The September 2020 Wildfires over the Pacific Northwest

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ABSTRACT: A series of major fires spread across eastern Washington and western Oregon starting on 7 September 2020, driven by strong easterly and northeasterly winds gusting to ~70 kt (1 kt = 0.51 m s⁻¹) at exposed locations. This event was associated with a high-amplitude upper-level ridge over the eastern Pacific and a mobile trough that moved southward on its eastern flank. The synoptic environment during the event was highly unusual, with the easterly 925-hPa wind speeds at Salem, Oregon, being unprecedented for the August–September period. The September 2020 wildfires produced dense smoke that initially moved westward over the Willamette Valley and eventually covered the region. As a result, air quality rapidly degraded to hazardous levels, representing the worst air quality period of recent decades. High-resolution numerical simulations using the WRF Model indicated the importance of a high-amplitude mountain wave in producing strong easterly winds over western Oregon. The dead fuel moisture levels over eastern Washington before the fires were typical for that time of the year. Along the western slopes of the Oregon Cascades, where the fuels largely comprise a dense conifer forest with understory vegetation, fire weather indices were lower (moister) than normal during the early part of the summer, but transitioned to above-normal (drier) values during August, with a spike to record values in early September coincident with the strong easterly winds. Forecast guidance was highly accurate for both the Washington and Oregon wildfire events. Analyses of climatological data and fuel indices did not suggest that unusual preexisting climatic conditions were major drivers of the September 2020 wildfires.

SIGNIFICANCE STATEMENT: This paper describes the meteorological conditions associated with major wildfires in eastern Washington and western Oregon during September 2020. It was found that unusual, extreme winds from the north and east played a critical role in initiating and supporting the fires.

KEYWORDS: Wildfires; Mesoscale processes; Mesoscale systems; Mesoscale forecasting; Mesoscale models

1. Introduction

On 7–8 September 2020, strong northerly/northeasterly winds, gusting to 40–70 kt (1 kt = 0.51 m s⁻¹) in exposed locations, pushed southward across eastern Washington and then westward across the Oregon Cascades, initiating and spreading multiple large fires in both states (Fig. 1). In eastern Washington, the wildfires were mainly limited to grass and range vegetation within the Columbia basin, with total burned area reaching 529 000 acres. Less than 10% of the total burned area was timber (45 000 acres).¹ Most of the loss in Washington State involved three fires (Cold Springs, Whitney, and Pearl Hill) covering 190 000, 127 000, and 224 000 acres, respectively. A smaller grass/range fire, the Babb-Malden/Manning Fire (18 000 acres), destroyed much of the town of Malden, located 29 miles (46 km) south of Spokane, Washington. Strong winds, in concert with dry rangeland vegetation, resulted in the rapid, explosive spread of the eastern Washington fires, with the Cold Springs/Pearl Hill Complex Fire spreading approximately 60 mi (97 km) in 20 h. The Washington State fires consumed at least 371 structures and were associated with one death, with the impacts mitigated by the sparse population of the predominantly grass and range environment. Prior to the 7–8 September event, the 2020 wildfire season in Washington had been characterized by below-normal burned acreage due to above-normal precipitation earlier in the summer.

In Oregon, the wind-driven September 2020 fires were larger and more impactful. Virtually all the major fires in Oregon were in timber, with approximately one million acres burned. Two of the major fires, Beachie Creek and Lionshead, were initiated by lightning on 16 August 2020. The Beachie Creek Fire was of minimal size (approximately 200 acres) prior to the September wind event and rapidly grew to 194 000 acres as winds increased, while the initially larger Lionshead Fire, which started on the arid eastern slopes of the Cascades, extended to 16 000 acres before the wind event and subsequently grew to 150 000 acres within a week, eventually growing to 204 000 acres. In Oregon, the September 2020 wildfires were associated with 9 deaths, with at least 4500 structures lost. The southern Oregon towns of Phoenix and Talent were destroyed by the wildfires.

Large fires (greater than 1000 acres) on the western slopes of the Oregon Cascades have been relatively uncommon during contemporary times (Oregon Forest Research Institute 2014...
with most western Oregon fires occurring in the mountains of southwest Oregon or within the coastal range. Since 1900, major fires over western Oregon have included the Yacolt Fire (1902), encompassing 500 000 acres on both sides of the Columbia River around Portland, the Bandon Fire (1936) that burned 287 000 acres in the south Oregon coastal range, the four Tillamook burns (1933, 1939, 1945 and 1951) that covered a total of 350 000 acres in the north Oregon coastal range, the Silver Complex Fire (1987) that burned 97 000 acres in the Siskiyou/Klamath mountains of southwest Oregon, the Biscuit Fire (2002) that covered approximately 500 000 acres and included the perimeter of the Silver Complex fire, the Chetco Bar Fire (2017) that consumed 191 000 acres within the boundaries of the Biscuit Fire, and the Eagle Creek Fire (2018) that burned 50 000 acres along the south side of the Columbia Gorge (Dague 1930, 1934; Zyback 2003).

