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Enhancing Aerosol Direct Feedback for Numerical Weather Prediction in NOAA's Rapid Refresh Forecast System–Smoke and Dust (RRFS-SD v1)

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Key Points:

- The RRFS-SD v1 has been developed with the Common Community Physics Package
- The RRFS-SD v1 with smoke direct feedback captures the feature of observed Aerosol Optical Depth
- The smoke and direct feedback has a significant impact on near surface temperature, wind speed and radiation fluxes

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Abstract Smoke from biomass burning has a significant impact on air quality, visibility, public health, aviation, and weather. We recently developed the Rapid Refresh Forecast System–Smoke and Dust model (RRFS-SD v1) at NOAA using the Common Community Physics Package (CCPP). We embedded the plume rise modules for smoke, and dust emission modules into the RRFS using CCPP as physics subroutines. There are three distinct aerosol tracers: smoke from biomass burning, fine and coarse dust aerosols. We conducted sensitivity simulations for September 2020, during which the western US experienced extreme wildfires affecting both air quality and weather. Two sets of experiments were conducted, one without aerosol feedback to radiation, and one with aerosol feedback to radiation. The smoke feedback run captures the observed feature of aerosol optical depth well, and significantly improves the radiation balance as well as the numerical weather forecast of near surface temperature and wind speed.

Plain Language Summary Wildfire smoke greatly affects air quality, visibility, health, aviation, and weather forecasts. We've developed a new forecasting model called the Rapid Refresh Forecast System–Smoke and Dust model (RRFS-SD v1) at NOAA to handle smoke and dust. This model uses the flexible Common Community Physics Package which now includes many different kinds of physics parameterizations. By integrating modules for smoke plume rise, fire weather conditions, and dust emissions into RRFS, we can simulate their impact on weather and air quality more accurately. In September 2020, when the western US faced severe wildfires, we ran simulations to see how well our model predicted the weather and air quality changes caused by smoke and dust. We compared two scenarios: one where our model included feedback from smoke and dust on radiation, and another where it did not. Our results showed that including this feedback improved modeling ability to predict things like radiation fluxes, surface temperatures, and wind speeds across North America.

1. Introduction

Wildfires are a type of extreme natural events that have been occurring with increasing frequency and intensity across North America in recent years. These fires are not only devastating to the environment (Ahmadov et al., 2017) but also pose serious risks to human health (Aguilera et al., 2021) and local economies. For instance, the September 2020 wildfires in the United States (Keeley & Syphard, 2021; Li et al., 2021; Mass et al., 2021) ravaged vast areas, resulting in substantial economic losses and severely impacting air quality across the region. Similarly, the Canadian wildfires of 2023 (Jain et al., 2024) were unprecedented in scale, causing widespread destruction and contributing to hazardous air pollution that affected millions of people. The consequences extend beyond immediate fire damage; they encompass long-term effects on biodiversity, ecosystem services, and public health. Due to global warming, the unpredictability and severity of wildfires are expected to grow, underscoring the urgent need for comprehensive strategies to mitigate their impacts and adapt to this evolving challenge. Aerosol particles of wildfire smoke, often submicron in size, scatter solar radiation through what is known as the aerosol direct effect (Twomey, 1977). This scattering diminishes the amount of solar energy reaching the Earth's surface, leading to lower air temperatures in the lower troposphere, as highlighted by various studies (Jung et al., 2019; Levy et al., 2013). Wildfire smoke also significantly influences the atmosphere indirectly by increasing aerosol concentrations, which subsequently affect cloud formation and lifetime (Grell et al., 2011; Li et al., 2024).

