Brief Communication: Meteorological and climatological conditions associated with the 9 January 2018 post-fire debris flows in Montecito and Carpinteria California, USA

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Abstract. The Thomas Fire burned 114,078 hectares in Santa Barbara and Ventura Counties, southern California, during December 2017-January 2018. On 9 January 2018, high intensity rainfall occurred over the Thomas Fire burn area in the mountains above the communities of Montecito and Carpinteria, initiating multiple devastating debris flows. The highest rainfall intensities occurred with the passage of a narrow rainband along a north-to-south oriented cold front. Orographic enhancement associated with moist southerly flow immediately ahead of the cold front also played a role. We provide an explanation of the meteorological characteristics of the event and place it in historic context.

1 Introduction

The Thomas Fire was ignited on 4 December 2017 and burned 114,078 hectares in Santa Barbara and Ventura Counties in southern California before it was 100% contained on 12 January 2018. It became the largest wildfire in California's modern history. Soil burn severity was predominately moderate with small areas mapped as high in the northern and western portions of the burn area (CAL FIRE 2018). In combination with the steep terrain and underlying geology, the United States Geological Survey (USGS) rated watersheds north of the Santa Barbara coastal plain and Ojai as having high debris flow hazard based on a design rainstorm of 15-minute rainfall intensity of 24 mm h^{-1} (USGS 2018a; Fig. S1).

In the first significant rainfall event of the wet season on 9 January 2018, high intensity rainfall occurred over the westernmost portion of the Thomas Fire burn area between 11:30-12:00 UTC (3:30-4:00 LST). Rainfall rates exceeded the USGS 15-minute design storm (USGS 2018a) by more than threefold at some locations. Large magnitude debris flow surges were triggered in multiple watersheds, overwhelming debris basins and issuing onto urbanized alluvial fans including the communities of Montecito and Carpinteria (Fig. 1). The debris flows were devastating, resulting in 23 deaths, 246 structures destroyed and 167 damaged (County of Santa Barbara 2018). Preliminary loss estimates for residential and commercial property alone have exceeded $421 million USD (California Dept. of Insurance 2018).

Over the past three decades, more than a dozen notable post-fire debris flow (hereafter "PFDF") events have been observed across the Transverse Ranges of southern California (Oakley et al. 2017), where steep terrain, highly erodible soils, and frequent wildfires create favorable conditions for PFDFs (Wells 1987). In the Montecito area specifically, damaging PFDFs last occurred following both the Coyote Fire of 1964 and Romero Fire of 1971 (U.S. Army Corps of Engineers 1974).

This manuscript describes the meteorological origins of the high intensity precipitation leading to the 9 January 2018 debris flow and places the event in a climatological context. This information is intended to appeal to a broad community of researchers and stakeholders (e.g., persons in engineering geology, geomorphology, social science, and floodplain and water resource management) to support understanding of meteorological triggers of PFDFs, which remains an information need in these communities (Garfin et al. 2016). The analysis presented here can also increase situational awareness for future events.

2 Meteorological analyses

2.1 Synoptic conditions

In the 36 h preceding the debris flow event (~12 UTC 9 January), an upper level trough approached and deepened along the U.S. West Coast (Fig. 2). By 06 UTC 9 January (Fig 2f), a 500 hPa closed low-pressure system had developed offshore of Point Conception (centered at ~34° N, 125° W) and moved eastward leading up to the event time, when it was situated at approximately 34° N, 122° W. At the time of the event, the attendant 1000 hPa surface low-pressure center was situated slightly further north and east, at approximately 36° N, 121° W (Fig. 2g, 3a).

Twenty-four to 36 h prior to the event (Fig. 2 a-c), the approaching mid-latitude trough and a weakening subtropical closed low-pressure system (centered at approximately 25° N, 130° W) facilitated the transport of subtropical moisture (shown as plumes of IWV in Fig. 2) to the West Coast. These plumes interacted and were modified in the 36 h preceding the event. By the time of the event (Fig. 2g), two distinct plumes were present: a weaker plume to the north making landfall in southern California, and a stronger plume (higher IWV) to the south making landfall in northern Baja California. Integrated water vapor (IWV) values in the flow impinging on the Santa Ynez Mountains at the time of the PFDF event were approximately 25-30 mm (Fig. 2g), and integrated vapor transport (IVT) of 250 to 400 kg m^{-1} s^{-1} was observed on the eastern side of the large-scale circulation over the Southern California Bight (Fig. S4). We define this moisture plume as a weak atmospheric river due to its long, narrow shape and associated IWV and IVT values (AMS 2018).

