Comments made by Anonymous Referee 1 are provided in black text.
Author responses are provided in blue text.

Anonymous Referee #1
Received and published: 3 July 2018
This manuscript describes the meteorological conditions and climatological reference
points (e.g., return period estimates) of the heavy rainfall that drove catastrophic debris flows following the 2017-2018 southern California wildfires. This is admittedly my first review of a "Brief Communication" submission, and in all honesty as I read it, I struggled to find novel aspects that were obviously worthy of publication. The event itself is interesting and high-impact, the data summary and meteorological analysis is sound, and the writing and communication is clear. Thus, the main issues that I have are more to do with what seems to be lacking, rather than problems with the material in the manuscript. However, suspecting that the problem may be with my own expectations of a full-length publication relative to the present manuscript type, I offer below only a few minor comments/suggestions that the editor and authors can consider as they deem appropriate.

The reviewer is correct, it was not our goal here to answer a question or test a hypothesis, but rather to document the incident in a way that hopefully provides insight to future research. Following the event, the authors saw misinterpretation of the meteorological characteristics of the event in the media and discussions with colleagues. We read and heard references to the event being a tropical storm, or being caused by orographic effects alone. We were concerned these misinterpretations may be damaging to the progression of research on the topics of short duration, high intensity rainfall in this region and post-fire debris flows. Many scientific publications related to this event are anticipated over the next few years. A peer-reviewed statement on the meteorological drivers of this event provides researchers in a variety of fields a reference to support their work, without having meteorology expertise. A brief communication, rather than a full-length article seemed the appropriate place to make a statement on the event.

General comment: 1.
If part of the purpose of this manuscript is to " support investigations on this and other PFDFs in a range of fields...," then I suggest adding at least some discussion of/references to relevant post-fire hydrologic or geologic concepts that might be of interest in future research, e.g.,
a..Neary et al. 2003: https://www.researchgate.net/publication/228510172_Post-wildfire_watershed_flood_responses
b.'Havel et al. 2018: https://doi.org/10.5194/hess-22-2527-2018
c. Brogan et al. 2017 https://onlinelibrary.wiley.com/doi/full/10.1002/esp.4194

Our intent is to focus on the meteorological triggers of the debris flow, rather than the geomorphic processes. Additionally, we are limited to 20 references and

~2500 words (NHESS author guidelines for Brief Communications can be found here: https://www.natural-hazards-and-earth-system-sciences.net/about/manuscript_types.html), so we chose to spend these on meteorological references and references specific to the event. To provide clarification, we have adjusted the paragraph at page 2, line 10 to explain that we are supporting the understanding of the meteorological triggers of PFDFs, which has been shown to be a knowledge gap in management communities (e.g. Garfin et al. 2016). This provides differentiation from the initial statement that could have been interpreted as if we were attempting to educate on post-fire debris flow processes in general.

As the reviewer alludes to, there is a large body of work on post-fire debris flow geomorphic processes, and here we choose to focus on the meteorological triggering process for this event and relate it to past events and climatology.

Specific comments: Lines 25 – 26: I'm not familiar with the language/terminology "having high debris flow hazard"...do you mean risk? Can you re-phrase/explain for a general audience?

The USGS model is a hazard model because it does not intersect the debris flow hazard with values exposed to and vulnerable to the hazard. Therefore in this case, it is correct to say that the USGS model provides information about debris flow hazards rather than risk.

Figs. 3a, b are highly suggestive of possible line echo wave pattern ("LEWP") dynamics. Again, in the interest of supporting/inspiring future investigations, perhaps a reference to this idea/possibility be added?

Line echo wave patterns are a type of squall line (Markowski and Richardson, 2010). NCFRs can be differentiated from squall lines based on their low-level cold pool maintenance by cold-air advection (CAA) rather than evaporational cooling in shallow rear-to-front flow (Geerts and Hobbs 1995). We see evidence of CAA in backing winds in vertical wind profile observed at Santa Barbara Airport following the frontal passage (Fig. S8).