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Usually, aerosol climatology is utilized in the weather prediction models. For example, ECWMF IFS applied the Copernicus Atmosphere Monitoring System aerosol climatology (Bozzo et al., 2020). Cheng and Yang (2023) implemented the MERRA2 (Ronald et al., 2017) aerosol climatology into the Unified Forecast System (UFS), which serves as a valuable aerosol resource for both global and regional modeling applications. However, these aerosol climatologies will miss the wildfire events. Recently, NOAA developed a new experimental NWP model, the Rapid Refresh Forecast System (RRFS) version 1 (RRFS.v1), which serves as the regional component of the Unified Forecast System (UFS; https://ufscommunity.org/). Because of the interactive and strongly coupled nature of atmospheric chemical and physical processes, it is natural to allow for the smoke, dust and other chemical modules' inline coupling in the physics suite. We have integrated smoke and dust modeling into the RRFS. v1 using the Community Common Physics Package (CCPP; Bernardet et al., 2024) and developed the RRFS-SD v1 model for this purpose. This study aims to evaluate the performance of wildfire smoke enhancing aerosol direct feedback in the RRFS-SD v1 model during the extensive wildfire season of September 2020 in the United States. Details on the model and experimental design can be found in Section 2, with results presented in Section 3. The summary and conclusions are discussed in Section 4.

2. Model Description and Experimental Design

2.1. Rapid Refresh Forecast System–Smoke and Dust (RRFS-SD)

The host model for this study is the RRFS, a state-of-the-art, convection-allowing, ensemble-based data assimilation and forecasting system based on the UFS framework. RRFS employs the e Finite-Volume Cubed-Sphere (FV3) nonhydrostatic dynamical core, which utilizes a cubed-sphere grid and a Lagrangian vertical coordinate system (Lin, 2004). The coupling of physical processes to the dynamical core is facilitated through the Common Community Physics Package (CCPP), as outlined by Heinzeller et al. (2023). The physics suite incorporates several advanced physics schemes: the Mellor-Yamada-Nakanishi-Niino eddy diffusivity-mass flux (MYNN-EDMF) scheme (Olson et al., 2019) for modeling the planetary boundary layer (PBL) and shallow convection; the aerosol-aware double-moment microphysics scheme developed by Thompson and Eidhammer (2014); the Grell-Freitas (GF) deep convection scheme (Freitas et al., 2021; Grell & Freitas, 2014); the RUC Land Surface Model (Smirnova et al., 2016); and the Rapid Radiative Transfer Model for GCMs (RRTMG; Mlawer et al., 1997; Mlawer et al., 2016) for both shortwave and longwave radiative processes.

Given the intricate interplay between atmospheric chemistry and physics in the atmosphere, it is essential to allow modules related to smoke, dust, and other chemical constituents to be directly called in the physics suite. Thus, the biomass burning and dust emissions and other processes are integrated as physics subroutines within the CCPP framework. There are three distinct aerosol tracers: smoke resulting from biomass burning, as well as fine and coarse dust particles from dust emissions. The model accounts for various aerosol processes, including dry deposition, large-scale wet deposition, an hourly fire weather potential index (HWP), and smoke plume injections (Freitas et al., 2006). The mixing of aerosols within the PBL is through the MYNN PBL scheme, while convective transport and wet deposition processes are resolved using the GF convection scheme. Furthermore, the model incorporates sea-salt and anthropogenic emissions, which are crucial for investigating potential aerosol indirect feedback effects in future studies.

2.2. Experimental Design

The model domain covers the Contiguous United States (CONUS) with 65 vertical levels and 3 km horizontal resolution. The study period is from 1 September 2020 to 20 September 2020. The Regional ABI and VIIRS fire Emissions (RAVE, Li et al., 2022) hourly biomass-burning emissions are ingested into the model. The initial and boundary conditions of meteorological fields and smoke are from the 13 km Rapid Refresh (RAP, https://rapidrefresh.noaa.gov/; Benjamin et al., 2016) analysis over North America.