Paleo evidence from fire scars and charcoal deposits suggests that stand-replacing fires typically occur every 200–300 years over any particular location of western Oregon (e.g., Marlon et al. 2012). An examination of newspaper accounts, available meteorological data, and accounts in meteorological journals (e.g., Dague 1930, 1934) indicate that large western Oregon fires were associated with strong easterly or northeasterly flow that contributes to both fire initiation and rapid growth. Such easterly flow is also characterized by very low relative humidity that contributes to both the drying of surface fuels and fire growth. As described below, strong easterly flow was also observed during the September 2020 fires.

This paper describes the meteorology of the September 2020 wildfires over Washington and Oregon. Several questions are addressed in this paper:

1) What were the synoptic and mesoscale evolutions associated with the period of fire initiation and rapid spread?
2) How unusual were the synoptic situation and the resulting lower-tropospheric conditions?
3) How unusual were the antecedent surface meteorological conditions and fuel moisture prior to the wildfire event?
4) How accurate were the forecasts of the meteorological conditions associated with this event?

2) How unusual were the synoptic situation and the resulting lower-tropospheric conditions?

The general synoptic evolution associated with the September 2020 event included a high-amplitude upper-level ridge along the West Coast and a mobile trough moving southeastward on the ridge’s eastern flanks (Fig. 2). Immediately before fire initiation in eastern Washington, the 500-hPa map at 1200 UTC 7 September shows an extensive east Pacific ridge stretching northward into southeast Alaska and a trough moving southward into British Columbia. Twelve hours later, this trough had sharpened and pushed southward into Montana, with large height gradients and strong northerly winds over eastern Washington. By 1200 UTC 8 September, the upper-level trough had amplified further and extended into Utah and a day later had become a closed low over the U.S. Four Corners region. The resulting omega-like pattern was persistent and remained in place through 11 September, when the configuration broke down as an approaching upper trough (not shown) resulted in the rapid weakening of the easterly flow and the onset of onshore flow at the coast.

The synoptic evolution at the surface and the lower atmosphere is shown in Fig. 3. Cool air and associated high pressure moved southward over the continental divide between 1800 UTC 7 September and 0000 UTC 8 September, first bringing strong winds to eastern Washington and then eastern Oregon. With an extension of the high pressure to the east of the Cascade crest, a large pressure gradient and strong easterly flow developed over and to the west of the barrier by 1200 UTC 8 September. Strong to moderate easterly flow was maintained to the west of the Cascade crest over the next two days, accompanied by low-level warming. The pressure gradient weakened by 0000 UTC 11 September with a subsequent switch to onshore flow on 12 September, bringing in cooler air from off the Pacific Ocean into western Oregon and Washington (not shown).

1 Figures 3a and 3b are 6- and 12-h forecasts from a 1200 UTC 7 September initialization, while Figs. 3c–ef are 12-h forecasts from initializations at 0000 UTC 8 September, 0000 UTC 9 September, 1200 UTC 9 September, and 1200 UTC 10 September, respectively. The time 0000 UTC is 1700 local time (PDT).
An important issue is the relative frequency of the synoptic conditions that drove the September 2020 wildfire event. Figure 4 shows the normalized anomalies calculated using 0.5° Climate Forecast System Reanalysis (CFSR) analyses from 1979 to 2009 (Bentley et al. 2019). These normalized anomalies were based on first calculating anomalies from CFSR climatology (31 years of data) at each point and time, and dividing the anomalies by the standard deviation of the 31 values. First examining 925-hPa heights, 925-hPa winds, and 925-hPa wind speed normalized anomalies, one notes that the northeasterly wind speeds over eastern Washington at 1800 UTC 7 September were over six standard deviations from the mean. Twelve hours later, the 925-hPa easterly winds over western Oregon were five to six standard deviations from the mean, suggesting an extraordinarily unusual event. Sea level pressure anomalies centered over the Rockies at the height of the event (1200 UTC 8 September) were four to five standard deviations from the mean. Twelve hours later, the 925-hPa easterly winds over western Oregon were five to six standard deviations from the mean, suggesting an extraordinarily unusual event. Sea level pressure anomalies centered over the Rockies at the height of the event (1200 UTC 8 September) were four to five standard deviations from the mean. Twelve hours later, the 925-hPa easterly winds over western Oregon were five to six standard deviations from the mean, suggesting an extraordinarily unusual event. Sea level pressure anomalies centered over the Rockies at the height of the event (1200 UTC 8 September) were four to five standard deviations from the mean. Twelve hours later, the 925-hPa easterly winds over western Oregon were five to six standard deviations from the mean, suggesting an extraordinarily unusual event. 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3. Evolution of surface parameters

The maximum surface (10 m) wind gusts (kt) observed on 7–8 September 2020, the period of strongest winds, are shown in Fig. 5. The maximum winds across the domain possess great variability, with the strongest gusts, some reaching 60–70 kt, found over the Columbia basin, the Columbia Gorge, and the Oregon coast. Over the western slopes of the Oregon Cascades, where many of the large wildfires occurred, the effects of differing exposure were evident with maximum winds varying from 10 to 20 kt in sheltered locations to as high as ~60 kt. Extreme wind speeds over Oregon during the event included 92 kt at Timberline Ski Area (elevation: 2347 m, 7700 ft), where there was a 12-h period with peak gusts exceeding 78 kt, and 85 kt at Hoodoo Ski Area (1737 m, 5700 ft), 80 kt at Mt. Hebo (963 m, 3160 ft) in the Coast Range, 57 kt at the Horse Creek USDA Remote Automatic Weather Station (RAWS) (1036 m, 3400 ft) southeast of Portland, and 54 kt at Lincoln City on the Oregon coast.