At the time of the event, the downstream side of a cyclonically-curved upper level (250 hPa) jet was located over southern California with a 50 m s^{-1} jet streak exit region situated over the Santa Barbara area (Fig. 3a; S3). Model soundings indicate cold air advection between approximately 450-600 hPa, increasing the lapse rate in this layer and creating a region of potential instability (Fig. S5, S6). This was collocated with a region of inferred absolute vorticity advection by the geostrophic wind at 500 hPa (Fig. S2). These conditions were also associated with a well-defined cold front parallel to and impinging upon the moist low-level jet ahead of the front (Fig. 3). This scenario positioned the Thomas Fire burn area in a favorable region for large-scale ascent and destabilization of the atmosphere (Markowski and Richardson, 2010).

2.2 Mesoscale conditions

At approximately 9 UTC 9 January, the north-to-south oriented cold front was located just offshore of Point Conception and was propagating eastward across the Southern California Bight (Fig. 2b). Radar and satellite imagery reveal a narrow band of intense rainfall and vigorous convection parallel to and in the vicinity of the cold front (Fig. 4, S7), a feature known as a Narrow Cold Frontal Rainband (NCFR; Markowski and Richardson 2010). These features tend to form when there is strong convergent flow along the surface front and divergent flow aloft. This facilitates the release of potential instability through forced ascent and the generation of intense convective precipitation bands (Hobbs and Persson, 1982; Markowski and Richardson 2010).

Ahead of the cold front, 10-20 ms^{-1} southeasterly winds were present below 1 km, as demonstrated in measurements from the 449 MHZ radar wind profiler situated at Santa Barbara Airport (SBA; Fig. S8). The cold front passed over Santa Barbara and Montecito between 11:00 and 12:00 UTC. The passage of the cold front can be observed as a shift from strong southeasterly winds to weak south to southwesterly winds below 2 km (Fig. S8). The convergence of this southeasterly flow ahead of the front and westerly flow behind the front helped support the development of the NCFR. As the cold front made landfall and encountered the complex coastal terrain, the NCFR became segmented and dissipated in some areas. One segment became well organized north of Santa Rosa and Santa Cruz Islands and intensified as it moved across the Santa Barbara Channel towards Montecito (Fig. 4b).

Strong, low-level south-to-southeasterly winds peaking near 1 km were observed immediately ahead of the cold front, a feature known as a low-level jet (LLJ; Neiman et al. 2004; Fig. 3b, S8). The presence of the LLJ orthogonal to the terrain combined with available moisture (Fig. 3b, S8) created a situation favorable for orographic precipitation enhancement (Lin et al. 2001). However, due to the forcings described and presence of high radar reflectivity values over the ocean before the NCFR impacted the terrain (Fig. 4b), it appears that the NCFR was the dominant feature producing short-duration high intensity rainfall in this case, with orographic forcing likely acting as secondary factor.

Radar and surface-based precipitation observations reveal that the segment of the NCFR impacting Montecito and Carpinteria began to dissipate near the Santa Barbara-Ventura County line just after 12 UTC (4:00 AM PST; Fig. 1, S9). The subsequent weakening of rainfall intensity likely spared other portions of the burn area from additional catastrophic debris flows.

3 Historical and climatological context

3.1 Historical context of precipitation event

The Santa Barbara County Public Works Department (SBCPWD) maintains a network of precipitation gauges used for flood hazard and water resource management, with records dating back to the 1960s. All precipitation data discussed herein have been archived and quality controlled by SBCPWD and can be accessed at: www.countyofsb.org/pwd/hydrology.sbc. Average return intervals (ARI) described in this section are sourced from NOAA Atlas 14 (hdsc.nws.noaa.gov/hdsc/pfds/; Bonnin et al. 2006) for the coordinates of each station. Tables S1-S3 provide further information on relevant observations in and around the Thomas Fire burn area.

