Improving WRF-Chem Meteorological Analyses and Forecasts over Aerosol-Polluted Regions by Incorporating NAAPS Aerosol Analyses

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ABSTRACT: When unaccounted for in numerical weather prediction (NWP) models, heavy aerosol events can cause significant unrealized biases in forecast meteorological parameters such as surface temperature. To improve near-surface forecasting accuracies during heavy aerosol loadings, we demonstrate the feasibility of incorporating aerosol fields from a global chemical transport model as initial and boundary conditions into a higher-resolution NWP model with aerosol–meteorological coupling. This concept is tested for a major biomass burning smoke event over the northern Great Plains region of the United States that occurred during summer of 2015. Aerosol analyses from the global Navy Aerosol Analysis and Prediction System (NAAPS) are used as initial and boundary conditions for Weather Research and Forecasting Model with Chemistry (WRF-Chem) simulations. Through incorporating more realistic aerosol direct effects into the WRF-Chem simulations, errors in WRF-Chem simulated surface downward shortwave radiative fluxes and near-surface temperature are reduced when compared with surface-based observations. This study confirms the ability to decrease biases induced by the aerosol direct effect for regional NWP forecasts during high-impact aerosol episodes through the incorporation of analyses and forecasts from a global aerosol transport model.

KEYWORDS: Aerosol radiative effect; Aerosols/particulates

1. Introduction

Observational-based studies have shown that the presence of thick aerosol plumes can significantly attenuate surface-reaching solar energy, thereby altering the heat budget and, perhaps, regional weather patterns. For instance, noticeable high biases in numerical weather prediction (NWP) model forecast near-surface air temperatures have been reported with the presence of heavy smoke plumes (e.g., Westphal and Toon 1991; Robock 1991; Zhang et al. 2016). Despite demonstrated impacts evidenced from these observational-based studies, aerosol effects are largely excluded from NWP forecasts because the inclusion of aerosols is computationally expensive. Nevertheless, some operational centers have recently identified aerosol impacts as a problem to forecasts and are currently working toward the incorporation of fully interactive aerosol components into NWP models. For example, prognostic dust aerosols have been incorporated into the Met Office's Unified Model for weather forecasts (Mulcahy et al. 2014). Additionally, the impact of aerosols on subseasonal forecasts was also investigated using the Integrated Forecast System for the European

Centre for Medium-Range Weather Forecasts (ECMWF-IFS; Benedetti and Vitart 2018).

While NWP systems with fully interactive aerosol components may be the long-term goal, the impacts of aerosols on short-range weather forecasts are often only noticeable for regional and temporally sporadic heavy aerosol events such as biomass burning events or dust plumes. Between the potentially unnecessary computational expense and possibly limited improvement to forecast skill, it may be counterproductive at present to fully incorporate aerosol effects into NWP models for regions and seasons with climatologically low aerosol loadings (e.g., Zhang et al. 2016). As a computationally cheaper alternative, it is desirable to only include aerosol effects for seasons where heavy aerosol events are likely or when sporadic individual aerosol events impact a region. Indeed, from a medium-range weather point of view, significant continental-scale biomass burning, such as that of the midlatitude and boreal regions, have the ability to disrupt forecasts over large areas (e.g., Westphal and Toon 1991; Robock 1991; Zhang et al. 2016).

To alleviate the computational expense of continuous inline aerosol modeling, we present a method by which aerosol loading is initialized and advected into the regional domain of an NWP model using aerosol forecasts from a lower cost operational global chemical transport model (CTM). Not only are aerosol forecasts and analyses from global offline CTMs computationally inexpensive and serve their purposes for operational aerosol, air quality, and visibility forecasts (e.g., Rubin et al. 2017; Zhang et al. 2008), but forecasts are also generated before the mesoscale models are initialized. Thus, a detected event can “trigger” and initialize inline aerosol impacts on mesoscale models with smaller domains. To demonstrate, we

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FIG. 1. True-color *Terra* MODIS imagery from 28 Jun to 1 Jul 2015 over the NGP region. The images are obtained from the NASA Worldview site (<https://worldview.earthdata.nasa.gov/>).

have selected an aerosol episode over the northern Great Plains (NGP) of the United States in 2015 for examining forecast improvements for the proposed method. Here, we use the Navy Aerosol Analysis and Prediction System (NAAPS; Lynch et al. 2016), which is a forecast-oriented offline chemical transport model driven by meteorological fields from the Navy Global Environmental Model (NAVGEM; Hogan et al. 2015). The NWP model used is the Weather Research and Forecasting (WRF) Model with Chemistry (WRF-Chem; Skamarock et al. 2008; Grell et al. 2005; Fast et al. 2006; Peckham et al. 2011; Powers et al. 2017). Although WRF-Chem has the capability of accounting for direct and indirect aerosol impacts on weather, we note that only the aerosol direct effect is included in this study.

This study is organized as follows: Sections 2 and 3 discuss the models and datasets used as well as the methods behind this study. Results are shown in section 4, and section 5 summarizes major conclusions of this study.

2. Datasets and models

To evaluate the feasibility of increasing regional forecast accuracy by using global CTM aerosol data as initial and boundary conditions, we focus our study on an extreme smoke event that occurred in the NGP region of the United States during a period from 28 June to 4 July 2015 (Fig. 1). This event captures a situation in which a subcontinental smoke plume

had substantial impacts on temperature forecasts despite the sources being well outside the study region. A more in-depth analysis and impact is provided by Zhang et al. (2016). The heavy smoke aerosol loading associated with this event originated from lightning-induced wildfires in the Northwest Territories and northern Alberta and Saskatchewan in Canada. Smoke began advecting over the Dakotas and Nebraska on 28 June 2015. An extreme amount of smoke was rapidly transported into the Upper Midwest and Upper Mississippi and Ohio River valleys throughout 29–30 June, with the plume's edges reaching as far east as the Carolinas and Georgia by 30 June. It was during this time that a significant aerosol optical depth (AOD) of more than 3 (550 nm) was recorded by the Grand Forks, North Dakota, Aerosol Robotic Network (AERONET) station. Although a large amount of smoke was still present in central Canada and the United States during the first week of July, the plume structure became more diffuse as a major weather pattern shift occurred and fire numbers and intensity had begun to slowly diminish.