The evolution of the wind gusts during the first day of the event is shown in Fig. 6. At 1800 UTC 7 September, strong northerly winds...
winds, gusting to 40–60 kt, surged into the Columbia River basin, contributing to the major grass/rangeland fires. Six hours later (0000 UTC 8 September), winds had relaxed over northeast Washington, while northeasterly flow increased rapidly over the northern Oregon Cascades and eastern Oregon. By 0600 UTC 8 September, the winds east of the Cascade crest had weakened, while strong easterly winds, gusting to ~60 kt, were observed along the Oregon coast and at some locations along the western slopes of the Cascades and in the Columbia Gorge. This wind pattern was still observed six hours later (1200 UTC 8 September).

Since the surface observing network is inadequate for describing the complex spatial distribution and temporal wind variability associated with the complex topography of the region, it is useful to examine the wind distribution from high-resolution simulations. Figure 7 shows the surface (10 m) wind gusts simulated by a WRF Model simulation.
run at 1.3-km grid spacing, that was initialized at 0000 UTC 7 September 2020. As discussed in the appendix, this simulation provided a highly realistic mesoscale simulation of the event.

The physics configuration of the WRF simulations is provided in the appendix.

At 1800 UTC 7 September, strong northeasterly winds, with gusts to 40 kt, extended over much of the Columbia River basin, forced by a large north-south pressure gradient. Six hours later (0000 UTC 8 September), strong northeasterly winds had pushed into eastern Oregon, including the northern Oregon Cascades. With cool air and associated high pressure extending over eastern Oregon, an intense pressure gradient developed near the Cascade crest resulting in easterly winds.
By 1200 UTC 8 September, the focus of the strong winds had moved to western Oregon, with downslope flow reaching 60 kt immediately west of the Cascade crest and near and immediately downwind of the crests of isolated terrain features. Strong easterly flow was also found over the Oregon coastal range, while winds were more modest over the lower-elevation Willamette Valley.

To illustrate the evolution of surface conditions during this event, observations at two representative USDA RAWS sites, one in eastern Washington and the other along the western slopes of the central Oregon Cascades, are shown in Fig. 8 for 5–9 September. At the Columbia NWR RAWS site (elevation: 261 m), located just south of Moses Lake in the central Columbia River basin, the wind accelerated rapidly to over 35 kt (18 m s$^{-1}$) during the morning of 7 September and weakened rapidly around 0100 UTC 8 September [1800 Pacific daylight time (PDT)]. Temperatures on 5 and 6 September were warm, reaching 34° and 36°C, respectively, but cooled to approximately 24°C on 7 September under the influence of cool, northeasterly flow. Relative humidity possessed a strong diurnal variation throughout the period, declining to less than 20% during the afternoons of 6–9 September. The 10-h dead fuel moisture was below 10% for nearly the entire period and dropped to less than 6%, without nighttime recovery, under the influence of the dry easterly flow. Low (under 15%) 10-h dead fuel moistures were in place for most of the summer (Fig. 16).

At the Sugarloaf RAWS site (1082 m), located in the Cascade foothills 50 km southeast of Eugene, Oregon, the winds accelerated during the evening of 7 September; at this
location, strong winds (gusting to ~17 m s$^{-1}$, 33 kt) continued for nearly two days. Temperatures were warm on 6–7 September, reaching 32°–33°C, but cooled to a high of 26°C with the strong easterly flow; cold advection overcame adiabatic warming during descent. Although relative humidity increased to as high as ~60% during the days prior to the wind event, it declined below 10% (and as low as 5%) for several days after the easterly flow was established. Finally, 10-h dead fuel moisture was generally low before the event (less than 10%), being at the tail end of the dry summer, but declined to less than 5%, with no nighttime recovery, after the easterly flow became established.

One of the most exceptional aspects of the September 2020 wildfire event was the extremely low relative humidity, dropping into the single digits at several locations, often for several days. To illustrate, Fig. 9 presents the daily minimum relative humidity on 7–10 September 2020. On 7 September, relative humidity declined into the low teens over the Columbia basin and central Puget Sound as dry northerly/northeasterly flow descended into lower elevations of the basin. A day later (8 September), relative humidities in the teens covered much of the Northwest, with single digits over the western slopes of the Cascades and across southeast Oregon. Several locations dropped to 5% or below. Extraordinary low relative humidity continued over Oregon on 9 September, with many sites in the single digits, while some recovery (into the teens) occurred across eastern Washington as the northerlies weakened. On 10 September, relative humidity increased along the Pacific coast with the advent of shallow onshore flow but remained in the single digits and teens throughout the interior. Moister air reached the Willamette Valley of western Oregon on 11 September, with relative humidity increasing to 25%–50% over most of the region west of the Cascade crest (not shown).

At several locations, the observed relative humidity experienced during this event was the lowest on record for August and September. For example, relative humidity at the Trout Creek RAWS site in the central Oregon Cascades dropped to a record 7% (period of record is 1986–2000), while at many western Cascade sites the observed relative humidity was in the driest 0.1% for August and September. To illustrate, the Field RAWS site, 70 km southeast of Eugene, Oregon, on the western Cascade slopes, had relative humidity drop to 5%, with that value or less only occurring 0.056% of the time in August or September.

