The Influence of Wildfire Smoke on Cloud Microphysics during the September 2020 Pacific Northwest Wildfires

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ABSTRACT: During late summer 2020, large wildfires over the Pacific Northwest produced dense smoke that impacted the region for an extended period. During this period of poor air quality, persistent low-level cloud coverage was poorly forecast by operational numerical weather prediction models, which dissipated clouds too quickly or produced insufficient cloud coverage extent. This deficiency raises questions about the influence of wildfire smoke on low-level clouds in the marine environment of the Pacific Northwest. This paper investigates the effects of wildfire smoke on the properties of low-level clouds, including their formation, microphysical properties, and dissipation. A case study from 12 to 14 September 2020 is used as a testbed to evaluate the impact of wildfire smoke on such clouds. Observations from satellites and surface observing sites, coupled with mesoscale model simulations, are applied to understand the influence of wildfire smoke during this event. Results indicate that the presence of thick smoke over Washington led to decreased temperatures in the lower troposphere, which enhanced low-level cloud coverage, with smoke particles altering the microphysical structure of clouds to favor high concentrations of small droplets. Thermodynamic changes due to smoke are found to be the primary driver of enhanced cloud lifetime during these events, with microphysical changes to clouds as a secondary contributing factor. However, both the thermodynamic and microphysical effects are necessary to produce a realistic simulation.

KEYWORDS: Wildfires; Aerosols; Air quality; Cloud microphysics; Cloud radiative effects; Clouds; Coastal meteorology; Forecast verification/skill; Forecasting; Mesoscale forecasting; Numerical weather prediction/forecasting; Cloud resolving models; Clouds; Mesoscale models; Wildfires

1. Introduction

Wildfire smoke has many impacts on the meteorological environment. Through the aerosol direct effect, solar radiation is scattered by smoke particles which typically exhibit submicron sizes (e.g., Rissler et al. 2006). Such scattering of solar radiation reduces solar heating at the surface and results in a reduction in air temperatures in the lower troposphere, as described in several studies (e.g., Robock 1988, 1991; Eck et al. 1998; Treffeisen et al. 2007; Stone et al. 2011; David et al. 2018). Along with cooler temperatures, attenuated solar radiation from wildfire smoke reduces turbulence (Wang et al. 2013; Ding et al. 2016; Petäjä et al. 2016) and boundary layer mixing (Geiß et al. 2017; Wang et al. 2018) by promoting more stable atmospheric conditions (Li et al. 2017; Su et al. 2020).

Wildfire smoke also has important indirect effects on the atmosphere, particularly through increases in aerosols, which in turn alter the composition of clouds. For example, through the Twomey Effect, an increase in aerosol concentration increases the number of small cloud droplets (Twomey 1974), increases cloud albedo, boosts cloud-top radiative cooling, and prolongs cloud longevity (Twomey 1977; Lohmann 2006; Christensen et al. 2020). This effect has been well documented in several observational studies (e.g., Warner and Twomey 1967; Coakley et al. 1987; Albrecht 1989; Ackerman et al. 2000; Hobbs et al. 2000; Oreopoulos and Platnick 2008; Wang et al. 2010; Costantino and Bréon 2013; Sena et al. 2016) and has

been integrated into many numerical weather prediction and climate models (e.g., Mansell et al. 2010; Thompson and Eidhammer 2014).

The combination of aerosols and low-level clouds is of considerable meteorological and societal importance. Reductions in visibility result from smoke-induced increases in cloud droplet number concentrations (Eldridge 1961; Niu et al. 2012; Duthon et al. 2020). The superposition of near-surface smoke and low clouds (fog) has been a major contributor to transportation incidents caused by prolonged periods of near-zero visibility (Achtemeier 2002; Collins et al. 2009). Such interactions between aerosols and low clouds, particularly during foggy periods, pose a considerable challenge for numerical weather prediction (NWP) models. It is reasonable to hypothesize that the presence of wildfire smoke results in more rapid formation of low-level clouds due to cooler low-level air temperatures. Furthermore, one might anticipate that cloud coverage will be retained longer when smoke is present due to the Twomey effect. Such hypotheses are examined in this paper.

The goal of this study is to assess the impact of wildfire smoke on the formation and retention of low clouds in WRF Model simulations over western Washington State. Specifically, we examine the interactions of low clouds and smoke during the September 2020 wildfires over the Pacific Northwest. While this study uses a single event for understanding these interactions, there were several periods of persistent low-level clouds concurrent with lower-tropospheric smoke over the region during this event. Figure 1 shows cloud cover from GOES-17 during September and October 2020 compared to 18- and 22-h

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FIG. 1. Cloud cover from the HRRR model and *GOES-17* satellite. The left block shows the 13 Sep 2020 event at (top) 1800 UTC and (bottom) 2200 UTC, with HRRR initialized at 0000 UTC 13 Sep 2020. The right block shows a similar event on 3 Oct 2020, with HRRR initialized at 0000 UTC 3 Oct 2020. The dark blue regions denote where clouds are present. HRRR cloud cover is based on a 10^{-6} g g^{-1} threshold of cloud water mixing ratio in the column.

forecasts of low clouds from the operational high-resolution HRRRv3 model. In both instances, HRRR forecasts did not reproduce the observed spatial extent or longevity of low-level cloud coverage. While other model errors may have contributed to the poor forecasts, this study will focus on whether including wildfire smoke into a modeling system can improve simulations of low-level clouds.

