## Response to Reviewers

## MATCHA, a novel regional hydroclimate-chemical reanalysis: System description and evaluation

Chayan Roychoudhury[1], Rajesh Kumar[2], Cenlin He[2], William Y. Y. Cheng[2], Kirpa Ram[3], Naoki Mizukami[2], and Avelino F. Arellano[1]

### Reviewer #1

### General Comments

Roychoudhary et al. present a detailed description and evaluation of newly developed hydroclimate-chemical reanalysis, called as 'MATCHA'. MATCHA is basically highresolution WRF-Chem simulations after enhancing key processes on aerosol-radiationsnow and assimilating satellite-observations (MODIS AOD, MOPITT CO). Authors thus provide a large volume of data (about 100 TBs, or so) covering 17-year period. A user guide has also been made available (Kumar et al., User Guide, https://doi.org/10.5067/CG4OT8DJX2Z7). Despite immense climatic significance, the High-Mountain Asia has been observationally scarce. High-resolution reanalysis using enhanced processes, as considered here, have also remained lacking. In this regard, this work is a huge effort and should be considered for publication in ESSD. The datasets can be valuable for air quality and hydroclimate studies. Data's higher-resolution and availability for 17-year makes is also ideal for training statistical or AI/ML models for the region. I have some comments and suggestions, which should be considered, while finalizing the manuscript for publication.

We thank Dr. Ojha for the positive assessment and for the helpful suggestions, including the independent $PM_{2.5}$ visualization, which we found particularly useful. We believe these comments have substantially strengthened the manuscript and thank the reviewer for their time and constructive input. We address each point below. Reviewer comments are in blue while responses are in black. Changes to the manuscript are quoted in green when helpful.

### Major Comment 1.1

Figures 8, 9, 12—15: MATCHA data is shown only at observation sites. This does not exploit the actual potential of 'high-resolution gridded data covering entire region' produced by the authors. In fact, large areas remain blank, including parts of HMA - focus of MATCHA. I do realize that authors aimed 'validation', but for that they may over-plot observed values -wherever available- on the same color scale, while keeping full data fields.

We thank the reviewer for this suggestion and for the independent visualization, which we found genuinely useful (it also prompted the diagnosis in our response to Major Comment 1.2). We agree that the full gridded fields are a major strength of MATCHA, and we considered overplotting the observations on complete model fields as suggested.

For the evaluation figures we have retained the collocated presentation, for the following reasons. The purpose of Figs. 8, 9, and 12-15 is quantitative evaluation, for which the model must be sampled at the observation sites and times. The in-situ records are temporally sparse and irregular over 2003-2019 and differ from site to site, so an all-days seasonal mean field behind the points would show a different statistic from the collocated values at the points, and apparent point-to-field mismatches would partly reflect sampling rather than model error. For PBLH (Figs. 8 and 9) this is compounded by the strong diurnal cycle, since the model is sampled at the radiosonde release times, which vary in local time across the domain.

We note, however, that the revised manuscript now does present full-domain seasonal fields of the model product: the new Fig. A5 shows total (unadjusted) seasonal PM10 maps over the entire domain, added in response to Reviewer 2, and complements the collocated evaluation in Fig. 14. The spatial correspondence between MATCHA and the observations is also assessed quantitatively in Tables 2-4, where the correlation coefficient per variable and season measures how well MATCHA reproduces the observed pattern across sites. Finally, we agree with the reviewer that educating potential users on the strengths and weaknesses of the full fields is important. The new summary table (Table 5) and the applications/limitations paragraph added to Sect. 4 (in response to Reviewer 2, Major Comment 2.1) are intended to serve this purpose.

## Major Comment 1.2

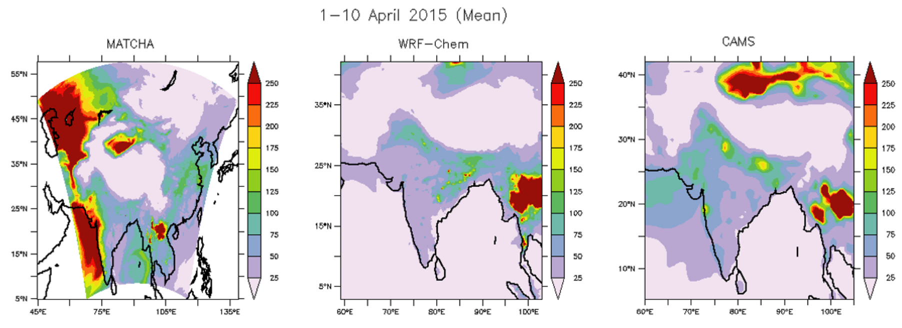



***Figure:*** *Mean distribution of $PM_{2.5}$ ($\mu g.m^{-3}$) from MATCHA data (presented in this manuscript), from 'a WRF-Chem simulation' and CAMS reanalysis. Domains and physics/chemistry are not identical and comparison is for broad inferences.*

Somehow on the western boundary of MATCHA fields, there seem anomalously high PM2.5 (since it is a diagnostic term in model, it could be coming through one or more of its constituents). Quick look does not show such pattern in a simulation of WRF-Chem (or in CAMS reanalysis). It is possible that I am making error in understanding MATCHA data, yet it is better that this is clarified / addressed (effect of lateral boundaries in the used set up or entering through satellite-assimilation!).

