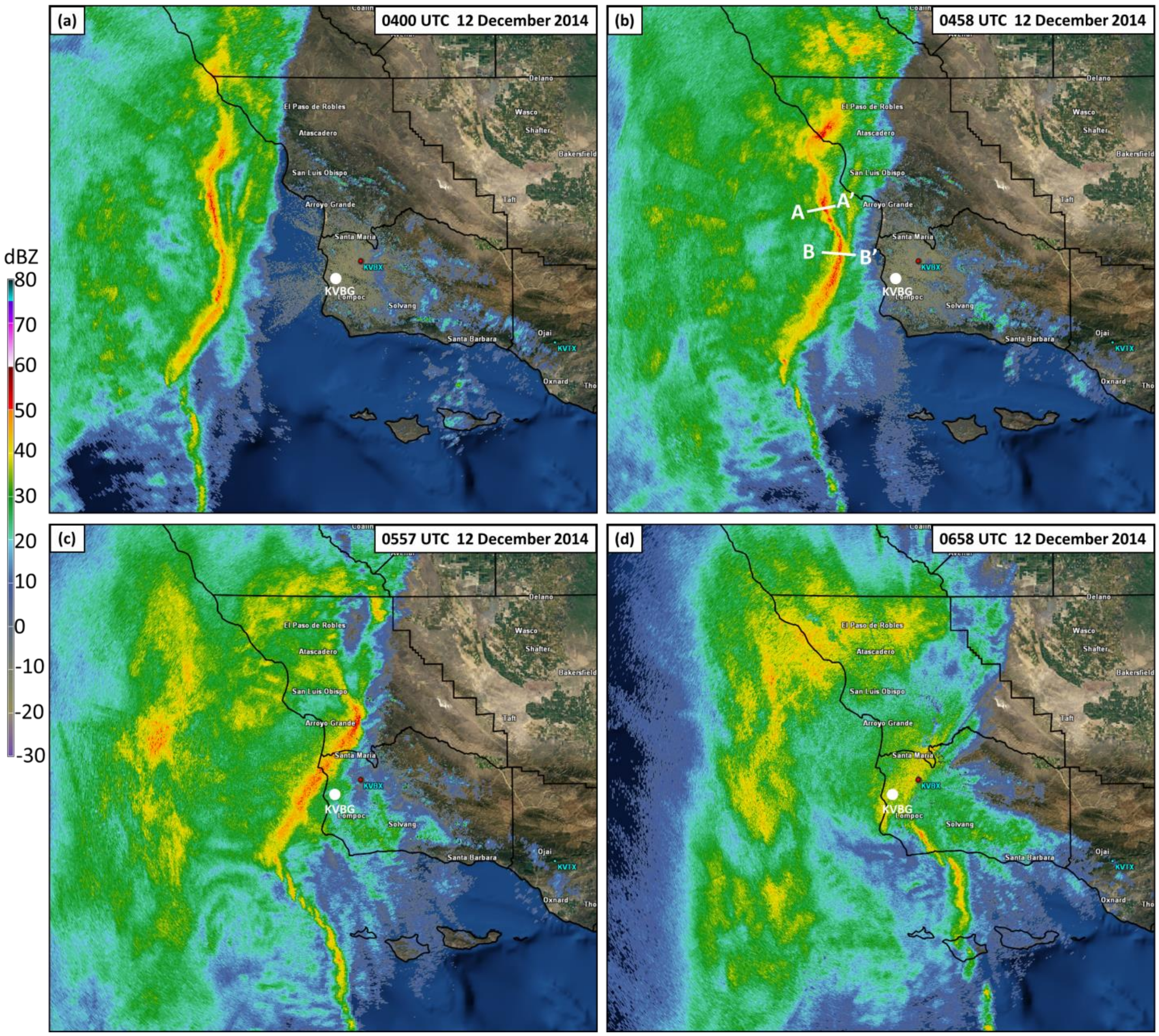

Fig. 5. 0.5° Base Reflectivity (dBZ) from the KVBX WSR-88D at (a) 0400 UTC, (b) 0458 UTC, (c) 0557 UTC, and (d) 0658 UTC 12 December 2014. The lines A-A' and B-B' in (b) indicate the cross-section lines for Figure 12. Images were created with GR2Analyst software.

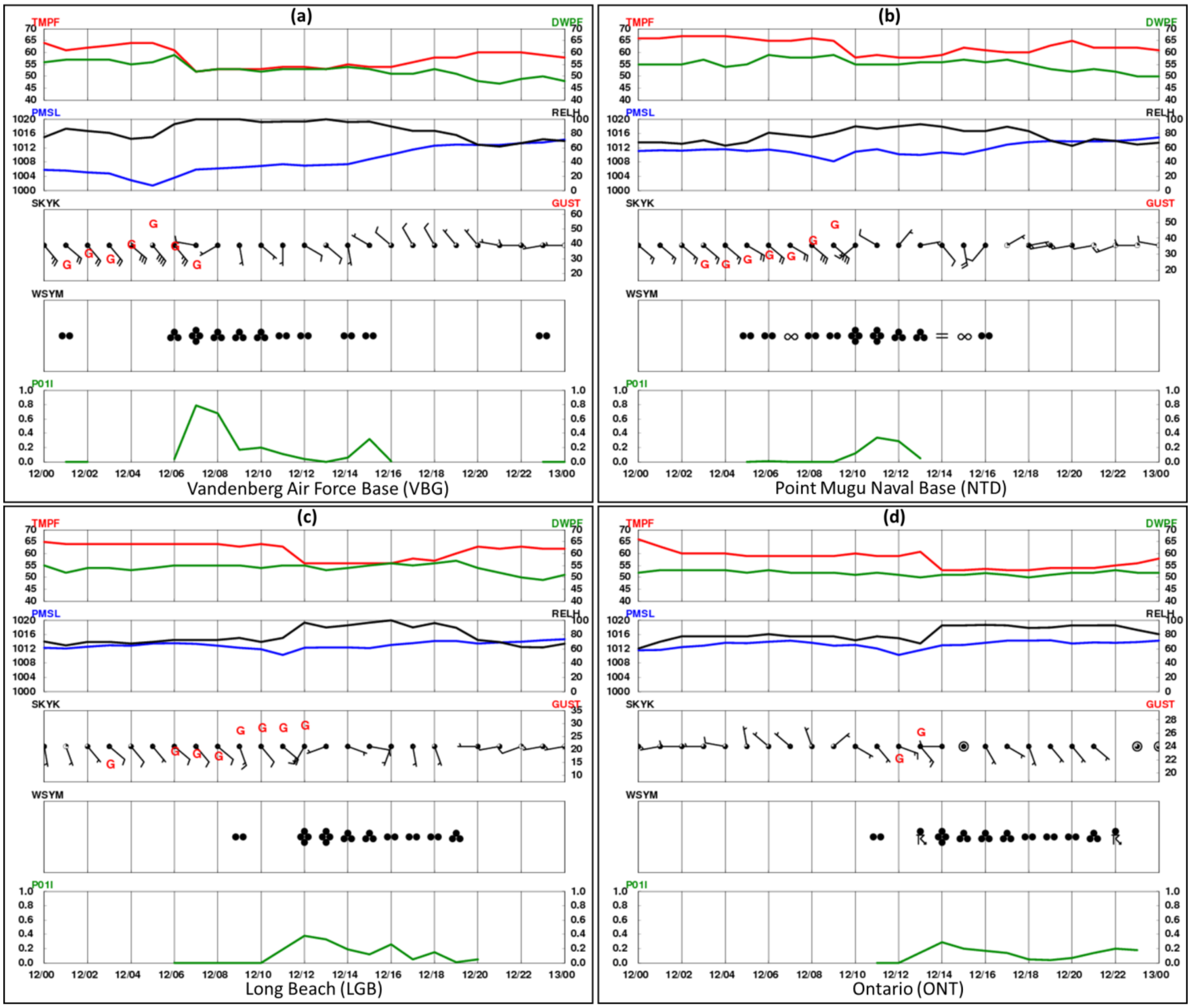

Fig. 6. Meteograms for (a) Vandenberg Air Force Base (KVBG), (b) Point Mugu Naval Base (KNTD), (c) Long Beach (KLGB), and (d) Ontario (KONT) for 0000 UTC 12 December 2014 through 0000 UTC 13 December 2014. Locations of KVBG and KNTD are shown in Figures 5 and 7, respectively. The locations of KLGB and KONT are shown in Figure 8. Variables shown are temperature and dewpoint temperature (°F), MSLP (mb), relative humidity (percent), wind and wind gusts (kt), present weather, and 1-hr rainfall (inches).

