The Synoptic and Mesoscale Evolution Accompanying the 2018 Camp Fire of Northern California

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ABSTRACT: The Camp Fire event was associated with dry, northeasterly winds that descended the western slopes of the Sierra Nevada of Northern California during the early morning hours of 8 November 2018. The downslope winds peaked around sunrise, with strong winds pushing the fire rapidly toward Paradise, California. Similar to recent central/Northern California wildfires associated with downslope winds, the synoptic pattern was characterized by building sea level pressure over the Intermountain West and a trough along the coastal zone, with both the synoptic evolution and low-level winds skillfully forecast by operational models. The maximum wind gusts along the western Sierra Nevada slopes ranged from 10–20 kt ($1 \text{ kt} \approx 0.51 \text{ m s}^{-1}$) at sheltered locations to 50–60 kt at exposed sites on the mid- to upper slopes of the barrier. The highest winds were not climatologically exceptional, and low-level temperatures were cooler than normal over and to the east of the Sierra Nevada, near normal over the western slopes, and warmer than normal over coastal California. Drier-than-normal conditions prevailed during the ~3 days preceding and during the event, as a result of downslope winds. The origin of the fire can be traced to strong winds interacting with a failing electrical transmission infrastructure, with highly flammable surface fuels fostering rapid fire movement between the ignition source and Paradise.

KEYWORDS: Forest fires; Katabatic winds; Wildfires; Mesoscale forecasting; Numerical weather prediction/forecasting; Forest fires

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On 8 November 2018, strong northeasterly winds interacting with a failing electrical transmission tower ignited a wildfire under power lines to the northeast of Paradise, California. Paradise is located between roughly 457 and 610 m (1,500 and 2,000 ft) above mean sea level (MSL) within the western foothills of the Sierra Nevada, the crest of which rises to approximately 1,980 m (6,500 ft) roughly 40 km to the northeast of the city. Over the next 5 days, the fire burned 153,000 acres (61,917 ha), destroyed nearly 20,000 structures, killed 85 people, and resulted in approximately 17 billion U.S. dollars in total loss, making it the deadliest and most destructive wildfire in California history (Cal Fire 2019).

According to California's Department of Forestry and Fire Protection (Cal Fire 2019), the primary initiation point of the Camp Fire was under Pacific Gas and Electric (PG&E) power lines near Camp Creek Road in Pulga (the location is indicated on Fig. 1) around 1415 UTC

Fig. 1. Three-dimensional terrain and overlain Landsat imagery looking northeastward up the Feather River Valley toward the crest of the Sierra Nevada. The initiation point of the fire is indicated by (top) a white arrow and (bottom) a red star. Produced using Google Earth Pro.

[0615 Pacific standard time (PST)] 8 November 2018. The fire then expanded rapidly to the west and southwest, reaching the northeast outskirts of Paradise around 1600 UTC (0800 PST). The fire rapidly moved through and south of Paradise, burning across approximately 70,000 acres during the first 24 h. The fire burned over approximately 30,000 acres the next day and then slowly increased in extent, mainly by expanding on its northern and southern flanks.¹

The Camp Creek Road fire initiation point (near the Camp Creek–Pulga Road intersection) lies within the Feather River Canyon, which extends eastward to the crest of the Sierra Nevada and provides a conduit for strong easterly canyon winds that are sometimes called “Jarbo Gap Winds”² (Fig. 1). California’s Cal Fire Agency, after an extensive investigation, concluded that the fire was initiated by the structural failure of a component on a 100-yr-old PG&E high-tension tower, with strong winds a probable contributor to that failure.³ Cal Fire also found a secondary fire ignition from a failing power transmission line near Concow, California, with the secondary blaze subsumed by the primary fire that started near Pulga.

Much of the region around Paradise had experienced large fires during the previous decades (Fig. 2). Of substantial importance, the route between the fire initiation point near Camp Fire Road (noted in Fig. 1) and Paradise encompassed the area of the BTU Lightning Complex Fire, which was initiated by lightning on 21 June 2008. As a result of the 2008 fire and others, as well as subsequent logging, fuels consisted of grass, brush, and scattered standing/fallen timber (with a grass and brush understory) along much of the path from the fire origin to Paradise. In some locations, fire crossing the West Fork of the Feather River also encountered areas of heavy timber with a brush understory that had not burned during the past several decades. Thus, the fire path predominantly encompassed grasses and shrubs that burn explosively when dry, thus fostering rapid fire spread. The California State tree mortality inventory⁴ did not indicate prior trees or tree mortality across a large portion of the fire zone, consistent with an environment of mainly grass and bushes that remained after previous fires and subsequent logging. More trees were found around homes in Paradise, but most of these trees did not burn, with many remaining green after the fire.⁵

Fig. 2. Location of previous wildfires in the region around Paradise, California. Map produced from data available from California, USA Fire History from 1950 to 2018 (<https://datasin.org/datasets/bf8db57ee6e0420c8ecce3c6395aceeb>) and Perimeters DD83 (http://rmgsc.cr.usgs.gov/outgoing/Geomac/historic_fire_data).