In this study, the WRF-Chem NWP system is used to simulate the smoke event. Aerosol concentration data from the NAAPS reanalysis are provided to WRF-Chem in the form of initial and boundary conditions. Emission sources are not initialized within the domain, as for this case, emissions within the domain are negligible relative to the dominant biomass burning sources being well outside of the WRF-Chem domain. Meteorological initial and boundary conditions for

the WRF-Chem simulations are from North American Mesoscale Forecast System (NAM) analysis data. NAM forecast data are also used in a separate experiment to simulate a more operational environment. Due to the study domain being largely limited to surface observations for the study period, emphasis is given to evaluate modeled near-surface properties such as temperature, downwelling shortwave radiation, and wind speed.

a. WRF-Chem

The WRF Model is a mesoscale NWP model designed for providing operational weather forecasts as well as for performing atmospheric-related research (Skamarock et al. 2008). Model version 3.9.1.1 is used in this study with the Advanced Research version of WRF (ARW) dynamical core.

The WRF-Chem simulation period of interest begins at 0000 UTC 28 June 2015 prior to heavy smoke aerosol loading entering the study domain and continues through 0000 UTC 1 July 2015 after the peak of the smoke event occurred in eastern North Dakota. This allows approximately 12 h of model spinup before the smoke plume advects into the region during the overnight hours between 28 and 29 June 2015. Still, as optimal spinup time for WRF is phenomena and domain dependent, uncertainty may exist with respect to spinup time (e.g., Kleczek et al. 2014; Bonekamp et al. 2018). The model domain contains 100 by 100 horizontal grid points at 12-km grid spacing that is centered in southeastern North Dakota (40.32°–51.11°N, 89.21°–105.92°W). In the vertical direction, terrain-following sigma coordinates are utilized with 40 layers. A further summary of model configuration is provided in Table 1. Parameterization schemes and model configurations used in the study, including microphysics, radiation, planetary boundary layer, cumulus, land surface model, aerosol, and dry deposition schemes, are summarized in Table 2.

In addition to the meteorological simulations provided by ARW, atmospheric chemistry is included in these simulations using the WRF-Chem package (Grell et al. 2005; Fast et al. 2006; Peckham et al. 2011; Powers et al. 2017). The ARW system built with the WRF-Chem package used in this study is simply referred to as WRF-Chem. To include the aerosol direct effect, this study utilizes the Georgia Institute of Technology/Goddard Global Ozone Chemistry Aerosol Radiation and Transport model (GOCART) aerosol scheme (Ginoux et al. 2001) and the Rapid Radiative Transfer Model for GCMs (RRTMG) longwave and shortwave radiation parameterizations (Iacono et al. 2008). Note that the RRTMG scheme is able to simulate direct aerosol effects through direct coupling with the GOCART aerosol module (UCAR 2017). As previously mentioned, the indirect effect is not investigated within this study.

b. NAAPS

The NAAPS model is an operational aerosol transport model that produces forecasts of three-dimensional aerosol concentrations on a global scale for four aerosol species including anthropogenic and biogenic fine (ABF) aerosols, smoke, sea salt, and dust (Lynch et al. 2016). Meteorology is provided to NAAPS by the NAVGEM, which is an operational global weather prediction system produced by the United States Navy (Hogan et al. 2015). Research-mode NAAPS simulations used

TABLE 1. WRF-Chem meteorological configurations.

Label	Description
Model	WRF-Chem, version 3.9.1.1
Simulation period	28 Jun–1 Jul 2015
Horizontal resolution	12 km
Dimensions (x, y)	100, 100
Vertical levels	40
Meteorological boundary conditions	NCEP NAM 12-km analysis
Chemistry boundary conditions	NAAPS
Boundary conditions interval	10 800 s (3 h)
Time step	60 s
Model top	5000 Pa (50 hPa)
Damping layer	5000 m

in this study have $1^\circ \times 1^\circ$ (latitude/longitude) horizontal resolution with 25 vertical sigma-pressure levels. Last, NAAPS analyses and forecasts are assisted with the assimilation of quality-assured and quality-controlled (QA/QCed) *Terra* and *Aqua* Moderate Resolution Imaging Spectroradiometer (MODIS) AOD data (e.g., Levy et al. 2013; Zhang and Reid 2006). For these research runs, QA/QCed *Terra* Multiangle Imaging Spectroradiometer (MISR) aerosol products are assimilated as well (Kahn et al. 2010; Shi et al. 2014). Note that both *Terra* and *Aqua* are sun-synchronous, near-polar-orbiting satellites, and, thus, each sensor provides approximately one overpass per day over the study region (Zhang et al. 2008, 2014). The NAAPS system has been shown to perform well over the eastern United States and North American boreal forests with R^2 values (correlation coefficient squared) at or above 0.84 and 24-h AOD forecast biases of 0.016 (Rubin et al. 2017).

To better represent the smoke event, NAAPS simulations are adjusted based on observed aerosol properties. In particular, the smoke injection height within the emission area in central Canada has been set to between 2 and 3 km based on lidar observations from Cloud–Aerosol Transport System (CATS) on board the International Space Station (Yorks et al. 2014). Next, the emission source smoke flux was arbitrarily doubled to nudge the NAAPS-simulated smoke plumes toward the ground-based AOD observations at the Grand Forks AERONET site (47.912°N, 97.325°W) as discussed in section 3. The AOD data assimilation frequency is increased from every 6 h to every 3 h to best capture the constantly evolving smoke plume.