We thank the reviewer for raising this issue. To diagnose it, we first decomposed surface PM into its constituents over the western domain for the period the reviewer examined (1 to 10 April 2015). The enhancement is carried almost entirely by dust. Dust surface concentrations there exceed sea salt, sulfate, nitrate, and ammonium by roughly an order of magnitude, and the dust field matches the $PM_{2.5}$ and $PM_{10}$ fields closely (Figure R1 below, panels a, b, and d).

We then analyzed whether this dust is emitted inside the domain or enters through the lateral boundary or the assimilation. Along west-to-east transects in the northwestern part of the domain (Figure R2 below), dust and $PM_{2.5}$ rise from the boundary to about 470 km inland (near 59° E), and the concentration profile follows the simulated dust emission flux (dotted line, correlation around 0.7). The outermost boundary cells (grey shaded region) carry lower emission and concentration than the interior. Lateral inflow or an assimilation increment would instead produce the opposite signature: a maximum near the boundary that decays inward with no co-located emission. The western dust is generated locally over the Central Asian and Caspian sources, so the near-boundary fields are not driven by inflow or by the AOD assimilation.

The reviewer's observation also points to two model biases over these source regions, which we address below.

1. The magnitude is too high. A 10-day-mean surface dust concentration above 1000 μg/m$^3$ is unrealistically high even over an active source. This reflects over-emission by the GOCART dust scheme, whose prescribed erodibility source function (Ginoux et al., 2001) assigns high erodibility to the Central Asian basins, combined with a low soil-moisture-dependent threshold over dry, sparsely vegetated soil. The same behavior has been linked to dust and PM overestimation in WRF-Chem over the arid regions of southwest Asia (Parajuli et al., 2019). Surface winds under the northern dust core are moderate (Figure R1, panel i), so here the over-emission follows from the source function and threshold rather than from the surface-wind high bias discussed in Sect. 3.1.3.
2. The modeled dust is too fine. The coarse fraction/contribution ($PM_{10}$ minus $PM_{2.5}$, Figure R1 panel c) is only about a third to a half of $PM_{10}$, whereas observed desert dust is generally coarse mode dominated. This points to the remapping of dust mass from the GOCART emission sections onto the MOSAIC size bins, which places too large a fraction below 2.5 μm (Pino-Carmona et al., 2024) and is why the bias appears in $PM_{2.5}$ and not only PM10. We therefore note in the revised manuscript that users should treat surface dust and PM near the western and Central Asian sources as an upper bound.

To reflect this analysis, we added a separate bullet in Section 3.3.2 as follows,

*Over the arid desert regions along the western edge of the domain, MATCHA overestimates surface dust and, in turn, $PM_{2.5}$ and $PM_{10}$ (Fig. A5). The GOCART dust emission scheme (Ginoux et al., 2001) used in the model setup of MATCHA combines a high prescribed erodibility over these regions with a low soil-moisture-dependent threshold, producing strong emission even under moderate winds, a behavior linked to dust and PM overestimation in WRF-Chem over the arid regions of southwest Asia (Parajuli et al., 2019). The emitted mass is also redistributed from the GOCART size sections onto the MOSAIC bins in a way that places an excessive fraction below 2.5 µm, so the overestimation also affects $PM_{2.5}$ and not only $PM_{10}$ (Pino-Carmona et al., 2024). Dust reaches the domain both through emissions generated within the domain and through the CAMS-EAC4 chemical boundary conditions (Table 1), which carry long-range transport from sources such as the Arabian and Thar deserts. Dust is not tagged as a tracer in MATCHA, so the two pathways cannot be partitioned quantitatively. The enhancement over the western source regions, however, is generated within the domain rather than advected through the lateral boundaries, as the concentration maximum sits several hundred kilometers inland and is co-located with the simulated emission flux. Surface dust and PM magnitudes over these western source regions should therefore be read as an upper bound.*

Ginoux, P., Chin, M., Tegen, I., Prospero, J. M., Holben, B., Dubovik, O., and Lin, S.-J.: Sources and distributions of dust aerosols simulated with the GOCART model, Journal of Geophysical Research: Atmospheres, 106, 20255–20273, https://doi.org/10.1029/2000JD000053, 2001.

Parajuli, S. P., Stenchikov, G. L., Ukhov, A., and Kim, H.: Dust emission modeling using a new high-resolution dust source function in WRF-Chem with implications for air quality, Journal of Geophysical Research: Atmospheres, 124, 10109–10133, https://doi.org/10.1029/2019JD030248, 2019.

