

1 **Numerical Analysis of Atmospheric Perturbations Induced by Large Wildfire**  
2 **Events**

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15 **Key Points:**

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- 17 • The plume-dominated fire was found to follow the diurnal cycle, while the wind-driven  
18 fire was much less variable.
  - 19 • Local winds in the plume-dominated fire had a much greater impact than those in the  
20 wind-driven fire, which had stronger non-local winds.
  - 21 • A plume-dominated fire may promote strong convection leading to more rainfall and  
22 decreased fire activity through increased fuel moisture.

23 **Abstract**

24 This study analyzes fire-induced winds from a wind-driven fire (Thomas Fire) and a plume-  
25 dominated fire (Creek Fire). Two numerical experiments, one without the fire present and the other  
26 with the fire, were used. The fire-induced perturbations were then estimated by subtracting a  
27 variable value in the “No Fire Run” from the “Fire Run” (Fire - No Fire). For this study, spatial  
28 and temporal variability of winds, geopotential height, and convergence were analyzed.  
29 Furthermore, cloud water mixing ratio, precipitation, and fuel moisture were analyzed during the  
30 Creek Fire to assess fire-induced rainfall and its impact on fuel moisture. It was found that the  
31 wind-driven Thomas Fire created more widespread and generally stronger fire-induced winds than  
32 the plume-dominated Creek Fire. In addition, fire-induced wind speeds during the Creek Fire  
33 followed a diurnal cycle, while the Thomas Fire showed much less temporal variability. When  
34 analyzing geopotential height, the results were very similar to other idealized simulations. A  
35 localized low-pressure region was observed in front of the fire front, with a preceding high-  
36 pressure area. When analyzing precipitation, it was found that the fire increased precipitation  
37 accumulation in the area surrounding the active fire. This created an increase in fuel moisture  
38 which could have helped locally decelerate the fire spread. Further research into the processes  
39 behind fire-atmosphere interactions will lead to a better understanding of fire behavior and the  
40 extent to which these interactions can impact the fire environment. These studies will help assess  
41 the limitations of uncoupled operational models and improve fire modeling overall.

42 **Plain Language Statement**

43 This study analyzes winds caused by fire from both the Thomas Fire and the Creek Fire. These  
44 fires were chosen because the Thomas Fire was driven by strong winds, while the Creek Fire  
45 generated a towering smoke plume which influenced its growth. In addition to wind speed,  
46 geopotential height at multiple levels was analyzed to understand how deep into the atmosphere  
47 the fire effects are visible. Furthermore, precipitation was analyzed for the Creek Fire to see if  
48 there was any effect on how moist the surface fuels around the fire were. It was found that the  
49 Thomas Fire created more widespread and generally stronger winds than the Creek Fire  
50 throughout the simulation duration. In addition, wind speeds during the Creek Fire followed a  
51 daily cycle of high and low speeds, while the Thomas Fire did not. Changes in geopotential  
52 height also were found in the upper atmosphere which shows the far-reaching effects of the fire.

53 When analyzing precipitation, we found that the fire increased precipitation amounts around the  
54 fire area. This increased the surface fuel moisture which likely helped slow the fire spread.

## 55 1 Introduction

56 Fires are known to enhance the winds in the vicinity of the fire front, which in turn drive  
57 fire propagation and impact overall fire behavior (Sun et al., 2009). To help understand this  
58 phenomenon, a number of previous studies have analyzed fire-wind enhancement. One of the first  
59 such studies was the field experiment conducted by Quintiere, (1989), in which a prescribed burn  
60 was carried out in forest debris in an extensively instrumented area. The results from this study  
61 found that fire-induced winds reached up to 12 m/s and indicated the possibility of fire-induced  
62 cloud formation as well as possible lightning. Filippi et al., (2009) then used the MesoNH-ForeFire,  
63 a mesoscale model coupled with a tracer-based fire model, in the first study to use a coupled  
64 simulation to estimate how much a wildfire's convection can alter surrounding atmospheric  
65 conditions. Based on the idealized simulations of three fires, they found that in the case of a fire  
66 with large line ignition, the acceleration of winds towards the plume base increased an order of  
67 magnitude compared to the ambient wind speed. They also found that the simulated fire-induced  
68 winds from the study matched with similar values from large-scale wildfire studies using standard  
69 plume theory (Filippi et al., 2009). This study was mainly conducted on relatively small-scale fires  
70 under conditions similar to that of a prescribed burn. Later, Eftekharian et al., (2019) used  
71 OpenFOAM, a computational fluid dynamics software, to model and investigate the effects of both  
72 a point ignition and a line ignition on a small, idealized fire simulated in a  $34 \times 9 \times 15$  m domain  
73 ( $X \times Y \times Z$ ). They found that longitudinal flow was greatly enhanced for the line ignition, while  
74 vertical flow was further enhanced by the point ignition. In a further study, Eftekharian et al., (2021)  
75 found that the greatest wind enhancement was co-located with elevated flame temperatures and  
76 occurred near the center lines of fire-induced vorticities.

77 Although many studies have indicated the importance of fire-induced winds in shaping the  
78 near-fire environment, none have quantified these effects in a case of a large wildfire. Also, the  
79 small scale of the numerical experiments conducted up to date precluded any analysis of the large-  
80 scale impacts of pyroconvection. For example, the vertical extent of the fire-induced perturbations,  
81 the impact on geopotential height, cloud development, precipitation, and resulting fuel moisture  
82 have not been studied in wildfire scenarios. In addition, none of the studies so far attempted to  
83 quantify both the temporal variability and the spatial extent of the fire-induced perturbations. Up  
84 to now, no numerical study has been conducted on the dynamical feedback loop involving fire-  
85 induced precipitation and its impact on fuel moisture and fire behavior. The only similar studies

86 used reanalysis datasets to understand fire-induced rainfall suppression mechanisms for convective  
87 rainfall in sub-Saharan Africa (Saha et al., 2017).