4. Smoke and air quality

The September 2020 wildfire event produced an extended period of dense smoke and poor air quality over the Pacific Northwest; in many areas smoke remained for over a week. Figure 10 shows visible imagery from the NASA MODIS Aqua satellite for several days during the event at approximately 1330 local standard time (PST). On 7 September, southward-directed smoke plumes from predominantly grass/range fires were evident over eastern Washington, forced by strong northerly winds. In addition, there was east-bound smoke from the pre-existing wildfires over the Oregon Cascades (Beachie and Lionshead Creek fires) that had been initiated by lightning in mid-August. One day later, the situation had changed.
dramatically, with dense smoke plumes directed due west from multiple fires over the western slopes of the Oregon Cascades (plus a single fire over the southwest Washington Cascades). Smoke from the eastern Washington fires, while still evident, was in decline. By 10 September, the smoke from the western Oregon fires had combined into a single dense smoke veil west of the Cascade crest from northern California to southwestern Washington, while smoke over eastern Washington was barely evident as the grass/range fires had rapidly declined. On 12 September, as the easterly winds weakened and southerly flow developed along the coast, smoke extended over the entire region, including Puget Sound and eastern Washington, and remained in place with only modest decline through 17 September. During the subsequent 3 days, a combination of lessening fire intensity and a shift to onshore flow resulted in little visual evidence of smoke on 20 September.

As a result of the September 2020 wildfires, surface air quality over the region declined to unhealthy levels for over a week, with many locations experiencing very unhealthy to hazardous conditions as quantified by the U.S. Air Quality Index. Figure 11 shows the regional air quality levels from the U.S. EPA AIRNOW website based on concentrations of PM 2.5. On 6 September, prior to the wildfire event, air quality was good (green) over most of the region, with the main exception (yellow, moderate air quality) downwind (east) of the lightning-initiated fires burning over the central Oregon Cascades. Two days later and after the wildfires had exploded over the western slopes of the Oregon Cascades (8 September), unhealthy air quality covered the Willamette Valley and spread across portions of eastern Washington near the remnants of the grass/brush fires of the previous day. On 10 September, air quality had declined to hazardous over the Willamette Valley and unhealthy across southwest Washington and the northeastern slopes of the Cascades. The situation worsened by 12 September, when air quality was either unhealthy or hazardous for the entire region, a situation that continued with slight improvement through 16 September, particularly along the coast. Increasing onshore flow of relatively clean air began on 18 September, with air quality first restored at coastal locations and subsequently improving to near-normal levels for most of Oregon and Washington by 20 September. Only in the vicinity of the fires in western Oregon did moderate air quality conditions remain after that date.

A review of the air quality data before, during, and after the September 2020 wildfire event found that the associated smoke exposed more Washington cities to hazardous air quality for a longer period than any other event since the early 2000s.7

5. Lower-tropospheric soundings: Event evolution and historical context

To gain insight into the evolution of the September 2020 wildfire event, sounding data from radiosondes launched at Spokane, Washington, and Salem, Oregon, were examined. At Spokane, located in the northeast corner of Washington State, the lower troposphere just prior to the event (0000 UTC 7 September) was dry, with moderate southwesterly flow from

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the surface to 700 hPa (Fig. 12). Twelve hours later, the winds had shifted to northerly, with sustained speeds reaching 35 kt and were accompanied by lower-tropospheric cooling of \(-10^\circ C\). At 0000 UTC 8 September, while the eastern Washington fires were still burning, winds remained strong but veered into the northeast, bringing drier and cooler air to the sounding site and a well-mixed lower troposphere. By 1200 UTC 8 September, winds had turned easterly aloft and weakened at the surface, with the formation of a surface-based inversion.

At Salem, located in the northern Willamette Valley and downstream of many of the largest fires of the western Oregon Cascades, the 1200 UTC 7 September sounding indicated light northerly winds aloft, except near the surface where the flow was weak easterly or calm. By 0000 UTC 8 September, northeasterly winds reaching 25 kt were evident from 950 to 800 hPa. Twelve hours later, around the time of maximum fire growth (1200 UTC 8 September), the lower-tropospheric winds strengthened and veered to the east. At 0000 UTC 9 September, a profound drying of the lower troposphere was evident, with dewpoint depressions exceeding 30°C between 750 hPa and the surface, with easterly flow exceeding 20 kt through the near-surface layer. During the subsequent 36 h, the winds weakened and a surface-based stable layer developed (not shown).

To examine the historical context and relative frequency of the low-level winds during the September 2020 event, frequency diagrams of 925 hPa (roughly 800 m ASL) wind speeds and relative humidity versus direction for the entire period of record are shown for the radiosonde sites at Spokane, Salem, and Medford (Oregon), with Salem located in the northern Willamette Valley and Medford within the terrain of southwest Oregon (Fig. 13). Since regional fires are typically limited to late summer and early fall, only the statistics for August and September are examined.