¹ www.fire.ca.gov/media/10167/progression_e_land_final_20181124_camp_cabtu016737_opt.pdf

² https://en.wikipedia.org/wiki/Feather_Canyon

³ www.fire.ca.gov/media/5121/campfire_cause.pdf

⁴ <http://egis.fire.ca.gov/TreeMortalityViewer/>

⁵ <https://ucanr.edu/sites/Rangelands/files/304942.pdf>

The surface and low-level meteorological conditions accompanying the Camp Fire event

Strong easterly and northeasterly winds helped initiate the Camp Fire and supported its rapid

movement to the west and southwest. Figure 3, which shows the maximum wind gusts (in knots; $1 \text{ kt} \approx 0.51 \text{ m s}^{-1}$) at the surface (10 m) for the 24-h period ending 0000 UTC 9 November 2018 using the NOAA/NWS Meteorological Assimilation Data Ingest System (MADIS) database, indicates substantial spatial variability in the maximum gusts. Many locations only experienced wind gusts between 10 and 30 kt (between 5 and 15 m s^{-1}), with the strongest winds, reaching 50–60 kt ($25\text{--}30 \text{ m s}^{-1}$), mainly at scattered locations over the middle to lower western slopes of the Sierra Nevada.

Plots of the direction and speed of the surface (10-m) wind gusts on the day of the event (8 November 2018) are shown in Fig. 4. Maximum winds were relatively weak (generally less than 20 kt or 10 m s^{-1}) at 0000 UTC 8 November, with modest northerly winds over the far northern portion of the domain. Six hours later, northeasterly flow reaching 30–40 kt ($15.4\text{--}20.6 \text{ m s}^{-1}$) was observed over the Sierra Nevada slopes, with north-northwesterly winds over the Central Valley of California. By 1200 UTC, 2–3 h before fire initiation, the northeasterly downslope winds had further increased [to approximately 50 kt (25 m s^{-1}) in the most exposed locations], with far weaker winds in sheltered locations. The general wind pattern was similar three hours later near fire initiation time (1500 UTC). Strong winds continued over the lower slopes at 1800 UTC, but decidedly weakened by 0000 UTC 9 November, as the pressure gradient over the region declined.

The 1-h peak winds (maximum gust over the hour) at the Jarbo Gap Remote Automated Weather Station (RAWS) site (2,490 ft MSL, 759 m, location marked on Fig. 3), situated on the slopes of the Feather River Canyon, indicated acceleration of northeasterly ($30^\circ\text{--}45^\circ$) winds

Fig. 3. Maximum observed surface wind gusts (kt) between 0000 UTC 8 Nov and 0000 UTC 9 Nov 2018. The fire initiation point, the town of Paradise, and the Jarbo Gap RAWS site are indicated by the red star, black triangle, and black square, respectively. Produced from NOAA/NWS MADIS data by Conor McNicholas.

Fig. 4. Speed (kt) and direction of maximum surface gusts around Paradise at 0000, 0600, 1200, 1500, and 1800 UTC 8 Nov and 0000 UTC 9 Nov 2018. The initiation location of the Camp Fire is indicated by a red star. As in Fig. 3, Paradise and the Jarbo Gap RAWS site are highlighted with the triangle and square, respectively. Produced from NOAA/NWS MADIS data by Conor McNicholas.

to 23 m s^{-1} (45 kt, 52 mph) during the early morning hours (0300–0500 PST) preceding fire initiation [which occurred at approximately 1415 UTC (0615 PST) 8 November], a rapid decline to approximately 12 m s^{-1} (24 kt, 28 mph) during the morning and afternoon, and strengthening during the subsequent evening (Fig. 5). This site was burned over by the fire during the next day, as demonstrated by a surge in temperature and winds as well as aerial imagery (not shown).

Surface air temperatures over the western slopes of the Sierra Nevada were relatively cool near the time of fire initiation (~1400 UTC 8 November), ranging from 7° to 13°C (from 45° to 55°F), and only rose to 16° – 18°C (~ 60° – 64°F) by midday (not shown). To illustrate, the surface air temperature at the nearby Jarbo Gap RAWS site during the hours immediately preceding and following fire initiation was approximately 9.5°C (49°F), followed by warming to roughly 17°C (~ 63°F) during the afternoon (Fig. 5). Thus, the average temperatures were $\sim 1.5^{\circ}\text{C}$ warmer than the climatological mean at Jarbo Gap for the date in question (the average range for the date is from a high of 14.8°C to a low of 8.4°C). Further perspective on temperature at Jarbo Gap is found in a plot for the year ending 9 November (Fig. 6a). Temperatures on 8 November had declined considerably from the peak in July, when temperature regularly rose to nearly 38°C (~ 100°F) at that location.

A plot of maximum wind gusts during the preceding year at Jarbo Gap (Fig. 6b) indicates the strongest wind on 8 November reaching $\sim 23 \text{ m s}^{-1}$ (45 kt, 52 mph); such winds, although strong, were not unusual, having been equaled or exceeded on 3 h during the prior month and 40 h the previous year. A review of the entire record at Jarbo Gap (April 2003–19) indicates that the strongest winds at this location are overwhelmingly from the north-northeast and/or northeast, with a second peak of substantially weaker winds from the west and/or southwest. Winds are highly constrained at Jarbo Gap, with the flow following the general orientation of the Feather River Valley (northeast to southwest).