Due to large and persistent smoke concentrations, the 12–14 September 2020 period is used as the case study for this paper. During the afternoons of 12 and 13 September, cloud coverage persisted in western Washington, and especially over Puget Sound, far longer than models predicted (Fig. 1). Specifically, this study will address the following questions:

- 1) Does including smoke aerosols in NWP models improve the representation and evolution of low clouds?
- 2) Does the presence of smoke change the microphysical/macrophysical properties of simulated low clouds?
- 3) Are smoke–cloud interactions dominated by the microphysical or thermodynamic impacts of smoke?

This paper is organized as follows. Section 2 presents information on the model and data used in this study. Section 3 describes the impact of smoke on temperature and cloud characteristics and offers an evaluation of the thermodynamic and microphysical effects of smoke aerosols. Section 4 discusses the results and concludes the study.

2. Model information

a. WRF configuration

The Advanced Research version of the WRF Model (WRF-ARW; Skamarock et al. 2008) version 4.1.3 was used in this

study to assess the impact of smoke aerosols on low-level clouds and fog. The simulations employed a single domain with 4-km grid spacing and 51 vertical levels (Fig. 2) arranged according to the WRF hybrid vertical coordinate system (Klemp 2011). Physics options include the Thompson–Eidhammer aerosol-aware microphysics parameterization (Thompson and Eidhammer 2014, hereafter TE14) and the Yonsei University (YSU; Hong et al. 2006) planetary boundary layer and surface layer schemes. The Rapid Radiative Transfer (RRTMG; Iacono et al. 2008) scheme is used for simulating shortwave and longwave radiation. Other model configuration options follow from the operational University of Washington WRF Model.¹

Initial and boundary meteorological conditions came from the NCEP High-Resolution Rapid Refresh model (HRRR) version 3 (Benjamin et al. 2016; Blaylock et al. 2017) hourly grids. WRF initial and boundary conditions were updated hourly with the latest initialization (forecast hour 0). For this study, we perform two primary simulations: a control run (CTL) with the default climatological aerosols from the TE14 microphysics parameterization and a smoke simulation (SMK) that uses a wildfire-based smoke aerosol field coupled with TE14 microphysics. Both aerosol datasets are described in the next sections. All simulations are initialized at 0000 UTC 12 September 2020 and integrated for 60 h until 1200 UTC 14 September 2020. Table 1 summarizes the model simulations performed in this study.

¹ For further information on the UW WRF Model, see: <https://a.atmos.washington.edu/wrfrt/info.html>.

FIG. 2. (left) The WRF simulation domain and its associated terrain (shaded). (right) Maps of the observation networks used in this study. Blue boxes indicate the model domain.

b. The Thompson–Eidhammer microphysics scheme

The Thompson–Eidhammer microphysical parameterization scheme is an aerosol-aware microphysical parameterization scheme that simulates the production and interaction of water vapor, cloud water, rain, graupel, snow, and cloud ice (Thompson and Eidhammer 2014). The scheme is partially double-moment because it contains prognostic expressions for the number concentrations of cloud water, rainwater, and cloud ice. The other hydrometeor species (graupel and snow) are single-moment with diagnosed number concentrations.

In its climatological aerosol configuration, the TE14 scheme assumes a single sulfate aerosol type that is spatially distributed based on an aerosol number concentration climatology from the NASA GOCART model. The scheme provides the user with options to control the radius and hygroscopicity of aerosols, which are applied uniformly to the entire domain. The default values are an aerosol radius of $0.04\ \mu\text{m}$ and a hygroscopicity of 0.4. Because the TE14 scheme provides a limited selection of aerosol properties that are not necessarily characteristic of smoke aerosols, we implemented an extended aerosol lookup table in TE14 as well as added wildfire smoke aerosols (see next section). The lookup table estimates the number of aerosols nucleated in a given volume based on ambient conditions of temperature, vertical velocity, and moisture. Appendix A describes the new lookup table.

c. Model aerosol fields

Several observational studies have found that wildfire smoke in the western United States often consists of small-diameter particles with very low hygroscopicity (Petters et al. 2009; Gomez et al. 2018) and a mean density of approximately $1500\ \text{kg m}^{-3}$ (McMeeking et al. 2005). For this study, we select an aerosol radius of $0.08\ \mu\text{m}$ and a hygroscopicity of 0.1, values

that are consistent with the average size of smoke particles observed across the western United States and elsewhere (Radke et al. 1990; McMeeking et al. 2005; Rissler et al. 2006; Petters et al. 2009; Gomez et al. 2018; Swistak 2019) and reflects the hygroscopicity of particles produced by the combustion of the predominant regional foliage types (pine and spruce trees; Petters et al. 2009) involved in the September 2020 wildfires.