The Spokane 925-hPa winds, representative of conditions just above the surface (726 m ASL), were northerly to east-northeasterly during the initial period (1200 UTC 7 September–1200 UTC 8 September 2020), with the wind speeds among the largest on record for those wind directions. Salem was immediately downstream of many of the largest September 2020 fires, and the 925-hPa pressure level (780 m, 2500 ft) is at an elevation similar to the major fires on the western slopes of the Cascades. The easterly wind at Salem at 1200 UTC 8 September, near the time of rapid expansion of the Oregon fires, was an extreme outlier: never in the 64-yr record has any easterly wind during August or September come close to the 32-kt wind observed that morning. Furthermore, the easterly to northeasterly winds at adjacent hours (e.g., 0000 UTC 8 and 9 September) were some of the strongest on record for those directions. The 1000-hPa wind at 1200 UTC 8 September

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8 The sounding data for Salem and Spokane were available every 12 h (0000 and 1200 UTC) from 1956 to 2020, while the Medford record began in 1948.
was also the strongest on record from an easterly direction (not shown). At Medford, the strongest winds were delayed by ~12 h compared to Salem and were from the southeast. Only four observations possessed stronger easterly winds during the historical record.

The frequency diagrams of 925-hPa relative humidity for the three radiosonde sites during August/September are also shown in Fig. 13 (right panels). At Spokane, the relative humidity during the event was low but not record-breaking, with values declining to ~20% during the initial fire period (6–7 September) and again on 9 September. In contrast, at Salem, 925-hPa relative humidity dropped to 10%–15% on 9–10 September, with some of the lowest relative humidities for easterly winds on record for August and September. The relative humidity was even lower at Medford at 925 hPa, with some observations breaking or nearly breaking record low values when winds were easterly. In summary, radiosonde reports of record to near-record easterly to northeasterly wind speeds combined with record to near-record low humidity documented an environment with unusual potential for fire initiation and rapid spread.

6. Model simulations of lower-tropospheric evolution

Although the overall synoptic forcing of the strong winds was similar for both eastern Washington and western Oregon (cool, high pressure to their north and east), the mesoscale winds that contributed to the September 2020 Northwest wildfires evolved differently in each region. Over eastern Washington, winds were more spatially uniform, arrived earlier, and were shorter in duration compared to western Oregon, where mountain-wave dynamics played an important role in focusing the strongest winds over the middle to upper slopes of the western side of the Cascades.

Figure 14 presents wind speed and potential temperature in a southwest–northeast-oriented vertical cross section extending from the central Columbia basin, across Spokane, and into the foothills of the Rocky Mountains, making use of the UW WRF simulation (1.33-km grid spacing) initialized at 0000 UTC 7 September 2020. The location of the cross section is shown in Fig. 14 (red line), with terrain in the cross section sloping upward steadily to the northeast. Just prior to the event (0300 UTC 7 September), winds were weak in the cross section, while by 1200 UTC winds had accelerated along the slope, reaching sustained speeds of 30–40 kt. This acceleration continued until approximately the time of peak winds (1800 UTC 7 September), with some winds above the surface reaching 40–50 kt. Over the next 6 h (through 0000 UTC 8 September), the winds rapidly declined to 20–30 kt. By 1800 UTC 8 September, surface winds had fallen below 10 kt along the terrain, with modest winds (15–25 kt) found only over the Columbia basin. The winds in this cross section compare well with the sounding at Spokane (Fig. 12), including the magnitude and elevated nature of the strongest winds as well as the well-mixed lower atmosphere at 0000 UTC 8 September.

The lower-tropospheric cross section directed east–west across central and western Oregon presents a very different evolution and structure than for eastern Washington, with the strongest winds associated with high-amplitude mountain waves (Fig. 15). At 1200 UTC 7 September, immediately before the event, near-surface winds were light, but by 0000 UTC 8 September,
accelerating easterly winds of 30–40 kt had begun to extend from
the plateau of eastern Oregon across the Cascade crest. Six hours
later (0600 UTC 8 September) there was rapid development of
high-amplitude mountain wave structures, with the strongest
winds (up to 70 kt) over and immediately downstream of the
crests of the Cascade and coastal mountains. As observed, strong
model winds did not descend to the lower elevations of the
Willamette Valley. Winds associated with the mountain wave
continued to accelerate to 75–80 kt on the Cascade slopes,
peaking around 1500 UTC 8 September and declining steadily to
35–45 kt by 0000 UTC 9 September. Weak easterly flow and
highly attenuated Cascade mountain waves were evident 24 h
later (0000 UTC 10 September).

7. Preceding fuel and climatic conditions
The surface fuels of the eastern Washington and western
Oregon September 2020 fires were very different, with the
former dominated by grass and range vegetation, while the latter was mainly timber, with dense understory vegetation. Both regions experienced a summer that was initially wetter than normal but turned drier than normal starting in late July. As a result of the varying fuels, the effects of the summer weather/climate conditions produced different rates of drying of surface fuels between the two regions. In the discussion below, the National Fire Danger Rating System (NFDRS) is used to quantify drying and fire danger in various types of surface fuel (National Wildfire Coordinating Group 2002).

a. Eastern Washington wildfires

Eastern Washington grass/range vegetation is mainly characterized by 1–10-h dead fuels, with the grasses typically cured...
(dried) by midsummer as a result of the region’s typical warm/dry summers. Eastern Washington is extensively covered by wheat fields and prairies, which are dominated by highly flammable cheatgrass (*Bromus tectorum*) and other nonnative plant species. Such light fuels are receptive to fire for much of the summer and even if wetted by a transient precipitation event (generally a convective system), these fuels can become dry enough to burn after only a few hours, with wind accelerating the process.