88 In the context of fire-atmosphere coupling, wildfires are often classified as wind-driven, or  
89 plume-dominated (Byram, 1959). It is generally assumed that in case of the wind-driven fires, the  
90 power of the wind dominates the buoyancy and the fire itself does not impact local weather  
91 conditions. The plume-dominated fires, on the other hand, are generally associated with the  
92 conditions when the fire-induced buoyancy significantly impacts local winds controlling fire  
93 behavior (Sullivan, 2007). The distinction between these two regimes can be determined by  
94 calculating the Clark Convective Froude Number ( $F_c$ ) or Byram's Convective Number ( $N_c$ ), see  
95 Morvan & Frangieh, (2018). If  $F_c^2 > 1$ , then the fire can be classified as wind-driven, and the near-  
96 fire flow does not significantly respond to the fire-induced buoyancy. If  $F_c^2 < 1$ , the fire can be  
97 classified as plume-dominated, as the flow responds strongly to the fire-induced heating and  
98 convection (Sullivan, 2007). If Byram's Convective Number is used, the critical value of 10 can  
99 be used as a threshold. In this case, if  $N_c > 10$  the fire is wind-driven, and if  $N_c < 2$ , the fire is  
100 plume-dominated (Morvan & Frangieh, 2018). For the purposes of this study,  $N_c$  was analyzed to  
101 confirm the fire regime.

102 The overarching goal of this study is to advance our understanding of the role of fire-  
103 atmosphere coupling processes in shaping the fire environment during large wildfires. To achieve  
104 this goal, the presented study investigates fire-atmosphere interactions, as well as quantifies the  
105 spatial and temporal effects of fire-induced perturbations in winds, geopotential height,  
106 precipitation, and fuel moisture, in two wildfires representing the wind-driven and plume-  
107 dominated regimes (Thomas Fire and Creek Fire, respectively).

## 108 **2 Methods**

109

$$110 \quad N_c = \frac{2gI}{\rho c_p \theta_a (u - ROS)^3} \quad \text{Equation 1}$$

111 To verify that the selected wildfires represent both the wind-driven and plume-dominated  
112 regime, an  $N_c$  analysis was performed.  $N_c$  was determined by Equation 1, in which  $g$  is the  
113 gravitational constant ( $9.8 \text{ m/s}^2$ ),  $I$  is the fireline intensity ( $\text{kW/m}$ ),  $\rho$  is air density ( $1.2 \text{ kg m}^{-3}$ ),  
114  $c_p$  is the specific heat of dry air ( $1.005 \text{ J kg}^{-1} \text{ K}^{-1}$ ),  $\theta_a$  is the absolute ambient air temperature (K),

115  $u$  is the mean wind speed (m/s), and  $ROS$  is the rate of spread of the fire (m/s). The average  $N_c$   
116 value over the studied period was 29.34 for the Thomas Fire (4 December 2017 18Z – 8 December  
117 2017 00Z) and 7.35 for the Creek Fire (5 September 2020 00Z – 15 September 2020 00Z). This  
118 confirmed the wind-driven character of the Thomas Fire, and the mixed character of the Creek  
119 Fire which transitioned from the wind-driven regime on the day of ignition, to the plume-  
120 dominated regime for the remainder of the studied period.

121 In order to analyze the fire-induced perturbations, first, historical fire progressions were  
122 reconstructed based on satellite observations and infrared perimeters. Fire detections from VIIRS  
123 and MODIS satellites along with the airborne infrared fire perimeters were used to reconstruct fire  
124 progression history using the Support Vector Machines (SVM) method proposed by Farguell et  
125 al., (2021). This method leverages the SVM to find a 3D surface defining the boundary between  
126 burnt and unburnt regions in the latitude/longitude/time space. Since the cross-sections of this  
127 surface at an arbitrary time represent fire extent, this method provides fire arrival maps by time  
128 step that enable reconstruction of fire spread over time.

129 In order to analyze the fire-induced perturbations, two different WRF-SFIRE runs were  
130 conducted, one with the fire present, and the other purely meteorological. WRF-SFIRE is a coupled  
131 fire-atmosphere model with a weather forecasting model coupled to a fire spread model (Mandel  
132 et al., 2011). These are called the Fire run and No Fire run, respectively. Both runs also utilized a  
133 fuel moisture model, containing 1, 10, and 100 hour moisture classes, to trace the fire impact on  
134 fuel characteristics. Subtracting these two runs (Fire - No Fire) allowed us to analyze the fire  
135 impacts on a given variable similarly as it was done to estimate the extents of fire effects in  
136 Kochanski et al., 2018. In the fire simulations, the fire progression was constrained using the fire  
137 histories derived using the SVM method mentioned above, in order to reduce the potential impacts  
138 of the inaccuracies in the fire spread representation. This approach mimics the widely used  
139 approach in meteorology where the reanalysis data is used to force the atmospheric model, but  
140 here the fire progression is used to force the fire spread model. The comparison between the Fire  
141 and No Fire runs enabled a detailed analysis of a wide range of fire-induced perturbations. For the  
142 purposes of this study, wind speed, geopotential height, and convergence were analyzed, along  
143 with cloud water mixing ratio, accumulated precipitation, and fuel moisture. Wind speed was  
144 studied in order to determine the temporal and spatial variability in fire-induced winds. Vertical  
145 cross-sections of winds and temperature were also studied to analyze the vertical extent of fire-

146 induced circulations. Additionally, geopotential height was examined to determine the vertical  
147 extent of the fire-induced pressure perturbation. Then, wind convergence was explored to provide  
148 reasoning for fire-induced behavior and spread. Finally, the cloud water mixing ratio, rain, and  
149 fuel moisture were investigated in order to investigate the fire-atmosphere coupling, including the  
150 impact of precipitation on fuel moisture.

151 To be able to analyze this coupling mechanism, a radar analysis was performed to assess  
152 whether days in which there were clouds ended up producing rainfall. Specifically, the Differential  
153 Reflectivity and Correlation Coefficient were utilized to isolate rain from other features present in  
154 the radar image. An elevation angle of  $1.82^\circ$  was used to eliminate most of the noise seen in the  
155 lower levels of the atmosphere and focus more on the mountainous regions. Differential  
156 Reflectivity and Correlation Coefficient were used to distinguish between rain and smoke (smoke  
157 has generally higher differential reflectivity and lower correlation coefficient than rain (Melnikov  
158 et al., 2009; Jones et al., 2009; Zrníc et al., 2020; Aydell & Clements, 2021).