In the control (CTL) simulation, the default TE14 climatological aerosol concentrations are used, as described previously. For our simulations using smoke aerosols (SMK), aerosol mass concentrations of black and organic carbon from the NASA Goddard Earth Observing System version 5 (GEOS-5; Rienecker et al. 2008) are converted to number concentration assuming a spherical aerosol particle with the aforementioned size and density properties. Spatially varying GEOS-5 aerosols are used throughout the troposphere, with the boundary layer consisting of a combined grid of GEOS-5 and interpolated surface PM_{2.5} observations from the EPA

TABLE 1. Simulations performed in this study and descriptions of their aerosol source, whether aerosol concentrations are prescribed, and whether the aerosol radiative forcing is prescribed. All simulations are integrated from 0000 UTC 12 Sep 2020 to 1200 UTC 14 Sep 2020.

Simulation identifier	Aerosol source	Prescribed smoke aerosols	Prescribed radiative effect
CTL	TE14 climatology	No	No
SMK	GEOS-5 + AirNow	Yes	Yes
SMK-THERMO	TE14 climatology	No	Yes
SMK-MICRO	GEOS5 + AirNow	Yes	No

FIG. 3. Maps of *GOES-17* visible satellite images at 1800 UTC 9–13 Sep 2020, with an overlay of ERA5 850-hPa wind barbs (kt; 1 kt $\approx 0.51 \text{ m s}^{-1}$) and geopotential heights (m).

AirNow network. Additional details on the EPA data are given in subsequent sections. Smoke conditions are updated every 10 min throughout the domain.

To simulate the impact of smoke aerosols more realistically during these events, the aerosol fields must be coupled to the model radiation scheme. There are two ways to accomplish this in WRF using the namelist option “aer_opt,” which only affects solar radiation. For our SMK simulations, we utilize aer_opt = 2, which allows for ancillary grids of aerosol optical depth and the aerosol Angstrom exponent to be imported into the RRTMG radiation scheme, both of which we obtain from GEOS-5. The aer_opt = 3 couples prognostic aerosol concentrations from the TE14 scheme directly to the radiation scheme, though this option resulted in excessive and unrealistic incident solar radiation at the

surface compared to aer_opt = 2. After an examination of the model code, the lack of scattering with aer_opt = 3 was determined to be the result of the model using fixed scattering coefficients, rather than being adaptive to aerosol properties. For the CTL simulation, we do use aer_opt = 3, which was developed specifically for use with the TE14 aerosol climatology. The radiation scheme applied in this work, RRTMG, does not account for the effects of aerosols on longwave radiation, although several studies have shown that these effects are small (Robock 1991; Stone et al. 2011; David et al. 2018).

Two other WRF Model options may impact the attenuation of incoming solar radiation: aer_asy_opt is the aerosol asymmetry parameter (default value: 0.9) and aer_ssa_opt is the single scattering albedo (default value: 0.85). The default

FIG. 4. Scatterplots and associated statistics for Pacific Northwest rawinsonde launch sites at (a),(d),(g) Quillayute, WA (UIL); (b),(e),(h) Salem, OR (SLE); and (c),(f),(i) Spokane, WA (OTX). Each panel compares observed and simulated meteorological data for 0000 and 1200 UTC launches from 12 to 14 Sep 2020. The simulation is initialized at 0000 UTC 12 Sep 2020.

values for these parameters are used and, per default WRF settings, are applied uniformly across the model domain for our simulations.

d. Surface and satellite data

To evaluate the impacts of wildfire smoke, several observational assets are used in this study. Meteorological data from Federal Aviation Administration (FAA) automated observing sites (ASOS/AWOS) were obtained from the NOAA/NCEP Meteorological Assimilation Data Ingest System (MADIS)

quality-controlled² data system (Fig. 2). The figure also shows locations of radiometers (Apogee SP-100) from the Washington State University (WSU) AgWeatherNet (AWN), which are analyzed in section 3b.

The Environmental Protection Agency (EPA) monitors the mass concentration of particulate matter with diameters

² MADIS quality control steps are described in NWS Techniques Specification Package (TSP) 88-21-R2 (1994).

smaller than $2.5\ \mu\text{m}$ (PM_{2.5}), which includes most smoke particles emitted by fires in the region (Radke et al. 1990; McMeeking et al. 2005; Rissler et al. 2006; Gomez et al. 2018; Swistak 2019). We used PM_{2.5} data from the EPA AirNow monitoring service, which provides quality-controlled data across the continental United States. PM_{2.5} data are used to adjust GEOS-5 smoke concentrations in the boundary layer for WRF Model initial and boundary conditions. The PM_{2.5} data are also validated against unadjusted GEOS-5 data and HRRR-Smoke data in the next section. AirNow locations are shown in Fig. 2.

Cloud coverage data were obtained from the NOAA Geostationary Operational Environmental Satellite Series 17 (GOES-17), which provides continuous observations over the western United States at high spatial resolution and a temporal resolution of 5 min at nominal operation. For this study, we utilize hourly data. To investigate the impact of smoke on cloud coverage and evolution, we use false-color images combining GOES-17 channels 6, 2, and 3 into the red, green, and blue fields, respectively, of an RGB image. Bands 6, 2, and 3 have corresponding central wavelengths of 2.2, 0.64, and $0.86\ \mu\text{m}$. This combination of bands closely emulates the MODIS 7–2–1 configuration, which facilitates the discrimination between smoke and low clouds.³ Because the 6–2–3 images rely on visible bands, the analysis of GOES-17 data in this study is limited to daylight hours with a high sun angle (approximately 1600–0000 UTC).