A 1-yr plot of relative humidity and 10-h dead fuel moisture (for 0.25–1-in.-diameter vegetation; 1 in. = 2.54 cm) at Jarbo Gap shows low values (around 10% RH and 5% 10-h fuel moisture) at the time of the fire ignition, with similarly low values observed several times since the late spring (Fig. 6c). Low fuel moisture values (5%–10%) also occurred at several times in midwinter during periods of easterly flow. One-hour fuels, with a diameter of less than 0.25 in. (such as grasses), would dry even more quickly and would be expected to possess lower fuel

Fig. 5. Peak wind gusts (kt scale on left, m s^{-1} scale on right), peak wind direction ($^{\circ}$, scale on left), and 2-m temperatures ($^{\circ}\text{F}$ on left, $^{\circ}\text{C}$ on right) at the Jarbo Gap RAWS site for 8 Nov 2018 PST.

Fig. 6. Jarbo Gap RAWs observations from 0000 UTC 9 Nov 2017 to 0000 UTC 9 Nov 2018: (a) surface air temperature ($^{\circ}\text{F}$, $^{\circ}\text{C}$), (b) maximum wind gust (kt, m s^{-1}), and (c) relative humidity (%) in blue and 10-h dead fuel moisture (%) in red.

moisture during dry periods. Thus, light fuels sufficiently dry to support a wildfire were in place for a considerable period of time prior to the Camp Fire; all that was required was fire ignition and strong wind. It should be noted that the observed 10-h dead fuel moisture at the time of fire initiation ($\sim 5\%$) was substantially lower than the average value for that date (17.3%) as a result of below-normal autumn precipitation.

How unusual was the combination of strong winds, low relative humidity, and low 10-h dead fuel moisture that was experienced the morning of 8 November at the Jarbo Gap RAWs site? To address that question, we determined all events at Jarbo Gap with winds between 20 and 40 m s^{-1} , a relative humidity at or below 24%, and a dead fuel moisture level of 5% or less; conditions equivalent to or worse than those observed during the hours immediately preceding and during the initiation and rapid movement of the Camp Fire. A total of 336 h during the period from April 2003 through March 2020 were found. Thus, the occurrence of such conditions, although unusual, is not unprecedented.

Synoptic evolution associated with the Camp Fire

Figure 7 shows the synoptic evolution at the surface and aloft (500 hPa) during the 24-h period encompassing the ignition and initial spread of the Camp Fire (0000 UTC 8 November to 0000 UTC 9 November). At the surface, high pressure moved into Washington State and then pushed southeastward into eastern Oregon and Nevada. As a result, an offshore-directed pressure gradient built over the central and northern Sierra Nevada between high pressure within the Intermountain area and troughing over coastal California.

At 500 hPa, an upper-level ridge just offshore amplified and extended into southern British Columbia, while troughing built southwestward into Southern California, a synoptic configuration similar to that observed during the initiation of the Wine Country Fire of October 2017 (Mass and Ovens 2019). As a result of these changes, 500-hPa winds turned from northwesterly to north-northeasterly over northeast California and Nevada and thus were oriented nearly perpendicular to the northern Sierra Nevada.

The lower-troposphere synoptic configuration during the Camp Fire event was substantially different from the climatological normal for the date. Using NOAA North American Regional

Fig. 7. NOAA/NWS NARR (top) sea level pressure analysis (hPa) and (bottom) 500-hPa heights (dm) and winds (kt) at (left) 0000 UTC 8 Nov, (center) 1200 UTC 8 Nov, and (right) 0000 UTC 9 Nov 2019. Green shading shows saturated areas at 500 hPa.

Reanalysis (NARR) grids (Mesinger et al. 2006), it is apparent that 925-hPa (~800 m) air temperatures on 8 November 2018 were colder than normal east of the Sierra Nevada crest, including more than 6°C colder than normal over northern Nevada, while temperatures were above normal along the coast and over the coastal waters (Fig. 8). Temperature at the Camp Fire location, between the two temperature anomalies, was near normal. Specific humidity at 925 hPa was drier than normal over the entire domain, and much drier than normal over northwest California and the offshore waters. As described in the modeling section, relative humidity was also below normal west of the crest of the Sierra Nevada. Geopotential heights at 925 hPa were higher than normal north and east of the Camp Fire area, with troughing over the coastal zone, resulting in a large 925-hPa height anomaly gradient over the northern Sierra Nevada. Finally, the 925-hPa vector winds had a northeasterly wind anomaly over northeast California and adjacent Nevada, with anomalous northeasterly winds of 10–12 m s⁻¹ over the western slopes of the Sierra Nevada.

Fig. 8. Anomalies from climatology of 925-hPa (top left) air temperature (°C), (top right) specific humidity (g kg⁻¹), (bottom left) geopotential height (m), and (bottom right) vector wind (m s⁻¹) for 8 Nov 2018. Fields are from the NOAA/NWS NARR, with the anomalies representing the difference of the 8 Nov fields from the 1981–2010 climatology for that date.