Pino-Carmona, M., Ruiz-Arias, J. A., Fernández-Carvelo, S., Bravo-Aranda, J. A., and Alados-Arboledas, L.: Intercomparison of WRF-Chem aerosol schemes during a dry Saharan dust outbreak in Southern Iberian Peninsula, Atmospheric Environment, 339, 120872, https://doi.org/10.1016/j.atmosenv.2024.120872, 2024.

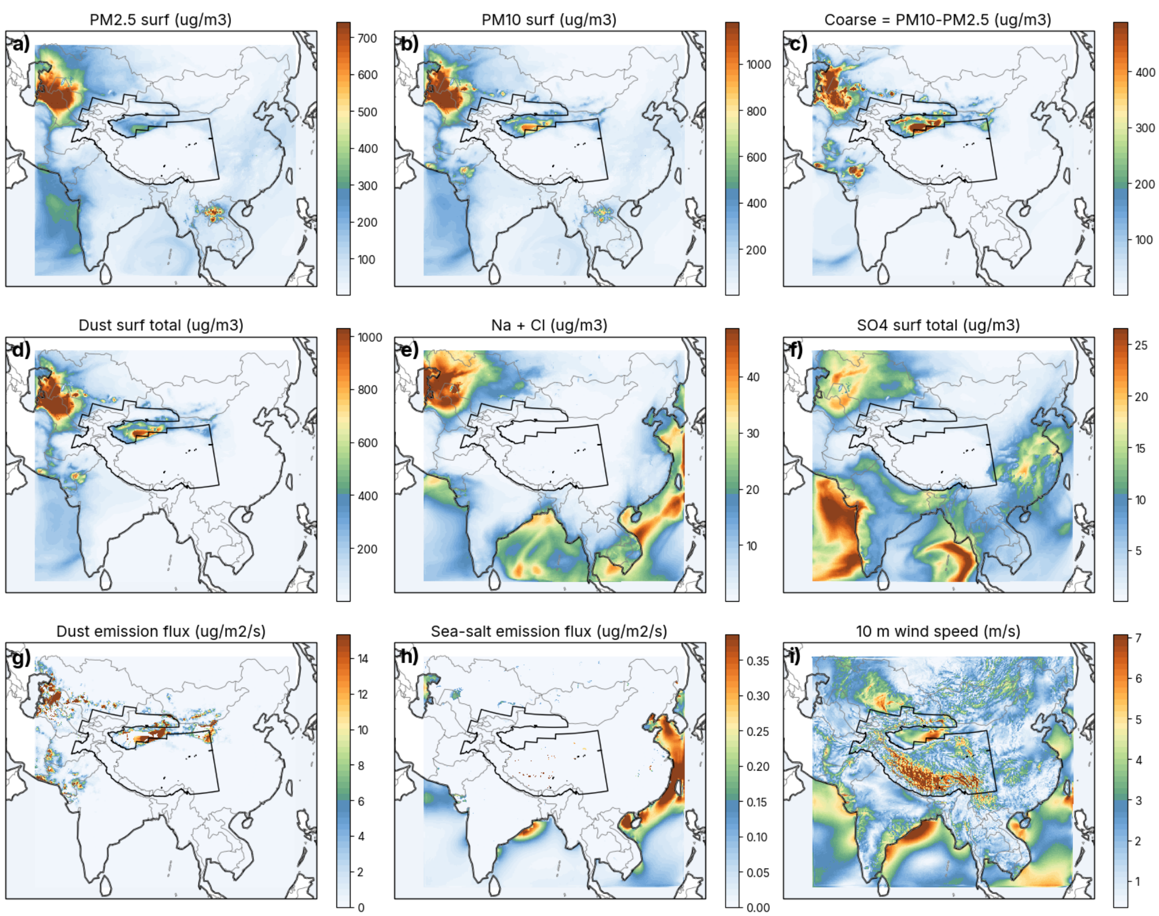



Figure R1: Mean surface concentrations over the western domain for 1 to 10 April 2015 from MATCHA: (a) PM2.5, (b) PM10, (c) coarse fraction (PM10 minus PM2.5), (d) dust, (e-h) sea salt, sulfate, nitrate, and ammonium, and (i) 10 m wind speed. The enhancement along the western boundary is carried almost entirely by dust.