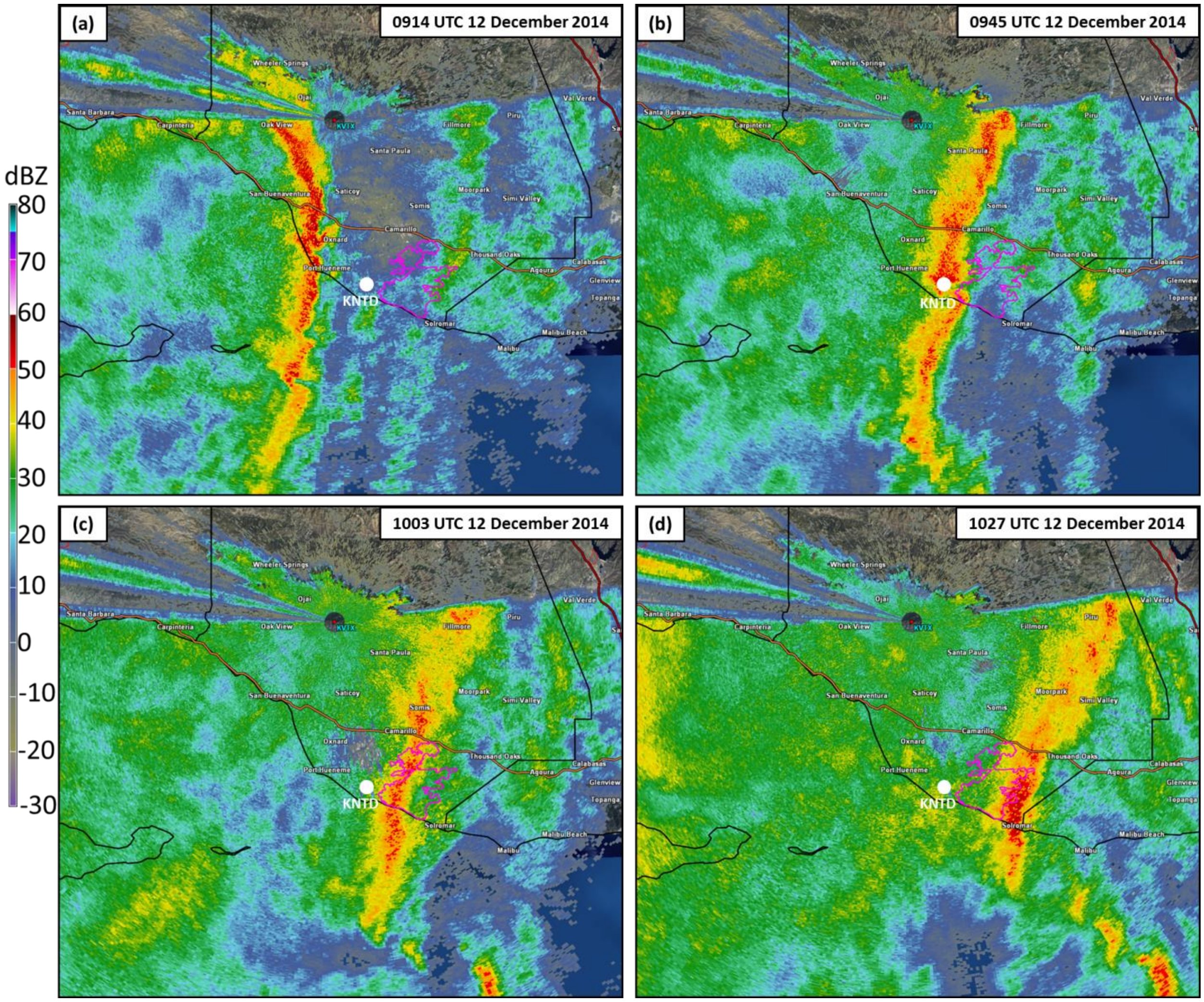

Fig. 7. 0.5° Base Reflectivity (dBZ) from the KVTX WSR-88D at (a) 0914 UTC, (b) 0945 UTC, (c) 1003 UTC, and (d) 1027 UTC 12 December 2014. The Springs Fire burn area is outlined in pink on each panel. Images were created with GR2Analyst software.

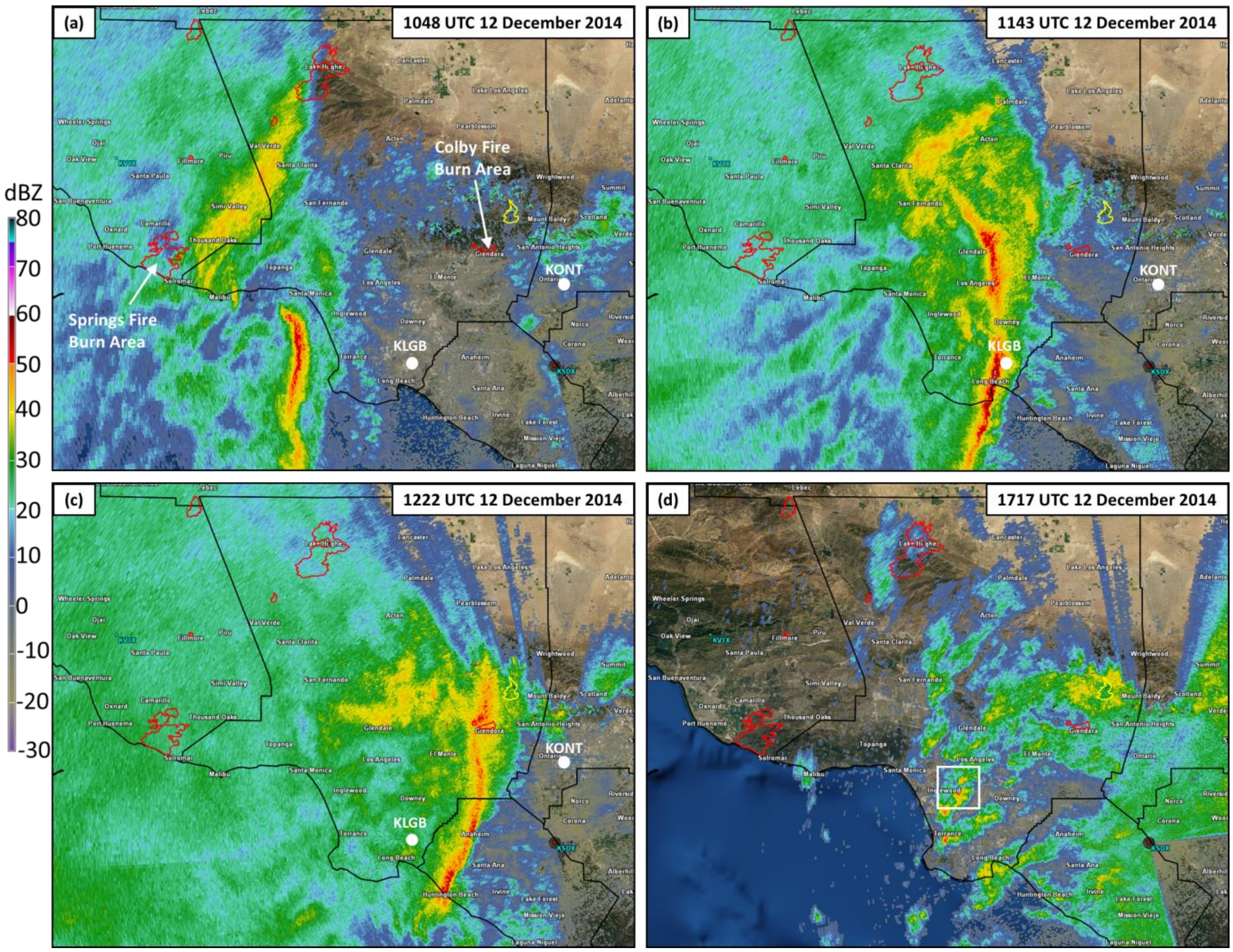

Fig. 8. 0.5° Base Reflectivity (dBZ) from the KSOX WSR-88D at (a) 1048 UTC, (b) 1143 UTC, (c) 1222 UTC, and (d) 1717 UTC 12 December 2014. Recent burn areas are outlined in red and yellow. The Springs Fire burn area and the Colby Fire burn area are labeled in (a). The area within the white box in (d) is the area shown in Figure 9. Images were created with GR2Analyst software.