We conducted two sets of model simulations with RRFS-SD. The CTL run only applies the MERRA2 aerosol climatology for radiation. For the EXP run, the smoke and dust aerosols are added on top of the MERRA2 climatology as aerosol anomalies, thus the radiation processes are aware of smoke and dust. Since the dust emissions were insignificant during this period over the northwestern US, here we focus on the smoke direct feedback only. Extinction, scattering, single scattering albedo, and asymmetry factor in each solar spectral band are from the look-up tables with MERRA-2 aerosol climatology. More details of the treatments of MERRA2 aerosol climatology within the RRTMG shortwave and longwave radiation are provided by Cheng and

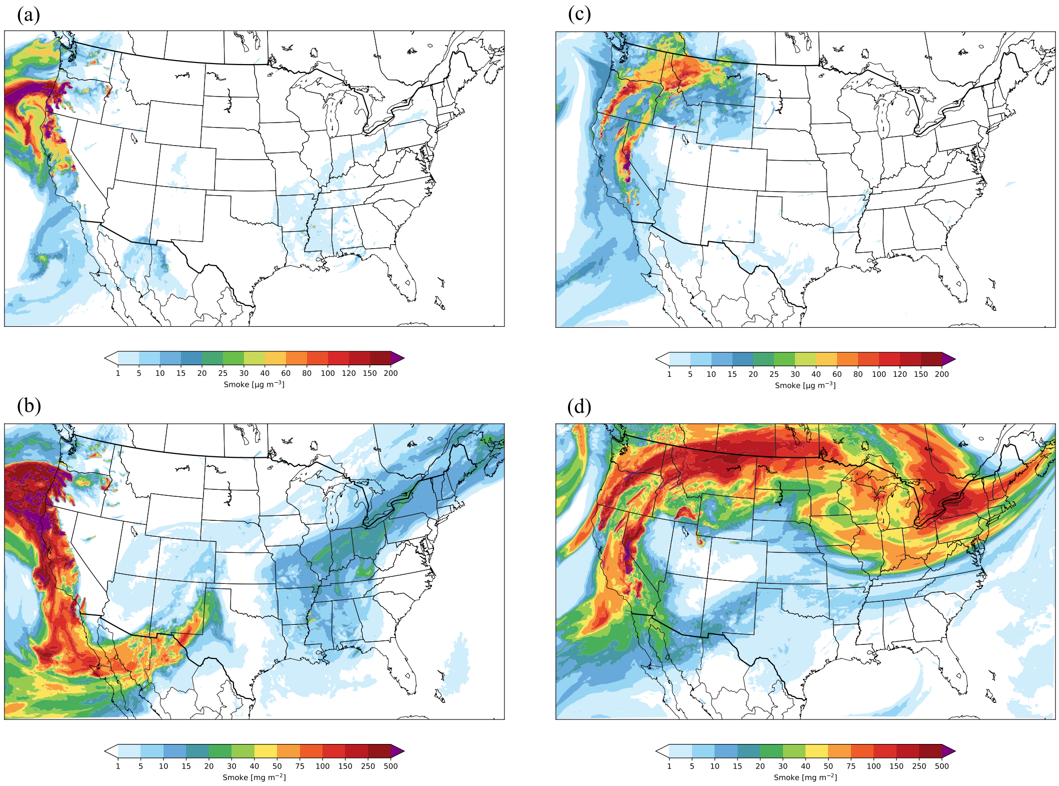

Figure 1. The (a) near-surface smoke (ug m^{-3}), and (b) the vertically-integrated smoke (mg m^{-2}) on 00 UTC 10 September 2020, and the (c) near-surface smoke (ug m^{-3}); and (b) the vertically-integrated smoke (mg m^{-2}) on 00 UTC 15 September 2020.

Yang (2023). The atmospheric fields are initialized at 00Z UTC every day from RAP analysis, since the meteorology data assimilation was not applied in this study. The model ran for 24 hr initialized at 00Z each day, then the smoke and dust tracers cycled for the next day. Lateral boundary conditions for the smoke tracer are initialized from RAP-Smoke analysis. Here, we use the model output after 7 days as spin-up in our analysis, and the verification is limited over the land of CONUS.