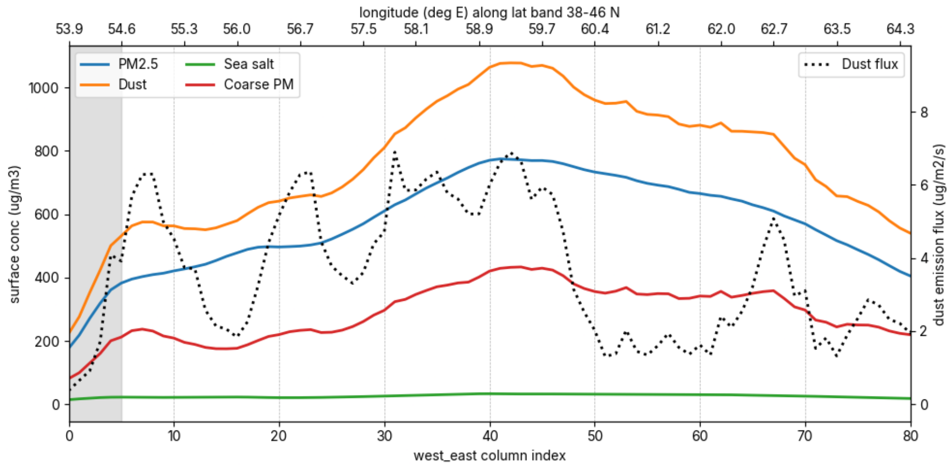



Figure R2: West-to-east transects across the northwestern domain, averaged over 1 to 10 April 2015: surface dust and $PM_{2.5}$ concentrations (solid lines, left axis) and simulated dust emission flux (dotted line, right axis). Grey shading marks the lateral boundary. Concentrations peak about 470 km inland near 59° E and follow the emission flux (R of 0.7), indicating locally generated dust rather than boundary inflow.

## Minor Comment 1.1

The abstract should be more crisp. Focus on describing the data and the few most important evaluation results, add 1–2 sentences on potential and applications, and reduce or optimize the rest.

We thank the reviewer for this suggestion. We have rewritten the abstract to be more concise (from 573 to roughly 361 words). The evaluation is now reduced to the most important results, retaining the meteorological skill, snow cover seasonality, precipitation, AOD/SSA, and the principal PM and CO biases while removing variable-by-variable detail (PBLH diurnal structure, Kanpur composition, and the per-country BC tracer breakdown) that is covered in the main text. We have added two sentences on potential applications, including aerosol-cryosphere feedback, air quality, and hydroclimate research, and use of the dataset as a high-resolution, multi-decadal training set for statistical and machine-learning models in this observationally sparse region, consistent with the potential the reviewer notes in the general comments. The revised abstract appears below.

*We present MATCHA (Model for Atmospheric Transport and Chemistry in Asia), a 17-year (2003-2019) regional hydroclimate-chemical reanalysis for Asia (58° – 140° E, 4° – 40° N) at 12 km resolution. MATCHA couples the Weather Research and Forecasting model with Chemistry (WRF-Chem), Community Land Model (CLM), and SNow, ICe and Aerosol Radiative (SNICAR) model, and assimilates aerosol optical depth (AOD) from the Moderate Resolution Imaging Spectroradiometer (MODIS) and carbon monoxide (CO) profiles from the Measurement of Pollution in the Troposphere (MOPITT) every three hours, to explicitly represent interactions between atmospheric composition and regional hydroclimate (including aerosol-snowpack interactions) across High Mountain Asia (HMA). MATCHA comprises hourly surface and column-integrated fields and 3-hourly three-dimensional fields across different light-absorbing aerosol species, e.g., black carbon (BC), dust, and brown carbon (BrC), trace gases, and a broad set of meteorological, hydrological, and land-surface variables over the region. We evaluate 12 key variables in the reanalysis against in-situ and satellite observations. Surface and upper-air meteorology is reproduced well, with Kling-Gupta efficiencies (KGEs) of 0.65 to 1, although high-elevation regions show a persistent winter cold and dry bias and too-strong surface winds. Snow cover fraction seasonality is captured across the major glacier regions, with a slight underestimation during snowmelt, and daily precipitation agrees most closely during the monsoon (KGE up to 0.6). MATCHA reproduces the spatial and seasonal patterns of AOD and single scattering albedo (SSA) at 550 nm but overestimates summer AOD over India and Southeast Asia; surface $PM_{2.5}$ and $PM_{10}$ are biased high and surface CO is underestimated relative to observations. A distinguishing feature of MATCHA is a set of tagged BC tracers that attribute concentrations to specific emission sectors and source regions. These tracers show anthropogenic BC peaking in winter (Chinese sources over eastern and northern HMA, Indian sources over the west and center) and biomass-burning BC dominating in March-April. MATCHA is the first high-resolution reanalysis over HMA to fully couple aerosols, radiation, and snow. It supports research on aerosol-cryosphere feedbacks, air quality, and hydroclimate over a region where observations are sparse, and its resolution and 17-year length make it suitable as a training set for statistical and machine-learning models. The dataset is publicly available at https://doi.org/10.5067/CG4OT8DJX2Z7.*

Ginoux, P., Chin, M., Tegen, I., Prospero, J. M., Holben, B., Dubovik, O., and Lin, S.-J.: Sources and distributions of dust aerosols simulated with the GOCART model, Journal of Geophysical Research: Atmospheres, 106, 20255–20273, https://doi.org/10.1029/2000JD000053, 2001.