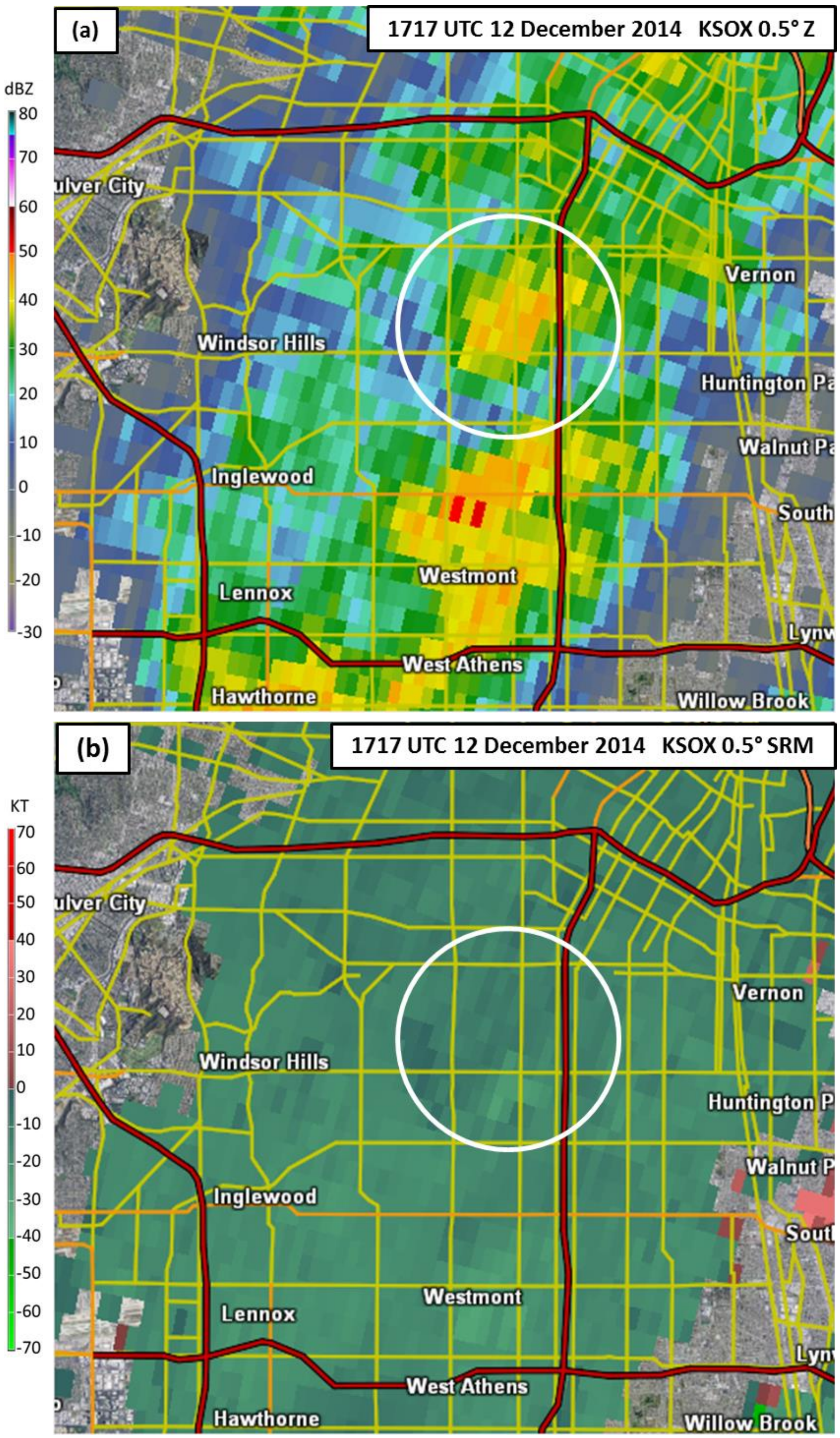

Fig. 9. 0.5° radar imagery from the KSOX WSR-88D at 1717 UTC 12 December 2014 showing the convective cell that produced an EF0 tornado several miles southwest of downtown Los Angeles. (a) Base Reflectivity (Z, dBZ) is shown in (a) and Storm Relative Velocity (SRM, kt) is shown in (b). The cell that produced the tornado is within the white circle. Images were created with GR2Analyst software.

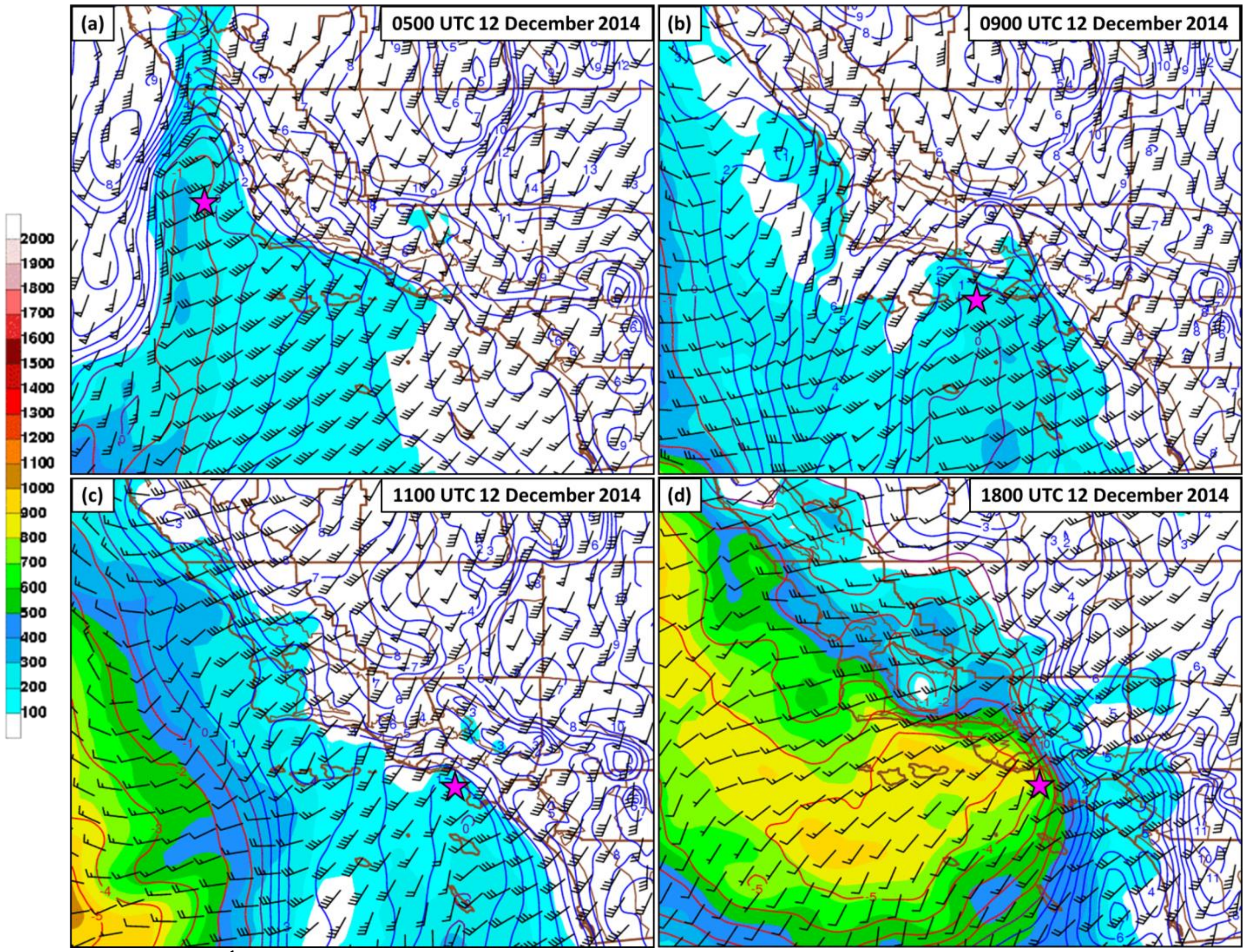

Fig. 10. CAPE (J kg^{-1}, shaded), Lifted Index (°C, contoured), and 0-3 km bulk shear (kt, wind barbs) for (a) 0500 UTC 12 December 2014, (b) 0900 UTC 12 December 2014, (c) 1100 UTC 12 December 2014, and (d) 1800 UTC 12 December 2014. Data source is the Rapid Refresh (RAP) initialization. The pink stars in each panel indicate the locations of the model soundings in the corresponding panels of Figure 11.