3. Case study: 12–14 September 2020

a. Synoptic situation and smoke distribution

During the week preceding 12 September 2020, a strong mid-latitude cyclone (995 hPa on 8 September 2020) traveled south-eastward out of British Columbia, impacting the Intermountain West and Great Plains of the United States. The passage of this cyclone was followed by an extraordinarily strong high pressure area (1038 hPa), forcing an unusually strong offshore-directed sea level pressure gradient and resulting strong northeasterly to easterly winds across the Pacific Northwest. Such winds combined with very dry late-summer conditions to promote the growth of numerous large wildfires across the western Cascades, the Sierra Nevada, and the Oregon Coast Range. Mass et al. (2021, manuscript submitted to *Mon. Wea. Rev.*) describes the 7–12 September 2020 period in greater meteorological and climatological detail.

Figure 3 presents the evolution of this event's smoke plume from 9 to 13 September using GOES-17 imagery, as well as associated 850-hPa fields from the ERA5 reanalysis. On 9–10 September 2020 (Figs. 3a–b), high geopotential heights were present to the northwest as wildfires were ongoing over the western slopes of the Oregon Cascades. Easterly and southeasterly winds over the western Oregon Cascades advected

FIG. 5. Cumulative frequency distributions (a) of surface aerosol mass concentration from the EPA AirNow sensors (black), the GEOS-5 model (green), and HRRR-Smoke (blue). (b) Boxplots of surface aerosol mass concentration from the same three datasets. All data are 3-hourly over the period from 0000 UTC 12 Sep to 1200 UTC 14 Sep at the locations of AirNow stations shown in Fig. 2.

a massive smoke plume more than 1000 km offshore. By 11 September (Fig. 3c), as coastal low pressure developed, onshore-directed winds began transporting the smoke plume eastward toward western Washington State. On 12 September, dense smoke had spread over Washington, Oregon, and southern British Columbia, with low-level smoke causing exceptionally poor air quality through 15 September.

Numerical model simulations of the events were highly skillful. Mass et al. (2021, manuscript submitted to *Mon. Wea. Rev.*) describes the fidelity of synoptic and mesoscale forecasts prior to 12–14 September, highlighting the accuracy of global and regional models during the initial stage of the event. The WRF Model simulations used in this study proved equally skillful, as illustrated in appendix B and Fig. 4. Appendix B compares observed and simulated rawinsonde profiles at Quillayute, Washington (UIL); Spokane, Washington (OTX); and Salem, Oregon (SLE). Figure 4 offers quantitative

³ See the GOES ABI Algorithm Theoretical Basis Document for additional details: https://www.star.nesdis.noaa.gov/goesr/documents/ATBDs/Baseline/ATBD_GOES-R_ABI_CMI_KPP_v3.0_July2012.pdf.

verification of the simulated environment against rawinsonde data, showing that the simulated conditions correlated well with observations. Mean absolute errors for air temperature, dewpoint temperature, and wind speed ranged from 0.83°C – 1.02°C , 4.63°C – 6.40°C , and 2.73 – 3.94 m s^{-1} , respectively. These error values are similar to those found during recent evaluations of the HRRR model (Beck et al. 2020; Fovell and Gallagher 2020).

The realism of model smoke grids is a critical issue for this study. Although the three-dimensional smoke distribution presents a challenge for evaluation, the unadjusted⁴ GEOS-5 grids verify well against available observations and were superior to the smoke grids in the HRRR-Smoke model (Ahmadov et al. 2017). To evaluate the realism of smoke grids, Fig. 5 compares 3-h surface smoke concentrations from GEOS-5 and the HRRR-Smoke system relative to the AirNow data at EPA surface observing sites during the 60-h period of interest (0000 UTC 12 September–1200 UTC 14 September). To produce an accurate comparison, we use 3-h HRRR-Smoke initialization data to more directly compare to the analysis dataset from GEOS-5. For this event, the median observed (EPA AirNow) PM_{2.5} was $149\text{ }\mu\text{g m}^{-3}$, which is remarkably close to the median GEOS-5 surface smoke concentration ($156\text{ }\mu\text{g m}^{-3}$). In contrast, the HRRR median smoke concentration at the surface was significantly lower ($96\text{ }\mu\text{g m}^{-3}$). Spatially, the magnitudes and distribution of smoke were analyzed qualitatively and quantitatively across the period.