LEWPs are most commonly described as a phenomenon impacting areas east of the Rockies during the spring and summer seasons (e.g. Johns 1993; Weisman 1993; Pryzybylinski 1995; Corfidi et al. 2018). LEWPs are typically associated with extreme convective instability owing to high amounts low-level moisture (Pryzybylinski 1995). Johns et al. (1990) found that long-lived derechos had an average of 2400 J/kg of CAPE in the initiation environment. It is much less likely for LEWPs to develop in low-instability environments such as the one observed here.

Additionally, LEWPs are commonly associated with straight-line strong wind events known as derechos (Pryzybylinski 1995 and references therein). The

NWS criteria for derechos requires wind gusts >57 mph at most points along the storm path (Corfidi et al. 2018). At stations near sea level in this event, we see gusts typically <=40 mph (37.8 mph at KSBA, 24 mph at Montecito #2 RAWS, 40 mph at Santa Barbara Botanic Garden RAWS, and 28 mph at Casitas RAWS; https://raws.dri.edu/). At higher elevation stations like San Marcos Pass RAWS (457 m), wind speed was slightly higher, with a maximum of 48 mph. For all these cases, maximum gusts were out of the S/SE. The increase in wind speed with elevation is consistent with the presence of a strong low-level jet (Neiman et al. 2004). The LLJ also displays well in the vertical wind profile from KSBA (Figure S8) and a burst of wind at the surface consistent with a derecho event is not present in the profiler data. The lack of strong "downburst"-type winds weakens the case for the consideration of this event as a LEWP.

References:

Corfidi, S., Evans J., Johns, R (last updated 2018). About Derechos. https://www.spc.noaa.gov/misc/AbtDerechos/derechofacts.htm Accessed online 31 Aug 2018.

Garfin, G., LeRoy, S., Martin, D., Hammersley, M., Youberg, A., Quay, R. (2016). *Managing for future risks of fire, extreme precipitation, and post-fire flooding. Report to the U.S. Bureau of Reclamation, from the project Enhancing Water Supply Reliability*. Tucson, AZ: Institute of the Environment. https://bit.ly/2LRhCtQ

Geerts B., P.V. Hobbs, 1995: A squall-like narrow cold-frontal rainband diagnosed by combined thermodynamic and cloud microphysical retrieval. *Atmos. Res.* **39**, 287-311.

Johns, R. H. (1990). Conditions associated with long-lived derechos-An examination of the large-scale environment. In *16th Conf. on Severe Local Storms, Kananaskis Park, Albert, Canada, Amer. Meteor. Soc., 1990* (pp. 408-412).

Johns, R.H., 1993: Meteorological Conditions Associated with Bow Echo Development in Convective Storms. *Wea. Forecasting,* **8**, 294–299, https://doi.org/10.1175/1520-0434(1993)008<0294:MCAWBE>2.0.CO;2

Przybylinski, Ron W. "The bow echo: Observations, numerical simulations, and severe weather detection methods." *Weather and Forecasting* 10.2 (1995): 203-218.

Weisman, M. L. (1993). The genesis of severe, long-lived bow echoes. *Journal of the atmospheric sciences*, *50*(4), 645-670.

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Reviewer #2 Comments

A bit puzzled on the whole process here. Not seeing any open scientific discussion having occurred at all, just the comments made weeks ago by Anonymous Referee #1.In the absence of the former, fail to see how the process of peer review and publication in Natural Hazards and Earth System Sciences (NHESS) differs from traditional scientific journals. Also unclear on what the expectations are for a “Brief Communication” submission and am unable to find information in that regard. It is with those caveats that this review is provided, and I leave it to the editor and authors as to how they wish to consider my comments. Recommendation: Accept for publication after suitable moderate to major revision.