Fig. 9. (left) Observed and (right) WRF Model 1.33-km domain vertical soundings at Reno, Nevada, for (a) 0000 UTC 8 Nov, (b) 1200 UTC 8 Nov, and (c) 0000 UTC 9 Nov 2018. Temperature ($^{\circ}\text{C}$) and dewpoint temperature ($^{\circ}\text{C}$) are indicated by red and green lines, respectively, with wind barbs (kt) shown.

Both observed and WRF Model (1.33-km grid spacing) upper-air soundings in the lower troposphere at Reno, Nevada, are shown in Fig. 9 for 0000 UTC 8 November through 0000 UTC 9 November, a period encompassing the acceleration of the winds around Paradise and the explosive growth of the fire. Reno is the only available radiosonde site that provides relevant information about the characteristics of the lower atmosphere upwind of the central and northern Sierra Nevada for easterly flow. At 0000 UTC 8 November, winds were primarily westerly or northwesterly above 850 hPa and northerly near the surface, but by 1200 UTC, roughly 2 h before fire initiation, the winds had turned easterly in the lowest 2 km and northeasterly immediately above. By 0000 UTC 9 November, when the fire had already moved into Paradise, easterly and northeasterly winds reaching 25 kt were observed below 500 hPa. During this 24-h period, there was considerable drying between 750 and 350 hPa, with the development of a stable layer between 700 and 600 hPa at 1200 UTC 8 November that subsided to 700–800 hPa by 0000 UTC 9 November.

Smoke and its impacts

The Camp Fire produced extensive smoke over central California, producing the worst air quality on record over San Francisco and the surrounding region.⁶ Figure 10 shows the midday

⁶ www.kqed.org/news/11712211/the-camp-fire-caused-nearly-two-straight-weeks-of-the-bay-areas-worst-air-quality-on-record

Fig. 10. NASA MODIS visible imagery over central California at approximately 2100 UTC on 8, 10, 12, 14, and 16 Nov 2018.

distribution of smoke from NASA MODIS visible satellite imagery for 8–16 November 2018. Initially (8 November), the densest plume was advected west-southwest by strong easterly winds, but over the next few days the smoke became more diffuse and extensive.

The dense smoke plume greatly lessened solar radiation reaching the surface, resulting in substantial reduction of the maximum temperatures observed during the afternoon of 8 November and during the subsequent week. Solar radiation at three USDA RAWS sites (Jarbo Gap, Santa Rosa, and San Jose, California) are shown in Fig. 11. At Jarbo Gap, in close proximity to the fire, solar radiation declined from a peak of $\sim 560 \text{ W m}^{-2}$ before the fire to $\sim 160 \text{ W m}^{-2}$ during the 3 days after its initiation. Santa Rosa, located $\sim 175 \text{ km}$ to the southwest of Paradise, experienced a lesser but still considerable loss of solar radiative flux, declining

Fig. 11. Solar radiation measured at the Jarbo Gap, Santa Rosa, and San Jose USDA RAWS sites from 0000 UTC 7 Nov through 0000 UTC 12 Nov 2018.

about half in the first day (to $\sim 290 \text{ W m}^{-2}$), with a slow recovery over the next 2 days. Finally, at San Jose, located farther south, there was only a small decline in solar radiation the first day, with the maximum loss on 10 November (to $\sim 400 \text{ W m}^{-2}$).

The impacts of the smoke on surface air temperature were substantial. To estimate the cooling effect of the smoke, 24-h WRF Model 2-m temperature forecasts (4-km grid spacing) were made without including radiative impacts of smoke aerosol, with the forecasts compared to the observed surface temperatures near the time of maximum temperature each day (0000 UTC, 1600 PST). For model forecasts verifying at 0000 UTC 8 November, roughly 12 h before fire initiation, the temperature biases were small throughout the region and of variable sign (Fig. 12a). Two days later, after smoke extended over central California (0000 UTC

Fig. 12. Bias of 24-h WRF 4-km-domain temperature forecasts ($^{\circ}\text{C}$) verifying on (a) 0000 UTC 8 Nov, (b) 0000 UTC 10 Nov, and (c) 0000 UTC 12 Nov 2018.

The daily-average air quality index (AQI) in the San Francisco Bay area (Fig. 13) indicates highly degraded air quality for nearly two weeks (8–21 November), with several days reaching very unhealthy levels (over 200). On the more extreme days, stations in the San Francisco Bay area had some of the worst air quality in the world, competitive with the most polluted areas of India and China.⁷ On 16 November, San Francisco experienced the worst air quality during the entire period of measurement (an AQI of 271), resulting in school cancellations and reduced flights into San Francisco International Airport (SFO).