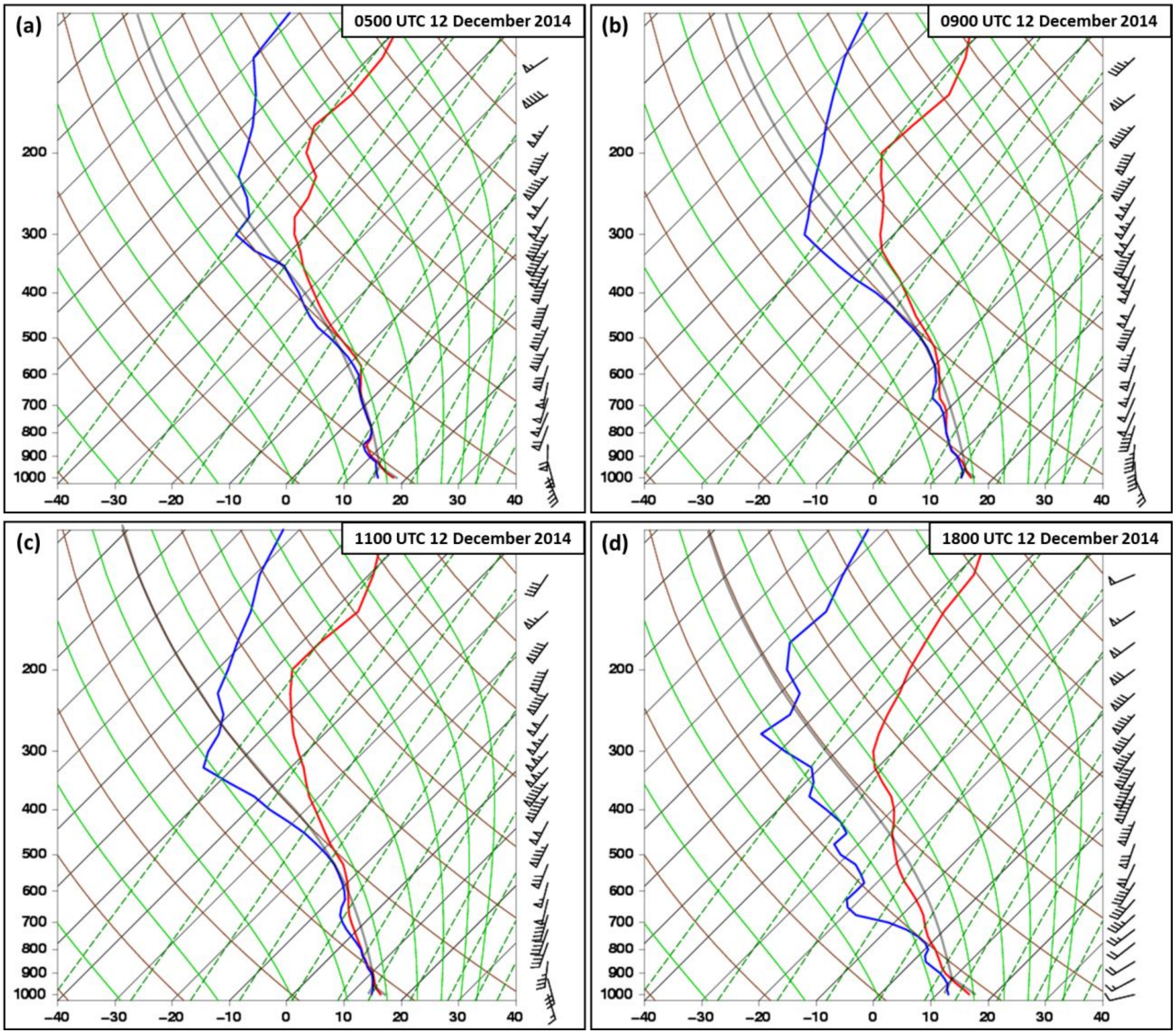

Fig. 11. Model soundings for (a) 0500 UTC 12 December 2014, (b) 0900 UTC 12 December 2014, (c) 1100 UTC 12 December 2014, and (d) 1800 UTC 12 December 2014. The locations of each sounding are indicated in Figure 10. Data source is the Rapid Refresh (RAP) initialization.

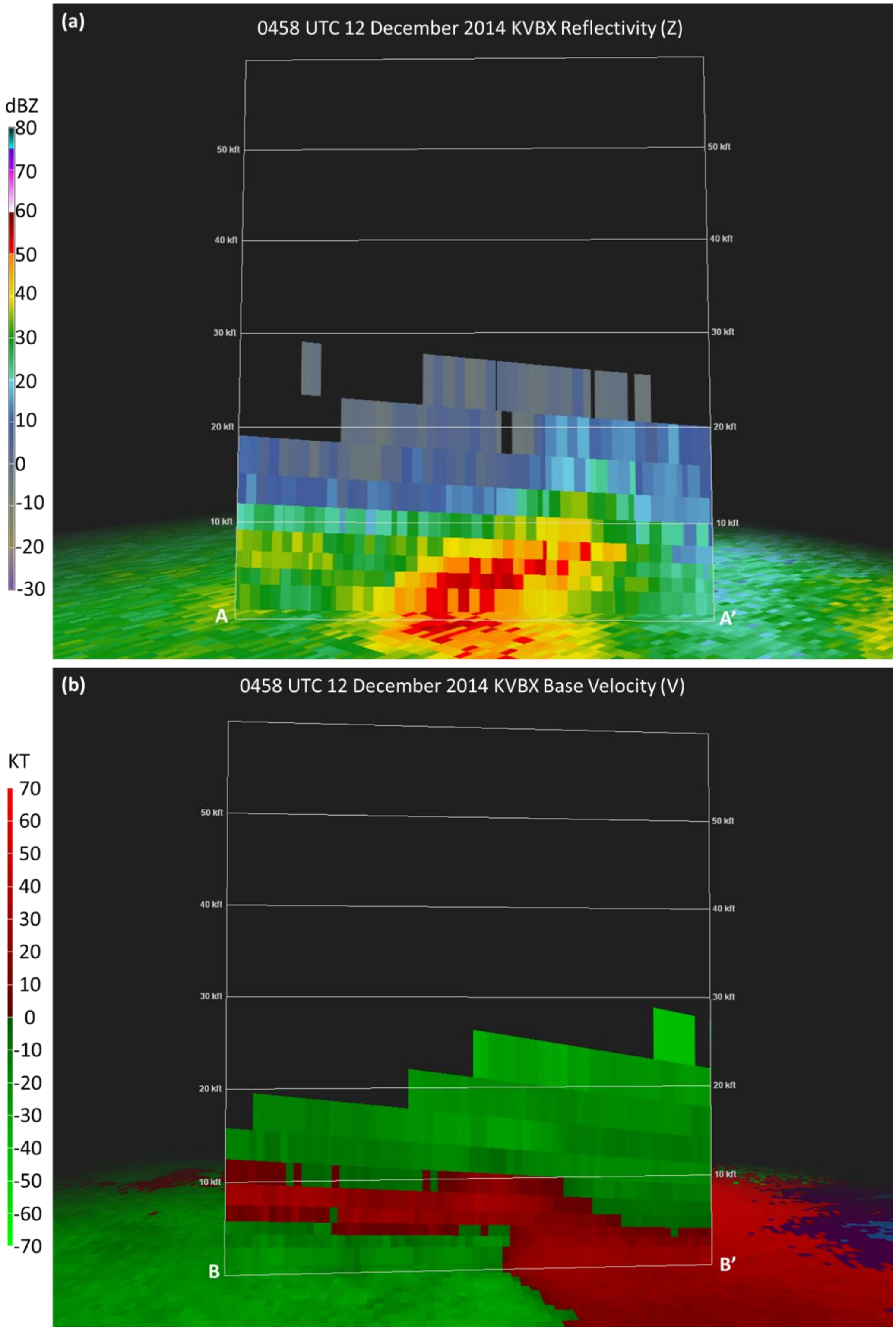

Fig. 12. Cross-sections of (a) Base Reflectivity (dBZ) and (b) Base Velocity (kt) at 0458 UTC 12 December 2014 from the KVBX WSR-88D. The cross-sections are taken through lines A-A' and B-B' in Figure 5b. Image was created with GR2Analyst software.