In this discussion context, both reviewer or public comments and author responses are available to the public during review and after publication. At the beginning of the manuscript open discussion process in late June 2018, the link to the discussion was posted on the National Weather Service Los Angeles/Oxnard Facebook and Twitter pages, which have 35K and 20K followers, respectively. The same week, we sent the link to over 100 attendees of the International Atmospheric Rivers Conference as well as to a group of approximately 30 scientists and emergency managers who had attended a workshop on the Montecito debris flows in February 2018 at the University of California, Santa Barbara. Despite our efforts to make the discussion paper known and invite commentary, we did not receive any beyond the anonymous reviewer evaluations. NHESS statistics do show over 700 views and 146 downloads of the discussion paper.

Major Comment #1: Would like to see this focused down to what the key triggering meteorological event was, the accompanying hydrometeorological circumstances that resulted in the extreme outcome, and the basic synoptic and mesoscale evolution. Much of that is already there, but believe it could be better organized to present a clearer picture.

- In section 2.1, just give the basic synoptic evolution – say 500 mb, SLP and IWV every 12 hours for the 36 or so hours leading up to the event. Can omit the rest of it.

In the initial submission we were limited to three figures, ~2500 words, and 20 references. We propose the following additional figure to address the synoptic evolution of the event. We have updated the text in section 2.1 to describe this sequence.