3. Results

3.1. Smoke Concentrations and Aerosol Optical Depth (AOD)

Figure 1a shows surface smoke in 00Z on Sept 10th, 2020. The surface smoke is distributed over the coastal areas of North California, and Oregon. The vertically integrated smoke (Figure 1b) spreads across the entire west coastal region of CONUS, reaching Baja California and Texas due to the southeastward near surface coastal winds and a cyclone over the western CONUS. By 00Z Sept 20th, 2020, there is significant surface smoke over California, Oregon, Washington, Idaho, and Montana (Figure 1c). The extensive vertically integrated smoke covers the western CONUS, its northern boundaries, and extends into the northeastern CONUS due to the prevailing westerly winds (Figure 1d).

At 00Z on 10 September 2020, there is a distribution of AOD with a magnitude larger than 1 over the western CONUS as observed by the VIIRS satellite observation (Figure 2a), and ECMWF reanalysis (Figure 2b). However, this feature is not present in the CTL run (Figure 2c). In contrast, the EXP run with smoke feedback to radiation well captures this AOD feature (Figure 2d). At 00Z 20 September 2020, a strong AOD distribution is evident over the western CONUS, northern CONUS, and northeastern CONUS from VIIRS satellite observation (Figure 2e). The AOD from ECMWF reanalysis (Figure 2f) is similar to that from VIIRS although with weaker values over the northeastern CONUS. None of these AOD features are observed in the CTL run without smoke

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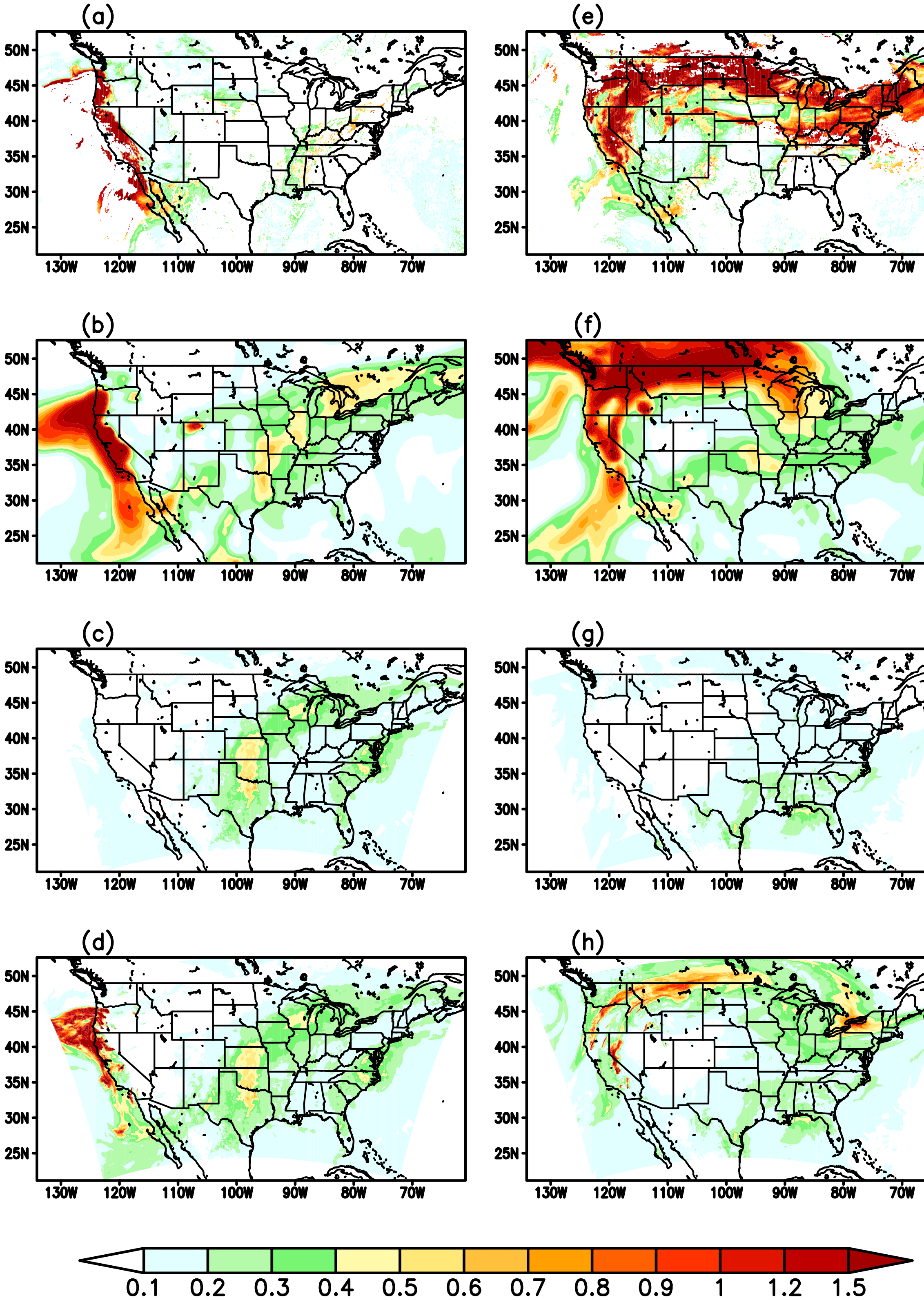