The short duration intense precipitation (Fig. 1, 4c) observed during the 9 January 2018 debris flow event was exceptional and in some cases broke individual station records, but was not unprecedented for Santa Barbara County. At the 5-minute duration, a maximum of 15.24 mm was recorded at both Jameson Dam (a 25-year ARI event; 25-1000 year at 90% confidence) and Doulton tunnel (a 100-year ARI event; 25-1000 year at 90% confidence). This exceeded the previous record 5-minute observations at both stations, whose records began in 1965. In Montecito, 13.72 mm was observed in 5 minutes, setting a record for this station, though the station record is very short, beginning in 2009. This registers as a 200-year ARI event (100-1000 year at 90% confidence). Values discussed in this section can be reviewed in Table S1 and Fig. 1.

The 15-minute duration provides the most accurate prediction of PFDF generation (Staley et al. 2017). At this duration, Doulton Tunnel set a record of 26.16 mm, exceeding the previous record of 22.35 mm set in WY2015. Jameson Dam also set a record at 25.15 mm, exceeding the previous record of 13.46 mm set in WY1998. Additionally, a 15-minute record of 18.54 mm was set at the Montecito station. At Doulton Tunnel, this was a 100-year ARI event (25-1000 year at 90% confidence). At Jameson, this is a 25-year ARI event (10-500 year 90% confidence) and for Montecito, this is a 50-year ARI event (25-1000 year at 90% confidence). Values discussed in this section can be reviewed in Table S2.

The records set at individual stations at the 5- and 15-minute durations were well shy of the extremes observed in Santa Barbara County. At the 5-minute duration, the County record is 18.29 mm at the UCSB station set in WY1998. The County record at the 15-minute duration is 35.31 mm set at the San Marcos Pass station in WY2015.

At the 1-hour and longer durations, precipitation intensities were generally less than the 10-year return interval (Table S3). Storm total precipitation over a 24-hour period was roughly 50-75 mm at low elevations and 100-125 mm at higher elevations (Fig. 3d). These 24-hour precipitation totals were mostly less than the one-year return interval.

3.2 Context of intense rainband

No known documentation exists on the abundance of NCFRs or similar frontal convection in southern California, though several resources acknowledge their occurrence and impacts. We hypothesize that these features occur multiple times in a given year and are not uncommon in association with landfalling atmospheric rivers with strong cold fronts impacting the region. NCFRs such as the one observed during the 9 January 2018 event (Fig. 4a, b) have been previously associated with post-fire debris flows in the Transverse Ranges of southern California.

On 12 December 2014, an NCFR produced intense rainfall over the Springs Fire burn area in Camarillo, CA, initiating a debris flow that destroyed several homes (Fig. S10; Sukup et al. 2016; Oakley et al. 2017). More recently, on 20 January 2017, a narrow band of high intensity rainfall occurring along a cold front produced a debris flow on the Sherpa Fire burn area in western Santa Barbara County (Fig. S11). Five cabins and over 20 vehicles were damaged in El Capitan Canyon, and nearly two-dozen people had to be rescued (Lin et al. 2017). Neiman et al. (2004) used observations from an intensive field campaign in 1998 to detail the synoptic and mesoscale forcing associated with a cold front that also generated high-intensity precipitation in this region of Southern California. Observations of convective precipitation bands in the area and their precipitation impacts date back to the early 1960s (Elliot and Hovind 1964). However, NCFRs are not the only mechanism for producing high intensity precipitation and post-fire debris flows in Southern California. Other types of convection embedded within the cyclone system, thunderstorms and orographically forced precipitation have also historically resulted in post-fire debris flows (Oakley et al. 2017).

Intense precipitation associated with NCFRs is not unique to southern California and commonly occur in other parts of the world where there is also complex terrain. These features have been observed to impact Chile (Viale et al. 2013) in South America, and Western Europe (Roux et al. 1993; Gatzen 2011). These areas may experience severe wildfires, and NCFRs may serve as PFDF triggers in these regions as well.

4 Conclusion

The Transverse Ranges of southern California are prone to post-fire debris flows (PFDFs). Following a wildfire of moderate to high burn severity on steeply sloping terrain, short-duration, high intensity precipitation over these areas may trigger a debris flow, as occurred on the morning of 9 January 2018.