NAAPS-simulated smoke aerosols are represented by four biomass burning related aerosol species in the GOCART aerosol scheme implemented in WRF-Chem: hydrophobic black carbon, hydrophilic black carbon, hydrophobic organic carbon, and hydrophilic organic carbon. Therefore, NAAPS smoke aerosol data must be converted into the four smoke aerosol categories for ingest into WRF-Chem. For this conversion, the ratio of black carbon to organic carbon in a smoke plume is assumed to be 1:7 (Liousse et al. 1996). Black carbon is assumed to be 80% composed of hydrophilic black carbon particles, with the remaining 20% being hydrophobic; organic carbon is assumed to be 50% composed of hydrophilic organic carbon particles, with the remaining 50% being hydrophobic

TABLE 2. WRF-Chem model parameterizations.

Option	Scheme	Reference
Microphysics	Lin et al.	Chen and Sun (2002)
Longwave radiation	RRTMG	Iacono et al. (2008)
Shortwave radiation	RRTMG	Iacono et al. (2008)
PBL	Yonsei University (YSU)	Hong et al. (2006)
Cumulus	Kain–Fritsch	Kain (2004)
Land surface model	Noah	Chen and Dudhia (2001)
Aerosol mechanism	GOCART simple aerosol	Ginoux et al. (2001)
Aerosol model	GOCART	Ginoux et al. (2001)
Dry deposition	Included	—

(Cooke et al. 1999). A sensitivity study was conducted using the Liou et al. (1996) ratio of 1:8.2 (following a range from 6.9 to 8.2); however, results were consistent with the 1:7 ratio.

c. NAM analyses and forecasts

The 12-km NAM analyses are used as meteorological initial and boundary conditions for the WRF-Chem simulations (<https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/north-american-mesoscale-forecast-system-nam>; last accessed 22 April 2020). NAM analyses cover the continental United States with a 12-km spatial resolution and are available every 6 h (0000, 0600, 1200, and 1800 UTC) for 40 pressure levels. In addition to using the NAM Analysis data, a forecast sensitivity study using NAM Forecast data is conducted to simulate an operational environment (see section 4). WRF-Chem forecasts are initialized every 6 h from 0000 UTC 28 June 2015 to 0000 UTC 29 June 2015 using the NAM 12-km forecast data archived by the National Centers for Environmental Information as initial and boundary conditions.

d. ASOS and NDAWN data

Surface meteorological observations from the Automated Surface Observing System (ASOS) and North Dakota Agricultural Weather Network (NDAWN) observation networks are used to evaluate WRF-Chem simulations. The ASOS station data provide measurements of 2-m air temperature and 10-m wind speed. The ASOS data are obtained from the Iowa State University Environmental Mesonet (<https://mesonet.agron.iastate.edu/>; last accessed on 22 April 2020). A total of 214 ASOS stations are used within the study domain. NDAWN observations (<https://ndawn.ndsu.nodak.edu/>; last accessed 23 July 2020) are available at weather stations throughout North Dakota and selected sites in Montana and Minnesota towns near the North Dakota border. Observations of surface downward shortwave radiative fluxes from NDAWN provide a validation set for the North Dakota region of the study domain. NDAWN 2-m air temperature is also used for simulation evaluation. Note that, while wind speed and direction data are also available from the NDAWN data, they are recorded at 3 m as opposed to 10 m as reported by ASOS. Thus, NDAWN wind data are not used for evaluation purposes. A total of 75 NDAWN stations are used in this study. Figure 2 shows the spatial distribution of the ASOS and NDAWN stations used for evaluation.

e. AERONET data

NAAPS and WRF-Chem simulated AOD values are also intercompared with AERONET observations recorded at four AERONET sites located within the study domain: Grand Forks (47.912°N, 97.325°W); Sioux Falls, South Dakota (43.736 48°N, 96.625 99°W); Woodworth, North Dakota (47.128 23°N, 99.241 36°W); and Ames, Iowa (42.021 36°N, 93.774 78°W). AOD values from the AERONET sites are derived by measuring the attenuated solar energy at seven wavelengths ranging from 340 to 1020 nm using Beer's law (Holben et al. 1998). The cloud-cleared and quality-assured level-2 AERONET data with the version-2 direct sun algorithm are used. The accuracy of AERONET AODs are on the order of 0.01–0.02 (Eck et al. 1999). Spatial distribution of the AERONET sites can be seen in Fig. 2.

f. MODIS aerosol data

The level-2 combined Dark Target (DT; Levy et al. 2013) and Deep Blue (DB; Sayer et al. 2013) aerosol retrievals from MODIS aboard the *Terra* and *Aqua* satellites are used for the

FIG. 2. The ASOS (yellow circles), NDAWN (pink triangles), and AERONET stations (white stars) used in this study, shown over the WRF-Chem model domain.

FIG. 3. Flowchart representing the basic steps for running WRF-Chem with and without NAAPS data. The black-outlined box includes the extra steps necessary for including NAAPS aerosol data in WRF-Chem modeling.

intercomparison of WRF-Chem-simulated AOD over the study region. The DT/DB combined product for *Terra/Aqua* MODIS aerosol retrievals are available at a spatial resolution of 10 km. The expected error for DT overland AOD retrievals is reported to be $\pm(0.05 + 0.15 \text{ AOD})$ (Levy et al. 2013). The expected uncertainty for DB retrievals is on the order of $0.05 + 0.2 \text{ AOD}$ (Sayer et al. 2013).