## 159 2.1 Numerical Analysis of Fire-Induced Perturbations

### 160 2.1.1 Wind-Driven Fire

161 The Thomas Fire began in Ventura County on 4 December 2017 during the longest period  
162 of Santa Ana Wind conditions recorded over the past 70 years (Fovell & Gallagher, 2018). These  
163 winds fanned two independent ignitions into a giant conflagration which ultimately became the  
164 largest wildfire for that time in modern California history. Winds near the areas of ignition were  
165 gusting up to 35 m/s and quickly fanned the fires rapidly toward the ocean (Fovell & Gallagher,  
166 2018). By the time the fire was fully contained on 12 January 2018, the fire had scorched 281,893  
167 acres, destroyed 1060 structures, and burned through both Ventura and Santa Barbara Counties  
168 (CAL FIRE, n.d.).

169 The Thomas Fire was modeled using two nested domains (1.33 km and 444 m resolution),  
170 as shown in Figure 1, for three days and six hours. The simulation covered the period from 4  
171 December 2017 18Z until 8 December 2017 00Z. Table 1 shows the model configuration used for  
172 this simulation. The boundary and initial conditions were derived from the 3km High-Resolution  
173 Rapid Refresh (HRRR) product (Benjamin et al., 2016), using the WRFx forecasting system  
174 (Mandel et al., 2019).

175

176 Table 1

177 *Configuration of the Thomas Fire simulation*

<b>Domains</b>	<b>d01</b>	<b>d02</b>
<b>Dimensions</b>	118 x 82 x 41	211 x 118 x 41
<b>Fire Mesh</b>	N/A	2110 x 1180
<b>Horizontal Grid Spacing (Atmosphere)</b>	1333 m	444 m
<b>Horizontal Grid Spacing (Fire)</b>	N/A	44 m
<b>Time Step</b>	3 s	1 s
<b>Microphysics</b>	Thompson ARW NMM Option 8	Thompson ARW NMM Option 8
<b>PBL Physics</b>	ACM2 Option 7	ACM2 Option 7
<b>Surface Model</b>	ACM2 Option 7	ACM2 Option 7
<b>Cumulus Parameterization</b>	Kain-Fritsch Option 1	Kain-Fritsch Option 1
<b>Radiation</b>	RRTMG Option 4	RRTMG Option 4
<b>Meteorological Forcing</b>	HRRR	d01

178 2.1.2 Plume-Dominated Fire

179 The Creek Fire began in Fresno County on 4 September 2020, between the San Joaquin  
180 River and Shaver Lake (CAL FIRE, n.d.). Right after ignition, it was driven by powerful winds up  
181 the San Joaquin drainage, which caused it to explode in size and create a massive pyroCb cloud  
182 which continued to affect fire behavior (Jenner, 2020). Due to the effect of the massive plume, the  
183 Creek Fire was later able to spread quickly, despite weak diurnal winds in the fire region. It  
184 managed to become the largest wildfire in modern California history by 2020 standards after  
185 burning 379,895 acres in both Fresno and Madera Counties. The fire also destroyed 856 structures,  
186 damaged 71 structures, and caused 26 injuries. It was fully contained on 24 December 2020 (CAL  
187 FIRE, n.d.).

188 The Creek Fire was modeled using three nested domains (Figure 2). Table 2 shows the  
189 domain configuration used for this simulation. The simulation was conducted from 5 September

190 2020 00Z until 15 September 2020 00Z, for a period of 10 days. The resolution of the outer domain  
 191 (d01) was 5000m, the intermediate domain (d02) was 1666 m, and the fire domain (d03) was 555  
 192 m. The boundary and initial conditions were generated from the Climate Forecast System  
 193 Reanalysis (CFSR) data (Saha et al., 2010).

194

195 Table 2

196 *Configuration of the Creek Fire simulation.*

<b>Domains</b>	<b>d01</b>	<b>d02</b>	<b>d03</b>
<b>Dimensions</b>	196 x 196 x 41	196 x 196 x 41	196 x 196 x 41
<b>Fire Mesh</b>	N/A	N/A	3920 x 3920
<b>Horizontal Grid Spacing (Atmosphere)</b>	5000 m	1666 m	555 m
<b>Horizontal Grid Spacing (Fire)</b>	N/A	N/A	27 m
<b>Time Step</b>	30 s	7 s	2 s
<b>Microphysics</b>	Thompson ARW NMM Option 8	Thompson ARW NMM Option 8	Thompson ARW NMM Option 8
<b>PBL Physics</b>	MYNN2 Option 5	MYNN2 Option 5	MYNN2 Option 5
<b>Surface Model</b>	GFS Option 3	GFS Option 3	GFS Option 3
<b>Cumulus Parameterization</b>	Kain-Fritsch Option 1	0	0
<b>Radiation</b>	RRTMG Option 4	RRTMG Option 4	RRTMG Option 4
<b>Meteorological Forcing</b>	CFSR	d01	d02

197

### 198 3 Results

#### 199 3.1 Wind-Driven Fire

200 The Thomas Fire was primarily wind-driven and fanned by strong, gusty winds and burned  
201 in mountainous terrain. For this fire event, wind speed and geopotential height were analyzed to  
202 see how these factors were influenced over and in the vicinity of the fire. First, the spatial  
203 variability of 10 m winds was analyzed, then we investigated the vertical wind speed cross sections  
204 along two lines parallel and perpendicular to the main fire direction, and finally, the temporal  
205 variability in the wind perturbation was investigated.

### 206 3.1.1 Analysis of Surface Fire Winds During a Wind-Driven Fire

207 The fire-induced wind speed perturbation analyzed here is the difference between the wind  
208 speed from the Fire and No Fire Runs and will be referred to in the text as fire-induced wind or  
209 fire wind. According to Figure 3, intense fire winds occurred around the start of the fire on 5  
210 December, with values exceeding 10 m/s downwind of the fire front. The areas of fire-induced  
211 winds occurred directly downstream from the areas of active fire, which indicates that these areas  
212 occurred within or surrounding the smoke plume as it was advected by the strong Santa Ana Winds.  
213 It was also noticed that areas of strong positive fire-induced winds were usually surrounded by  
214 weaker negative fire-induced winds, which could be associated with the inflow zones to that region  
215 of the fire. The fire rate of spread in deceleration regions (blue) was significantly slower compared  
216 to acceleration regions highlighted in red.