Figure 2. The 550 nm Aerosol Optical Depth (AOD) on 00 UTC 10 September 2020 from (a) VIIRS satellite observation, (b) ECMWF Copernicus Atmosphere Monitoring System (CAMS) aerosol reanalysis, (c) CTL, and (d) EXP; and the 550 nm AOD on 00 UTC 15 September 2020 from (e) VIIRS satellite observation, (f) ECMWF CAMS aerosol reanalysis, (g) CTL, and (h) EXP.

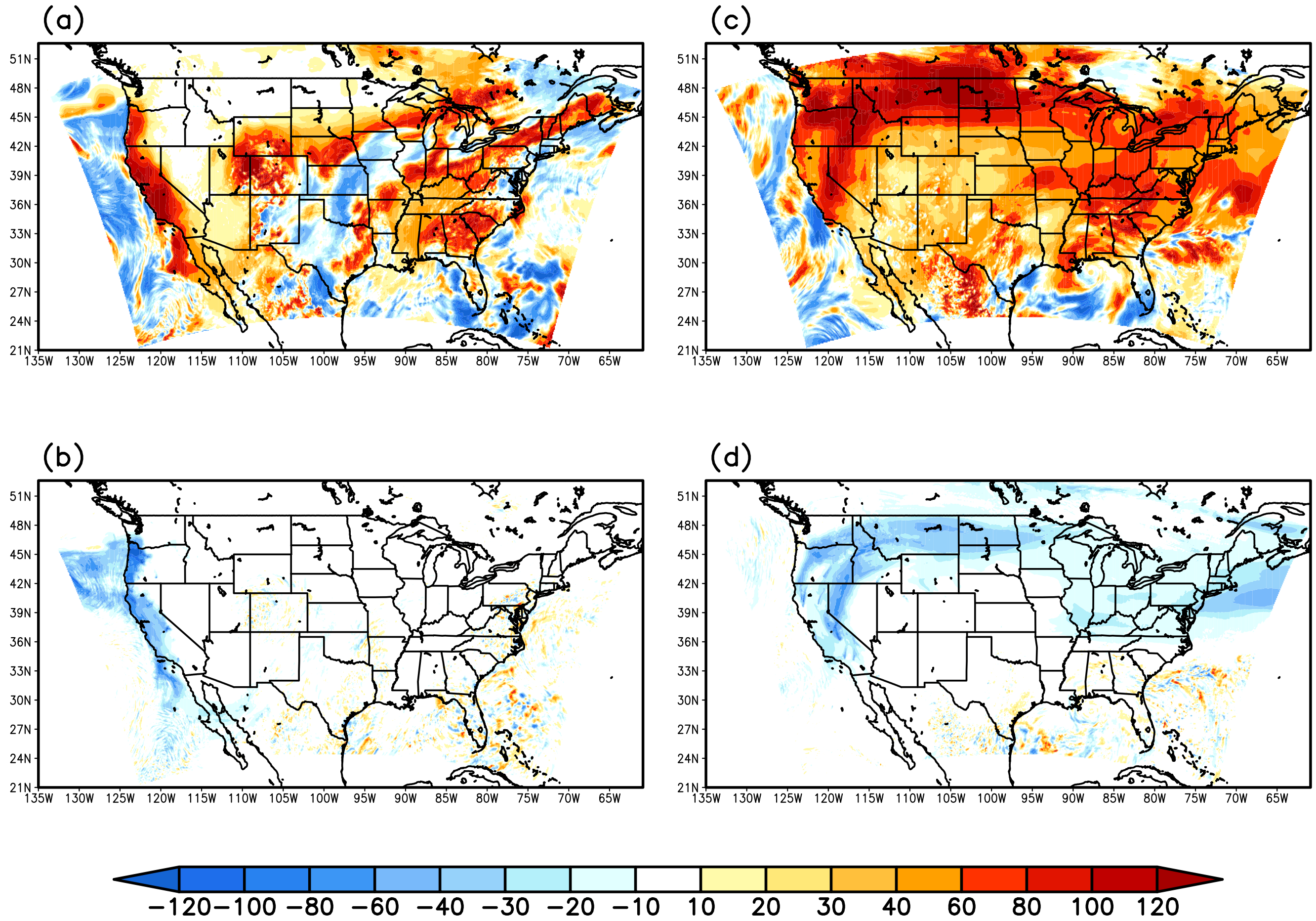

Figure 3. The differences in daily mean surface downward shortwave radiation (W m^{-2}) on 10 September 2020 between (a) CTL and CERES observation, and (b) EXP and CTL; the difference in daily mean surface downward shortwave radiation (W m^{-2}) on 15 September 2020 between (c) CTL and CERES observation, and (d) EXP and CTL.

feedback (Figure 2g), while the EXP run with smoke feedback (Figure 2h) captured these AOD patterns, albeit with weaker magnitudes.

3.2. Meteorological Fields

We focus on studying the impacts of smoke aerosol direct feedback on near surface meteorological fields. Figure 3a shows the daily mean surface downward shortwave radiation (SFCDSW) bias from the CTL run against CERES satellite observation on Sept 10, 2020. The CTL exhibits a strong positive SFCDSW bias over the western CONUS, which is significantly reduced in the EXP run (Figure 3b). On 20 September, 2020, an even more severe positive SFCDSW bias is evident over the entire CONUS domain in the CTL run (Figure 3c). The EXP run shows a significant reduction in bias over western, northern, and northeastern CONUS (Figure 3d).

The 2-m air temperature (T2m) and 10-m wind speed (WSD10 m) are verified against ground observations from September 1 to 20 September 2020, using the NOAA Global Systems Laboratory's Model Analysis Tool Suite (MATS, https://gsl.noaa.gov/mats/). The time series of bias and root mean square error (RMSE) for T2m and WSD10 m over northwestern CONUS at 1p.m. Local solar time are presented in Figure 4. The CTL run is red, while the EXP run is in blue. The average T2m bias (Figure 4a) and RMSE (Figure 4b) in the CTL run are 0.72℃ and 2.92℃ respectively, and are significantly reduced to 0.36℃ and 2.57℃ in the EXP run. Similarly, the average WSD10 m bias (Figure 4c) and RMSE (Figure 4d) in the CTL run are 0.35 m/s and 3.17 m/s respectively, and also exhibit notable reductions in the EXP run, decreasing to 0.27 m/s and 3.10 m/s.