3. Methods

a. Experiment design

The impacts of the smoke aerosol plume on WRF-Chem forecasts are studied by examining the differences in WRF-Chem simulations with (i.e., chemistry simulation) and without (i.e., control simulation) the aerosol direct effect as illustrated in Fig. 3. For the control simulations, WRF-Chem is run without inclusion of chemistry or aerosol data nor aerosol/chemistry interactions. Thus, while the system is built to include the WRF-Chem package, the control run does not call this package and is identical to WRF without the chemistry package. Geological and meteorological data are preprocessed and

reformatted using the WRF Preprocessing System (WPS) for all simulations. Since NAM data are only provided for every 6 h, the WPS performs an interpolation to achieve boundary conditions for every 3 h. For the chemistry simulations, additional steps are taken for inclusion of NAAPS aerosol fields as initial and boundary conditions (see steps outlined by black box in Fig. 3). In this study, aerosol boundary conditions from NAAPS are updated every 3 h. To use NAAPS as the initial conditions, a trilinear spatial interpolation is implemented to interpolate NAAPS aerosol data horizontally and vertically to the WRF-Chem model grid. Concentrations for each of the hydrophobic black carbon, hydrophilic black carbon, hydrophobic organic carbon, and hydrophilic organic carbon are estimated based on the methods described in section 2b.

In addition, the lateral boundary conditions file is modified to include NAAPS aerosol data. Besides the necessary modifications as mentioned in section 2b (i.e., conversion of aerosol mass concentrations to mixing ratio), aerosol mixing ratio tendencies are calculated for each boundary grid point. In this study, the boundary extends five gridpoint rows/columns from the domain edge into the domain space. This boundary contains a “specified zone” where variables are not modified by

the model (i.e., aerosol mixing ratio is always equal to the interpolated NAAPS analysis). For this study, the specified zone is one grid point wide. The remainder of the boundary is used for “relaxation.” That is, boundary conditions from NAAPS are nudged toward model-simulated values in this relaxation zone.

b. Evaluation methods

Model performance is determined by comparing simulated meteorological fields with collocated ASOS and NDAWN observations. Wind speed observations less than 2.5 kt (1 kt $\approx$ 0.51 m s⁻¹) are considered to be light and variable, and these observations are set to zero (Nadolski 1998). Likewise, simulated wind speeds of less than 2.5 kt are also set to zero. WRF-Chem-simulated AOD is verified against AERONET data. Unless specifically mentioned, AOD refers to AOD at 550 nm in this study.

To spatially and temporally collocate WRF-Chem data and near-surface observations, all near-surface observations within ± 15 min of the WRF-Chem simulation hourly output are averaged and used. Note, we also calculated statistics based on a ± 30 -min time window, but changes were negligible. Spatial collocation for comparison with surface-based observations is achieved using bilinear interpolation.

Terra MODIS visible satellite imagery is used as a visual intercomparison of the smoke plume with the WRF-Chem modeled AOD. As pointed out in Zhang et al. (2016), aerosol loadings are likely underreported in MODIS retrievals because of the misidentification of high aerosol loadings as cloud.

4. Results and discussions

In this section, the performance of WRF-Chem using initial and boundary aerosol conditions from NAAPS is investigated through intercomparison of ground-based measurements for both WRF-Chem control and chemistry simulations. Improvements in WRF-Chem-forecast meteorological parameters through the use of NAAPS aerosol data as initial and boundary conditions for aerosol properties are also investigated.

a. Aerosol optical depth analysis

Total column AODs at 550 nm from the NAAPS-reported total column AODs (Figs. 4a–c) are compared to the WRF-Chem chemistry simulation (Figs. 4d–f) for the study domain. After the 12-h spinup time (i.e., at 1200 UTC 28 June 2015), WRF-Chem AOD compares well to NAAPS, though finer-scale features are evident in the WRF-Chem simulation. For example, a vortex-like feature is evident in southwestern Minnesota (Fig. 4d). Additionally, a small band of higher AOD located in central and western South Dakota does not appear in NAAPS. Otherwise, both NAAPS and the WRF-Chem simulated AOD have very similar structure and magnitude.

For the purpose of comparison, Figs. 4g–i show AOD retrievals from the temporally closest overpass of *Terra/Aqua* DT/DB MODIS for the corresponding days. DT/DB MODIS AOD retrievals are unavailable over regions with cloud as well as regions with the densest smoke (as indicated by WRF-Chem chemistry simulation). Regions with dense smoke are likely not

passing QA/QC due to the misclassification as clouds and, thus, are excluded in the aerosol retrieval QA/QC process (Alfaro-Contreras et al. 2016). As such, an attempt can be made to compare both NAAPS and WRF-Chem AODs to *Terra* MODIS in Fig. 4g, and in fact, it appears as if there is smoke aerosol present on the Saskatchewan–Manitoba border where NAAPS and WRF-Chem simulations both show the highest AOD for this time (albeit MODIS having higher AODs than the simulations). Alas, insufficient data are available for the remainder of the study region, thus, rendering the comparisons to MODIS AOD retrievals to be of limited use for 28 June.

At 1500 UTC 29 June 2015, more discrepancies are apparent between the NAAPS (Fig. 4b) and WRF-Chem (Fig. 4e) model simulations of total column AOD as the smoke event nears its optical peak in the NGP. First, an area of enhanced AOD (i.e., >1.0) exists near the northeast Montana–northwest North Dakota border in the WRF-Chem simulation, which is not present in NAAPS. Additionally, a tight band of high AOD (i.e., >3.0) stretches from the Saskatchewan–Manitoba border into eastern North Dakota. While NAAPS does have a band of enhanced AODs in this region, the band is slightly more east by about 0.5° longitude. Likewise, the maximum AOD in the NAAPS analysis (>2.0) is lower than the WRF-Chem simulation. Finer-scale features are present in the WRF-Chem simulation that do not appear in NAAPS (e.g., AOD maxima in northeastern Minnesota). Despite these differences, the structure of the plume is generally similar.

The *Terra* MODIS AOD retrieval in Fig. 4h shows the apparent outline of the smoke plume at 1745 UTC 29 June (the temporally closest MODIS retrieval available). It is important to consider the nearly 3-h difference between the simulations (1500 UTC) and the MODIS AOD retrievals (1745 UTC). Even still, plume structure is relatively similar with the plume extending from the Saskatchewan–Manitoba border into eastern North Dakota. Unlike the simulations, however, the MODIS AOD retrievals show the plume stretching into western Minnesota and eastern South Dakota. Furthermore, MODIS AOD indicates higher AODs on the outskirts of the plume than in the simulations.