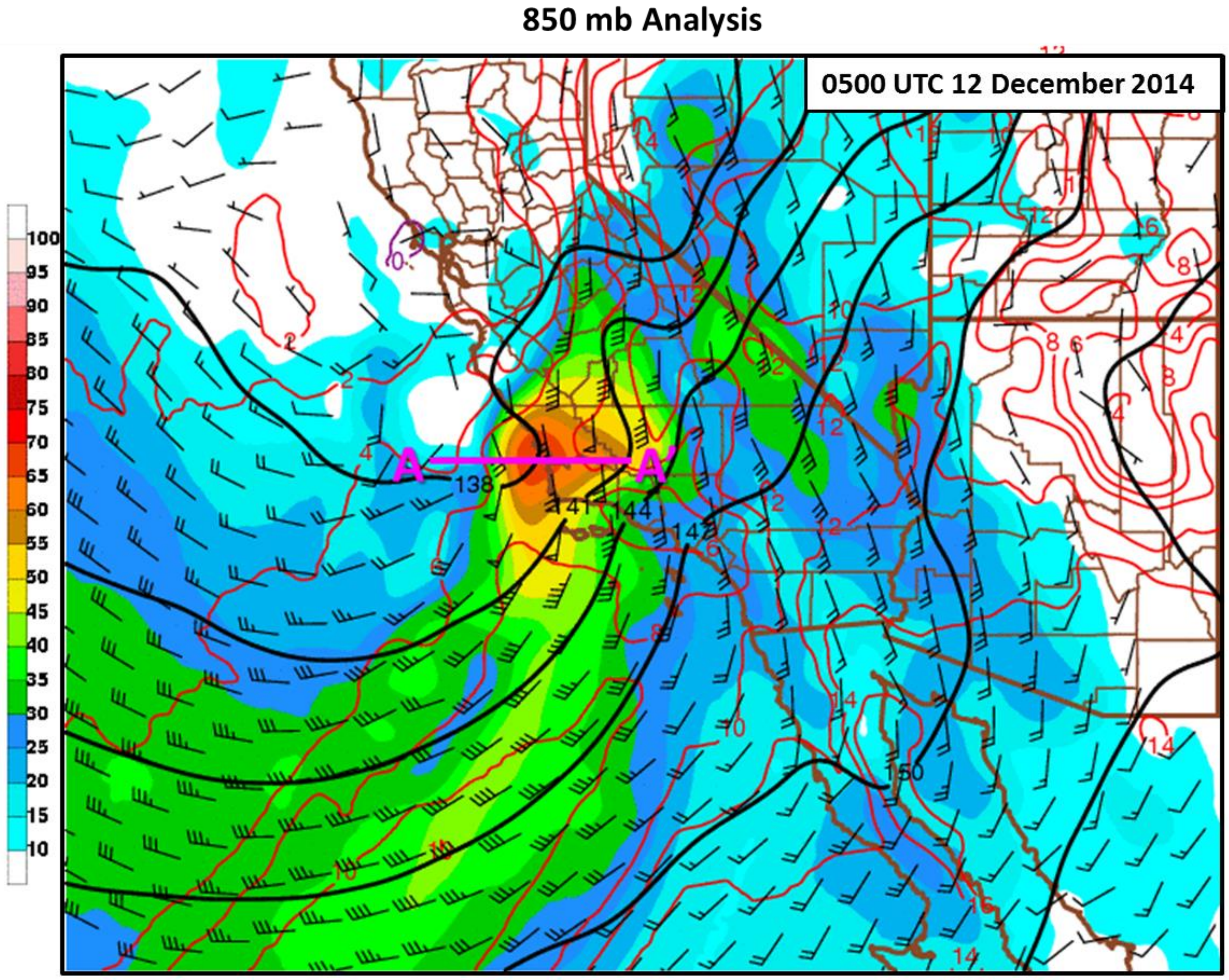

Fig. 13. 850 mb heights (dam, black contours), winds (kt, wind barbs), wind speeds (kt, shaded), and temperature (°C, red contours) at 0500 UTC 12 December 2014. Data source is the Rapid Refresh (RAP) initialization. Line A-A’ indicates the cross-section line for Figure 14.

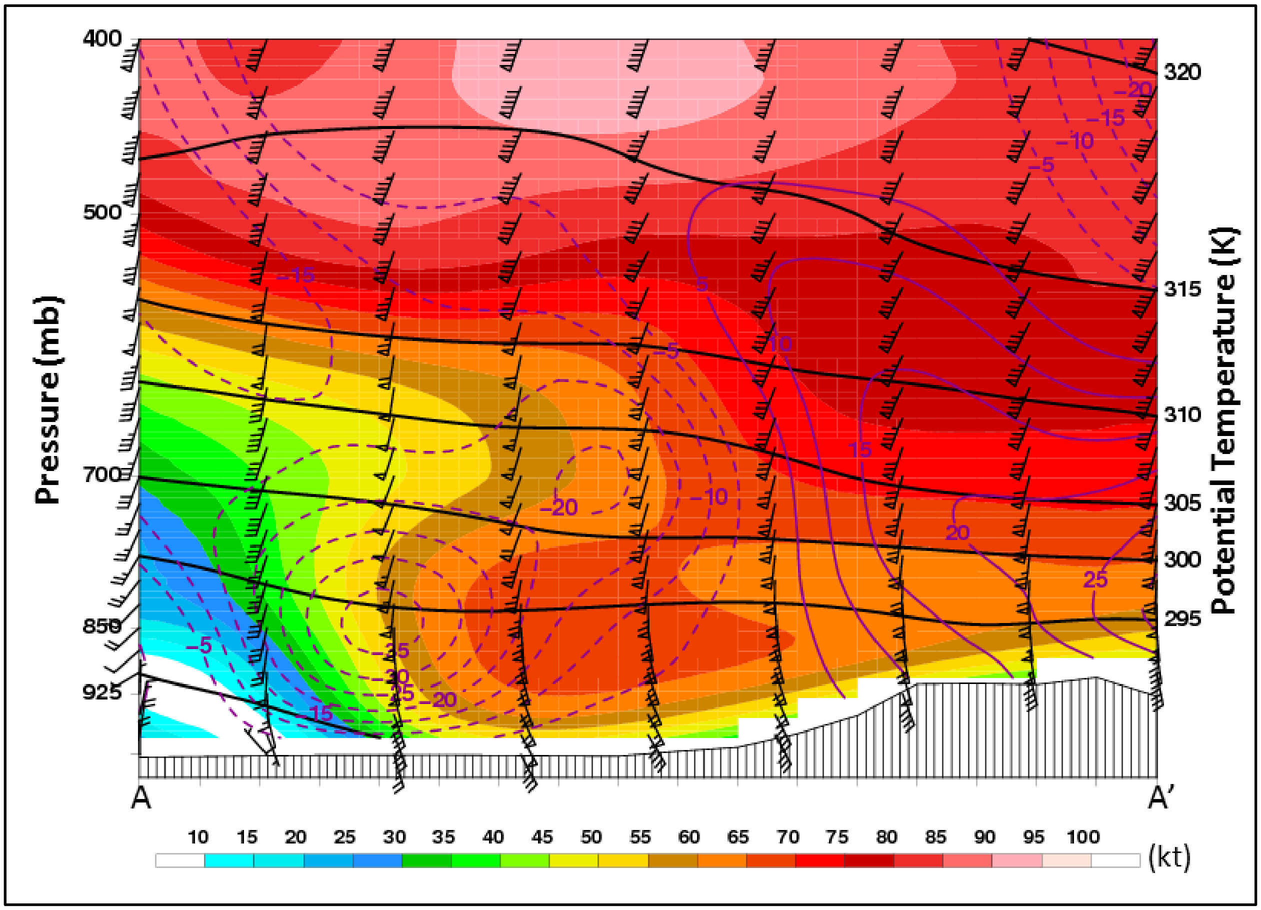

Fig. 14. A cross-section through the line A-A' shown in Figure 13, showing winds (kt, wind barbs), wind speeds (kt, shaded), omega (μb s^{-1}, purple contours), potential temperature (K, black contours). Time shown is 0500 UTC 12 December 2014. Data source is the Rapid Refresh (RAP) initialization.