Parajuli, S. P., Stenchikov, G. L., Ukhov, A., and Kim, H.: Dust emission modeling using a new high-resolution dust source function in WRF-Chem with implications for air quality, Journal of Geophysical Research: Atmospheres, 124, 10109–10133, https://doi.org/10.1029/2019JD030248, 2019.

Pino-Carmona, M., Ruiz-Arias, J. A., Fernández-Carvelo, S., Bravo-Aranda, J. A., and Alados-Arboledas, L.: Intercomparison of WRF-Chem aerosol schemes during a dry Saharan dust outbreak in Southern Iberian Peninsula, Atmospheric Environment, 339, 120872, https://doi.org/10.1016/j.atmosenv.2024.120872, 2024.

**Minor Comment 1.2**

Introduction, L60: "Short-lived climate forcing agents called light-absorbing particles." Short-lived climate forcing is a more general term than light-absorbing aerosols; it also includes scattering aerosols and tropospheric ozone (e.g., IPCC AR6, Chapter 6). Please reframe the sentence.

We thank the reviewer for this comment. We no longer equate short-lived climate forcers (SLCFs) with light-absorbing particles. The revised sentence (L60) now reads: *The changes observed in HMA are driven by a combination of factors, including precipitation and temperature patterns, greenhouse gas (GHG) dynamics, and the emissions of light-absorbing particles (LAPs), including black carbon (BC), dust, and brown carbon (BrC).*

**Minor Comment 1.3**

*L84: Large uncertainty in satellite retrievals. Then how can assimilating them improve the model data fields?*

Thank you for this comment. We have added a clarifying sentence. Although individual satellite retrievals carry non-negligible uncertainty, assimilation combines them with the model background under a specified observation-error covariance, so that the analysis is weighted by relative uncertainty rather than taking observations as truth. The benefit comes from correcting systematic model errors (e.g., emissions, transport) using the spatial and temporal coverage of the retrievals, while the assigned observation errors prevent over-fitting to noisy individual pixels. We reference the MOPITT and MODIS error characterizations used in our error specification.

*This issue can be partially addressed by global and regional reanalyses that assimilate available in situ and satellite observations into models. Although individual satellite retrievals carry uncertainty, what assimilation does is weigh observations by their error covariances relative to the model background, so that noisier retrievals exert less influence on the analysis. This allows the spatio-temporal coverage of the retrievals to correct systematic model errors while keeping the model state as close to observations as possible within the constraints of model and observation errors.*

**Minor Comment 1.4**

L95–96: Provide supporting references and be quantitative. Several studies analyze CAMS and MERRA-2 over the Himalaya and foothills.

We agree and have added quantitative, referenced support. The introduction now characterizes global-reanalysis performance over HMA with specific magnitudes instead of a general statement. For precipitation, ERA5 overestimates gauge-constrained flows across HMA river basins by 33% to 106%, driven by overestimated precipitation (Sun et al., 2021). For aerosols, the mean AOD bias of MERRA-2 and CAMS over Asia (up to about 0.15) exceeds that over any other region of the globe (Ansari and Ramachandran, 2024), and over the Indo-Gangetic Plain the two reanalyses disagree even in the sign of the error, with MERRA-2 underestimating AOD and CAMS overestimating it, and MERRA-2 single scattering albedo biased low from overestimated black carbon absorption (Ansari and Ramachandran, 2023).

We have added this text in the Introduction near L149:
*For precipitation, ERA5 overestimates gauge-constrained flows across HMA river basins by 33% to 106%, traced largely to overestimated precipitation, so that bias correction is needed before hydrological use (Sun et al., 2021). For aerosols, the mean AOD bias of MERRA-2 and CAMS over Asia (up to about 0.15) is larger than over any other region of the globe (Ansari and Ramachandran, 2024); over the Indo-Gangetic Plain the two products even disagree in the sign of their error, with MERRA-2 underestimating AOD and CAMS overestimating it, and MERRA-2 single scattering albedo biased low from overestimated black carbon absorption (Ansari and Ramachandran, 2023).*