To illustrate the situation during the summer of 2020, Fig. 16 presents the 10-h dead fuel moisture at the Columbia NWR USDA RAWS site within the central Columbia basin from mid-May through the September wildfire event. Two wet periods in May and June pushed the 10-h dead fuel moisture to approximately 25% before quickly declining below 10%. From late June to the September 2020 fire period, the 10-h dead fuel moisture was between 5% and 10%, a range suitable for grass/range fire assuming ignition and supporting wind (private communication, Dr. Brian Potter, USDA Forest Service).

Figure 16 also presents live fuel moisture levels of sagebrush at the Washington State Fishtrap site, located in the Columbia basin scablands near the town of Sprague. The live fuel moisture declined rapidly from approximately 250% in early June to roughly 100% in late July, followed by a decline to approximately 60% in late August. Live-fuel moisture below ~80% is associated with moderate or higher fire danger (Weise et al. 1998). The dead fuel moisture evolution at the Columbia NWR site was similar to that observed at other RAWS sites within the Columbia basin. Furthermore, the live fuel moisture evolution observed at Fishtrap was also noted at nearby sites.

The summer drying of live and dead fuels noted above is typical for the region and was apparent during prior years. To gain climatological perspective into the 10-h dead fuel moisture immediately before the September wildfire event in eastern Washington, Fig. 17 shows the distribution of hourly 10-h dead-fuel moisture observations over 1–7 September both for 2020 and the entire period of record (1999–2020) at the Columbia NWR RAWS site. For the 21-yr period encompassing that week, the most frequent values of dead fuel moisture were from 5% to 10%, with a long tail of low
FIG. 14. Vertical cross sections of wind speed (kt) and potential temperature (K) with the location shown by the red line in the bottom-right panel. Wind direction vectors within the cross section are also displayed.
Fig. 15. Vertical cross sections across Oregon of wind speed (kt) and potential temperature (K) along the blue line shown in the bottom-right panel of Fig. 14. Wind vectors within the cross section are also displayed.
frequencies of higher moisture values (from isolated convective rain events). The distribution during 1–7 September 2020 had its peak at the same values as climatology (6%–8%), suggesting that 10-h dead fuel moistures observed in 2020 were not unusual or extreme. For that week, other RAWS sites in the Columbia basin also possessed low values of 10-h dead fuel moisture that were similar to climatology.

The threat of grass/range fires over eastern Washington increased greatly over the summer, a situation illustrated by a plot of the NFDRS78 burning index (BI) over the Northwest Interagency Coordination Center Predictive Service Area (PSA) Northwest 10 (encompassing the lower elevations of eastern Washington) from 1 June to 1 October 2020 (Fig. 18). The BI, which combines a spread component dependent on wind speed and an energy release component (ERC) related to the available potential energy resident in the fuels, is highly correlated with the spread of grass/range fires. The BI for NFDRS Fuel Model C was used as the most representative of PSA Northwest area 10 since model C is weighted toward 1- and 10-h dead grassy fuels predominant in the PSA. During June, the BI was normal or below normal as a result of several precipitation events. A return to typical dry conditions in July resulted in near-normal BI for much of that month. In August, a lack of precipitation increased BI to above normal, with several days approaching or attaining daily record levels. The most extreme value of BI (70) was reached on 7 September, driven by strong, dry northeasterly winds, and was the 11th highest value out of 5704 recorded during 30 fire seasons. Since the underlying fuels of each fire were described in the Northwest Wildfire Coordinating Group online Inciweb reports.

b. Oregon wildfires

The large wildfires on the western side of the Oregon Cascades occurred in conifer stands with an understory of smaller vegetation and downed woody material. To document the potential for wildfire growth over western Oregon during the summer of 2020, Fig. 20 presents the BI and ERC for NWCC Predictive Service Areas 3/4 (western slopes of central/south Oregon Cascades) using an appropriate environment fuel model (NFDRS78 Fuel Model G); also shown is the climatology of these parameters for 1 June–1 October. As noted earlier, ERC is a measure of the energy potential of the available fuels, considering fuel amount and dryness, while BI combines this potential with wind speed to determine the potential of rapid fire growth. ERC was below normal through mid-July due to a relatively wet spring and early summer. Drier than normal conditions in late July and August pushed the ERC to above normal levels for several periods in August, but within one standard deviation of the climatological mean. The situation became far more extreme during the first week of September as an upper-level ridge developed over the region, resulting in warm, dry conditions that rapidly pushed ERC upward. Finally, the strong easterly winds associated with the immediate event caused ERC to surge to record levels on 8–13 September, equaling or exceeding the previous daily extreme values in the 30-yr history. The BI followed a similar pattern: below normal during the first half of the summer, transitioning to above normal in August. The BI, with a wind-based spread component, had a much briefer but more extreme spike on 7 and 8 September than ERC, not only exceeding the climatological extreme for that date but representing the greatest value ever observed at that site. Extreme wind was more of a factor than underlying fuel dryness on those two days.