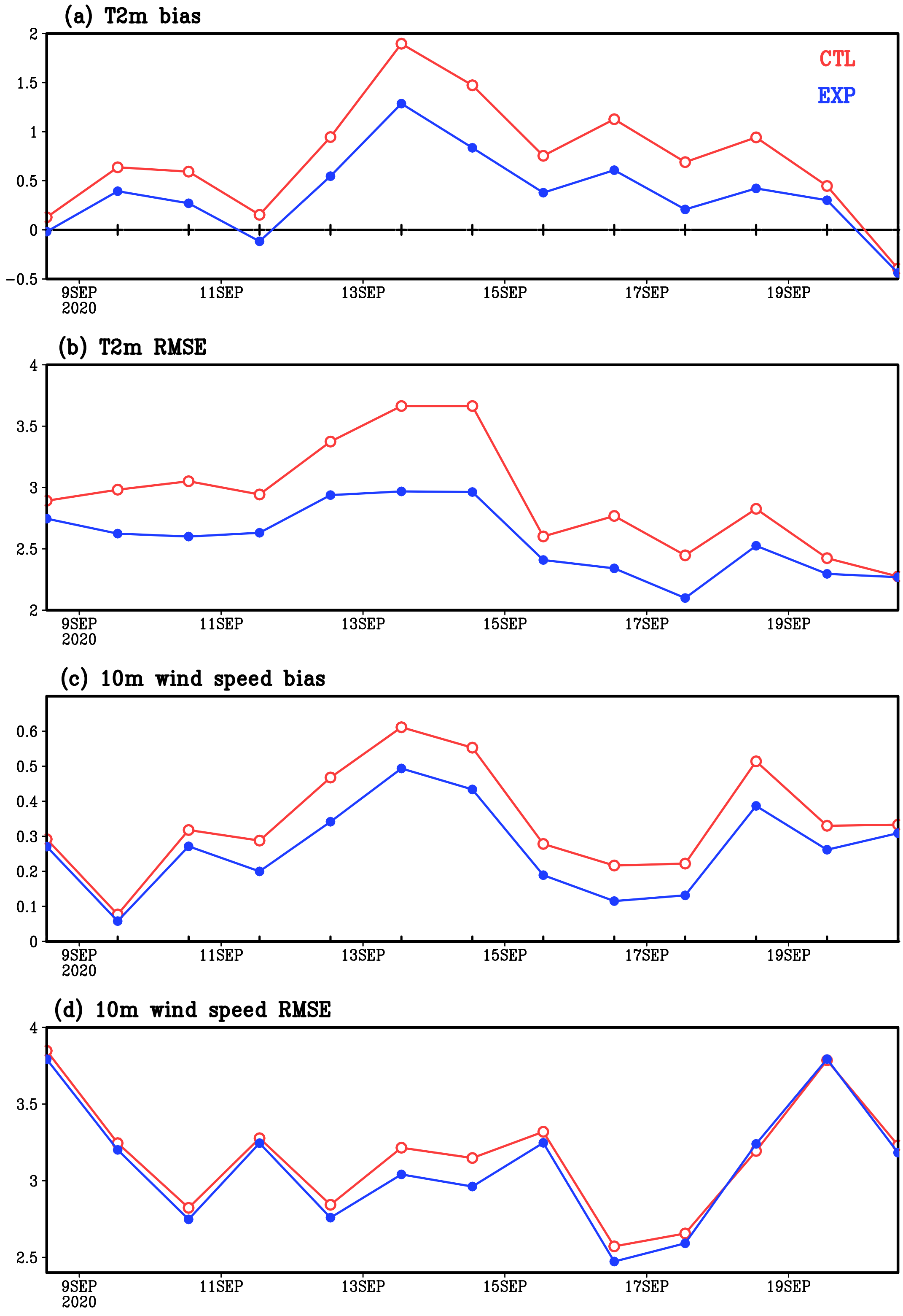

Figure 4. (a) 2 m air temperature bias (℃), (b) 2 m air temperature root-mean-square-error (℃), (c) 10m wind speed bias (m/s), and (d) 10m wind speed root-mean-square-error (m/s) against station observation over Northwest CONUS at 1p.m. local time during 20200908–20200920. The run without and with smoke/dust feedback to radiation are in red and blue, respectively.