By 1800 UTC 29 June, the time of peak-AOD per the Grand Forks AERONET observations (see Fig. 5a), there are similar differences between NAAPS and WRF-Chem-simulated aerosol (Figs. 4c,f, respectively) as compared to 3 h prior (i.e., 1500 UTC). The WRF-Chem-simulated plume remains more longitudinally compressed than, exhibits higher AODs than, and is located approximately 0.5° longitude west of the NAAPS plume. Again, finer-scale features are present such as the local minima/maxima throughout much of Minnesota. Note that despite these differences, the structure of the WRF-Chem simulated plume compares well to visible imagery and AOD retrievals from *Terra* MODIS approximately 15 min prior (i.e., 1745 UTC; Figs. 1b and 4h).

MODIS AOD retrievals for the study region on 29 June are shown in Figs. 4h (*Terra* MODIS at 1745 UTC) and Fig. 4i (*Aqua* MODIS at 1925 UTC). While the two images show small differences between the two overpasses ~ 100 min apart (e.g., location of highest AOD-retrievals in eastern South Dakota), the plume structure is relatively consistent between

FIG. 4. Spatial distributions of (a)–(c) NAAPS total column AOD for the WRF-Chem domain and (d)–(f) WRF-Chem simulated total column AOD from the chemistry simulations for (top) 1200 UTC 28 Jun 2015, (middle) 1500 UTC 29 Jun, and (bottom) 1800 UTC 29 Jun. Also shown are DT/DB MODIS satellite observations of total column AOD for (g) 1700 UTC 28 Jun from *Terra*, (h) 1745 UTC 29 Jun from *Terra*, and (i) 1925 UTC 29 Jun from *Aqua*.

the two overpasses. However, comparisons to the simulations for 1800 UTC 29 June show MODIS AOD retrievals extend farther southeast of the WRF-Chem-simulated plume (Fig. 4f) and with higher AODs at the edges of the plume than the NAAPS-simulated plume (Fig. 4c).

As suggested in Fig. 4, differences exhibited in the simulated smoke plume structure, location, and AOD magnitude between the WRF-Chem and NAAPS simulations can largely be attributed to ingestion of coarser NAAPS aerosol grids at the WRF-Chem boundaries (discussed below) and better resolved horizontal convergence. Specifically, the higher

magnitude AOD within the longitudinally more concentrated plume in the WRF-Chem simulation may be due to better resolved horizontal convergence within the 2–6-km layer containing the smoke plume. Further analysis of WRF-Chem wind fields show enhanced convergence along the long axis of the plume (not shown), which may also account for the location change of the plume between the two simulations. It is worth noting that differences in AOD between NAAPS and WRF-Chem could also be caused by differences in the aerosol optical properties used in NAAPS as compared to WRF-Chem.

FIG. 5. Time series of total column AOD (550 nm) for the WRF-Chem simulation and the AERONET observations from the (a) Grand Forks, (b) Sioux Falls, (c) Woodworth, and (d) Ames sites.

Overall, similar AOD patterns are observable between NAAPS-simulated, WRF-Chem-simulated, and MODIS-retrieved AODs, thereby suggesting that aerosol plumes are reasonably well-represented by both the NAAPS and WRF-Chem chemistry simulations. Still, with much of the MODIS AOD-retrievals missing due to the presence of cloud and/or misclassifications of aerosol as cloud, further analyses are conducted using available AERONET observations.

Time series of WRF-Chem-simulated AOD at the Grand Forks, Sioux Falls, Woodworth, and Ames AERONET sites and observations from the respective AERONET sites are shown in Fig. 5. At the Grand Forks AERONET site (Fig. 5a), WRF-Chem simulation AODs are slightly overestimated for much of the period prior to 0000 UTC 29 June, though both the simulation and observations indicate AOD values near 0.5. Similarly, the Sioux Falls AERONET site (Fig. 5b) indicates the period prior to 0000 UTC 29 June is overestimated with AOD observations of ≤ 0.5 . These early period overestimations may be due to influences from the advection of spatially smoothed NAAPS aerosol plume into the WRF-Chem domain. Conversely, the Grand Forks and Sioux Falls AERONET-reported AODs around 1800 UTC 29 June (3.0–4.0) are greater than that of the AODs simulated by

WRF-Chem (≤ 3.0). While this may be attributable to the ingested NAAPS data, it is of note that a peak in simulated AOD with similar magnitude to that afternoon's AERONET-reported values at both Grand Forks and Sioux Falls AERONET sites happened at ~ 0000 UTC 30 June. As a result, the simulation may have a time lag at this time, which would be consistent with the westward displacement of the smoke plume as seen in the comparison with NAAPS in Fig. 4. However, it must be noted that a limited number of observations inhibits further validation of this hypothesis.

Two additional AERONET sites within the study domain are located in Woodworth and Ames (Figs. 5c,d, respectively). It is worth noting that much of the study domain was under cloud cover on 30 June, thus, limiting the availability of AOD retrievals or observations. Still, Woodworth and Ames AERONET sites are largely located outside of the densest portions of the smoke plume based on qualitative analysis of MODIS satellite imagery. This is evidenced by WRF-Chem-simulated and AERONET-observed AODs in Woodworth being < 2.0 for a majority of the study period. However, AERONET observations are only available for a 6-h period. Furthermore, most of the WRF-Chem-simulated and AERONET-observed AODs are < 1.0 at the Ames AERONET site prior to 30 June.

FIG. 6. (a) Surface downward SW flux for 1800 UTC 29 Jun from the WRF-Chem (a) control simulation and (b) chemistry simulation. (c) Difference in SW flux between WRF-Chem chemistry and control runs. (d) WRF-Chem chemistry simulated AODs. (e) Differences in SW flux between control simulation and NDAWN observations. (f) As in (e), but for the chemistry simulation.