⁷ <https://sf.curbed.com/2018/11/16/quality-bad-worst-bay-area-smoke>

Northern Zone

Stations	November, 2018																														Monthly
Days	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	AQI
Napa - Napa Valley College	30	30	24	26	23	27	27	88	120	159	147	158	161	135	170	183	179	171	161	125	58	18	10	11	22	22	28	25	15	25	183
San Rafael	26	32	31	40	29	25	30	88	110	166	158	163	166	181	218	184	161	170	138	45	2	4	10	17	21	29	18	24	26	218	
Sebastopol	6	13	2	5	12	4	22	163	226	209	156	168	172	131	153	168	160	149	152	133	52	4	5	11	14	20	24	15	15	16	226
Vallejo	37	45	51	38	27			155	72	160	165	171	165	157	186	247	186	166	169	158	103	19	17	23	42	48	40	38	26	25	247

Coast & Central Bay

Stations	November, 2018																															Monthly
Days	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	AQI	
Berkeley Aquatic Park	37	34			57	54	53	87	162	178	163	165	158	164	198	216	176	153	166	154	50	23	22	28	43	52	39	34	42	32	216	
Laney College	39	42	38	52	38	41	39	79	157	177	167	165	160	169	202	219	177	157	167	155	49	10	11	19	42	48	46	19	22	22	219	
Oakland East	35	48	45	40	37	32	44	92	168	174	163	165	153	165	203	222	184	156	170	136	39	16	12	17	30	43	36	18	19	22	222	
Oakland West	58	55			52	52	49	83	118	180	167	167	162	164	199	220	178	156	168	154	46	14	15	23	36	46	44	27	23	21	220	
San Francisco - Arkansas St.	47	50	49	46	42	46	52	76	156	172	167	165	164	173	197	228	158	151	174	156	55	10	14	16	40	43	39	23	27	28	228	
San Pablo - Rumrill	37	41	32	49	32	27	24	125	117	168	160	160	152	162	196	245	183	160	176	141	53	21	12	14	24	40	37	32	27	25	245	

Eastern Zone

Stations	November, 2018																															Monthly
Days	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	AQI	
Concord	20	25	22	21	11	18	22	73	76	167	159	159	133	152	184	230	210	176	173	157	89	9	4	8	17	30	22	20	8	14	230	
Livermore - Rincon Ave.	18	32	24	21	23	14	18	56	161	160	154	162	138	186	193	223	191	176	156	153	76	7	3	11	23	38	35	18	8	16	223	
Pleasanton - Owens Ct	32	40	30	38	37	26	30	63	158	165	157	160	151	165	193	215	191	173	162	156	83	7	5	9	17	37	32	16	8	16	215	

Air Quality Index (AQI) Values

0–50	51–100	101–150	151–200	201–300
Good	Moderate	Unhealthy for Sensitive Groups	Unhealthy	Very Unhealthy

Levels of Health Concern

Fig. 13. Daily averaged AQI at locations around San Francisco. Data acquired from the Bay Area Air Quality Management District.

WRF Model simulations

To explore the structure and dynamics of this wind and wildfire event, a WRF-ARW (Advanced Research version of the Weather Research and Forecasting Model) simulation was initialized at 0000 UTC 8 November and run through 0600 UTC 9 November 2018. A nested configuration with 36–12–4–1.3–0.444-km grid spacing was applied, with the 1.3-km and 444-m domains encompassing the area associated with the wind and fire event. The model configuration was the same as the highly tested University of Washington real-time WRF system,⁸ using WRF-ARW v3.7.1, YSU planetary boundary layer (PBL), Thompson microphysics, RRTMG radiation, and the Noah-MP land surface model, but with one exception: the number of vertical levels was increased from 38 to 75. The runs were initialized with and secured lateral boundary conditions from the operational NOAA/NWS Global Forecast System (GFS) model grids.

⁸ <https://atmos.washington.edu/mm5rt/>

The model evolution for this event was highly realistic, with the simulation closely following the observed synoptic and mesoscale development. For example, the observed and simulated vertical soundings at Reno, Nevada during the downslope wind period (0000 UTC 8 November to 0000 UTC 9 November) were very similar; both developed a midlevel stable layer that descended in time, with similar evolution in horizontal winds and moisture in the lower troposphere (Fig. 9). As described below, the observed and simulated synoptic evolutions were virtually identical, as was the development of sustained winds at the surface. To provide further documentation of model fidelity to observations, Fig. 14 shows a comparison between observations at the USDA RAWS site at Jarbo Gap and the model forecasts from the higher resolution domains. The highest resolution nest (444-m grid spacing) provided the best forecast of the strong northeasterly winds leading up to the event, but delayed the decline of the winds by 3–4 h compared to observations at that site. Both temperature and relative humidity predictions had only minor errors with respect to amplitude and timing.

The WRF Model forecasts of sea level pressure, 10-m winds, and 925-hPa temperature fields at 0000, 0600, 1200, and 1800 UTC November 2018, a period encompassing the initiation and explosive growth of the Camp Fire, are shown in Fig. 15. At 0000 UTC high sea level pressure and cooler temperatures were simulated over Washington and Oregon, while a pressure trough, associated with warmer air, was over coastal California. During the next 12 h, cooler air and higher pressure pushed into eastern Oregon and northern Nevada, resulting in northeasterly flow and a large sea level pressure gradient (~8 hPa over 100 km) over the crests of the northern Sierra Nevada. This gradient was enhanced further at 1800 UTC, near the time of maximum spread of the fire, with a mesoscale pressure trough over the western slopes of the Sierra Nevada. This surface evolution closely matched the observed development (Fig. 7).

Fig. 14. Comparison between observations and WRF Model forecasts for (top) winds and (bottom) temperature and relative humidity.

Fig. 15. WRF Model forecasts 12-km-domain for sea level pressure (solid lines, hPa), 10-m winds (wind barbs, kt), and 925-hPa temperature (°C) at (a) 0000, (b) 0600, (c) 1200, and (d) 1800 UTC 8 Nov 2018.