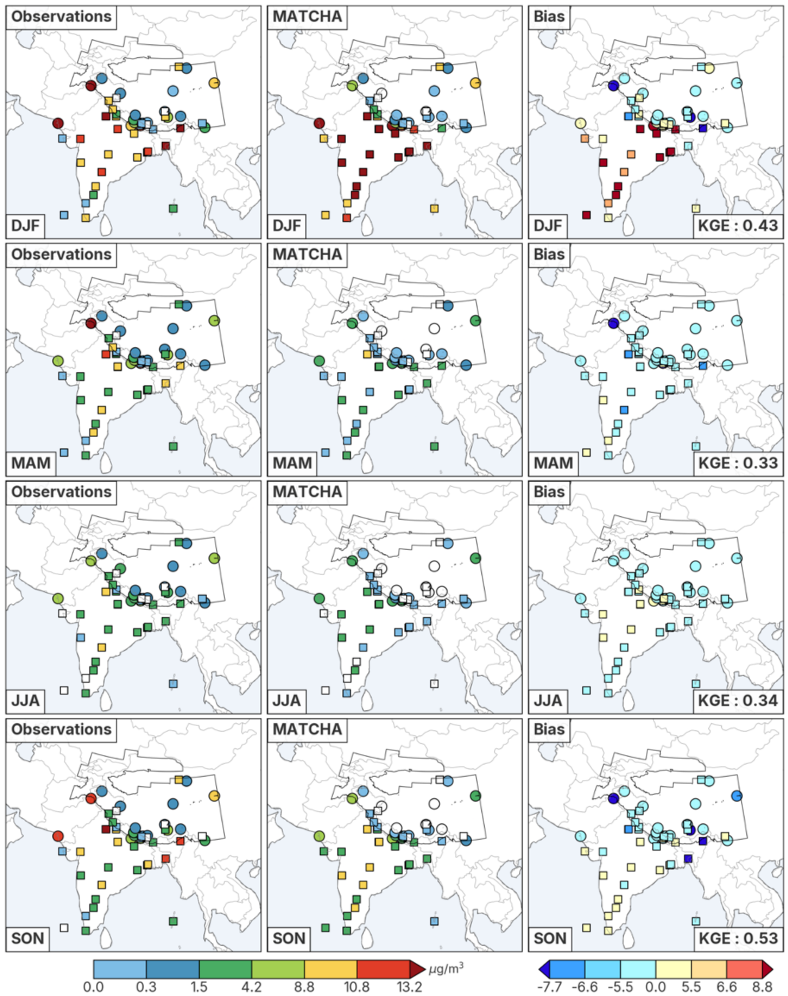
Sun, H., Su, F., Yao, T., He, Z., Tang, G., Huang, J., Zheng, B., Meng, F., Ou, T., and Chen, D.: General overestimation of ERA5 precipitation in flow simulations for High Mountain Asia basins, Environmental Research Communications, 3, 121003, https://doi.org/10.1088/2515-7620/ac40f0, 2021.

Ansari, K. and Ramachandran, S.: Aerosol characteristics over Indo-Gangetic Plain from ground-based AERONET and MERRA-2/CAMS model simulations, Atmospheric Environment, 293, 119434, https://doi.org/10.1016/j.atmosenv.2022.119434, 2023.

## Minor Comment 1.5

Fig. 16: BC variability is not clearly visible because the same color, in different shades, is used for 0 to 9 µg $m^{-3}$.

We have revised Figure 16 to use a perceptually uniform, multi-hue colormap with a rescaled range (and, where appropriate, a nonlinear or capped scale) so that the spatial variability of BC is clearly resolved across the 0–9 µg $m^{-3}$ range.



**Minor Comment 1.6**

Table 4 (surface CO): WRF-Chem typically overestimates lower-tropospheric CO except during monsoon, yet MATCHA shows systematic underestimation (~200 ppbv) across seasons. This should be discussed.

We thank the reviewer for this point. While free-running WRF-Chem tends to overestimate lower-tropospheric CO outside the monsoon, MATCHA underestimates surface CO in all seasons (MB of -197 to -246 ppbv in Table 4 & Fig. 15). We attribute this difference to MOPITT CO assimilation. The forward operator convolves the WRF-Chem CO profile with MOPITT a priori profiles and averaging kernels, so the analysis is constrained mainly in the free troposphere, where the MOPITT version 9 averaging kernels are most sensitive, and is weaker near the surface (Deeter et al., 2022; Jiang et al., 2015). When the model background overestimates free-tropospheric CO, the analysis reduces it toward MOPITT. This decrease propagates to the weakly constrained surface through the vertical background-error covariance and is over-corrected, potentially producing the negative surface bias seen in Table 4 and Fig. 15. The apparent deficit is likely amplified by the mismatch between near-source OpenAQ monitors and 12 km grid-cell averages and by residual surface-emission uncertainty over India and China (Gaubert et al., 2020; Ojha et al., 2016). We have reordered the discussion in the manuscript, so the assimilation effect is the leading factor, and emission uncertainty is secondary. The revised paragraph follows:

*Surface CO, in contrast, is consistently underestimated by MATCHA across all seasons, although the biases are smaller compared to $PM_{2.5}$ and $PM_{10}$. In winter, high surface CO concentrations are observed over the Indo-Gangetic Plain and eastern China in both OpenAQ and MATCHA (Fig. 15). MATCHA exhibits strong seasonality in surface CO, similar to OpenAQ, albeit with a negative bias persistent across the domain and all seasons. The domain-wide smallest negative biases occur in summer (MB of -197 ppbv), while the largest is seen in fall (MB = -246 ppbv). Correlation values for CO are consistently moderate across seasons (R of 0.3-0.4), with the highest correlation in winter (R of 0.35). KGE values suggest similar moderate agreement across the seasons (0.2-0.3), with the best performance during winter (KGE of 0.3).*