After 0000 UTC 30 June, simulated AODs in Ames hover between 3.0 and 4.0 while AERONET-observed AODs are found to be around 2.5–3.5.

b. Impacts to surface downward shortwave radiative fluxes

As expected, the presence of a significant smoke plume causes simulated surface downward shortwave radiative fluxes (SW flux) to substantially decrease, as shown at 1800 UTC 29 June 2015 in Fig. 6. The WRF-Chem simulated SW flux at 1800 UTC 29 June for the control and chemistry simulations

are shown in Figs. 6a and 6b, respectively. Differences between the control- and chemistry-simulated SW fluxes are shown in Fig. 6c. Higher and relatively uniform SW flux values of around 800–1000 Wm^{-2} are found throughout the domain for the control simulation (except for the speckled areas of cumulus cloud). In comparison, SW flux values from the chemistry simulation outside of the most optically dense smoke are approximately 100–200 Wm^{-2} lower than in the control simulation, thereby suggesting optically thin smoke exists throughout the domain.

Directly beneath the smoke plume, SW flux values from the chemistry simulation as low as $\sim 300\text{--}400\text{ W m}^{-2}$ correspond with maximum differences between the control and chemistry simulations of $\sim 600\text{ W m}^{-2}$. When compared to NDAWN SW flux observations (Figs. 6e–f), the control simulation clearly overestimates SW flux whereas the chemistry simulation compares well. Although some underestimation is present in the thickest portions of the smoke plume, this may be due to underestimation of the aerosol loading, cloud that is not simulated, uncertainties associated with optical properties of smoke in RRTMG, or a combination of these three. The chemistry simulation seems to also be oversuppressing downward SW flux outside of the smoke plume—likely due to an overestimation of smoke throughout the domain. This may be a symptom of ingesting the coarse aerosol fields from NAAPS along the boundaries, as mentioned earlier. Regardless of these differences, the marked improvement in SW flux is encouraging. It is interesting to note that the areal extent and frequency of cumulus clouds are lower in most of the domain of the chemistry simulation. This suggests that the smoke plume may be inhibiting cumulus cloud production (e.g., Ackerman et al. 2000; Koren et al. 2004). However, the impact of aerosols on cloud formation is not a focus of the paper and we will leave the topic for a later study.

Figure 7 shows the time series of SW flux RMSE (Fig. 7a) and mean bias (Fig. 7b) from the WRF-Chem control and chemistry simulations relative to NDAWN observations. Prior to significant transport of smoke into the domain (i.e., 0000–1200 UTC 28 June), similar daytime RMSE values of SW flux are found for both the control and chemistry simulations. After 1200 UTC 28 June, RMSE and mean bias for the two simulations diverge with the chemistry simulation exhibiting $\sim 50\text{ W m}^{-2}$ lower RMSE from 1200 to 1800 UTC and $\sim 50\text{ W m}^{-2}$ higher RMSE through 0000 UTC 29 June. Throughout the 1200 UTC 28 June–0000 UTC 29 June period, the chemistry simulation mean bias is $\sim 100\text{ W m}^{-2}$ more negative than control simulation mean bias. While a negative mean bias is expected given the presence of aerosol decreases SW flux, it seems the chemistry simulation has decreased SW flux too aggressively during the afternoon/evening hours that results in higher RMSEs. By 29 and 30 June, when smoke is optically thickest, daytime RMSE values from the control simulation increased $200\text{--}300\text{ W m}^{-2}$ as compared to RMSE values from 28 June. Comparatively, the chemistry simulation exhibits consistent diurnal cycles of SW flux RMSEs throughout the study period despite the introduction of heavy smoke advection. Interestingly, the chemistry simulation fluxes are low-biased on 29 June (indicative of too much aerosol suppression of SW flux) and high-biased on 30 June (indicative of not enough aerosol suppression of the SW flux). Overall, the stability of the chemistry simulation RMSEs throughout the period suggest that the increases in daytime SW flux RMSE associated with aerosol plumes can be mitigated with the inclusion of aerosol and, by extension, the direct effect.

c. 2-m temperature

The impacts of aerosol radiative effects on WRF-Chem-simulated near-surface temperatures for 1800 UTC 29 June 2015

FIG. 7. (a) RMSEs of surface downward SW flux from WRF-Chem throughout the 72-h WRF-Chem control and chemistry simulations, with red dots being for the control simulation and blue for the chemistry simulation. A total of 75 NDAWN stations are used to calculate the values for each time step. (b) As in (a), but for mean bias.

are shown in Fig. 8. Figures 8a–c are the WRF-Chem-simulated 2-m temperature from the control and chemistry simulations and the difference between the two, respectively. Of note is the substantial decrease in simulated 2-m temperature in areas beneath the optically heaviest smoke when NAAPS aerosol fields are ingested. Eastern North Dakota in particular experiences temperatures $5^{\circ}\text{--}10^{\circ}\text{C}$ cooler in the chemistry simulation. While areas with lower AOD values have smaller temperature differences, these areas are still cooler in the chemistry simulations. Lower temperatures in areas with relatively insignificant amounts of smoke are expected given the earlier mention of optically thin aerosol throughout the domain.