The debris flows were triggered by a band of intense precipitation along a cold front, known as a narrow cold frontal rainband (NCFR; Fig. 3b and 4a, b) that impacted the westernmost portion of the Thomas Fire burn area. Such rainbands develop due to vertical circulations along the front that facilitate low-level convergence and lifting, which can force convection and intense rainfall. This mesoscale process may also benefit from destabilization at large-scales through the inferred synoptic forcing for ascent.

A weak atmospheric river was present at the time of the event, demonstrating that catastrophic hydrologic impacts can occur even in the absence of substantial water vapor transport (i.e., a strong atmospheric river) due to synoptic-to-mesoscale forcing. A majority of PFDFs in southern California occur in the presence of atmospheric river conditions, but there are several examples of PFDF events that do not (Oakley et al. 2017). Observations suggest that the NCFR, and to a lesser extent, orographic forcing, produced high intensity rainfall in this event, with the weak atmospheric river serving as a moisture source.

Precipitation in this event was extreme at the 5- and 15-minute durations. Three locations recorded >13 mm in 5 minutes and records were set at a few stations with 50+ years of observations. Several stations demonstrated notable differences in the average return interval for these two durations. The Montecito station reported a 200-year precipitation event at the 5-minute duration. At the 15–minute duration, most pertinent to PFDF activity, the station reported a 100-year event. The maximum rainfall intensities observed in this event are not unprecedented for Santa Barbara County. Storm total precipitation was unremarkable for the area, with 24-hour totals at the <1-year return interval, demonstrating that significant storm total precipitation is not required to produce rainfall capable of initiating a post-fire debris flow.

This analysis supports improved situational awareness and understanding of rainfall events producing post-fire debris flows for the natural hazards community in California and other mid-latitude regions of the world that experience wildfires in complex terrain. It also serves as a meteorological description to inform research on a variety of topics related to the 9 January 2018 debris flows. Future work will examine the role of terrain in modifying the NCFR and precipitation processes described herein, the predictability of forced convection and extreme precipitation rates, and their relation to post-fire debris flows in other regions of the world.

Data Availability

All data can be accessed at the web addresses provided within the text or references.

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Competing Interests

The authors declare they have no conflict of interest.

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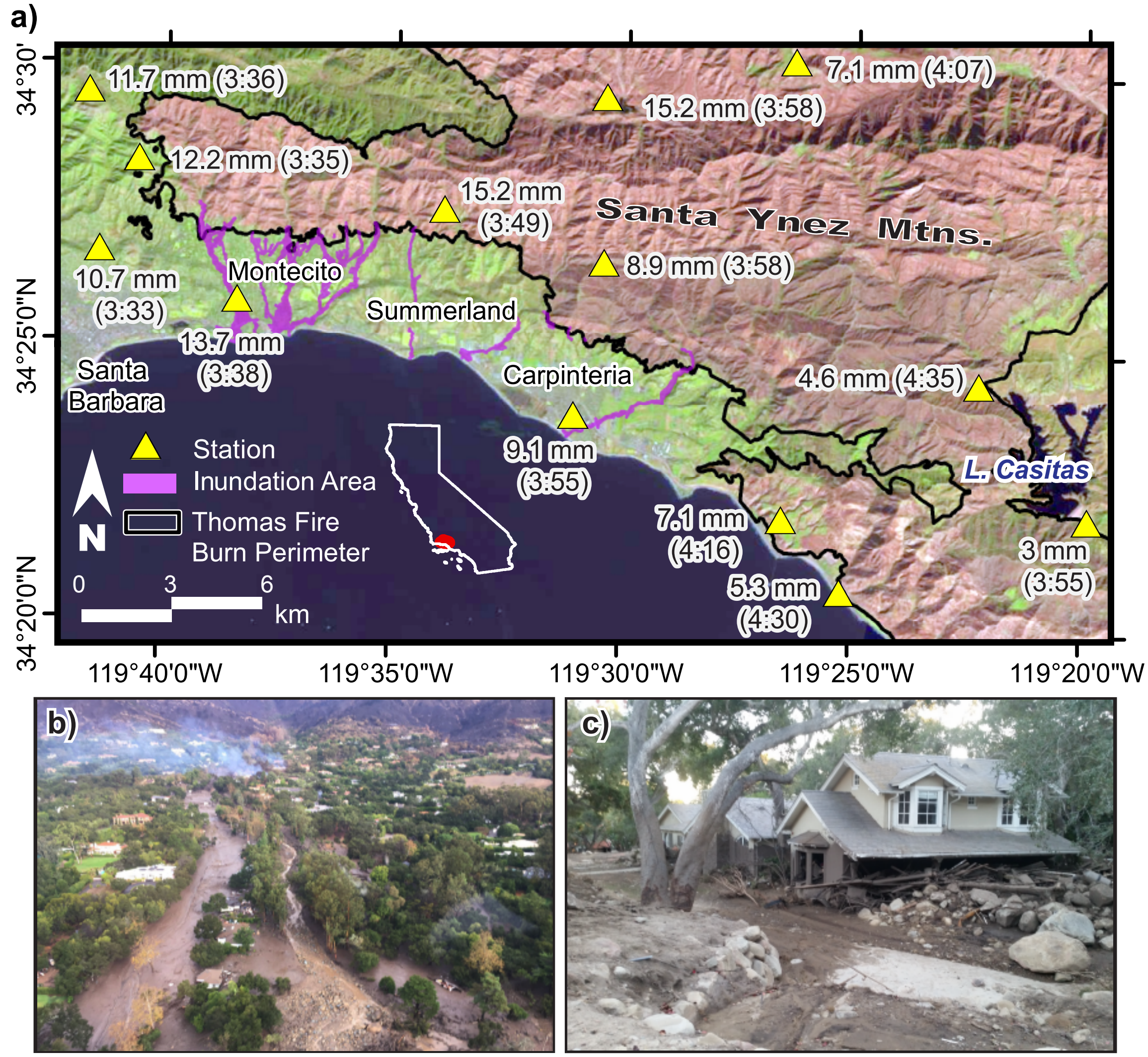