*The persistent negative bias across all seasons is likely due to constraints imposed by the daily data assimilation (DA) system used in MATCHA. MOPITT has limited sensitivity to near-surface CO and constrains mainly the mid- and free troposphere (Deeter et al., 2022; Jiang et al., 2015), so the analysis weakly constrains the surface CO, bringing its magnitude below the in-situ OpenAQ values (Hooghiemstra et al., 2012). Underestimated regional surface CO emissions over India and China likely contribute as a secondary factor (Gaubert et al., 2020; Ojha et al., 2016).*

**Minor Comment 1.7**

Data archival: the data has significant potential usage, but please review how it is archived. Instead of hourly files, key variables could be packed into monthly files, as some other chemical reanalyses do. Downloading many files delayed the assessment. (Framed as a general usability suggestion, not a quality concern.)

We thank the reviewer for this constructive suggestion and agree that reducing the number of files is important for usability. The files in the current format and resolution were archived in coordination with the NSIDC DAAC and follow their archival standards, so changing the structure rests with NSIDC. We will, however, raise this with the relevant team to see whether a future version can incorporate it. In the meantime, we point the reviewer to NSIDC's access services, where the collection can be filtered by date, spatial region, and file name and retrieved through downloadable *wget, curl*, or *Python* scripts via the NSIDC Data Access Tool, and is also available for direct access from the NASA Earthdata Cloud.

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Chayan Roychoudhury[1], Rajesh Kumar[2], Cenlin He[2], William Y. Y. Cheng[2], Kirpa Ram[3], Naoki Mizukami[2], and Avelino F. Arellano[1]

**Reviewer #2**
**General Comments**

The manuscript presents a 17-year regional hydroclimate-chemical reanalysis for Asia (MATCHA) at 12 km spatial resolution using WRF-Chem, including assimilation of MODIS AOD and MOPITT CO and coupling between aerosols, radiation, and snow processes. The development of such a system represents a significant technical effort and the study provides a comprehensive dataset that is likely to be very valuable for the community. In particular, the manuscript includes extensive comparison against independent observations for multiple variables including meteorology, snow cover and atmospheric composition, which is an important strength.

We thank Reviewer #2 for the supportive evaluation and for recognizing the technical effort and the value of the dataset. We believe these comments have substantially strengthened the manuscript and thank the reviewer for their time and constructive input. Reviewer comments are in blue while responses are in black. Changes to the manuscript are quoted in green when helpful.

**Major Comment 2.1**
It is unclear who the primary target users are. If the dataset is intended to support emission mitigation strategies, more discussion is needed on whether data quality is sufficient. Clarifying intended applications and associated limitations would improve usefulness to the community.

We thank the reviewer for this comment, which helped us state the dataset's intended use and purpose more precisely. We agree that the original wording implied a broader applicability to emission mitigation than the documented data quality supports, and we have addressed this in the following ways:

1. We state the primary target users explicitly, that MATCHA is a research dataset for the atmospheric-composition, cryosphere, and hydroclimate researchers, with strongest value for (i) aerosol-snow-radiation feedback studies, (ii) regional and sectoral BC source attribution via the tagged tracers, (iii) use as dynamically consistent, high-resolution forcing for offline snow, hydrology, or chemical-transport studies, (iv) the statistical and machine-learning community, for which the 17-year, 12 km dataset is well suited as training data, and (v) regional benchmarking of coarser global reanalyses over complex terrain.
2. We have softened the framing on mitigation. Rather than claiming the product is directly sufficient for quantitative mitigation accounting, we state that the BC source-attribution tracers (Sect. 3.3.5) are intended to inform mitigation-relevant questions, namely which sources and regions dominate deposition, while explicitly listing the limitations such as, the CAMS-GLOB-ANT anthropogenic inventory (which does not capture recent declines over China) and the positive biases in absolute surface $PM_{2.5}$/$PM_{10}$ (Sect. 3.3.2). We clarify that MATCHA is not intended for regulatory air-quality assessment or human-exposure estimation without observational bias correction.
3. We clarify that the emission-relevant value of MATCHA derives from the relative source attribution of the BC tagged tracers rather than from absolute surface concentrations, and we have revised the abstract and conclusions accordingly, so the claim matches the supporting evidence. A new applications-and-limitations paragraph has been added to Sect. 4 as follows,

   *MATCHA is intended for (i) aerosol–cryosphere and hydroclimate researchers studying LAP deposition and snow feedback over HMA, with well-constrained meteorology (KGE 0.65–1.0), snow cover fraction (R 0.7–0.9), and the coupled aerosol–radiation–snow simulations that distinguish MATCHA. (ii) air-quality and atmospheric-composition researchers needing a long, dynamically consistent, high-resolution regional record, and (iii) the statistical and machine-learning community, for which the 17-year, 12 km dataset can be used as training data. Users should weigh these strengths against the biases documented in Section 3* *when selecting variables. In particular, surface $PM_{2.5}$ and $PM_{10}$ concentrations carry substantial positive biases, especially in winter (Sect. 3.3.2), so MATCHA might not be suitable for direct regulatory air-quality assessment or human-exposure estimates without observational bias correction. Where MATCHA informs emission mitigation, that value derives from the relative source attribution provided by the BC tagged tracers (Sect. 3.3.5), which identify the regions and sectors dominating BC delivery to HMA's cryosphere across seasons.*

**Major Comment 2.2**

Provide more detail on the anthropogenic emission inventories. Over ~17 years emissions changed substantially across regions, which could contribute to PM2.5/PM10 biases. If possible, compare with more recent or alternative inventories.