217 While Figure 3 shows the maximum surface fire winds over the entire domain of the fire  
218 from a horizontal vantage point, Figure 4 provides vertical cross-sections through the fire in order  
219 to investigate the vertical structure of fire winds. Figure 3 demonstrates the locations of these  
220 cross-sections. The cross-section in Figure 4a was chosen as it follows the wind direction of the  
221 Santa Ana Winds, as well as the rapid initial expansion of the fire. It shows that the strongest fire-  
222 induced wind speeds align with the time when the fire passes through cross-section a) as seen in  
223 Figure 3, thus demonstrating that the wind perturbation is associated with the fire activity. In  
224 addition, the isotherms indicate the mountain wave pattern, which is very apparent over the higher  
225 mountains, as well as several hydraulic jumps (not pictured) at later time steps. When looking at  
226 the areas of strong fire-induced winds, there are areas of much stronger winds around the surface,  
227 and much weaker winds just above the surface. These two lobes are separated by an isotherm,  
228 which demonstrates that the presence of fire-induced winds shown in Figure 4a disrupts the  
229 mountain wave pattern. These factors all suggest that the fire aids in altering the vertical thermal  
230 gradient by pushing isotherms upward in the atmosphere near the fire front. This helps alter wind

231 speeds and patterns over the mountain range by disrupting the mountain wave and transferring  
232 upper-level momentum to the surface and leads to an increase in the surface winds at the expense  
233 of the winds aloft.

234         The vertical cross-section b), shown in Figure 4b, was chosen to demonstrate the fire-  
235 induced winds across the main fire propagation direction. This cross-section, perpendicular to the  
236 predominant wind direction, was studied to verify if the mountain wave perturbation also occurs  
237 across the fire. Unlike the streamwise cross-section presented in Figure 4a, the region of  
238 accelerated surface winds is much wider here but is still associated with the upper-level wind speed  
239 decrease. This indicates an energy transport from higher elevations to the surface in response to  
240 the fire-induced buoyancy, which extends across the fire area. Unlike the streamwise cross-section,  
241 the look at the wind structure perpendicular to the wind indicates the secondary lobe of strong fire-  
242 induced winds, which occurred away from the fire front. This remote acceleration zone, located  
243 right from the peak of the fire heat flux in Figure 4b, corresponds to the region of accelerated winds  
244 evident in the northwest direction from the fire front in Figure 3a.

### 245 3.1.2 Temporal Variability of Fire Winds

246         The time series of maximum magnitude of surface (10 m) fire winds is shown in Figure 5.  
247 This figure highlights that the period of strongest fire-induced winds (up to 15 m/s) occurred during  
248 the initial expansion of the fire when it was getting fanned by strong Santa Ana Winds. After this  
249 initial period (ending 12-05 18z), the fire winds decreased, but remained generally in the 4 – 8 m/s  
250 range, with few isolated spikes exceeding 9 m/s. There was no diurnal cycle present either in the  
251 winds or the fire activity because of consistent high fire intensity in response to low relative  
252 humidity and persistent Santa Ana Winds present throughout that period.

253

### 254 3.1.3 Statistics of local and non-local fire-induced wind perturbations

255 The boxplots are a good way to visualize how the range of the surface fire winds changes  
256 from day to day on both non-local and local scales. In this case, non-local refers to the fire winds  
257 over the entire domain (as in Figure 5), and local refers to fire winds surrounding areas of active  
258 fire or areas already burned. Figure 6a shows that on a daily basis, the average non-local fire winds  
259 vary significantly, with an average speed ranging up to 7 m/s on 5 December. There are also several  
260 outliers with fire-induced speeds up to 12 m/s on 7 December.

261 In terms of local fire winds around the burned areas (Figure S1), fire-induced winds  
262 averaged around near zero, but there were many outliers here as well, with fire-induced speeds as  
263 low as -0.5 m/s, and ranging up to 1.9 m/s. The same overall pattern was seen around areas of  
264 active fire (Figure 6b) but with more extreme speed outliers, particularly on 6 December and 7  
265 December. Of note is that on 7 December, there were outliers indicating -1.0 m/s and 0.9 m/s.  
266 These observations demonstrate that most of the stronger fire-induced winds are advected  
267 downstream of the main fire front and are non-local. Thus, local fire-induced winds tend to be  
268 much weaker, with occasional stronger gusts, as indicated by the outlier values.

### 269 3.1.4 Geopotential Height Analysis

270 In order to analyze the fire's influence on the atmospheric conditions around it,  
271 geopotential height perturbations were analyzed at three different levels: surface, 600mb, and  
272 500mb. These levels have been selected to investigate the spatial pattern of the pressure  
273 perturbation associated with the surface winds directly interacting with the fire, as well as the  
274 vertical extent of the fire-induced wind perturbations. Geopotential height was analyzed due to its  
275 relationship with temperature and the density of air. It is also particularly useful to analyze trends  
276 associated with surface pressure in the upper atmosphere, as it can inform about how much the  
277 height of a pressure level has changed due to the presence of fire. The fire-induced surface  
278 geopotential height perturbation, as well as the wind vector field for both the Fire (red) and No  
279 Fire (blue) runs, are shown in Figure 7. The surface level (745 hPa) was chosen as the level just  
280 above the highest elevation of the terrain within the domain. The wind field indicates the  
281 characteristic Northeast direction of the Santa Ana Winds pushing the fire very quickly to the  
282 Southwest during the initial rapid expansion to the coast on 5 December. During this time, there  
283 were relatively intense geopotential height perturbations of up to 5.20 m and -3.10 m. These

284 perturbations occurred directly downstream from where the fire was burning and tended to drift  
285 off downwind, advected by the ambient winds. This occurred due to the buoyancy of the smoke  
286 plume, as the smoke was carried into the upper atmosphere, and the air density decreased. At the  
287 same time, the Santa Ana Winds pushed the plume downstream, resulting in a tilt and increased  
288 perturbations, as well as increased fire-induced winds downwind from the firefront. Faster fire rate  
289 of spread (associated with higher intensity) tended to produce stronger geopotential height  
290 perturbations, and these perturbations influenced the direction and strength of the wind field as  
291 they were carried off with the smoke plume. In some cases, the perturbations helped steer the fire  
292 to the West and push it downwind. In addition, areas of lower geopotential height tended to occur  
293 right in front of the firefront, with areas of higher geopotential height preceding the lower  
294 geopotential height.

