

Assessing the Impact of Aeolus Wind Profiles in WRF-Chem Model Dust Simulations in September 2021 [†]

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Abstract: Windblown dust plays a crucial role in the Earth system, impacting climate, ecosystems, human activities, and health. The spatiotemporal evolution of dust plumes during transport is determined by wind, the primary driver of dust emission. In this study, we utilize outputs from the ECMWF-IFS, assimilating quality-assured Aeolus wind profiles, to initialize dust simulations with the WRF-Chem model. The aim is to assess the impact of Aeolus wind observations on modeling the desert dust cycle. Focusing on the ASKOS/JATAC campaign in September 2021 near Cabo Verde, we qualitatively and quantitatively evaluate the simulated dust-related outputs, revealing that even small differences in wind significantly affect the simulated dust emission rates and dust optical depth.

Keywords: dust; emissions; transport; ASKOS; JATAC; WRF; LIVAS; lidar



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1. Introduction

Strong desert winds mobilize substantial quantities of dust aerosols, which are transported across various distances and directions. Quantifying the contribution of dust components to the total budget remains uncertain due to the complex mechanisms involved [1]. The “dust belt” [2] from the western Sahara to East Asia serves as major global dust sources, with northern African deserts contributing about 55% and the Middle East 15–20% [3]. The ALADIN instrument, onboard ESA’s Aeolus satellite, is capable of enhancing weather forecasts and atmospheric dynamics understanding, including dust transport. Assimilating Aeolus wind profiles into numerical models shows positive impacts on short- and medium-term forecasts [4]. This study investigates the potential improvements in the WRF-Chem dust simulation performance using Aeolus wind profiles and evaluates its performance against the LIVAS pure dust dataset during the ASKOS/JATAC campaign [5].

Section 2 describes the data and the methodology in detail. Section 3 includes the analysis of the model performance in terms of the simulated dust concentration fields, the aerosol optical depth, and the emission rates. Section 4 summarizes the main conclusions and future work.

2. Data and Methodology

2.1. Aeolus Winds Assimilation in IFS Datasets

Numerical experiments in this study utilized the WRF model with meteorological fields from ECMWF's Integrated Forecasting System. Two sets of outputs are used: a control run and an experimental run. The experimental run incorporated Aeolus wind profiles (Rayleigh-clear and Mie-cloudy HLOS) [6]. Quality screening was applied to the Aeolus profiles [4]. Both simulations assimilated observations to generate an analysis, employing the 4D-Var technique with LWDA (Long Window Data Analysis) to maximize the inclusion of observations within specific time windows (00:00 and 12:00 UTC analyses).

2.2. LIVAS Pure Dust Dataset

Dust vertical concentrations from the LIVAS dust products [7,8] are used. The product is based on the dust signature in the particle depolarization ratio measurements, and is developed using the methodology described in [8]. The product has the vertical resolution of the Level 2 CALIPSO curtain products (60 m) and a horizontal resolution of 1×1 degree. The LIVAS dust product has been used in numerous studies dealing with the evaluation of dust model outputs (e.g., [9–13]).

2.3. WRF Model Set-Up and Methodology

We utilized the WRF-ARW-Chem version 4.2.1 model (Advanced Research Weather version of the Weather Research and Forecasting coupled with Chemistry), [14] coupled with the Georgia Institute of Technology-Goddard Global Ozone Chemistry Aerosol Radiation and Transport (GOCART) aerosol model and the Air Force Weather Agency (AFWA) dust emission scheme [15] for studying the life cycle of mineral aerosols in the region of interest (ROI, Sahara Desert and Atlantic Ocean). See Table A1 in the Appendix A for the chosen physics and dust parameterization options.

The model domain configuration ($12 \text{ km} \times 12 \text{ km}$, spatial resolution and 70 vertical levels up to 50 hPa) covers mainly North Africa, the southern part of the European continent, and the dust outflow region of the Atlantic Ocean (Figure 1).