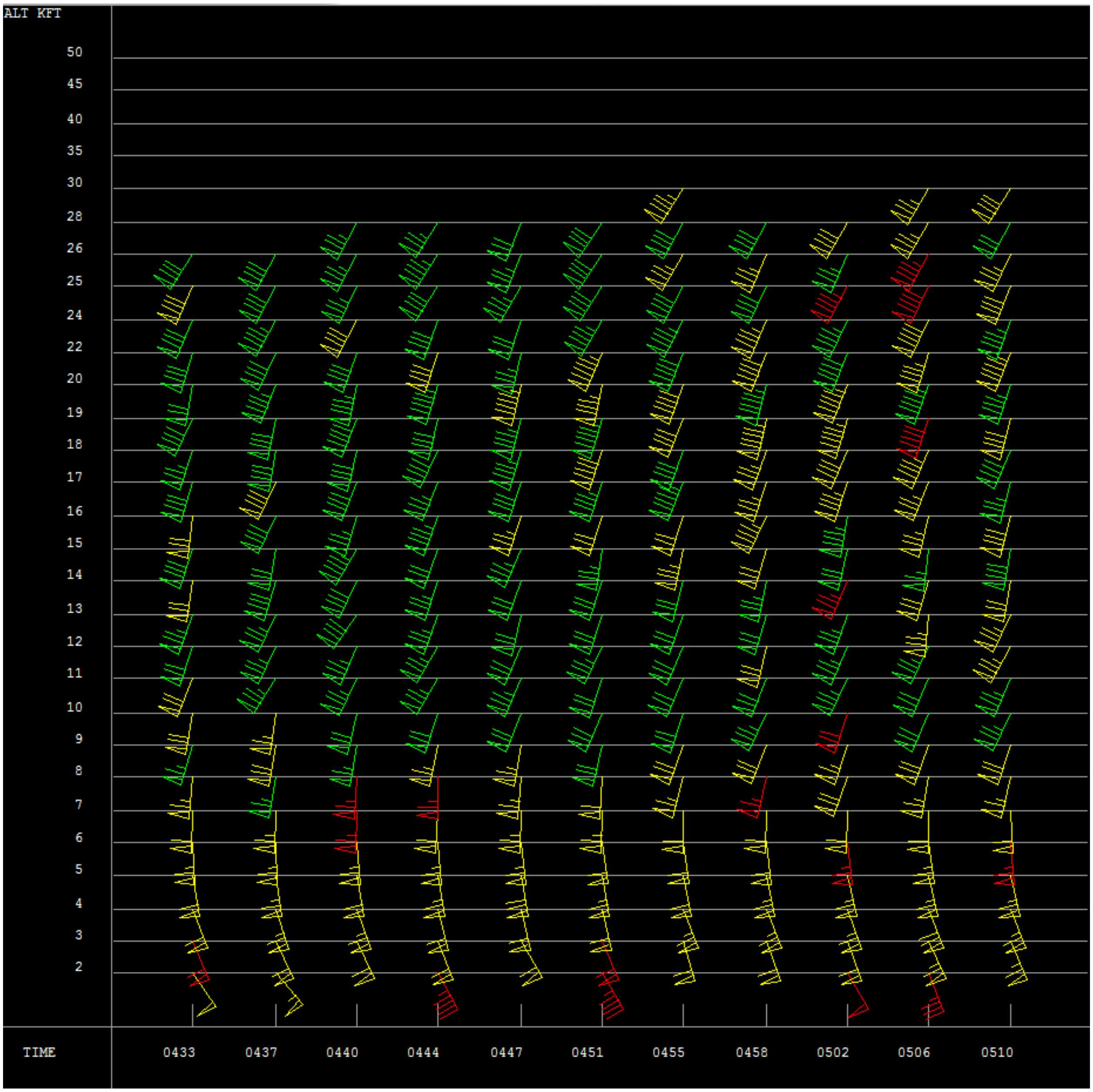

Fig. 15. 0433 – 0510 UTC 12 December 2014 Velocity Azimuth Display (VAD) wind profile data from the KVBX WSR-88D. Image was created with GRLevel3 software.

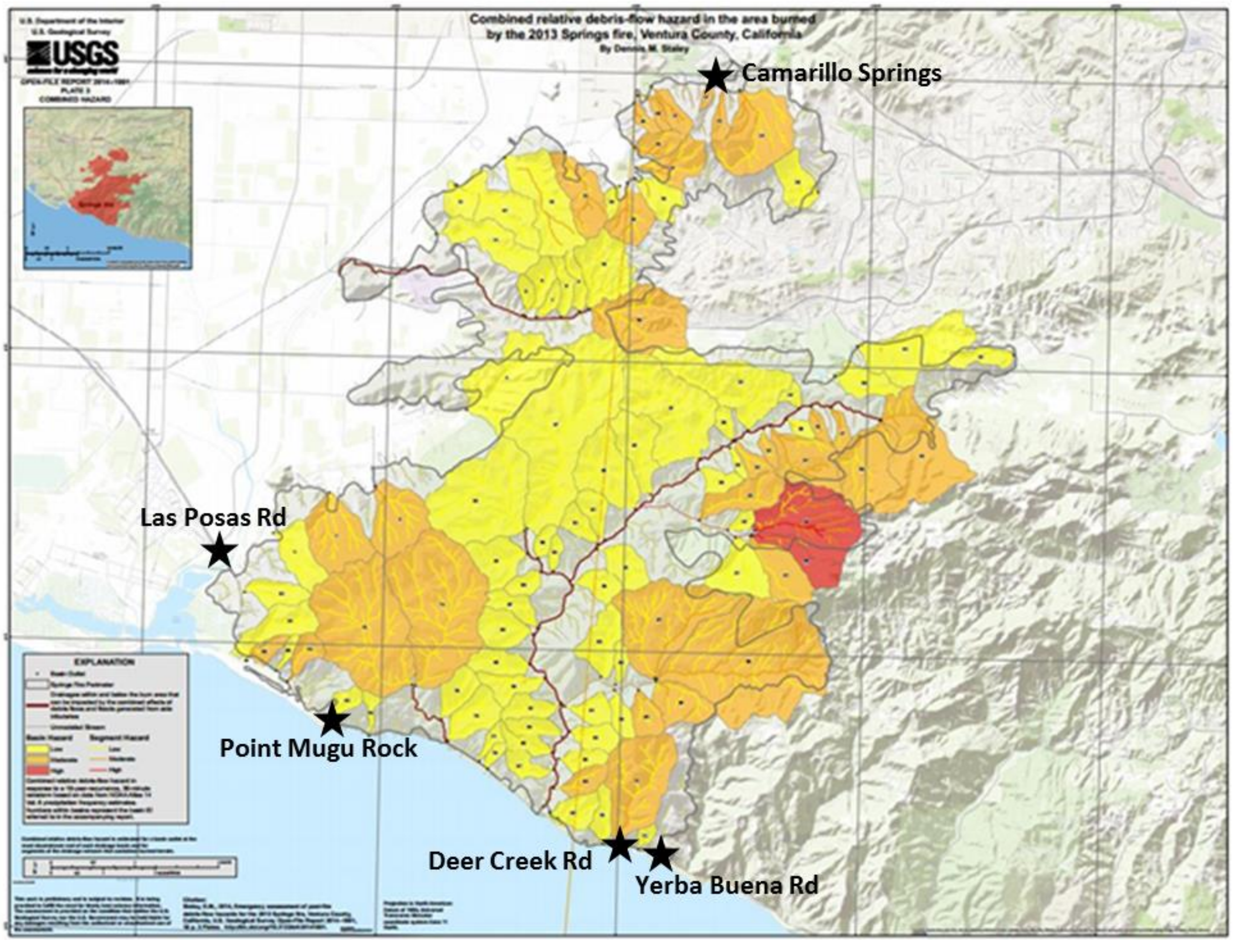

Fig. 16. United States Geological Survey (USGS) modeling results showing the combined relative debris-flow hazard for the Springs Fire burn area. Modeling results in this image are based on a 30-minute rainfall recurrence frequency of 10 years, or a 30 minute rainfall intensity that has a 10 percent chance of occurring in any given year. Output from the USGS model provides hazard information for each of the separate drainage basins within the burn area. Low hazard areas are shown in yellow, moderate hazard areas in orange, and high hazard areas in red. The thin gray lines represents the outline of the burn area. Since 2005 the USGS and the NWS have been coordinating on a flash flood and debris flow early warning system for recently burned areas in Southern California. As a part of the cooperative effort, the USGS provides these maps for use by the NWS for many of the fires that burn in coastal Southern California. Staff at NWS Los Angeles/Oxnard use these hazard maps to assist them in identifying areas that may be at increased risk for flash flooding and debris flows.

Fig. 17. Google Earth image showing the terrain near the Camarillo Springs debris flow.