The simulated maximum winds (kt) in the lowest 250 m (a proxy for gusts) from the 444-m domain are shown in Fig. 16. Earlier the previous evening (0300 UTC), northeasterly winds were found over the region, but wind speeds were relatively weak, with maximum near-surface winds of 30–40 kt ($15\text{--}21\text{ m s}^{-1}$) above the middle slopes of the western side of the Sierra Nevada. By 0900 UTC, the midslope winds had strengthened and extended toward lower elevations, with maximum winds reaching about 50 kt (26 m s^{-1}). Three hours later

Fig. 16. WRF Model forecasts from the domain with 444-m grid spacing of the maximum winds (kt) within the lowest 250 m above the surface at (a) 0300, (b) 0900, (c) 1500, and (d) 2100 UTC 8 Nov 2018. White line shows location of vertical cross section in Fig. 18.

(1500 UTC), close to the time of the initiation of the Camp Fire, the maximum winds had accelerated to 60–70 kt ($31\text{--}36\text{ m s}^{-1}$) at the Camp Fire initiation location and surrounding area. As observed, by 2100 UTC winds had substantially diminished, with the strongest winds limited to a narrow zone on the upper slopes.

The evolution of simulated surface (2-m) relative humidity is shown in Fig. 17. At 0300 UTC, prior to the acceleration of the northeasterly winds, relative humidity was lowest (15%–35%)

west of the Sierra Nevada crest, with higher values over the Pacific Ocean. There were only modest declines during the next 12 h (through 1500 UTC), but the combination of strong downslope/easterly flow and diurnal heating resulted in large reductions in relative humidity by 2100 UTC (1300 PST), particularly over the western slopes of the Sierra Nevada and coastal mountains, where some locations had relative humidity drop below 10%.

Fig. 17. WRF Model 1.33-km grid simulated 2-m relative humidity (%) and terrain height (m) at (a) 0300, (b) 1500, (c) 1800, and (d) 2100 UTC 8 Nov 2018. Relative humidities up to 40% are shown (color scale at bottom) overlaid on terrain (grayscale at right). Locations of a vertical cross section (white line) and fire initiation (Camp Fire marker) and the upstream sounding location used in Fig. 19 (Upstream marker) are also shown.

Southwest–northeast vertical cross sections from the Central Valley, across Paradise, and over the crest of the Sierra Nevada were constructed within the 444-m domain (location noted in Figs. 16 and 17). These cross sections, valid at 0300, 0900, 1500, and 2100 UTC 8 November 2018, are shown in Fig. 18. At 0300 UTC, there was a modest acceleration to 30–40 kt in a shallow near-surface layer, with very light winds over the lower portions of the slope. By 0900 UTC, near-surface downslope winds had accelerated to 40–50 kt and increased in depth on the middle-elevation slopes, with enhanced wave amplitude downstream of minor ridges. The downslope winds and associated wave amplitude strengthened at 1500 UTC, with sustained winds reaching 50–60 kt over the middle to upper western slopes of the Sierra Nevada, and a zone of enhanced winds moving westward about 100 hPa

Fig. 18. Vertical cross sections across the western slopes of the Sierra Nevada at (a) 0300, (b) 0900, (c) 1500, and (d) 2100 UTC 8 Nov 2018 showing potential temperature (solid blue lines, K), wind vectors in the cross section, and wind speed (kt). The position of the cross section is shown in Figs. 16 and 17.

above the Central Valley. By 2100 UTC, the character of the wave activity had changed, with strong downslope flow descending the Sierra slopes replaced by shorter wavelength activity on the upper slopes. Winds on the lower and middle slopes had dramatically weakened at this time.

To explore the dynamics underlying the mountain wave amplification and strengthening of the downslope winds during the morning of 8 November 2019, vertical soundings at a location immediately upstream of the Sierra Nevada crest (position shown in Fig. 17), are presented in Fig. 19. At 0100 UTC 8 November, winds were weak immediately above the Sierra Nevada crest (~ 800 hPa), strengthening and turning northwesterly aloft. By 0600 UTC, the flow above crest level had turned easterly, with cooling evident below crest level. At 1000 UTC, easterly flow had strengthened above crest level (to ~ 20 kt) and a stable/isothermal layer had formed at and above the crest. Four hours later, near the time of the Camp Fire initiation (1400 UTC), incoming winds near crest level had accelerated to ~ 30 kt as the stable layer was maintained. A critical level was evident at ~ 600 hPa, having ascended from ~ 760 hPa at 0100 UTC. This flow configuration (strong winds approaching the barrier at nearly a right angle, stable layer near and above the crest level) are favorable for the development of mountain waves and downslope wind acceleration (e.g., Durran 1990, 2003).

Fig. 19. Model soundings upstream of the Sierra Nevada (40.22°N , 121.11°W , see Figs. 16 and 17) at (a) 0100, (b) 0600, (c) 1000, (d) 1400, and (e) 1800 UTC 8 Nov and (f) 0000 UTC 9 Nov. Temperature ($^{\circ}\text{C}$) and dewpoint temperature ($^{\circ}\text{C}$) shown by red and green lines, respectively, with model winds (kt) indicated by wind barbs.