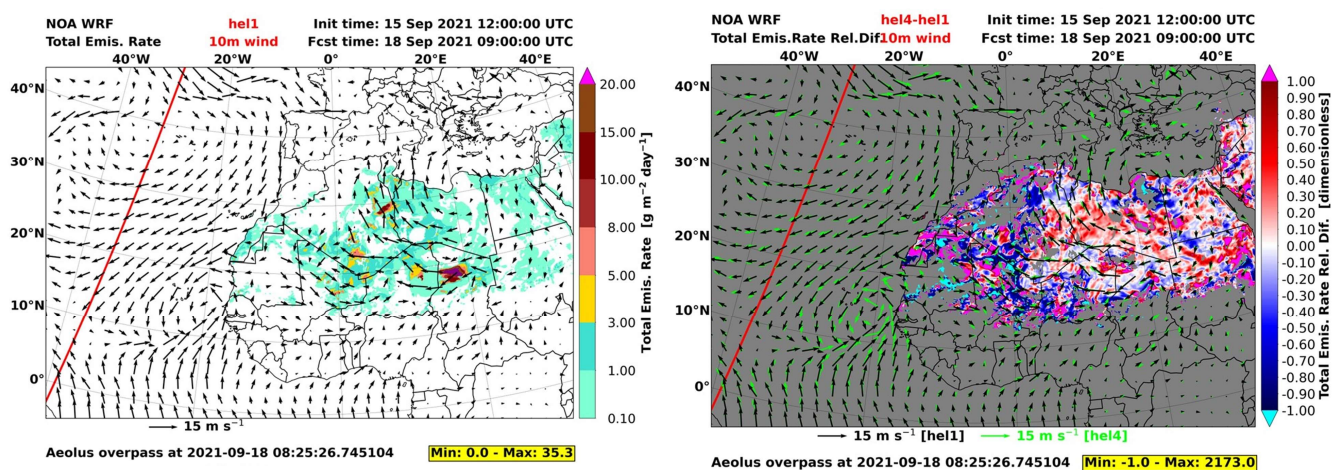


Figure 1. Dust emission rates for hel1 (left) and relative differences ((hel4 – hel1)/hel1, right) of the model emission rates on 18–09–2021_09:00:00 UTC. Arrows show the wind speed vectors at 10 m above surface for hel1 (black) and hel4 (green) experiments. Red lines correspond to Aeolus overpasses closest to the time of the WRF-Chem hourly output.

For short-term WRF-Chem dust forecasts, 84 h cycles are performed using high-resolution ($0.125^\circ \times 0.125^\circ$) outputs from the ECMWF IFS. Two scenarios are compared: one with Aeolus wind profiles assimilated (hel4 IFS analysis) and one without (hel1 IFS analysis). WRF-Chem outputs from 1 September 2021 to 30 September 2021, after a 15-day dust spin-up period, are compared to the LIVAS pure dust dataset (2.3) to assess the

potential improvements in dust field representation due to Aeolus wind assimilation in the ROI.

3. Results

3.1. Impact on Simulated Emission Rates

In Figure 1, a comparison of WRF-Chem simulated emission rates between hel1 (no-Aeolus) and hel4 (with-Aeolus) experiments demonstrates the impact of the Aeolus assimilated winds in the emission rates. The arrows show the simulated winds at 10 m above surface. Even slight differences in the wind speed can cause significant differences in the emission rates, which are more evident near the main Sahara sources and at lead times near the Aeolus overpasses.

3.2. Impact on Dust Optical Depth (DOD)

In Figure 2, a comparison with WRF-Chem of the absolute and relative differences of the winds at 850 hPa between hel1 (no-Aeolus) and hel4 (with-Aeolus) experiments is presented, which demonstrates how the assimilation of Aeolus data changes the predicted wind speed and alters the atmospheric circulation.

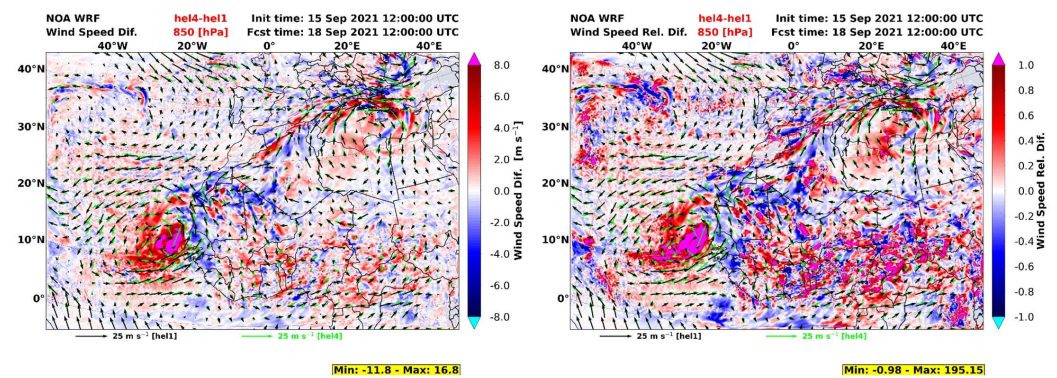


Figure 2. Wind speed absolute (left) and relative (right) differences ((hel4 – hel1)/hel1). The depicted model WRF-Chem outputs correspond to 18–09–2021_12:00:00 UTC. Arrows show the wind speed vectors at 850 hPa for hel1 (black) and hel4 (green) experiments.