295         The time series of geopotential perturbations directly around the fire were analyzed in order  
296 to quantify the local impact of the fire on the surrounding atmosphere and to analyze its time  
297 evolution. The perturbations were calculated by subtracting the values of the No Fire run from the  
298 values of the Fire run (Fire – No Fire). The maximum difference from each time step was then  
299 plotted. This enabled the analysis of how changes in the fire activity alter the geopotential height  
300 over time. The analysis was done first by looking at the geopotential height within the entire burned  
301 area, but these differences (not shown) came out to be minor, indicating that most significant  
302 perturbations were associated with regions of the active fire front itself not within the whole fire  
303 perimeter. This is more easily observed by looking at Figure 8, which shows the perturbation time  
304 series for each level analyzed around areas of actively burning fire. When the fire first started  
305 rapidly expanding on 5 December, the perturbations were mainly positive, with differences up to  
306 2.2 meters for the surface level (Figure 8a). As the fire started to grow larger, the perturbations  
307 increased, with perturbations of up to 4.7 m. After this point, the perturbations decreased, with  
308 occasional intense spikes on each day, with the most intense ones occurring on 7 December, with  
309 a value of 5.2 m. Each set of the spikes, particularly on 5 December, occurred at the same time as  
310 the spikes in fire-induced winds shown in Figure 5, demonstrating the linkage between fire winds  
311 and surface geopotential height perturbations.

312         The patterns in the two upper levels of the atmosphere were similar as well, except with  
313 much smaller variation in perturbations. In Figure 8c, at the 500 hPa level, perturbation variation  
314 increased up to 2.3 meters, which demonstrates that the effects of the fire extend into the upper

315 atmosphere. This spike also matched with the peak in fire-induced wind speeds on 5 December,  
316 likely indicating the development of pyrocumulus clouds which reached the upper levels of the  
317 atmosphere during this time. Minimal variability occurred after 5 December at the 600 hPa layer  
318 (Figure 8b), indicating that the strongest perturbations were occurring downwind from the fire  
319 itself. However, at the 500 hPa layer (Figure 8c), small spikes occurred intermittently throughout  
320 the day. These spikes occurred at the same time as those from the 600 hPa layer (Figure 8b) but  
321 with slightly lower magnitudes on 5 December and slightly higher magnitudes at later times. This  
322 suggests that fire-induced perturbations expand vertically as more smoke reaches the upper levels  
323 of the atmosphere at later times during the Thomas Fire.

324 When analyzing the minimum perturbations for each level (Figure S2), patterns were seen  
325 to be similar, but negative, indicating the presence of both positive and negative perturbations  
326 along the firefront. The only exception to this pattern was at the 500 hPa level where a major spike  
327 of -4.8 meters occurred on 5 December. This aligns with the major spike in the maximum  
328 perturbation as well, which could suggest the presence of strong updrafts and downdrafts in the  
329 upper levels, which could create erratic fire behavior at the surface.

### 330 3.1.5 Spatial Analysis of Wind Convergence

331 To complement the fire wind speed and geopotential analysis, we also analyzed wind  
332 convergence, a phenomenon in which winds are pulled toward a given area, usually an area of low  
333 pressure. As seen in Figure 9, convergence occurs mainly in front of the fire front, with divergence  
334 preceding the convergence zone. The zoomed-in image of Figure 9 shows the streamlines  
335 converging ahead of the fire front, which produced the convergence zone, or area of low pressure,  
336 there. This behavior does not occur with the No Fire run (see the blue vectors in Figure 7), which  
337 indicates the local flow modification due to the fire. This is consistent with the findings of Clark  
338 et al., (1996), indicating a convective column forming above a low-pressure center in front of the  
339 fire front which alters local wind speed and direction.

### 340 3.2 Plume-Dominated Fire

341 The Creek Fire is an important fire to analyze as it was mainly plume-dominated. This  
342 means that there were overall weak winds, and the fire was primarily driven by conditions induced,  
343 or enhanced by, the pyroconvective column above it, or by other forces such as terrain and fuels.  
344 The Creek Fire started amidst some gusty up-canyon winds during its initial explosive expansion,

345 but after the first day, it continued to expand at rapid rates without the presence of strong  
346 atmospheric forcing. For the Creek Fire, the variables of wind speed (Figure 10 – Figure 12),  
347 geopotential height (Figure 13 – Figure 14), and convergence (Figure 15) were analyzed. Due to  
348 significant pyroactivity, water vapor mixing ratio (not shown), precipitation (Figure 17), and fuel  
349 moisture (Figure 18) were also examined. Spatial variability of wind speed and geopotential height  
350 were first investigated, followed by a temporal analysis. The rest of the variables were analyzed in  
351 the context of spatial patterns.

### 352 3.2.1 Analysis of Surface Fire Winds During a Plume-Dominated Fire

353 After the initial explosion of the fire on 5 September, when the fire-induced winds were  
354 both strong and widespread, the character of fire-induced wind perturbation changed. They became  
355 more localized and consistent with the diurnal pattern corresponding to large periods of growth  
356 during the day and reduced activity at night. Figure 10a shows the initial explosive growth of the  
357 fire. After this point, there was a lot of fire growth under conditions very similar to the No Fire run  
358 (no significant fire-induced winds), except for localized areas of stronger winds outside of the fire  
359 perimeter. As seen in Figure 10a, an area of weaker fire-induced winds (inflow zone) appears  
360 ahead of the fire front and is accompanied by large areas of much stronger fire-induced winds.  
361 This same pattern occurs throughout the period studied, with areas of inflow almost always  
362 accompanying times of high fire-induced winds. This behavior is consistent with findings from  
363 idealized simulations by Clark et al., (1996), indicating a low-pressure area ahead of the fire front  
364 drawing winds in from all directions. This leads to enhanced winds along the fire front and  
365 decreased winds throughout the inflow zone. However, after the Creek Fire's initial wind-driven  
366 expansion, areas of fire-induced winds became very localized and did not extend downwind, as  
367 seen in Figure 10b. This indicates a significant change in the character of the fire winds from  
368 remote mostly downwind from the fire to more local associated directly with the fire activity.