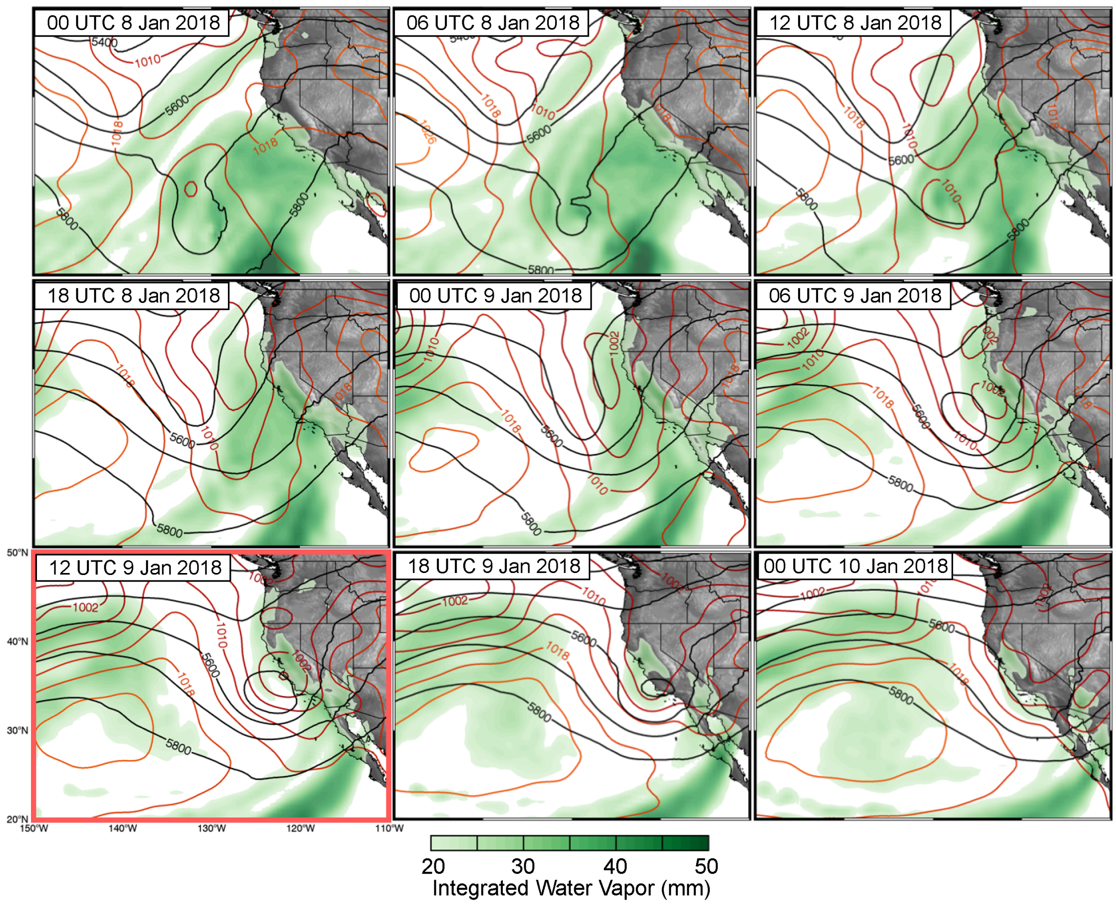

Figure 2: 500 hPa geopotential heights (black contour lines), sea level pressure (pink contour lines) and integrated water vapor (IWV; green filled contours) at 6-hour intervals for 36 h preceding to the event, time nearest event (outlined in pink), and twelve hours following the event.

- Not immediately seeing the connection between this event and atmospheric rivers. Page 2, lines 20-26:
  - (i) need to provide evidence in support of the claim that the moisture plume resulted from re-organization of the remnant moisture from the AR that moved through the previous day.

Removed reference to this reorganization (to describe this process in full detail is beyond the scope of the project) and introduced figure above to help describe the evolution of moisture plumes in this event. In lines 20-26, we now provide a simple narrative of the evolution of the moisture plumes.

- (ii) Are you really making the claim that this event itself was associated with a weak AR? Are the spatial scales consistent with the definition of an AR? And then might want to expand a bit on the consequent implication that weak ARs can potentially result in catastrophic hydro events
- On the other hand, if it isn't an AR, would be worth noting that catastrophic hydro events can occur in coastal California that are not associated with ARs. Either way, it's interesting and important, just needs to be clarified.

We do indeed interpret this as a weak AR. Restructured this section to state that both the IWV and IVT values and the shape and orientation of this moisture plume are consistent with the definition of an atmospheric river, though a weak one. Additionally, to address the important point the reviewer makes, we added to the conclusion that, "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."

- In section 2.2, just need clear sequences of satellite images, radar images, and surface analyses leading up to the event.

Given the brevity of this manuscript, it is not feasible to include all variables suggested. We focus on a few key features of interest to make a short communication on some of the main features observed. We do provide satellite imagery in the supplementary material (Fig S7), radar imagery in Fig 4 and S9, and now have SLP in Fig 2 (see above) and timeseries of surface winds available in the profiler data in Fig S8.

- New section 2.3: focus down on the microscale event itself, when and where the 5 to 15 minute extreme precip bursts occurred, how much fell, and in relation the exact locations and time frame of the debris flows.

Our intention is to show the 5-minute high intensity rainfall, its timing, and locations of the debris flows in Fig 1, with additional info in Tables S1-S3. It is well established that post-fire debris flows occur within moments of intense rainfall (e.g. Kean et al. 2011), thus the times provided can be considered associated with debris flow occurrence. We have added additional references to section 3.1 (historical context of precipitation).

Major Comment #2: After reducing down to and organizing key figs, recommend including all in the manuscript itself rather than some as "supplemental material."

We are limited to three tables/figures in an NHESS Brief Communication, though we are hoping to include a fourth figure (that shown above) with the editor's approval. Our audience is primarily non-meteorologists, so we have chosen to focus on a few basic variables to communicate a concise message on key characteristics of the event. We want to demonstrate that the event was not caused by orographic enhancement alone, an extreme atmospheric river, or a tropical storm (all descriptions observed in the media). We include several supplementary figures to help support those who would like additional information.

Major Comment #3: Strongly recommend confining the focus to this event, especially given the "Brief Communication" nature of the submission (and thus eliminating Figs S10, S11 and accompanying discussion, etc)

One of our main goals is to put this event in context of historic events, both in terms of rainfall amounts and the meteorological conditions surrounding the event. We would like the reader to understand this was not a rare meteorological event for the area, and that mesoscale features such as NCFRs producing short duration, high intensity rainfall capable of initiating PFDFs are relatively commonplace in this region.