This differences in the atmospheric circulation led to differences in the simulated dust optical depth (DOD), which is verified with DOD absolute values and the absolute and relative differences given in Figure 3, where model results show that both dust circulation and areas of minimum and maximum DOD are modified, compared to hel1 simulations.

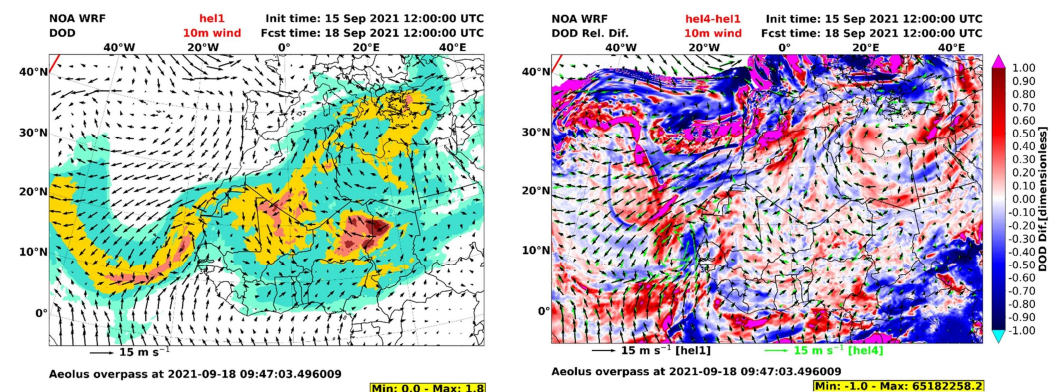


Figure 3. DOD for hel1 (left), and DOD relative differences ((hel4 – hel1)/hel1, right). The depicted model WRF-Chem outputs correspond to 18–09–2021_12:00:00 UTC. Arrows show the wind speed vectors at 10 m above surface for hel1 (black) and hel4 (green) experiments. Red lines correspond to Aeolus overpasses closest to the time of the WRF-Chem hourly output.

3.3. Impact on the Vertical Distribution of Dust

Figure 4 depicts the collocated vertical dust concentration ($\mu\text{g m}^{-3}$) observed by LIVAS and simulated in hel1 and hel4 over the Eastern Tropical Atlantic on the 5th of September, 2021, assessing the impact of Aeolus data in the vertical distribution of dust.