### 369 3.2.2 Temporal Variability of Fire Winds During a Plume-Dominated Fire

370 The most notable aspect of the time evolution of the fire-induced winds presented in Figure  
371 11 is the consistent diurnal pattern. This is unlike the Thomas Fire, which initially experienced  
372 very strong fire winds, which decreased significantly after the first day. The Creek Fire, for the  
373 most part (except on 12 September), saw fire-induced winds following the diel trend. On each day,  
374 wind speeds peaked at approximately 1:00 AM local time (08:00 UTC) and saw a sharp decrease

375 at around 7:00 PM local time (02:00 UTC). This shows that the fire-induced winds peak during  
376 the early morning hours and last throughout the day, and subsequently decrease during the evening  
377 and late-night hours. This can be because winds in the early morning are generally very calm, but  
378 with the presence of the fire creating its own wind, there is a much larger difference between Fire  
379 and No Fire wind speeds. On 12 September, the whole day experiences relatively calm fire-  
380 induced winds, which can be attributed to increased cloud cover and rainfall associated with fire-  
381 induced precipitation. With reduced solar heating and convective activity, the winds became  
382 calmer.

### 383 3.2.3 Statistics of local and non-local fire-induced wind perturbations During a Plume- 384 Dominated Fire

385 The boxplots shown in Figure 12 help to visualize the Creek Fire's non-local and local fire-  
386 induced wind speeds over each day. Figure 12a shows that over the whole domain, the average  
387 maximum wind speed is consistent at around 7 m/s on each day. This is different than during the  
388 wind-driven fire which experienced more day-to-day variability. The greatest variability occurred  
389 on 12 September, when fire winds ranged from 11.5 m/s to 0.8 m/s. The days with the least range  
390 between the first and fourth quartiles are 5 September and 6 September, which were the days with  
391 a major wind event that caused the initial blow-up of the fire. Unlike during the wind-driven  
392 Thomas Fire, here no outlier wind speeds were observed. This is significant because it indicates  
393 that in the plume-dominated fire, the fire winds were less random and more closely related to the  
394 fire activity, thus supporting the notion that plume-dominated fires can create their own local  
395 weather conditions.

396 Figure 12b investigates the winds only over areas of active fire progression (where fire-  
397 released heat flux is positive). For each day, the average maximum fire-induced wind speed is  
398 slightly positive at around 0.2 m/s. It indicates that the fire generally accelerates winds near the  
399 fire front. Additionally, each day has lots of positive fire-induced wind outliers, indicating regions  
400 of strong fire-induced winds. The analysis of the local and non-local fire effects during the plume-  
401 dominated regime reveals that it has a unique character when compared to the wind-driven fire.  
402 Here, the non-local effects are weaker than during the wind-driven fire, however, the local fire  
403 effects are much stronger (up to 9 m/s compared to 0.75 m/s). The strong local fire effects show  
404 that the plume-dominated fire creates stronger near-fire winds than the wind-driven fire. This  
405 effect means that despite the weaker remote fire winds compared to the wind-driven case, strong

406 local fire-induced winds in a plume-dominated fire can be a much more significant driving force  
407 of fire spread than during a wind-driven fire.

### 408 3.3 Geopotential Height Analysis During a Plume-Dominated Fire

409 According to the conducted analysis, the geopotential height perturbations for the Creek Fire  
410 were the strongest and most widespread at the surface level (629 hPa). Other perturbations,  
411 particularly those seen in Figure 13, could be due to outside forces such as thunderstorms. In  
412 addition, all figures demonstrate that the strongest perturbations around the fire perimeter were  
413 associated with increased fire activity. During these times, the surface perturbations were generally  
414 over 0.7 m. When the fire became more plume-dominated, the geopotential height perturbations  
415 became much smaller and much more localized. Perturbations stretched out from the fire in the  
416 direction of the predominant wind. Therefore, it can be deduced that these perturbations were  
417 associated with the advection of the positively buoyant plume. Similar to the Thomas Fire, the  
418 perturbations for the Creek Fire also caused a change in wind speed and direction as they  
419 propagated away from the fire.

420 Aside from the spatial variability, the time evolution of the geopotential perturbation at  
421 various heights was investigated as well. The analysis of the time series presented in Figure 14  
422 reveals many interesting phenomena that occurred with these perturbations over the active fire.  
423 The same analysis was performed for minimum perturbations (figure not shown), and many of the  
424 same patterns were found for each level. At the surface level (Figure 14a), a spike was noted on 9  
425 September with a perturbation of 48 m at the surface (spike extending beyond the plot) and 4.8 m  
426 at 600 hPa (Figure 14b). This spike did not reach the upper atmosphere in any large way, which  
427 suggests potentially intense fire behavior at the surface. Some similar spikes of up to 6.5 m on 6  
428 September and 7 September also occurred. The same spikes were noticed at both the 600 hPa and  
429 500 hPa levels as well. At the 600 hPa level (Figure 14b), these spikes were very similar at around  
430 4.9 and 7.0 m, respectively. Similar perturbations occurred at the 500 hPa level (Figure 14c), but  
431 to a much greater extent, around 17.7 meters. These major perturbations signify the presence of  
432 pyrocumulonimbus clouds hitting the upper levels of the atmosphere over the fire area. Mostly  
433 small perturbations occurred throughout the remaining period studied, alluding to the plume-  
434 dominated nature of this event. Since much larger perturbations were seen outside of the fire  
435 perimeter in Figure 13, a detailed analysis was carried out to determine whether these outside  
436 perturbations were due to rain-causing thunderstorms or other factors.

### 437 3.4 Spatial Analysis of Convergence

438 Many of the similar findings are present when analyzing the wind convergence field during  
439 the Thomas and Creek Fires. The streamlines still converge ahead of the firefront, creating a  
440 convergence zone in Figure 15. However, here, it is clearer that convergence tends to occur in  
441 valleys, while divergence occurs along ridges and mountain tops. This could be another  
442 explanation as to how the Creek Fire spread so fast despite the lack of strong winds present.  
443 Naturally forming convergence zones likely played a large part in the fire's spread as well.

### 444 3.5 Analysis of Fire Effects on Cloud Activity and Precipitation

445 Since the Creek Fire was associated with significant cloud activity, here we investigate fire-  
446 induced impacts on cloud formation. The goal is to determine whether the geopotential height  
447 perturbations over and nearby the Creek Fire were associated with thunderstorms/cloud  
448 development. Additionally, we investigate if the fire-induced cloud activity resulted in  
449 precipitation that could increase the fuel moisture.

450 The first step in determining whether geopotential perturbations were associated with  
451 thunderstorms was to see if any clouds were simulated over the area. To do this, the cloud water  
452 mixing ratio was examined. Over the full ten days of the simulation, clouds formed on September  
453 5, 6, 7, 8, and 11. To validate if these results were realistic, and if any precipitation was present,  
454 historical radar data was analyzed (see Figure 16).