For the NOAA Oregon Climate Division 4 (northern Oregon Cascades) over the period 1920–2020, July–August temperatures were 0.55°C (1°F) above normal, the 24th warmest of the 101 years, while the 0.32 in. (8.1 mm) over those two months were 8th driest for the 101 years [mean of 1.97 in. (50 mm)]. As in eastern Washington, there has been modest (≈1°C) warming

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10. The fuels of each fire were described in the Northwest Wildfire Coordinating Group online Inciweb reports.
during the past 25 years. Considering most extreme dry summer (July/August) months, with less than 50% of normal precipitation, there was a declining trend in frequency in occurrence from the 1920s through the 1990s, a major spike between 2000 and 2010, followed by a return to just below the century-long average value (3.2) during the present decade (Fig. 19).

8. Predictability of the winds and wildfire conditions

An important aspect of this event was the highly skillful model guidance during preceding days, leading to timely warnings by the National Weather Service and state/local agencies. Similar to the UW WRF Model forecasts described previously, both global (e.g., NOAA GFS/ECMWF) and regional (e.g., UW WRF and NOAA HRRR) models provided highly skillful wind forecasts during the preceding days. Even three days prior to the event, the UW WRF Model, initialized at 0000 UTC 5 September and used by air quality and fire management agencies throughout the region, skillfully predicted strong winds first over eastern Washington and subsequent stronger flow over western Oregon (not shown).

A new wildfire forecast diagnostic developed by the USDA Forest Service called hot-dry-windy (HDW; Strock et al. 2018; McDonald et al. 2018) was available during this event both on a dedicated website11 and the UW WRF website. HDW is the product of the highest wind speed in the lowest 500 m of the atmosphere, multiplied by the highest water vapor pressure deficit (adjusting the air to surface temperature) in that layer. Values above approximately 200 hPa m s$^{-1}$ have been associated with historical fires over the western United States (Strock et al. 2018; McDonald et al. 2018). The short-term (15 h) HDW forecast verifying at the initiation time of the western Oregon fires (0300 UTC 8 September) indicated a major threat, with maximum values reaching 800 hPa m s$^{-1}$ (Fig. 21). The 75-h forecast initialized Friday afternoon (0000 UTC 5 September) was qualitatively similar and quantitatively ominous, with HDW values reaching 600 hPa m s$^{-1}$. Based on this and other forecast guidance, the National Weather Service’s Storm Prediction Center on the previous day explicitly warned of an extreme wildfire threat (Fig. 22), and a similar forecast was made the evening before. Local agencies tasked with wildfire management, such as Washington State’s Department of Natural Resources (DNR) put out strong warnings of potential major wildfires starting on Labor Day (7 September). Such excellent forecasts contributed to minimizing loss of life for these severe events and led to a limited pre-emptive de-energizing of powerlines near Mount Hood, Oregon, by Portland Gas and Electric. Furthermore, the three-dimensional smoke distributions produced by the NOAA High-Resolution Rapid Refresh (HRRR)-Smoke modeling system were generally highly skillful.

A deficiency of some model forecasts was evident during the days after the easterly winds had subsided when weak onshore flow led to the development of low-level fog over the lowlands of Puget Sound and the Willamette Valley. Specifically, the fog was more persistent than predicted by most major regional modeling systems, suggesting unrealistic simulation of the microphysical impacts of the smoke particles (e.g., providing large numbers of cloud condensation nuclei) or problems in simulating the smoke’s radiative effects (Conrick et al. 2021).

9. Discussion and conclusions

A series of historic, major fires spread across eastern Washington and western Oregon starting 7 September 2020, driven by strong easterly and northeasterly winds gusting to 40–70 kt at exposed locations over the eastern Washington lowlands and western Oregon terrain. Over eastern Washington, the wildfires were mainly limited to grass and range vegetation within the Columbia basin, with a total burned area of 529000 acres, while in western Oregon approximately one million acres burned, mainly in timber and understory. Ten deaths (one in Washington and nine in Oregon) were associated with the wildfires, with 371 and 4500 structures destroyed in Washington and Oregon, respectively.

11 https://www.hdwindex.org/.
The September 2020 wildfire event was associated with a high-amplitude upper-level ridge over the eastern Pacific and a mobile trough that moved southward on its eastern flank. This configuration brought cool air and associated high pressure across Alberta, Idaho, and Montana and troughing along the U.S. West Coast, resulting in an intense pressure gradient at low levels that produced strong northwesterly and easterly flow. Easterly winds bring dry air into western Oregon and Washington, in contrast to the relatively cool, moist onshore flow that dominates for most of the summer. Comparisons to an extended reanalysis climatology suggest that the low-level synoptic configuration over the region was highly unusual, if not unprecedented, in the historical record.

The September 2020 wildfire event occurred in several stages. First, during the morning and afternoon of 7 September, northerly/northeasterly winds of up to 70 kt spread across eastern Washington and resulted in several grass/range fires. Later in the day, with high pressure building over eastern Oregon and troughing over the coastal zone, strong easterly winds, gusting to 60–70 kt in exposed locations, descended the western slopes of the Cascades, initiating new fires and greatly enhancing lightning-initiated fires that had started in mid-August. Near-surface relative humidity plummeted to less than 10% over large portions of western Oregon as dry continental air subsided as it moved westward. Strong easterly winds continued into 8 September and subsequently slowly weakened. In the final stage of the event, many of the fires continued under weak easterly flow, with the development of persistent fog, enhanced by smoke, at lower elevations.