Figure 1: a) Burned areas within the perimeter of the Thomas Fire are depicted in red and unburned areas in green, as derived from the Landsat 8 thermal infrared sensor and surface reflectance imagery (USGS 2018b). Inundated areas, as mapped by the California Geological Survey, are displayed in purple. Station-based observations of greatest event 5-minute precipitation and the start time of the interval (LST) are labeled. b) Aerial photo of San Ysidro Creek in Montecito following the debris flow; areas that were once roads and homes appear as rivers of mud and debris. Photo: Ventura County Air Unit. c) A home destroyed in the debris flow. Photo: Brian Swanson, CGS.

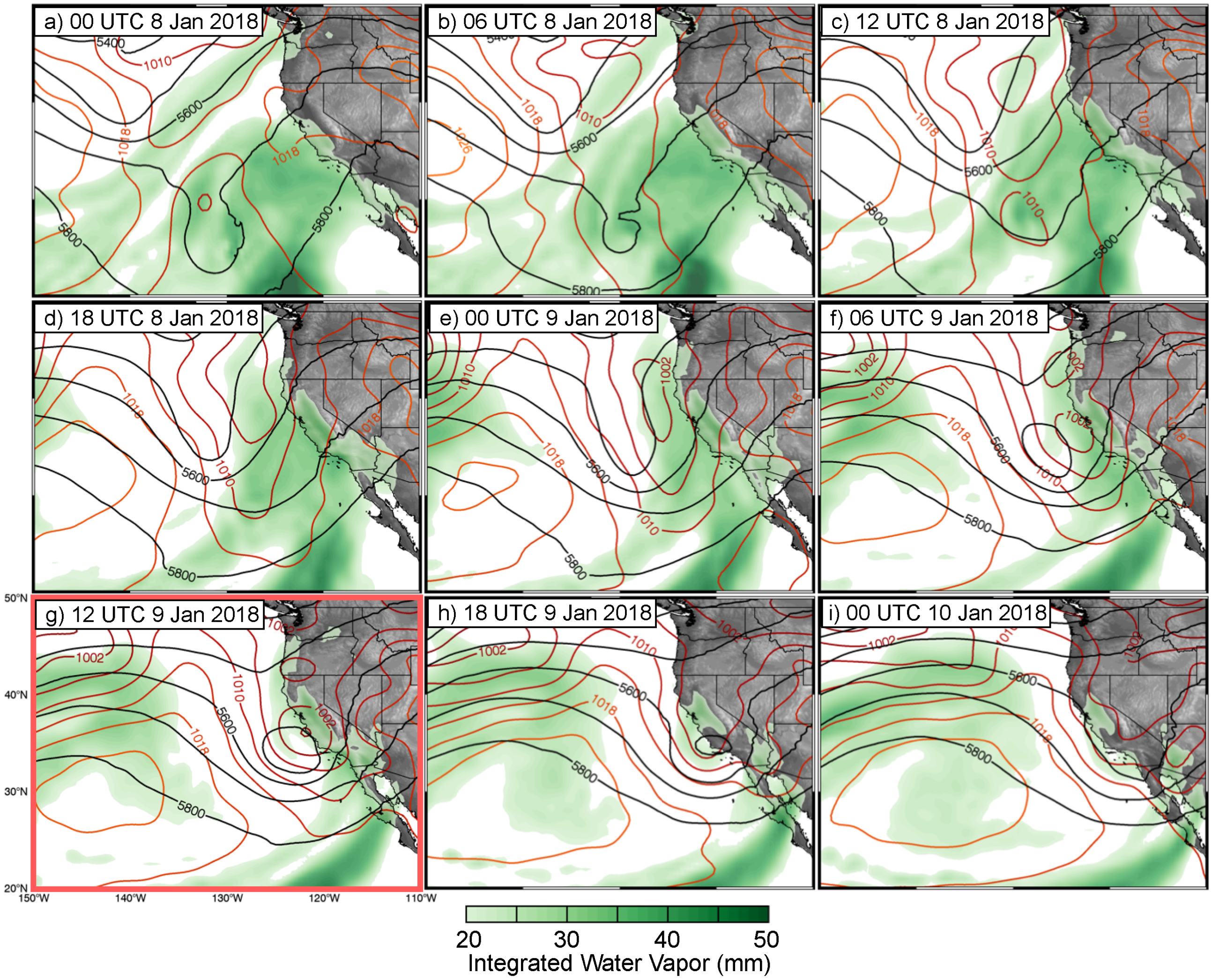

Figure 2: 500 hPa geopotential heights (black contour lines), sea level pressure (hPa; pink contour lines) and integrated water vapor (IWV; green filled contours) at 6-hour intervals for 36 h preceding to the event, time nearest event (outlined in pink), and twelve hours following the event.