Figure 6 offers a qualitative comparison of the various smoke distributions for 1800 UTC 12 September 2020, showing an extensive smoke plume that was over the Pacific Northwest and eastern Pacific. At that time, HRRR-Smoke (initialized at 1800 UTC 12 September 2020) had a slightly more realistic smoke extent along the eastern portion of the domain, but GEOS-5 had a better offshore (upstream) smoke plume distribution.

b. Impact of smoke on solar radiation and surface air temperature

Wildfire smoke in the troposphere substantially attenuates incoming solar shortwave radiation, with only minor impacts on longwave radiation (Robock 1991; Stone et al. 2011; David et al. 2018). The inclusion of smoke aerosols into the WRF modeling system caused a median reduction of incident solar radiation at the surface of 180 W m^{-2} across the domain (median CTL shortwave radiation was 405 W m^{-2} compared to 225 W m^{-2} in SMK). Figure 7a illustrates this graphically, showing a systematic reduction of radiation in SMK compared to CTL. Moreover, solar radiation was attenuated by smoke throughout daylight hours on 13 September 2020, as shown in Fig. 7b. There is overlap during early portions of the diurnal cycle, which can be attributed to the cloud differences described in the next section.

Comparisons of simulated solar radiation against observations from the Washington State University (WSU) AWN network indicate that without the inclusion of smoke in the model, the CTL simulation dramatically overpredicted solar radiation at the surface by an average of nearly 250 W m^{-2} during peak solar insolation (Fig. 8). In contrast, the inclusion of wildfire smoke aerosols substantially improved the radiation forecast, although radiation was approximately 40 W m^{-2} too high during peak solar insolation. The 40 W m^{-2} error is similar to values obtained in other studies evaluating simulated radiation from the WRF Model (Ruiz-Arias et al. 2016; Kim et al. 2017).

In response to the reduced incoming solar radiation, the lower troposphere exhibited cooler temperatures when smoke was present. Compared to the observed 2-m air temperatures, the CTL run temperatures were nearly 5°C too warm during 12–13 September (Fig. 9). In contrast, the SMK run was more realistic, with a maximum average mean temperature error of 1°C . Nighttime temperatures on 13 September were similar in both simulations, though the SMK run was approximately 0.25°C more accurate than CTL.

The shape of the diurnal cycles shown in Fig. 9 highlights the attenuated diurnal warming during the event and differences in model performance. Compared to the observed mean temperature, the CTL simulation warmed more rapidly during the morning hours, as evident by the slope of the lines in Fig. 9a. By contrast, the SMK simulation produced a more gradual, more accurate rate of warming. Following peak insolation, CTL cooled more rapidly than SMK, though in the late evening (after 0300 UTC) the observations and both simulations followed similar rates of temperature change.

To understand the three-dimensional structural changes caused by wildfire smoke, we analyze air temperature along a north–south cross section aligned with the long axis of Puget Sound (location in Fig. 10) for 1000, 1400, and 1800 UTC 12 September (Fig. 11). Cooler low-level air temperatures were generally confined to the 0–750-m layer for the Puget Sound region. At 1000 and 1800 UTC, CTL had an attenuated near-surface cool layer and a weaker inversion compared to SMK, a situation that was particularly evident at 1800 UTC when most clouds had dissipated in CTL. In contrast, at 1400 UTC, low-level cool air had similar magnitudes and locations in both simulations. As will be shown later, the areas of cooler air temperatures occurred within cloudy regions.

The differing diurnal cycles of temperature for CTL and SMK are illustrated in Fig. 12 time–height cross section averaged over the line shown in Fig. 10. From 1200 to 1800 UTC each day, when cloud coverage is greatest, CTL is slightly warmer ($<1^{\circ}\text{C}$) than SMK. However, after clouds dissipate in CTL after 1800 UTC, the warm bias of approximately 5°C becomes apparent. Furthermore, the depth of the warm bias increases rapidly to 1.25 km MSL after clouds dissipate in CTL, which implies less vertical mixing in SMK due to the effects of aerosols.

c. Low cloud development

As the upper-level offshore ridge translated eastward on 11 September 2020 and onshore flow increased along the Washington coast (Fig. 3c), the infiltration of cool, moist

⁴ “Unadjusted” refers to the GEOS-5 grids whose boundary layer was not forced by EPA PM_{2.5} data.

FIG. 6. Maps of smoke coverage from the *GOES-17* satellite and two model sources. (a) A false-color satellite image from *GOES-17* at 1800 UTC 12 Sep 2020. (b) A mask of smoke coverage from the

FIG. 7. Comparisons of shortwave radiation at the surface in the CTL and SMK simulations. (a) A two-dimensional histogram of all nonzero shortwave radiation data points from the CTL simulation compared to the SMK simulation. The bin spacing is 25 W m^{-2} , and the black dashed line indicates the 1:1 line. (b) The interquartile range of shortwave radiation over the model domain during 1200–0200 UTC 13–14 Sep 2020.

marine air occurred, with the greatest inland penetration over western Washington State. Marine air was noted in other areas as well, such as along the Columbia River and the Willamette Valley of Oregon.

In western Washington, the influx of marine air led to the development of low stratus and fog over Puget Sound. Although such low-cloud formation is not uncommon during late summer, the persistence of low clouds past noon local time was unusual and poorly forecast, as highlighted in Fig. 1. The retention of low clouds presents an important question: Did the presence of smoke contribute to the long-lasting cloud coverage observed on 12–13 September 2020?