Other Comments:

- Page 1, this event occurred on January 9 but the Thomas Fire not 100% contained until January 12?
    - This is correct, the Thomas Fire was not declared fully contained until Jan 12. Rains on Jan 9 helped firefighters to extinguish the fire. http://www.latimes.com/local/lanow/la-me-thomas-fire-contained-20180112-story.html
- Page 1, might want to note how long it had been since last significant precip
    - This was the first significant rainfall event of the season, and this piece of info is likely of interest to readers. It has been added on page 1, ~line 27

- Page 1, lines 28-29: cite ref re exceeding USGS 15-min design storm
    - Added citation
- Page 3, line 2: Markowski and Richardson, 2010 not found in Reference section.
    - Reference was present, however, in formatting ended up tacked on to the end of the preceding reference. They have now been properly spaced.
- Page 3, line 9: intense convective precip bands? But sounding in Fig S6 shows zero CAPE.
    - This event does not feature substantial CAPE, typical for cool season events in this region. We have added to the Supplement Figure S5, which shows the sounding at the model timestep prior to the event (09 UTC) to complement Fig S6, sounding at the model timestep immediately following the event (12 UTC). In the sounding prior to the event, the most unstable parcel CAPE is 168 J/kg. At the timestep following the event, most unstable parcel CAPE is 42 J/kg. In a study of 19 historic events that produced post-fire debris flows, median CAPE is typically <50 J/kg at the time of the event; most events feature a moist-neutral profile (Oakley et al. 2017). A narrow cold frontal rainband is a line of intense (sometimes forced rather than free) convection associated with the density-current action of the low level leading edge of the cold front (Houze 2014). The documented cases of this type of rainband indicate that is can be produced by the forced ascent of stable or only slightly unstable air (Houze et al. 2014). If you get dynamical forcing in the moist neutral layer, as in this case along the cold front, you can release potential instability by moving the moist-neutral parcel to a higher elevation. We describe this process in Section 2.2, lines 10-12.

- Page 3, line 21: created
    - Made change
- Page 4, lines 30-31: thought this NCFR developed behind the primary AR, not in it.
    - Added “in association with” to clarify
- References: not entirely in alphabetical order.
    - Made change

References:

Houze Jr, R. A. (2014). *Cloud Dynamics* . Academic Press, 573 pp.

Kean, J. W., Staley, D. M., & Cannon, S. H. (2011). In situ measurements of post-fire debris flows in southern California: Comparisons of the timing and magnitude of 24 debris-flow events with rainfall and soil moisture conditions. *Journal of Geophysical Research: Earth Surface*, *116*(F4).

Oakley, N. S., Lancaster, J. T., Kaplan, M. L., & Ralph, F. M. (2017). Synoptic conditions associated with cool season post-fire debris flows in the Transverse Ranges of southern California. *Natural Hazards*, *88*(1), 327-354.

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.

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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).

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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).

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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.

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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

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Deleted: At the Carpinteria Fire Station (FS), the maximum 5-minute precipitation observation was 9.14 mm, a 10-year ARI event (10-25 year at 90% confidence). This observation tied the existing record set in WY1969. Records considered for Carpinteria FS began in 1964.

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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.

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Deleted: facilitating moisture availability. Conditions along and ahead of the cold front were favorable for orographic enhancement in the Santa Ynez Mountains above Montecito and Carpinteria.