455 When analyzing Reflectivity, there are many areas of energy present, with blue  
456 representing light disturbances and green/yellow representing heavier disturbances. However, it is  
457 necessary to determine which of these disturbances are actually rain and which are due to other  
458 factors, such as the smoke plume. When looking at Correlation Coefficient, areas of rain can be  
459 seen in areas of yellow to red (0.8 – 1). In Figure 16b, an area of rain puts a dent in the eastern  
460 flank of the fire and seems to slow down its eastward progression. Figure 16a also shows the  
461 Reflectivity plot at the same time to indicate the importance of using polarimetric radar variables  
462 to distinguish between the smoke plume, clouds, and rain (Ansari et al., 2008).

463 The estimates of rainfall from the radar analysis were then compared to the precipitation  
464 from the WRF-SFIRE model and the observations match up very well. Over the entire period  
465 studied, there was ~10 mm of precipitation from the Fire run, as seen in Figure 17a. To better  
466 understand how much of this precipitation was caused by the fire itself, fire-induced precipitation

467 was quantified. As presented in Figure 17b, ~4.2 mm of the total precipitation can be attributed to  
 468 the presence of the fire. This shows that during plume-dominated fires, aside from the positive fire  
 469 feedback through the fire winds, there may be negative feedback where fire promotes stronger  
 470 convection and cloud formation that leads to increased precipitation which can potentially decrease  
 471 fire activity by increasing the fuel moisture.

472 In order to determine how much of an impact the rainfall had on the surrounding fuels, the  
 473 overall dead fuel moisture was plotted in Figure 18. As seen there, these fuels change a lot,  
 474 especially in places where it has rained. When comparing fuel moisture values in Figure 18 to the  
 475 precipitation regions in Figure 17, it is apparent that fuel moisture values are between 21-27% in  
 476 areas where it rained, and between 5-17% elsewhere. To determine how this impacted the fire  
 477 itself, the potential rate of spread values over these regions from the Fire and No Fire runs were  
 478 investigated. Values presented in Table 3, indicate that this rainfall, and the subsequent increase  
 479 in fuel moisture, had the potential to slow down the spread of the fire by about 10% in regions  
 480 affected by precipitation. These values for the rate of spread analysis were calculated by looking  
 481 at the variable for fire rate of spread (ROS) within WRF-SFIRE, choosing the days in which it  
 482 rained the most along the fire perimeter, and then choosing the spots along the fire perimeter which  
 483 received the most rainfall.

484 Table 3

485 *The rate of Spread comparison between the Fire and No Fire runs on two dates that had the most*  
 486 *rainfall.*

Date: 11 September 2020		Date: 12 September 2020	
Fire ROS	0.1725 m/s	Fire ROS	0.2476 m/s
No Fire ROS	0.195 m/s	No Fire ROS	0.2661 m/s
Percent Difference	13.04%	Percent Difference	7.47%

487

#### 488 **4 Summary and Conclusions**

489 The purpose of this study was to analyze large-scale changes to surrounding atmospheric  
 490 variables due to large wildfires in order to quantify the effect that a wildfire has on the conditions  
 491 surrounding it. This is especially important for improving wildfire modeling, as well as providing

492 better situational awareness to firefighters involved in fire suppression. Two different types of  
493 wildfires were analyzed, a wind-driven fire (Thomas Fire) and a plume-dominated fire (Creek Fire).

494 It was found that during the Thomas Fire, which was fanned by strong Santa Ana Winds,  
495 winds were up to 15 m/s faster in the simulation domain than they would have been if no fire were  
496 present. These maximum fire-induced winds also occurred when the prevailing Santa Ana Winds  
497 were strongest and most steady. Due to the presence of these strong winds, there was no diurnal  
498 cycle present. The fire-induced winds had a non-local character and extended up to 15-20 km  
499 downwind from the active fire. This could be particularly important in the context of fires  
500 exhibiting significant spotting. The fire embers landing in the regions of strong fire winds could  
501 result in spot fires propagating much faster than expected based on the ambient wind conditions.

502 During the plume-dominated Creek Fire, fire-induced winds experienced strong diurnal  
503 fluctuations and generally peaked in the early morning hours (around 08:00 UTC) and lasted  
504 throughout the day (around 02:00 UTC). Also unlike in the wind-driven case, here the fire winds  
505 were locally induced by the plume and the fire didn't cause widespread areas of strong wind  
506 acceleration as seen during the wind-driven Thomas Fire. Fire-induced winds were boosted by up  
507 to 12 m/s in localized areas. This is less than during the wind-driven Thomas Fire, however, the  
508 very local character of these winds could result in unexpected erratic fire behavior. The main  
509 differences between the two regimes are that wind-driven fires show little diurnal variability in the  
510 wind patterns and the strongest fire-induced winds occur downwind from the fire front, whereas  
511 plume-dominated fires follow a diurnal wind pattern and have very localized regions of fire-  
512 induced winds over the active fire regions.

513 In terms of geopotential height perturbations, it was found that in both fires, areas of  
514 positive and negative perturbations emanated out from the fire front following the primary wind  
515 direction and the buoyant column advected by the wind. For the Thomas Fire, these perturbations  
516 increased with atmospheric height, whereas they tended to decrease with height over the Creek  
517 Fire, except in very localized areas, which were found to be due to convective rain-producing  
518 clouds. Wind speed and direction around areas of perturbations were usually found to be drastically  
519 altered, which could have changed the fire behavior and spread to be more erratic. In addition,  
520 areas of lower geopotential height were found in front of the fire line, with higher geopotential  
521 heights preceding the lower height areas. This is consistent with the findings from Clark et al.,

522 (1996) on parabolic fire spread and convective columns, which produced an area of convergence  
523 ahead of the fire front, thus increasing the fire-induced winds.

524         Aside from highlighting the complexities in the character of the fire winds in wind-driven  
525 and plume-dominated fires, this study also affirmed that while fire can create winds that can  
526 quicken its spread and cause extreme fire behavior, it can also induce weather conditions reducing  
527 its activity. The analysis of fire-induced precipitation and its effect on the fuel moisture indicated  
528 that fire-induced precipitation could have helped slow fire growth by up to 13% in areas where it  
529 rained. This could have increased the effectiveness of fire suppression operations primarily on the  
530 eastern and northern flanks where the most rain occurred.