1) MICROPHYSICAL CHANGES DUE TO SMOKE

An increase in the concentration of aerosols should increase the number of cloud droplets, while also decreasing their average size. From the CTL and SMK simulations, mean in-cloud vertical profiles of cloud droplet number concentration, cloud

←

satellite image shown in (a). (c) The GEOS-5 model smoke area and (d) the HRRR smoke area. Both (c) and (d) are based on an integrated smoke threshold of 0.2 g m^{-2} .

FIG. 8. Observed (Obs.) and simulated (CTL and SMK) incident solar radiation at the ground at AWN observing sites over Washington state. (a) A single cycle of solar radiation for 1200–0200 UTC 13–14 Sep. Thick solid lines denote the average incident solar radiation from observations and model simulations. Individual observing stations are shown by thin lines. (b) The data presented in (a) as a boxplot.

median volume diameter, and cloud liquid water content were examined in an analysis region (shaded region of Fig. 10) during all hours of the simulations. As hypothesized, cloud droplets in SMK were $12\text{ }\mu\text{m}$ smaller and 220% more numerous

than CTL (Fig. 13). The median cloud water mixing ratio in SMK also increased by 0.017 g m^{-3} compared to CTL, which we suspect is partially attributable to greater saturation in the lower troposphere due to the cooler ambient temperatures.

FIG. 9. (a) Time series of hourly mean 2-m air temperatures (K) from 1200 UTC 12 Sep to 1200 UTC 14 Sep at the ASOS/AWOS surface observing sites shown in Fig. 2. The shaded regions correspond to the interquartile range (IQR) for the CTL simulation (blue) and the SMK simulation (red), calculated over all observing sites. The IQR of observations is shown inside the black dashed area. (b) 2-m air temperature errors (forecast minus observations) for the CTL simulation (blue) and the SMK simulation (red).

FIG. 10. Map of western Washington State and adjacent areas showing the cloud analysis domain (shaded) and the north-south cross section used in cloud and temperature analyses.

2) CLOUD COVERAGE

Next, the impact of smoke on cloud area is examined. As hypothesized, the presence of smoke coincided with greater areal coverage of clouds. The spatial coverage of simulated clouds at 1800 UTC 12 and 13 September is compared with observations from *GOES-17* in Fig. 14. Cloud cover is defined for the WRF simulations in the same manner as the HRRR: Any location with at least 10^{-6} g g^{-1} of cloud water

is considered cloudy. At both times, observed cloud coverage extended over the majority of areas over and adjacent to water where low-level marine air was present, including the Puget Sound region. The CTL simulation failed to produce adequate cloud coverage over regions where it was observed, with particularly poor performance over Puget Sound and south and east of the Olympic Mountains. SMK, on the other hand, more realistically simulated low clouds over the region, including within the region's low-lying river valleys. While cloud cover was simulated more accurately in SMK than CTL, both simulations struggled to produce sufficient cloudiness over the nearshore waters of the Pacific Ocean.

Compared to the observed cloud area, CTL produced an average of 41% too little cloud cover across the analysis area (shaded area of Fig. 10), with SMK averaging 10% too much cloud cover (Fig. 15). Because of the limitations of the satellite imagery, the first and last observation points in each diurnal cycle are contaminated by low sun angle or insufficient near-infrared radiation being emitted from the viewing surface, but are included for completeness. Figure 15b shows the same data from Fig. 15a as a scatterplot, highlighting the linear relationships between observed and simulated cloud cover in each simulation, with CTL dramatically underpredicting cloud area. This result is indicative of a systematic bias in the CTL simulation's cloud production, rather than random error.

To investigate the importance of smoke aerosols for daytime cloud dissipation, we examine the rates of change in cloud area over time (Fig. 16). During periods of cloud dissipation (D1, D2), cloud cover in CTL dissipated approximately 3 h sooner than SMK. Furthermore, cloud development (I1, I2) was much slower in CTL compared to SMK, with peak cloud development

FIG. 11. North-south 0–1.5-km vertical cross sections of air temperature ($^{\circ}\text{C}$) along Puget Sound from the (left) CTL and (right) SMK simulations. Three times (1000, 1400, and 1800 UTC) on 12 Sep are shown.

FIG. 12. Time-height difference plots averaged along the north-south Puget Sound cross section for 0–1.5 km MSL. (a) The air temperature difference and (b) the cloud water content difference between CTL and SMK.

occurring 2 h sooner in SMK. The SMK simulation developed clouds very rapidly and over a shorter period during the overnight hours compared to CTL.