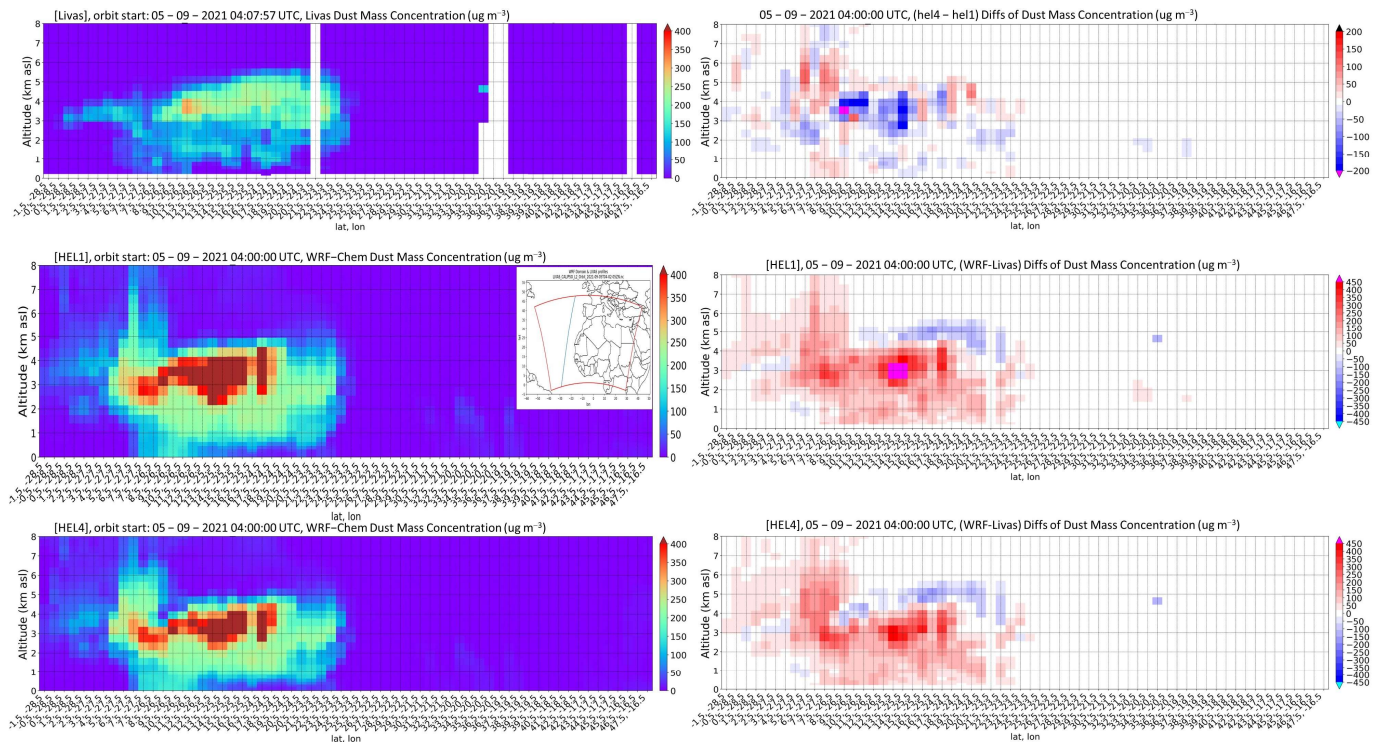


Figure 4. Collocated hel1 and hel4 to LIVAS depicting vertical dust concentrations ($\mu\text{g m}^{-3}$) on 05–09–2021 04:00 UTC along the CALIPSO track represented by the blue line within the WRF model domain, (red polygon, top right). The top-left image shows the original CALIPSO pure dust backscatter coefficient at 532 nm. Given in rows 2 to 3, on the left column, are the collocated CALIPSO-LIVAS, hel1 and hel4 dust concentration curtain plots, respectively. In rows 1 to 3, on the right column, calculated differences of hel4 vs. hel1, hel1 vs. LIVAS and hel4 vs. LIVAS are presented, respectively.

As seen in Figure 4 (mid row) the CALIPSO overpass (blue line on domain map) crosses the dust outflow zone off the African coasts, capturing the dust plume that is moving westwards over the Atlantic. The comparison of the collocated LIVAS dust observations against the model outputs for hel1 and hel4 (Figure 4, left column, rows 1 to 3) shows a reduction of the positive WRF biases (Figure 4, right column, rows 2 and 3) when WRF is initialized with IFS hel4 outputs, as it is also seen when calculating concentration differences between hel1 and hel4 (Figure 4, right column, row 1).

4. Conclusions

Aeolus assimilated winds have a significant impact on the WRF-Chem model simulated emission rates, dust optical depth, and circulation. Comparison with LIVAS observations show improved representation of dust fields when WRF is initialized with Aeolus data (hel4), reducing positive biases and enhancing agreement with observations.

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Data Availability Statement: LIVAS pure-dust products are available upon request from Eleni Marinou (elmarinou@noa.gr), Vassilis Amiridis (vamoir@noa.gr), and Emmanuil Proestakis (proestakis@noa.gr).

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. WRF-NOA model configuration with the basic parameterization schemes and their corresponding (number) runtime option.

Parameterization	Scheme	Parameterization	Scheme
Surface Model	Unified Noah [16]	sf_surface_physics	2
Surface Layer	Monin-Obukhov [17–21]	sf_sfclay_physics	2
Radiation (SW, LW)	RRTMG [22]	ra_sw(lw)_physics	4
Microphysics	Morrison 2-moment scheme [23]	mp_physics	10
Cumulus	Grell-3D [24,25]	cu_physics	5
Boundary Layer	MYNN [26–28]	bl_pbl_physics	5
Chemistry	GOCART simple [24,25]	chem_opt	300

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