## 531 **5 Limitations and Future Work**

532         While these simulations provided a new way to analyze fire-induced circulations, much  
533 more work still needs to be conducted to fully understand these processes. For instance, these  
534 simulations were conducted with relatively low spatial resolution. For that reason, the estimates of  
535 the magnitude of fire-induced winds presented here are rather conservative. In reality, at small  
536 scales, these perturbations may be stronger. In addition, fuel load and fire intensity may have been  
537 underestimated due to instances of tree mortality and overall vegetation health that were not  
538 accounted for in this study. Having better knowledge and data on the vegetation in the modeled  
539 area would be needed to investigate and address these issues. Overall, conducting simulations in a  
540 higher spatial resolution could be beneficial to further understanding of these fire-induced  
541 circulations. However, it is important to note that the resolution used for the current study  
542 corresponds to the resolution used in operational fire forecasting with WRF-SFIRE and WRFx  
543 (Mandel et. al 2019). Therefore, this study shows to what degree fire-induced winds can be  
544 captured in coupled fire-atmosphere forecasts. In addition, extending the presented methodology  
545 to a larger number of fires, as well as direct measurements of the wind field near active wildfires,  
546 would help to further expand this study.

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560

561 **Open Research**

562 The WRF-SFIRE model used for the Fire and No Fire simulations in the study is available at  
563 GitHub via <https://github.com/openwfm/WRF-SFIRE> with public access (WRF-SFIRE, 2022). In  
564 addition, the data used for the radar analysis was found via NOAA’s Weather Climate Toolkit,  
565 which can be downloaded for public use at <https://www.ncdc.noaa.gov/wct/> (WCT, n.d.). The  
566 codes and data analysis used for this study can be found at [https://github.com/wirc-sjsu/Fire-](https://github.com/wirc-sjsu/Fire-Induced-Circulations)  
567 [Induced-Circulations](https://github.com/wirc-sjsu/Fire-Induced-Circulations) (wirc-sjsu, 2023).

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## 662 **Figure Captions**

663 *Figure 1: Setup of 2 domains for the Thomas Fire with fire ignition points shown.*

664 *Figure 2: Setup of 3 domains for the Creek Fire with fire ignition point shown.*

665 *Figure 3: Fire-induced 10 m wind speed over Domain 2 of the Thomas Fire on 5 December 2017 12:30:00 UTC. The black lines a)*  
666 *and b) correspond to the location of vertical cross sections shown in Figure 4a and Figure 4b.*

667  
668 *Figure 4: Vertical cross section a) over the Thomas Fire showing fire-induced winds and temperature on 5 December 2017*  
669 *12:30:00 UTC is shown on the left. Vertical cross section b) over the Thomas Fire showing fire-induced winds and temperature on*  
670 *5 December 2017 12:15:00 UTC is shown on the right. The location of the fire front is denoted by the peaks in the Ground Heat*  
671 *Flux time series.*

672  
673 *Figure 5: Maximum fire-induced wind speed in the Thomas Fire domain.*

674 *Figure 6: Boxplot a) shows the distribution of maximum fire-induced winds in the whole computational domain over each day. Boxplot b)*  
675 *shows the distribution of maximum fire-induced winds over each day around areas of active fire. The minimum and maximum*  
676 *values for the given day (excluding outliers) are represented by the lowest and highest lines, respectively. The box*  
677 *represents the 2<sup>nd</sup> and 3<sup>rd</sup> quartiles of the data, with the middle line representing the median of the data. Any outliers are*  
678 *represented by circles above or below the minimum and maximum value lines.*

679 *Figure 7: Fire-induced surface geopotential height perturbations and wind field over Domain 1 of the Thomas Fire on 5 December*  
680 *2017 13:00:00 UTC. Blue arrows indicate wind vectors from the No Fire run and red arrows indicate wind vectors from the Fire*  
681 *Run.*

682 *Figure 8: Fire-induced surface geopotential height perturbations for the a) surface, b) 600 hPa, and c) 500 hPa pressure levels,*  
683 *over the regions of positive fire heat flux.*

684  
685 *Figure 9: 10-meter Horizontal Convergence around the Thomas Fire as seen on 5 December 2017 12:30:00 UTC.*

686 *Figure 10: a) Fire-induced wind speeds over Domain 3 of the Creek Fire on 5 September 2020 23:00:00 UTC and b) fire-induced*  
687 *wind speeds over Domain 3 of the Creek Fire on September 6 23:30:00 UTC.*

688 *Figure 11: Maximum fire-induced wind speed over Domain 3 of the Creek Fire.*

689 *Figure 12: Boxplot a) shows the distribution of maximum fire-induced winds in the whole domain over each day. Boxplot b)*  
690 *shows the distribution of maximum fire-induced winds over each day around areas of active fire. The minimum and maximum*  
691 *values for the given day (excluding outliers) are represented by the lowest and highest lines, respectively. The box represents*  
692 *the 2<sup>nd</sup> and 3<sup>rd</sup> quartiles of the data, with the middle line representing the median of the data. Any outliers are represented by*  
693 *circles above or below the minimum and maximum value lines.*

694  
695 *Figure 13: Fire-induced 500 hPa geopotential height perturbations and wind field over Domain 2 of the Creek Fire on 5*  
696 *September 2020 23:30:00 UTC. Blue arrows indicate wind vectors from the No Fire run and red arrows indicate wind vectors*  
697 *from the Fire Run.*

698 *Figure 14: Maximum fire-induced surface geopotential height perturbations for a) surface, b) 600 hPa, and c) 500 hPa pressure*  
699 *levels over the regions of positive fire heat flux. The maximum spike on panel c) is outside of the plot scale and reaches 17.7 m.*

700  
701 *Figure 15: 10-meter Horizontal Convergence of the Creek Fire on 5 September 2020 22:45:00 UTC.*

702 *Figure 16: Radar analysis for the Creek Fire on 8 September 2020 UTC where a) is Reflectivity and b) is Correlation Coefficient*

703 *Figure 17: a) Accumulated Precipitation for the Fire run of the Creek Fire over the full ten-day period. b) Fire-Induced Accumulated*  
704 *Precipitation for the Creek Fire for the full ten-day period.*

705 *Figure 18: Overall dead fuel moisture content for vegetation of the Creek Fire on 12 September 2020 12:00:00 UTC.*