Next, the vertical extent and temporal evolution of clouds are investigated along the north-south cross section. At 1000 UTC 12 September, CTL simulated scattered cloud cover along the cross section, with SMK producing modestly more coverage and cloud water content (Fig. 17). Four hours later, 1400 UTC, both simulations had nearly indistinguishable spatial coverage. However, at 1800 UTC the CTL simulation had dissipated all but a small region of clouds over south-central Puget Sound, while the SMK simulation retained the clouds from four hours prior. Two noteworthy characteristics of the low clouds over Puget Sound were their depth and cloud water contents. The vast majority of clouds along the cross section were contained within the 0–500 m MSL layer in both simulations, though the magnitude of cloud water content was very different, with SMK having larger cloud water contents approaching 1 g kg^{-1} in southern Puget Sound at 1000 UTC. Moreover, throughout the diurnal cycle, SMK had ubiquitously larger cloud water contents than CTL (Fig. 12). Comparing Figs. 12a and 12b, it is apparent that the largest air temperature differences occurred after CTL dissipated cloud coverage.

d. Thermodynamic versus microphysical effects

There are two pathways, thermodynamic and microphysical, through which high aerosol concentrations can affect low clouds. To understand the importance of each for this event, we perform two additional simulations. The first, labeled SMK-THERMO, uses the GEOS-5 prescribed radiative forcing (AOD and Angstrom exponent) but has climatological aerosols present. This simulation is used to assess the thermodynamic (radiative) effect of smoke. The second simulation, SMK-MICRO, uses GEOS-5 smoke aerosols but does not consider those aerosols' radiative

impacts. This simulation is used to assess the microphysical effect of smoke. Each simulation is evaluated using air temperature and cloud cover observations. Table 1 summarizes all model simulations.

Figure 18 shows a time series of mean temperature and temperature errors at the FAA ASOS/AWOS surface observing sites in Fig. 2. The SMK-MICRO simulation, which had a maximum temperature error of 5°C , performed nearly the same as CTL throughout the period, with the largest differences noted around 1800 UTC (1100 LST). The SMK-THERMO simulation performs more similarly to SMK, though is approximately 1°C warmer during daylight hours of 12 and 13 September.

Next, cloud coverage is examined. As with the temperature analysis in the previous paragraph, the microphysical impacts of smoke (SMK-MICRO) resulted in only slightly more cloud coverage compared to CTL, especially around 1800 UTC. The SMK-THERMO simulation produced greater cloud coverage than SMK-MICRO but still was not able to produce the same amount of cloud cover as the SMK simulation or as observed (Fig. 19).

The results of these analyses indicate that the thermodynamic impact of smoke in the troposphere was substantially more important than the microphysical effect during this event. However, neither of these experiments alone was able to simulate the correct temperature changes or cloud cover that was present in SMK or observed. The results presented in Figs. 18 and 19 demonstrate that a combination of both the thermodynamic and microphysical effects was required to produce a realistic simulation of the event.

5. Discussion and conclusions

The Pacific Northwest wildfires of September 2020 had major impacts on regional air quality and meteorology. From 12 to 14 September 2020, a large plume of wildfire smoke advected westward over the northeast Pacific and then spread

FIG. 13. Mean 0–2 km MSL in-cloud vertical profiles of (a) cloud droplet median volume diameter (μm), (c) cloud droplet number concentration (m^{-3}), and (e) cloud water content (g m^{-3}) over the shaded analysis domain in Fig. 10. (b),(d),(f) Boxplots of the data.

north and east to impact the entire Pacific Northwest. The goal of this study was to investigate the meteorological effects of wildfire smoke on the development and maintenance of low clouds, incident solar radiation, air temperature, and other atmospheric variables. Particular emphasis is given to the low clouds that affected western Washington State, where they had greater longevity than forecast by numerical models.

The WRF-ARW Model was used to simulate the 12–14 September 2020 smoke event. Two simulations were compared: one with a climatological aerosol configuration (CTL) and the

other with realistic wildfire aerosol concentrations from GEOS-5 (SMK). Verified with rawinsonde observations, both simulations produced an accurate simulation of synoptic and mesoscale conditions, a situation also noted in a detailed review of the event by Mass et al. (2021, manuscript submitted to *Mon. Wea. Rev.*).

Simulations with smoke radiative effects indicated a significant reduction of solar radiation at the surface, resulting in a large drop in 2-m air temperatures that was confirmed by observations at ASOS locations. The SMK simulation proved superior compared to CTL, with maximum mean temperature errors of 1° and 5°C, respectively.

FIG. 14. (left) Observed (*GOES-17*) compared with (center) the SMK, and (right) CTL cloud coverage simulations at (top) 1800 UTC 12 Sep and (bottom) 1800 UTC 13 Sep. The dark blue shading represents regions where clouds are present. Simulations were initialized at 0000 UTC 12 Sep.

The persistence of low clouds into the late afternoon and their unrealistic early dissipation by operational models were important aspects of this event. To determine whether the long-lived cloud cover was the result of the dense smoke concentrations, we evaluated simulations with (SMK) and without (CTL) wildfire smoke using *GOES-17* satellite observations. It was found that CTL produced 40% less cloud coverage compared to observations, with SMK producing slightly too much (10%) coverage. SMK retained cloudiness for longer periods than CTL, with clouds forming more rapidly during the night.

The apparent sensitivity of cloud coverage to smoke concentration prompted a final question: Do the differences in cloud cover result from the thermodynamic effects of smoke (i.e., reduction of lower tropospheric temperatures by reducing incoming solar radiation) or the microphysical effects (i.e., enhancing the number of small cloud droplets)?