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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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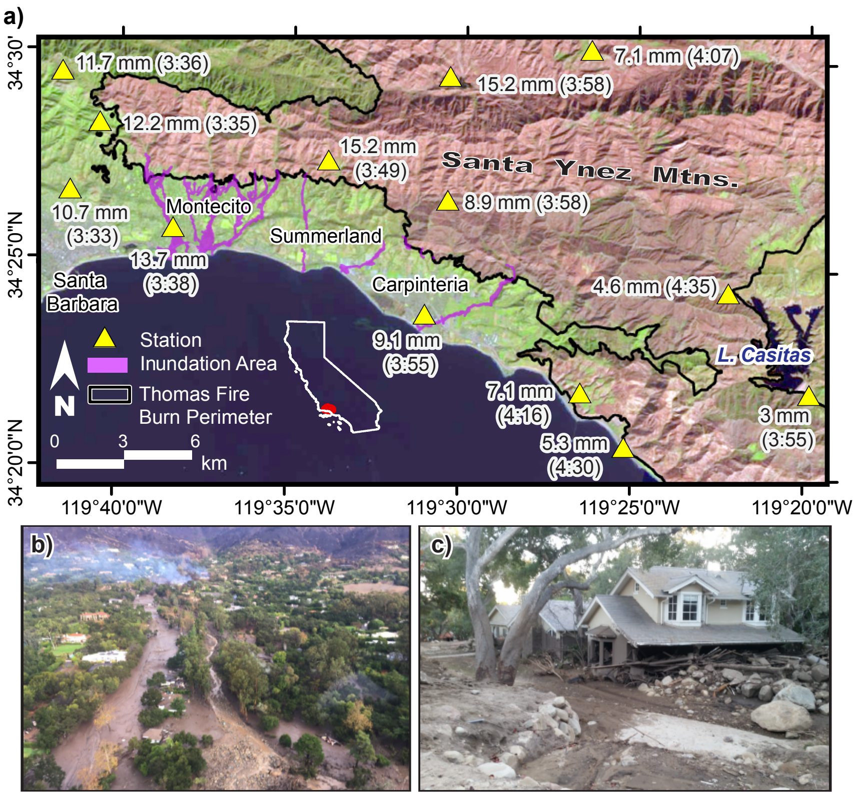

Figure 1: a) Burned areas within the perimeter of the Thomas Fire are depicted in red and unburned areas in green, as derived from the Landsat 8 thermal infrared sensor and surface reflectance imagery (USGS 2018b). Inundated areas, as mapped by the California Geological Survey, are displayed in purple. 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.

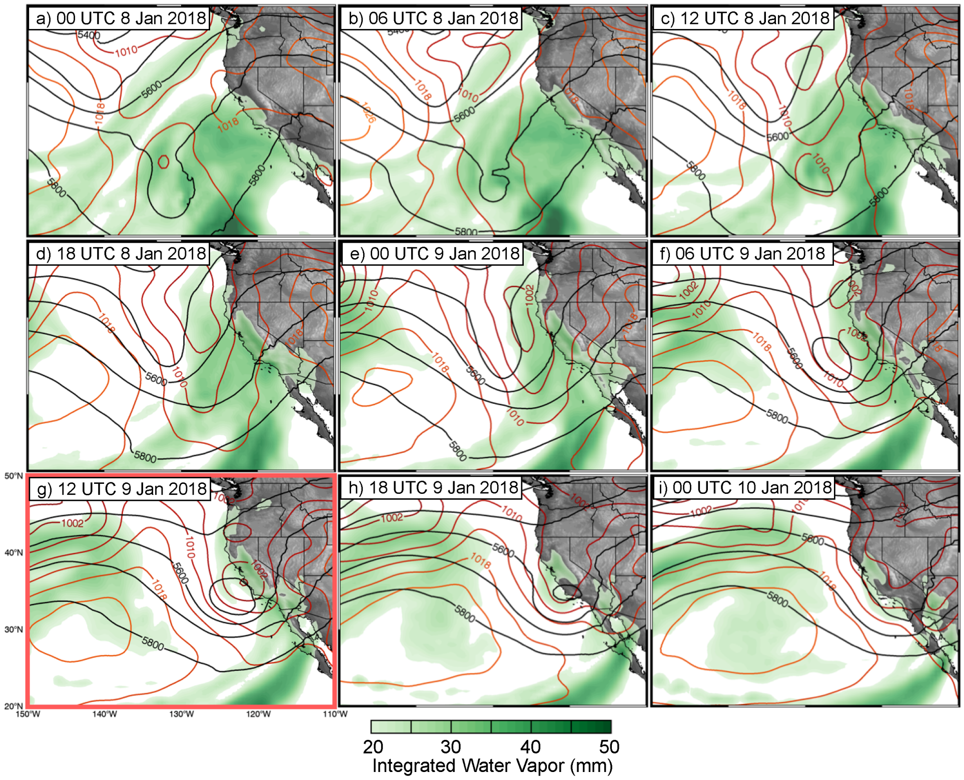

Figure 2: 500 hPa geopotential heights (black contour lines), sea level pressure (hPa; pink contour lines) and integrated water vapor (IWV; green filled contours) at 6-hour intervals for 36 h preceding to the event, time nearest event (outlined in pink), and twelve hours following the event.