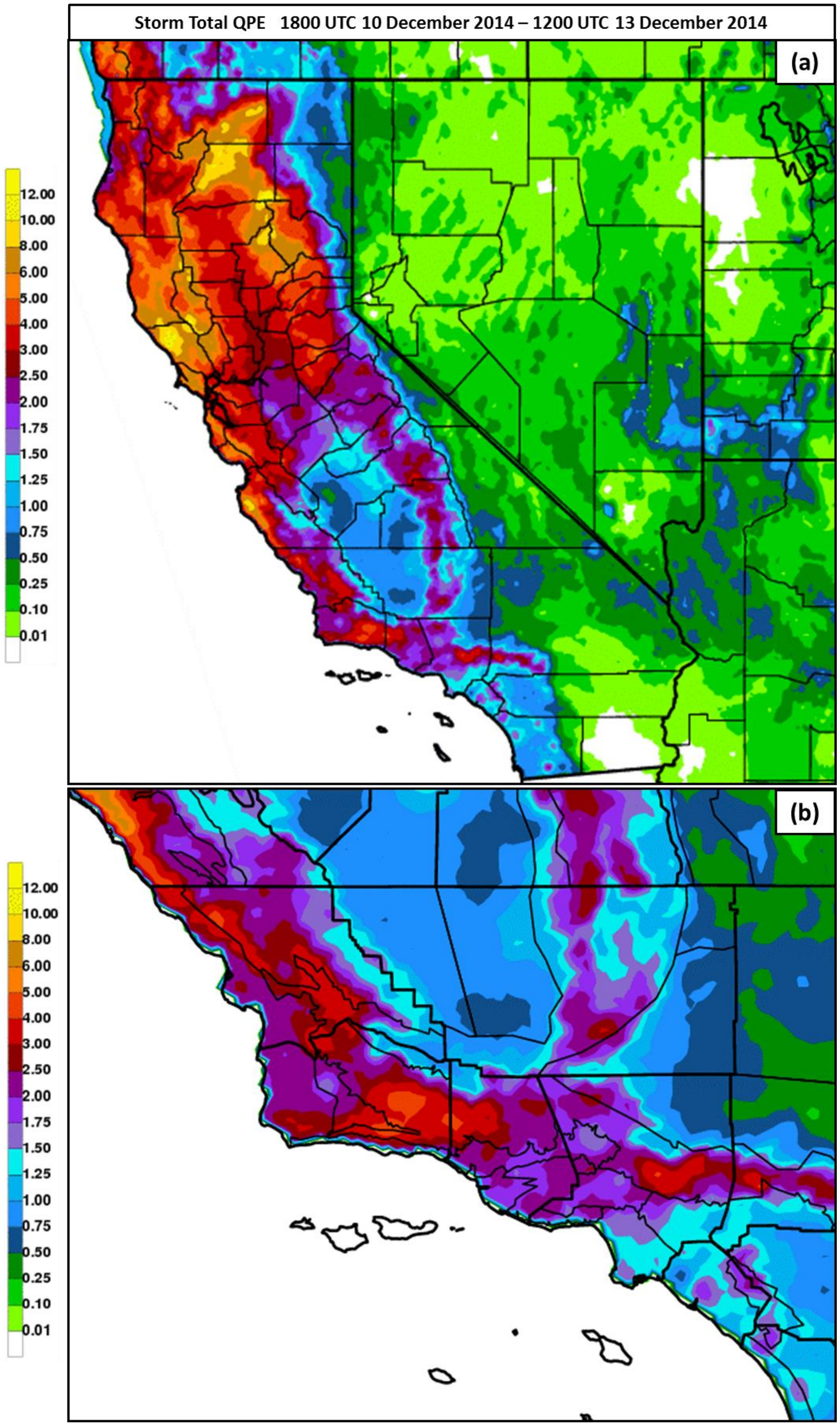

Fig. 18. Storm Total Quantitative Precipitation Estimate (inches) from 1800 UTC 10 December 2014 through 1200 UTC 13 December 2014. Data source is the 4-km Stage IV QPE analysis produced by NCEP.

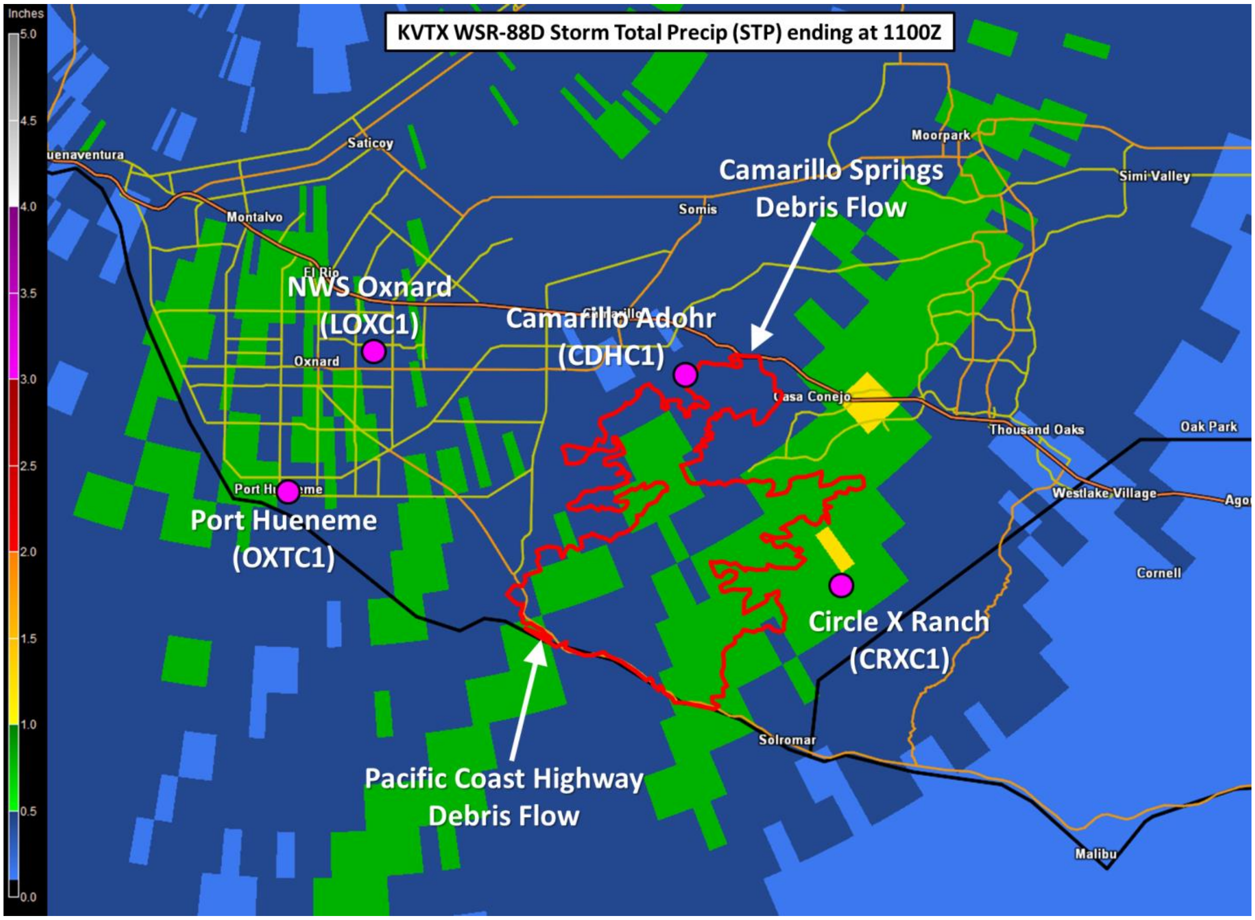

Fig. 19. KVTX WSR-88D legacy Storm Total Precipitation (STP, inches) ending at 1100 UTC 12 December 2014. The Springs Fire burn area is outlined in red. The locations of the ALERT rain gages shown in Figure 20 are also shown. Image was created with GRLevel3 software.