The wildfires that were initiated and rapidly grew over western Oregon on 7–8 September produced dense smoke that initially moved westward over the Willamette Valley but...
eventually was advected north and east, covering the entire Pacific Northwest. As a result, air quality degraded to unhealthy and hazardous levels over much of the region, representing the worst air quality period of recent decades at many locations.

An examination of the historical record of winds at Northwest radiosonde sites revealed the unusual nature of the strong northeasterly flow during the September event. For example, the 925-hPa wind speeds at Salem, Oregon were unprecedented for an easterly direction during the August–September period. High-resolution numerical simulations using the WRF Model suggested the importance of high-amplitude mountain waves in producing strong easterly winds over and to the west of the crest of the Oregon Cascades.

An analysis of surface fuel moisture showed that the predominantly light fuels of eastern Washington dried rapidly during early summer, with 1–10-h dead fuel moistures declining below 10% after late June. The dead fuel moisture levels immediately prior to the fires were typical for that time of the year and were supportive of wildfire development, needing only an ignition source and wind to promote rapid fire spread. The BI over eastern Washington documented a shift from

![Energy release component (ERC) and burning index (BI) averaged over NWCC Region NW03 and 04 domain, which encompasses the western slopes of the central and southern Oregon Cascades. Values during the summer of 2020 and climatological means and extremes are also shown. The gray shaded area indicates range within one standard deviation of the long-term means for that date.](image-url)
near-normal conditions from May to mid-July to above-normal BI in August, with a spike to daily record values under the strong northeasterly winds associated with the September 2020 event.

The fuel-moisture situation along the western slopes of the Oregon Cascades, where the fuels included a conifer forest with a dense understory, evinced a lower than normal energy release component (ERC) and burning index (BI) during the early part of the summer, but with a transition to above-normal values in August. A spike to record BI values, forced by strong, dry easterly winds, occurred in early September 2020 and represented a grave wildfire threat.

Forecast guidance for this event was highly accurate, with operational forecast models skillfully predicting both the winds and profound drying of the lower atmosphere several days in advance. As a result, official forecasts predicted and
communicated the potential for a severe wildfire event days in advance.

An important question is to what degree did anthropogenic global warming contribute to the extreme Northwest wildfires of September 2020. For the eastern Washington wildfires, the light grass/rangeland fuels were sufficiently desiccated by normal summer weather to sustain fire by late June, with the dead-fuel values before the event typical for that calendar period. Strong winds played a critical role in initiating and spreading the eastern Washington fires, and recent regional climate modeling work (Mass et al. 2021, manuscript submitted to J. Climate) suggests that extreme easterly winds during late summer and autumn will attenuate under increasing greenhouse gas emissions, as the interior of the continent warms more rapidly than coastal regions. Thus, considering the typical dead fuel moistures preceding the event and the critical importance of unusual, extreme winds in initiating and spreading the grass/rangeland fires, the contribution of global warming appears to be small. This conclusion is consistent with previous research for California and the western United States, which found little correlation between preceding climatic conditions and warm-season grass/rangeland/chaparral fires in the region (Abatzoglou et al. 2018; Keeley and Fotheringham 2003; Keeley and Syphard 2016, 2017, 2019; Williams et al. 2019).

The western Oregon fires were associated with extreme easterly winds, unprecedented in the modern era. ERC and BI values over the western slopes of the Oregon Cascades were not exceptional during the early and midsummer and only surged to extreme record values under the influence of record-breaking easterly winds. Temperatures were above normal and precipitation was below normal during the second half of the summer, both possible connections with anthropogenic global warming. The dominance of the unprecedented easterly winds in creating extreme ERC and BI, the role of the strong winds in initiating fires, the fact that such extreme winds should decline under global warming, and the dry, but not extreme, fuel moisture conditions in the preceding weeks, suggest that global warming was not a key element in the initiation and evolution of the Oregon wildfires.

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Data availability statement. The model grids for the forecasts used in this paper are stored on University of Washington servers and can be made available through anonymous FTP. The other datasets, such as the NOAA Climate Division data and upper air soundings, are publicly available through NOAA public servers.

APPENDIX
WRF Model Configuration and Verification

The model configuration was the same as the highly tested University of Washington real-time WRF configuration, using WRF-ARW V4.1.3, YSU planetary boundary layer (PBL), Thompson microphysics, RRTMG radiation, and the NOAH-MP land surface model. The simulations were
initialized and received boundary conditions from the operational NOAA/NWS GFS model, with an outer (36 km) domain grid-nudged to the GFS forecasts, and nested domains of 12, 4, and 1.33 km (Fig. A1).

The 0000 UTC 7 September 2020 model run was verified extensively against observations and appears to have simulated the mesoscale evolution of the event with considerable fidelity. To illustrate, Fig. A2 shows a comparison of model output to the soundings at Medford (MFR), Salem (SLE), and Spokane (OTX) during the time of generally strongest winds (1200 UTC 8 September). There is a close correspondence between the temperature, humidity, and wind fields between observations and the model forecasts. An analysis of all observed and simulated vertical profiles during the event, shown in Fig. A3, demonstrates excellent model accuracy in the frequency histogram and high correlation coefficients between simulated temperatures/winds and observations.

REFERENCES


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