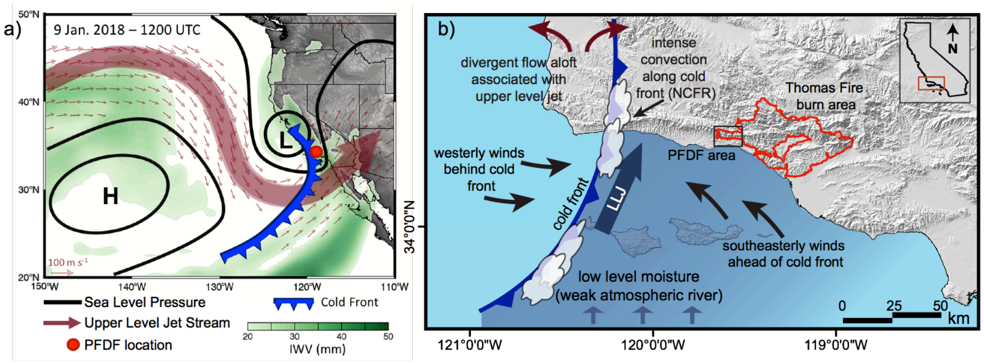

Figure 3: a) A conceptual synoptic view of conditions at 12 UTC 9 January 2018 based on information from the Climate Forecast System version 2 operational analysis (https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/climate-forecast-system-version2-cfsv2). b) A conceptual mesoscale view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

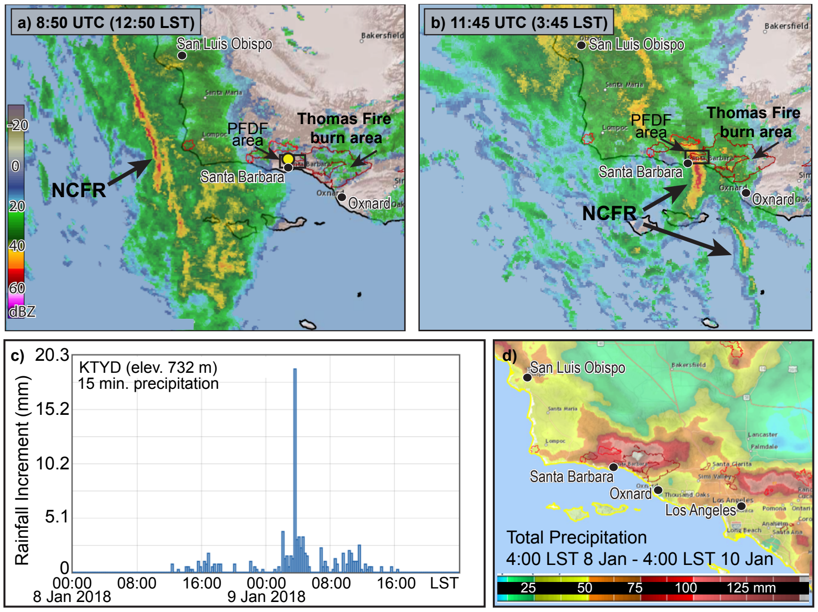

Figure 4: Panels a and b show radar imagery a) preceding and b) at the time of PFDFs on the Thomas Fire burn area. Yellow to red colors indicate higher intensity precipitation. Radar image source: California-Nevada River Forecast Center (CNRFC; cnrfc.noaa.gov). Panel c) shows precipitation observations 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.