Antecedent climatological conditions

This section reviews the precipitation that fell during the winter prior to the Camp Fire as well as the precipitation/temperature conditions during the months leading up to the conflagration. The previous winter's precipitation can be important because bountiful winter precipitation can lead to enhanced growth of grasses, which then dry during the summer (or during strong easterly flow periods) and thus provide fuel for wildfires. In fact, some studies suggest that prior winter precipitation provides the highest correlation with autumn wildfire activity in the region and that the grass/shrub environment is relatively insensitive to the temperature and precipitation of the preceding summer, since a normal summer is sufficient for drying most local fuels (e.g., Keeley and Fotheringham 2003; Abatzoglou and Kolden 2013; Keeley and Syphard 2016, 2017).

Figure 20a shows the time series of the October–April precipitation for 1948–2018 using NOAA/NWS climate division data (California division 2, Sacramento Drainage) encompassing the area of the Camp Fire. The precipitation during the previous cool season (26 in.) was below normal (by about 7 in.) but not exceptional (its ranking was 31st out of 70 years). The precipitation during the warm season (July–October) preceding the fire (Fig. 20b), was drier than normal (by approximately 2 in.) and was the 7th driest July–October period of the past 70 years. The two winters prior (2016 and 2017) were considerably wetter than normal, and may have enhanced the availability of light fuels (e.g., grasses) available to the Camp Fire (e.g., Keeley and Syphard 2017). Temperature for July–October 2018 was about 1°C above normal (ranked 61st out of 70 years). In summary, the relatively dry conditions the previous winter would not have been supportive of luxuriant grass growth, and, therefore, would have been expected to reduce the wildfire threat. On the other hand, carryover grasses from the 2016/17 anomalously wet winter could have contributed to above-average fine fuel loading. Furthermore, the warmer than normal and modestly drier than normal preceding months would have been supportive of drying, and thus wildfires.

Fig. 20. California climate division 2 (Sacramento Drainage) data for the years 1948–2018: (a) cool season (October–April) precipitation, (b) July–October precipitation, and (c) July–October temperature. Data acquired from the NOAA Earth System Research Laboratories.

Grass and brush, including scattered timber with a brush understory, characterized the fuels between the fire origin and Paradise with very dry fuels capable of supporting wildfire growth. Thus, it is of interest to examine the evolution of dead fuel moisture of larger fuels as illustrated by maps of 100-h (1–3-in. diameter) and 1,000-h (3–8-in. diameters) fuels available from the USDA Forest Service (Fig. 21). The 100-h fuels in the region of the fire dried considerably between May and July (from roughly 15% to 6%–10%) and, with little early autumn precipitation, moistened only slightly by 8 November. Such values of 100-h fuel moisture were near record or at record values for the previous 10–20 years (Brewer and Clements 2020). The 1,000-h fuels around Paradise evinced a more dramatic drying in late spring and early summer (from greater than 20% to 6%–10%) and only rebounded slightly by 8 November (to around 10%). Pike County Lookout (south of Jarbo Gap) also measured 1,000-h fuels at

Fig. 21. (top) 100- and (bottom) 1,000-h dead fuel moisture for 8 May–8 Nov 2018 available from the USDA Forest Service.

5% on 1 November 2018 with the normal value being 17%. Thus, larger dead fuels (such as scattered debris from previous logging) were also sufficiently dry to burn.

Operational warnings and forecasts

As shown above, the WRF Model forecasts initialized at 0000 UTC 8 November using the operational GFS forecast grids provided a skillful forecast of the strong winds and low-level conditions associated with the initiation and growth of the Camp Fire. Operational numerical forecasts produced by NOAA (e.g., GFS and NAM) were also highly skillful, predicting strong winds and low relative humidity over the region three days in advance, with the NOAA/NWS High-Resolution Rapid Refresh (HRRR) model providing highly accurate descriptions of wind magnitude and distribution up to 36 h before the event. To illustrate, Fig. 22 shows the 18-h forecasts of sustained winds and gusts from the HRRR model at 1800 UTC 8 November, when the fire was rapidly spreading into Paradise. Strong northeasterly winds, with sustained speeds of 15–25 kt and gusts of 35–50 kt, were predicted over the middle western slopes of the Sierra Nevada and encompassed both the fire initiation point (red plus sign) and Paradise (red triangle), with predicted conditions similar to those observed (e.g., Figs. 3 and 4).

Based on such operational models, the National Weather Service forecast office in Sacramento issued a red flag warning over the region 2 days prior to the event, warning of the potential for rapid spread of wildfires (Fig. 23). Furthermore, during the days preceding the fire, the Sacramento NWS office predicted strong northeasterly winds (44–61 kt) on Thursday over the Sierra Nevada slopes east of Chico. Thus, as with the previous year's Wine Country Fire (Mass and Ovens 2019), the meteorological conditions observed during the initiation and spread of the Camp Fire were accurately predicted by operational models, with skillful warnings of threatening conditions by the National Weather Service.

Based on these forecasts, PG&E provided warnings on 6 and 7 November of potential preemptive power outages over eight Northern California counties on 8 November.