When compared with observations (Figs. 8e–f) under the optically thickest portions of the smoke plume, the chemistry simulation has much smaller, yet still positive/warm, biases compared to the control simulation. Outside of this region, the chemistry simulation exhibits a nearly universal negative/cool bias. Note that a cool bias is present in western North Dakota in both the control and chemistry simulations, though this bias

FIG. 8. As in Fig. 6, but for 2-m temperature. Observations included in (e) and (f) are from both ASOS and NDAWN datasets.

is larger in the chemistry simulation. The influence of the number of cold-biased stations outside of the smoke plume in the chemistry simulation is more clearly captured in Fig. 9. A near-constant 1°C mean cold bias in the chemistry simulation exists from the afternoon of 29 June through the end of the study period despite the slight warm bias for stations most affected by the smoke plume. Interestingly, the previously mentioned lower-then-higher SW flux RMSE comparisons between the chemistry and control simulations on 28 June does not appear to have significant impact on 2-m temperature. We suspect this is due to limited availability of SW flux observations

compared to temperature. Regardless, it is important to note that the chemistry simulation performs much better overall than the control simulation for both RMSE and mean bias despite the cold bias in the chemistry simulation, thereby echoing the results of the SW flux analysis.

d. 10-m winds

The 10-m wind speeds are analyzed for differences between control and chemistry simulations and, then, compared to ASOS observations. The most noticeable difference occurred at 1800 UTC 29 June (i.e., Fig. 10) where the magnitude of

FIG. 9. As in Fig. 7, but for 2-m temperature. The right-hand axis and green bars indicate the number of observations used to calculate the RMSE or ME for that time.

differences in winds for the chemistry simulation are very slightly closer to observations in the Red River valley and northern and central Minnesota relative to the control simulation. This may be attributed to the lower surface temperatures

reducing momentum flux and preventing the typical summer thermals that would otherwise create wind. Aside from the slight improvement to chemistry-simulated wind speeds on the afternoon of 29 June, there is not a particularly apparent pattern for wind speeds.

Figure 11 shows the RMSE (Fig. 11a) and mean bias (Fig. 11b) for wind speed of both control and chemistry simulations evaluated against ASOS 10-m wind speed observations. Minor differences in the RMSE of wind speed are found between the simulations, although the largest RMSE differences are found in the afternoon of 29 June and are on the order of 0.5 kt. This corresponds with a notable decrease in wind speeds, as can be inferred from the mean bias plot (Fig. 11b), again, indicative of reduced momentum flux. Overall, substantial conclusions with regard to the impact of including aerosol via initial and boundary conditions cannot confidently be drawn from this case study.

Differences of wind fields are also analyzed for the control and chemistry simulations at 10 m and 850 hPa (see Fig. S1 in the online supplemental material). Wind differences for the 10-m wind field are around 5 kt at most. However, differences are upward of 10 kt between the control and chemistry simulations at 850 hPa, with the chemistry simulation suggesting higher wind speeds relative to the control. We hypothesize that this phenomenon may be caused by aerosol-induced regional warming as indicated in the next section with regard to Fig. 12. Yet, this topic is outside the scope of this paper, and, thus, we leave the topic for a future analysis.

e. Other meteorological parameters

Validation datasets are not available for vertical cross sections of meteorological profiles for this study. Thus, vertical cross-sections of aerosol extinction, ambient temperature, and ambient water vapor mixing ratio of WRF-Chem simulations are examined through the intercomparison of the WRF-Chem control and chemistry simulations as shown in Fig. 12. These vertical cross sections are for the study domain at approximately a latitude of 48°N at 1800 UTC 29 June when thick smoke plumes are observed.

FIG. 10. Difference in 10-m wind speed between WRF-Chem (a) control simulation or (b) chemistry simulation and observations from ASOS stations at 1800 UTC 29 Jun.

FIG. 11. As in Figs. 7 and 9, but for 10-m wind speed.

Figure 12a shows the vertical cross section of the aerosol extinction coefficient from the WRF-Chem chemistry simulation. A maximum extinction coefficient of approximately 1.5 km^{-1} exists with the plume extending from about 2 to 6 km in altitude and about 102° – 95.5° W longitude. It is interesting to note that warmer temperature (Fig. 12b) and higher water vapor mixing ratio values (Fig. 12c) are observed in locations where peak aerosol extinction coefficient values are found in the WRF-Chem chemistry simulation. These warmer temperatures may be due to absorption of SW radiation by the elevated smoke plumes. While $\sim 4^{\circ}\text{C}$ cooler surface temperatures exist directly beneath the smoke plume, this layer of cooler temperatures does not seem to extend much in the vertical. Conversely, there is a large difference in water vapor mixing ratio at an altitude of approximately 1.0 km underneath the thickest part of the plume, which indicates the chemistry simulation has lower mixing ratio values (e.g., nearly 3.0 g kg^{-1} less) relative to the control simulation. This area of decreased mixing ratios—in accordance with slightly increased mixing ratios at the surface—may be an indicator of the top of the planetary boundary layer (PBL) being lower in the chemistry simulation due to suppressed thermal mixing.

It is difficult to validate PBL height model performance because radiosonde balloon launches are spatially and temporally limited. As a result, the smoke plume's trajectory during the smoke event aligned poorly with existing balloon

FIG. 12. Vertical cross-section of model domain at approximately 48°N at 1800 UTC 29 Jun for (a) WRF-Chem chemistry simulation extinction coefficients greater than 0.05 km^{-1} , along with differences for chemistry minus control simulations for (b) temperature and (c) water vapor mixing ratio, with solid black contours indicating extinction coefficient.

launch locations at Bismarck, North Dakota, and Aberdeen, South Dakota—neither of which likely experienced an AOD of greater than 2.0. For these reasons, we are unable to make definitive conclusions about PBL heights during this particular smoke event. With that said, the chemistry simulation does have lower daytime maximum PBL heights compared to the control simulation likely due to the reduced SW flux and surface temperatures causing less convective turbulence as mentioned above.

f. Forecast sensitivity study

A sensitivity study is also conducted to analyze the impacts of including aerosol via initial and boundary conditions in a more operationally realistic setting. To achieve this goal, the archived NAM forecasts, instead of NAM analyses, are used as the initial and boundary conditions for WRF-Chem simulations.

FIG. 13. (a)–(c) RMSE and (d)–(f) mean bias error for 24-h forecast (top) surface downward SW flux, (middle) 2-m temperature, and (bottom) 10-m wind speed for WRF-Chem simulations binned by AODs of 0.5 for WRF-Chem forecasts initialized at 0000, 0600, 1200, and 1800 UTC 28 Jun 2015 with NAM forecast data.