4. Summary and Conclusions

We developed the RRFS-SD fire weather and smoke forecast model as part of NOAA's next-generation RRFS. v1 storm-scale weather forecast model. Smoke, and dust emissions, as well as fire plume-rise, are incorporated into the RRFS as physics subroutines within the CCPP framework. By treating smoke and dust emissions as physical processes, they are tightly coupled with other physics parameterizations. For example, planetary boundary transport and mixing are handled through the MYNN PBL parameterization, while the convective transport and wet deposition of smoke and dust aerosols are included in the GF convection scheme. With this implementation, we are able to estimate the smoke and dust aerosol direct feedback on radiation. At this point, the model does not include any anthropogenic or biogenic emissions, and assimilation of AOD.

We designed two sets of experiments to study the effects of smoke aerosol direct feedback to numerical weather prediction during September 2020, a period marked by extreme wildfires in the western United States. The extreme aerosol loadings impacted solar radiation and cloud microphysics across North America for multiple days. The first experiment, the CTL run, does not incorporate forecasted smoke aerosol feedback on radiation processes. For the experimental run (EXP) forecasted smoke and dust aerosol feedback to radiation is included. The RRFS-SD simulates the surface smoke distribution over the western coastal areas of CONUS, extending to the northeast CONUS.

At 00Z on 10 September 2020, high aerosol loading is observed over the western CONUS from both VIIRS satellite observation and ECMWF reanalysis. By 00Z on 20 September 2020, significant AOD distribution is noted over the western, northern, and northeastern CONUS (Figure 2f). These AOD features are not observed in the CTL run, whereas the EXP run well captures these AOD features although with lower magnitude. It is important to note that RRFS-SD is just a simple smoke model without any chemistry processes or aerosol data assimilation. A strong positive bias in surface downward shortwave radiation is observed in the CTL run over the western CONUS on 10 September 2020, and this bias is significantly reduced in the EXP run. On 20 September 2020, the CTL run showed a strong positive SFCDSW bias, which is notably reduced in the EXP run over the western northern, and northeastern CONUS. The 2-m air temperature and 10-m wind speed are verified against station observations in September. The T2m bias and RMSE in the CTL run are significantly reduced in the EXP run. Similarly, the WSD10 m bias and RMSE from the CTL run also exhibit significant reductions in the EXP run.

In this study, the numerical weather prediction of RRFS. v1 is improved by including the aerosol direct feedback from smoke and dust. More comprehensive evaluations of the RRFS-SD model will be presented in our future work. We are also attempting to replace the MERRA2 climatology with a more accurate forecast of aerosols, and include the direct and semidirect radiative feedback as well as the interaction of aerosols with precipitation physics (the indirect feedback) in the UFS modeling system.

Data Availability Statement

The source code for the RRFS-SD v1 is available at https://github.com/ufs-community/ufs-weather-model/tree/production/RRFS.v1. The aerosol reanalysis of ECMWF-CAMS is from https://www.ecmwf.int/en/research/climate-reanalysis/cams-reanalysis. The VIIRS observation is from http://air.csiss.gmu.edu/yli/paper_data/viirs/. The CERES radiation flux observation is available at https://ceres-tool.larc.nasa.gov/ord-tool/jsp/SYN1deg-Ed41Selection.jsp. The MATS verification is available at https://gsl.noaa.gov/mats/.

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