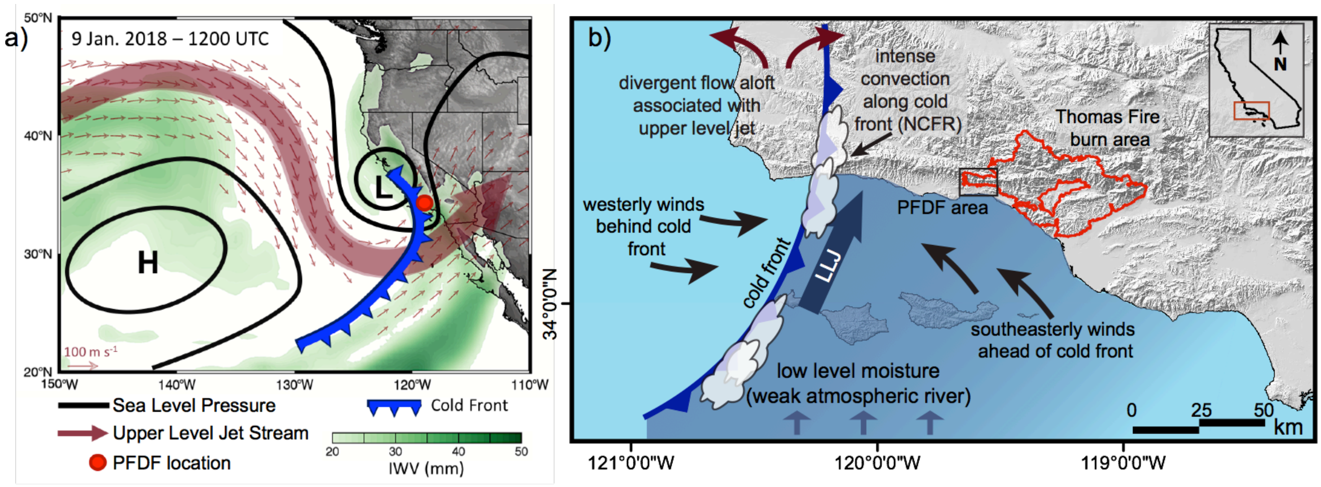

Figure 3: a) A conceptual synoptic view of conditions at 12 UTC 9 January 2018 based on information from the Climate Forecast System version 2 operational analysis (https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/climate-forecast-system-version2-cfsv2). b) A conceptual mesoscale view of conditions preceding the event as the cold front approaches the Thomas Fire burn area.

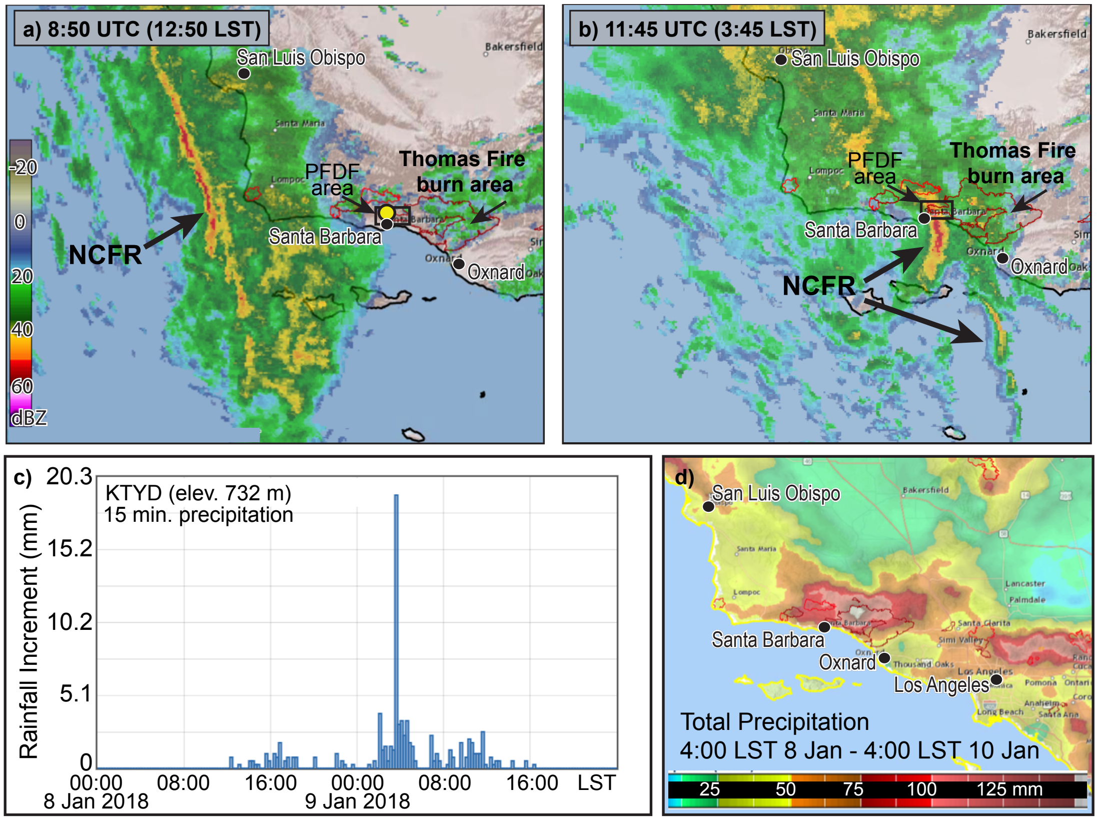

Figure 4: Panels a and b show radar imagery a) preceding and b) at the time of PFDFs on the Thomas Fire burn area. Yellow to red colors indicate higher intensity precipitation. Radar image source: California-Nevada River Forecast Center (CNRFC; cnrfc.noaa.gov). Panel c) shows precipitation observations at 15-minute intervals from the KTYD station operated by SBCPWD. The station position is indicated by the yellow marker in panel a). Panel d) provides regional 48 h precipitation totals from CNRFC.