Fig. 22. The 10-m (a) sustained winds and (b) wind gusts, both in kt, from the 18-h NOAA/NWS HRRR forecast valid at 1800 UTC 8 Nov 2018. The red plus sign shows the location of the Camp Fire initiation near Pulga, the red triangle indicates Paradise, and the terrain is shown. The plot was acquired from University of Utah HRRR archive provided by Brian Blaylock.

PG&E never went ahead with the outages, based on their evaluation that wind forecasts did not meet their criteria for such actions (relative humidity below 20%, sustained winds above 25 mph, and wind gusts in excess of approximately 45 mph).

Discussion and conclusions

The Camp Fire event of 8 November 2018 was associated with dry northeasterly winds that descended the western slopes of the Sierra Nevada of Northern California, and occurred after low-level cool air and associated high sea level pressure moved into the Pacific Northwest and subsequently into Nevada.

As a result, an offshore-directed pressure gradient developed over Northern California and the northern Sierra Nevada between high pressure over Nevada and a trough that developed over coastal California. The mesoscale wind pattern associated with this synoptic configuration possessed low-level northerly flow pushing southward into the northern Central Valley of California, while easterly/northeasterly flow descended the upper and middle slopes of the Sierra Nevada. Historically, such downslope flow on the western slopes of the central/northern Sierra Nevada was known as a North Wind

(e.g., Whiteman 2000), but more recently has frequently been called a Diablo wind, with its general characteristics described in a number of papers (Monteverdi 1973; Bowers 2018; Nauslar et al. 2018; Smith et al. 2018; Mass and Ovens 2019; McClung and Mass 2020). Such strong, dry downslope winds have been associated with many of the large wildfires of the region, including the Wine Country Fire of October 2017 (Mass and Ovens 2019).

Low-level easterly and northeasterly winds accelerated during the early morning hours of 8 November over the western slopes of the Sierra Nevada as cooler air moved into Nevada and the pressure gradient over the barrier increased; winds reached a maximum before sunrise and remained strong for several more hours (through roughly 2100 UTC, 1400 PST), during which time the Camp Fire was initiated and drove quickly toward Paradise. A combination of nighttime cooling along the slopes, the advection of low-level cool air from the east, and midtropospheric subsidence established a stable layer at and immediately above the Sierra Nevada crest, which coupled with strengthening winds approaching the barrier and the development of a critical level above the Sierra Nevada crest, resulted in amplified mountain wave activity and enhanced downslope flow. As frequently observed on the western side of the Sierra Nevada, the strong winds did not descend to the surface on the lower Sierra Nevada slopes or over the Central Valley. Since the northern Sierra Nevada crest extends to 2,500–3,000 m, with a gentle and extended western slope, it is difficult for downslope flow associated with mountain waves to reach lower elevations (Miller and Durran 1991). Similar

Fig. 23. Warnings and forecasts disseminated by the Sacramento National Weather Service office on 7 Nov 2018.

to other recent downslope wind events of the region, operational models produced highly skillful forecasts for both the synoptic evolution and mesoscale downslope winds along the western slopes of the Sierra Nevada.

The maximum wind gusts along the western Sierra Nevada slopes during the Camp Fire event varied substantially over short distances, ranging from 10–20 kt in sheltered locations to 50–60 kt for exposed sites on the middle to upper slopes. The highest winds were not exceptional, having been observed multiple times in the historical period without the outbreak of a major fire. Low-level temperatures were cooler than normal over the Sierra Nevada and to the east, near normal over the western slopes, and warmer than normal over the coastal zone of California. Drier-than-normal conditions prevailed in the days and weeks leading up to the fire.

The extraordinary economic and human losses of this downslope wind event can be traced to ignition caused by strong winds interacting with a failing electrical transmission infrastructure (a century-old high-tension tower owned by PG&E), the continuous path of highly flammable grass and shrubs between the ignition source and Paradise, and the vulnerability of the many homes in Paradise, where embers and firebrands blown by the wind enabled ignitions far in advance of the surface fire front (Keeley and Syphard 2019). A drier-than-normal summer and autumn left both light (1 and 10 h) and larger (100 and 1,000 h) dead fuel moisture content lower than normal, resulting in an environment susceptible to ignition by the failing PG&E electrical tower. The delay in the initiation of significant autumn rains during autumn 2018 was a contributory factor to the unusually dry conditions preceding the fire.

Most of the fire path had burned during the 2008 BTU Lightning Complex fire and had been subsequently logged, leaving mainly grasses and bushes, with scattered timber, both standing alive and on the ground. The prevalence of fine fuels and the critical fuel dryness of all fuels created an ideal environment for a rapidly spreading wind-driven wildfire. The strong, dry downslope winds preceding the Camp Fire would have ensured that the 1- and 10-h dry fuels that dominated the path would likely have been highly flammable irrespective of the longer-term meteorological anomalies in the preceding months, a conclusion also made by Keeley and Syphard (2019). Furthermore, delayed autumn precipitation contributed to unusually dry larger fuels. Another contributor to the catastrophic nature of the fire was the rapid expansion of Paradise during the previous decades, which not only put many more people at risk, but provided large amounts of fuel (e.g., wood homes, propane tanks) that supported fire growth and movement (Cal Fire 2019).

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