To answer this question, two additional simulations were performed, in which the thermodynamic or microphysical effects of smoke were excluded from the model. Results showed that the thermodynamic contribution was the main mechanism

FIG. 15. (a) Time series of cloud area from the *GOES-17* satellite (black icons) compared to the control run (blue; CTL) and the smoke run (red; SMK). (b) Scatterplot showing the relationship between simulated and observed cloud areas. Regression lines are shown (dashed), as are the 1:1, 1:2, and 2:1 lines (solid). All data are from the shaded region in Fig. 10.

FIG. 16. Time series of the cloud area rate of change from the control (blue; CTL) and the smoke simulation (red; SMK) over the analysis domain. The shaded areas (D1 and D2) denote periods when cloud coverage was decreasing, and areas I1 and I2 denote periods of increasing cloud coverage.

producing the 2-m air temperature and cloud coverage effects, with a much smaller contribution from microphysics. However, only when both effects were included could an accurate simulation of temperature and cloudiness be produced, implying interactions between microphysics and thermodynamics were necessary to adequately simulate the 12–14 September event.

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Data availability statement. All data used in this manuscript are available online or by request from the corresponding author. The WRF Model data, including namelists and input fields, are available upon request from the corresponding author. All HRRR model data used can be obtained either from [Blaylock et al. \(2017; https://doi.org/10.7278/S5JQ0Z5B\)](https://doi.org/10.7278/S5JQ0Z5B) or the Google Cloud Repository (<https://console.cloud.google.com/marketplace/product/noaa-public/hrrr?project=python-232920&pli=1>). The HRRR-Smoke grids can be obtained by contacting the HRRR-

FIG. 17. North-south 0–1.5-km vertical cross sections of cloud water content (g kg^{-1}) along Puget Sound from the (left) CTL and (right) SMK simulations. Three times (1000, 1400, and 1800 UTC) on 12 Sep are shown.

FIG. 18. As in Fig. 9, but including temperature data from the SMK-MICRO and SMK-THERMO experiments.

Smoke development team: <https://rapidrefresh.noaa.gov/hrrr/>. *GOES-17* satellite data can be obtained from NOAA via an online portal: <https://registry.opendata.aws/noaa-goes/>. Surface observing site data from the FAA ASOS/AWOS program is made available through the NCEP NOAA MADIS program: <https://madis.ncep.noaa.gov/>. An account is required to access data.

APPENDIX A

Description of Changes to Aerosols in Thompson–Eidhammer Microphysics

The Thompson–Eidhammer microphysics scheme (Thompson and Eidhammer 2014) predicts the number concentration of aerosols and uses those aerosols in the cloud droplet nucleation

FIG. 19. As in Fig. 15, but displaying additional cloud coverage data from the SMK-MICRO and SMK-THERMO experiments.

FIG. B1. Vertical profiles of the 5th–95th percentile ranges (shaded) of (a)–(c) temperature, (d)–(f) dewpoint temperature, (g)–(i) east–west wind (u wind), and (j)–(l) north–south wind (v wind) at the OTX, SLE, and UIL rawinsonde launch sites. The blue shading is the observed profile and the red shading indicates the simulated profile using the CTL simulation (control run with climatological aerosols). All 0000 and 1200 UTC launches, four total per station, are included.

process. In the version of WRF used in this study (v.4.1.3), there are a limited number of choices for aerosol properties, which are coupled to the simulated vertical velocity, temperature, and relative humidity to estimate the number of aerosols that are nucleated to cloud droplets. The number of activated aerosols was determined by a single-column model as described in Thompson and Eidhammer (2014). WRF accesses this information via a lookup table, whose default aerosol radii and hygroscopicities range from 0.01 to 0.16 μm and from 0.2 to 0.8, respectively.

For this study, we implemented a larger aerosol lookup table, provided by Trude Eidhammer (NCAR). The larger table is capable of simulating a greater range of aerosol types, with radii from 0.01 to 0.96 μm and hygroscopicity values from 0.05 to 1.28. This new table allows the microphysics parameterization to utilize aerosols ranging from small smoke particles with a low hygroscopicity to large, very hygroscopic sea salt aerosols.

APPENDIX B

Rawinsonde Evaluations

In section 4a, we presented quantitative rawinsonde evaluations from 0000 UTC 12 September to 1200 UTC 14 September. Those evaluations, presented in Fig. 4, demonstrated that our WRF simulations accurately represented the meteorological conditions during this period. Below, we offer further qualitative evidence of accurate model simulations by comparing simulated and observed rawinsonde profiles at the locations shown in Fig. 2.

Figure B1 shows observed and simulated (from the CTL simulation) vertical profiles of the 5th–95th percentile ranges for temperature, dewpoint temperature, and wind components (u , v) containing all standard rawinsonde times (0000 and 1200 UTC) at all of the observing sites (UIL, OTX, SLE). For the period of interest, the figure includes four profiles for each station. All locations exhibit similar ranges of air temperature, dewpoint temperature, and wind components. Notable deviations between observations and simulations are found in the middle- and upper-level dewpoint temperature profiles at SLE and OTX. Surface air temperatures, too, are warmer in the model than were observed, but this error is addressed in section 4 of the text.

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