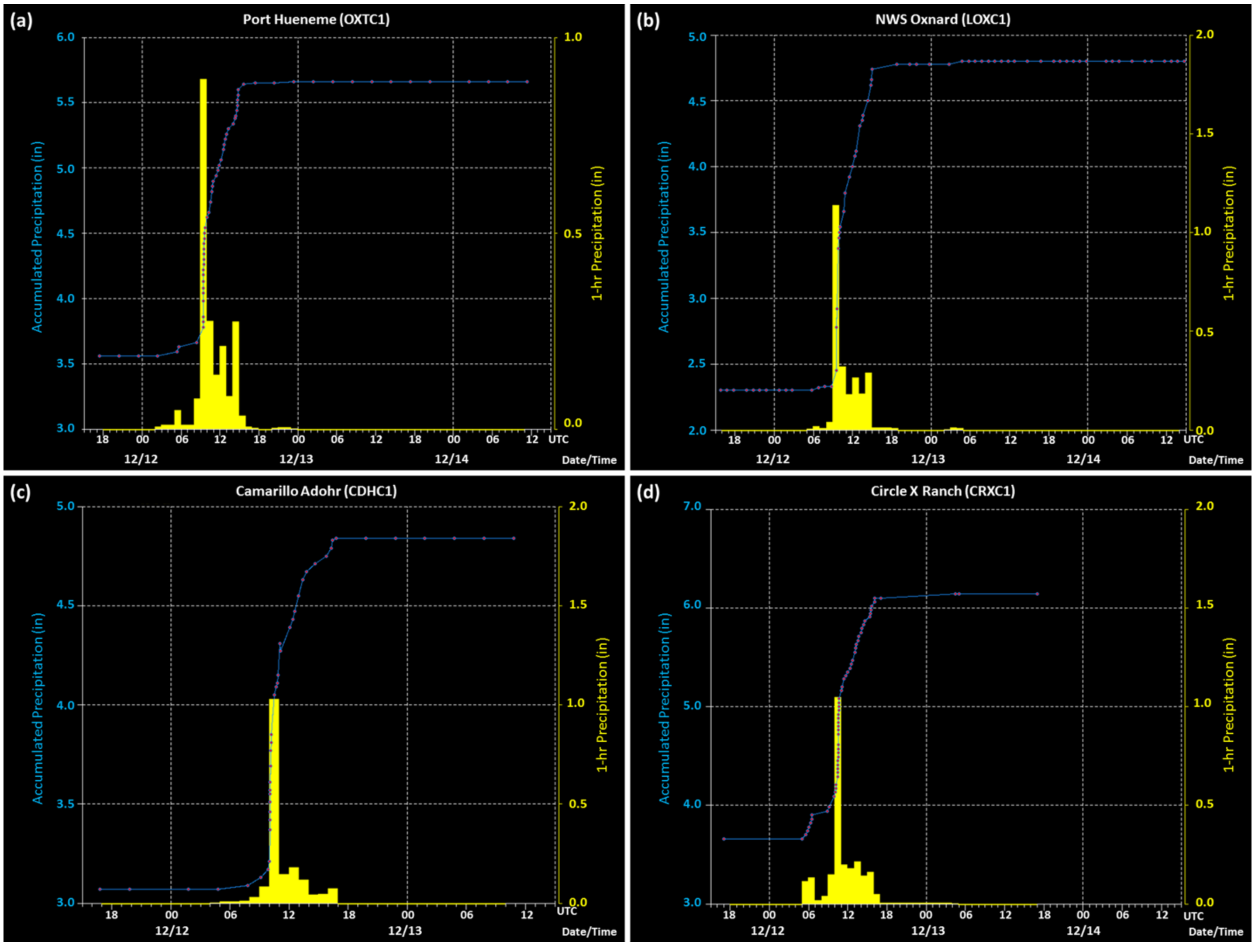

Fig. 20. Graphs for ALERT rain gages at (a) Port Hueneme (OXTC1), (b) NWS Oxnard (LOXC1), (c) Camarillo Adohr (CDHC1), and (d) Circle X Ranch (CRXC1). The locations of these rain gages are shown in Figure 19. Accumulated precipitation (inches) is referenced on the left axis and is depicted as the blue line with red dots. Hourly precipitation (inches) is referenced on the right axis and is depicted as yellow bars. Gage data is courtesy of the Ventura County Watershed Protection District.

Fig. 21. Image from San Como Lane in Camarillo Springs on the morning of 12 December 2014, several hours following a major debris flow. Image courtesy of NBC.

Fig. 22. Image from 12 December 2014 showing an area of the Pacific Coast Highway (PCH) just north of Deer Creek Road that was inundated with mud and rocks following flash flooding and debris flows. Image is courtesy of NBC.

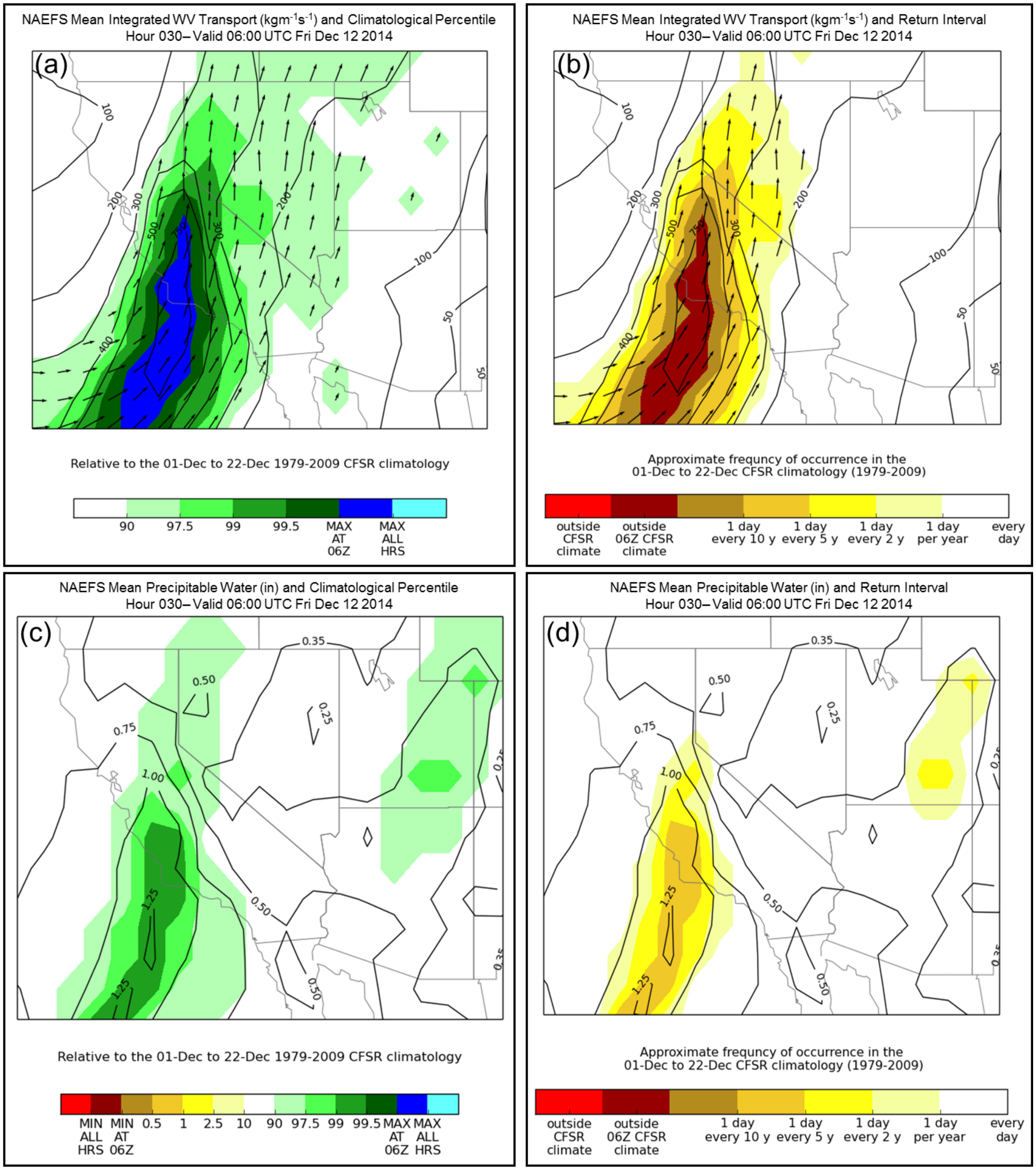

Fig. 23. North American Ensemble Forecast System (NAEFS) 30-hr forecasts valid at 0600 UTC 12 December 2014, showing (a) mean IVT ($kgm^{-1}s^{-1}$, contoured) and climatological percentile (shaded), (b) mean IVT ($kgm^{-1}s^{-1}$, contoured) and return interval (shaded), (c) mean PWAT (inches, contoured) and climatological percentile (shaded), and (d) mean PWAT (inches, contoured) and return interval (shaded). The climatological percentiles and return intervals were calculated relative to NCEP's Climate Forecast System Reanalysis (CFSR) for 1 December – 22 December and for the years 1979-2009. Graphics were courtesy of the NWS Western Region Science and Technology Infusion Division (STID) and were obtained from the following web address: http://ssd.wrh.noaa.gov/satable/.