Due to the significant differences between the research mode used here and the operational mode of NAAPS, we continue to use the same NAAPS aerosol fields as above. Consequently, this creates a somewhat unrealistic scenario in which the aerosol forecast is as accurate as analysis and may not be applicable for inaccurate forecasts, though, does ensure accurate representation of the smoke plume. Regardless, the use of NAM forecast data allows for an evaluation of the smoke plume's influence on the meteorological forecast as if it were occurring in real-time from a simulated operational environment.

Forecast sensitivity with respect to initialization time (between 0000 UTC 28 June and 0000 UTC 29 June) is very small (see Fig. S2 in the online supplemental material). A total of

four WRF-Chem 24-h forecast simulations initiated at 0000, 0600, 1200, and 1800 UTC 28 June 2015 are examined here. The forecasts are relatively consistent with each other with minor differences occurring largely on 28 June during the day (i.e., prior to advection of the smoke plume). RMSE and mean bias binned by AOD for the 24-h forecast SW flux (relative to NDAWN), 2-m temperature (relative to NDAWN and ASOS), and 10-m wind speed (relative to ASOS) are shown in Fig. 13. For SW flux, the chemistry simulations have lower RMSE for areas with WRF-Chem reported AODs ≥ 1.0 . In regions with AOD < 1.0 , RMSEs are the same or larger in the chemistry simulation, due to a more negative mean bias. This reiterates the limited usefulness of attempts to include aerosols in operational NWP models for improving forecasts of standard

FIG. 14. As in Fig. 13, but for WRF-Chem forecast initialized at 0000 UTC 29 Jun 2015 with NAM forecast data.

meteorological variables in “clean” regions/seasons. Conversely, the chemistry simulations have consistently lower RMSE and are closer to zero mean bias in areas of heavy aerosol loading. These results are echoed in both temperature and, interestingly, wind speed. While all variables are less impacted by increasing AOD in the chemistry simulations as compared to the control simulations, it is important to note that the 2-m temperature RMSE and mean bias seem to be only slightly a function of optical depth. Overall, these results are extremely encouraging for our hypothesis that aerosol from CTMs like NAAPS could be included on an as-needed basis to increase surface variable forecast accuracy.

We also present the 24-h forecast initialized at 0000 UTC 29 June 2015 (Fig. 14). This case is analyzed separately than the four forecasts initialized on 28 June due to the SW flux RMSE for the chemistry simulation being larger than that of the

control, even in regions with high aerosol loading. Despite the unusual SW flux, chemistry simulated 2-m temperature and 10-m wind speed seem to have similar or better RMSE compared to the control simulation. That said, all three variables (particularly SW flux) have negative/cool biases. It follows that the accuracy of this forecast may be limited because of an overestimation of smoke within the domain. Furthermore, this forecast is initialized at 0000 UTC 29 June with heavy smoke loading within and advecting into the domain. The forecast may, in fact, be dealing with the effects of coarse aerosol initial conditions from NAAPS combined with an analysis complicated by the meteorological effects of heavy aerosol loading. While the impacts of a poorly and/or unresolved aerosol plume at initialization is not studied here, this forecast suggests that future research into this topic may be necessary.

5. Conclusions

Studies have shown that through the interaction of solar and longwave radiation, atmospheric aerosols can directly affect meteorological phenomena at regional weather scales (e.g., Zhang et al. 2016). To account for the impacts of aerosols on weather, numerical weather prediction (NWP) centers have examined the effects of incorporating aerosols into global NWP models (Mulcahy et al. 2014; Benedetti and Vitart 2018, etc.). While the impacts of heavy aerosol plumes on weather have been reported, it remains a debate as to whether the computational time is justified by incorporating aerosols in numerical forecasts for regions and seasons with low aerosol loadings.

In this study, an alternative approach is attempted by ingesting aerosol analyses and forecasts from a global chemical transport model (CTM) into an NWP model via initial and boundary conditions for improving the accuracy of forecast near-surface meteorological variables for more rare significant events. This concept is tested through using the Navy Aerosol Analysis and Prediction System (NAAPS; Lynch et al. 2016) and the Weather Research and Forecasting Model built with the WRF-Chem chemistry package for a June–July 2015 biomass burning aerosol episode over the northern Great Plains. This study finds the following:

- 1) Surface downward shortwave radiative fluxes (SW flux) are significantly overestimated in WRF-Chem during the daytime without the consideration of solar energy attenuation by aerosol plumes (i.e., the aerosol direct effect). The RMSE of SW flux is found to be $\sim 300 \text{ W m}^{-2}$ higher for the control run as compared with the chemistry run at 1800 UTC 30 June 2015.
- 2) Noticeable reductions in the RMSE of surface temperature analyses and forecasts when aerosol fields are incorporated into the model using NAAPS aerosol data as compared with the control simulations (i.e., WRF-Chem simulations without inclusion of aerosol fields). Forecast near-surface temperature can achieve reductions of up to 5°C in RMSE and bias over dense smoke regions (i.e., $\text{AOD} \geq 3.0$) through the use of NAAPS aerosol analyses.
- 3) Marginal impacts to wind speed due to inclusion of aerosols can be seen in the WRF-Chem-simulated wind speeds. For forecasts, however, simulated wind speed exhibits lower RMSEs of $\sim 1 \text{ kt}$ when the aerosol direct effect is included—likely due to reduction in lower momentum flux that follows from reduced temperature and turbulent mixing. Still, it is worth noting that this was not a high wind event.

While only a single case, this study demonstrates the new concept of incorporating the impact of aerosols on NWP model forecasts. In comparison with the full incorporation of aerosols in NWP models, aerosol analyses and forecasts from CTMs are computationally inexpensive. Thus, the proposed method may be used as an alternative for accounting aerosol impacts in NWP models in the future.

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