We thank the reviewer for this comment. We have made the following changes to provide more detail on anthropogenic emission inventories. We want to mention that our companion study (Roychoudhury et al. 2026) on inverse modeling of BC estimates addresses this comment as well.

1. We added a short description of the anthropogenic inventory to Sect. 2.1. The paragraph is as follows, *Anthropogenic emissions are from CAMS-GLOB-ANT v4.2 (Granier et al., 2019; Soulié et al., 2024), providing monthly, sector-resolved emissions at 0.1° for gas-phase species and aerosols including BC and OC. Year-specific monthly emissions for 2003-2019 were regridded to the MATCHA domain, so MATCHA represents the interannual emission evolution. Open biomass burning is from FINN v2.5 (Wiedinmyer et al., 2023). A detailed treatment of both inventories and an observation-constrained assessment of their BC biases is given in Roychoudhury et al. (2026)*

2. We clarified the regional behavior of the emission inventory-related bias in PM. In Roychoudhury et al. 2026, we showed that over China, CAMS-GLOB-ANT shows emissions stabilizing around 2013 rather than the steeper observed decline, contributing to the positive PM bias (Sect. 3.3.2, bullet number 5), shown here: *The high positive biases in $PM_{2.5}$ over eastern China can be attributed to discrepancies in the emission inventory. pecifically, the CAMS-GLOB-ANT inventory used in MATCHA shows emissions stabilising around 2013 rather than the steeper observed decline over China (Soulié et al., 2024), likely resulting in an overestimation of PM2.5 in MATCHA for this region. This discrepancy likely results in an overestimation of $PM_{2.5}$ in MATCHA for this region.*

3. Regarding comparison against alternative emission inventories, we cite our recent inversion study using the MATCHA dataset (Roychoudhury et al., 2026). It uses the MATCHA tagged BC tracers and 91 surface sites across HMA and finds the prior underestimated by up to fourfold over the Tibetan Plateau and Bangladesh, within 20% over China and India, and underestimating biomass-burning over Southeast Asia. A full re-simulation with a different bottom-up inventory is beyond the scope of this dataset paper. *Our recent inversion study using the MATCHA BC tracers and 91 surface sites over HMA found prior BC (model/MATCHA) underestimated by up to fourfold over the Tibetan Plateau and Bangladesh, within ±20% over China and India, and underestimated biomass-burning over Southeast Asia (Roychoudhury et al., 2026).*

*Roychoudhury, C., He, C., Kumar, R., and Arellano, A. F.: Revisiting black carbon emission estimates in the Third Pole: a hierarchical Bayesian synthesis inversion perspective, Environ. Res. Commun., 8, 035019, https://doi.org/10.1088/2515-7620/ae4858, 2026.*

**Major Comment 2.3**

Without sensitivity analysis it is hard to attribute model performance to the assimilation of AOD and MOPITT CO. Also, a key novelty is representing LAPs and their feedback in HMA, yet the manuscript lacks quantitative analysis of BC-on-snow deposition impacts on snow/hydrology. Additional analysis or discussion would strengthen this.

We thank the reviewer for this thoughtful comment, and we agree that both points would strengthen the study. We address them as follows,

1. *On assimilation performance*. We agree that sensitivity analysis, perhaps observing system experiments, would be the ideal way to quantify the contribution of MODIS AOD and MOPITT CO assimilation to the evaluated skill. Given the 17-year simulation length, such experiments are computationally demanding and would constitute a substantial study in their own right, which we consider beyond the scope of this dataset

description and evaluation paper. We note that the assimilation configuration itself (Section 2.1.3) follows previously validated implementations (Kumar et al., 2019, 2020, 2025), and that the impact of assimilation is partly visible in the evaluation. For e.g. surface CO being more tightly constrained than surface PM, and the surface CO low bias being consistent with MOPITT constraining free-tropospheric CO. We have added text to Sect. 2.1.3 and Sect. 4 to clarify this and to consider dedicated assimilation-impact experiments as planned future work.
We have added this text in Sect. 2.1.3,
*The assimilation configuration used here is adopted from previously validated implementations (Kumar et al., 2019, 2020, 2025). Quantifying the contributions of AOD and CO assimilation to the skill reported in Sect. 3 (Results) would require dedicated observing-system experiments which are beyond the scope of this dataset description and evaluation study.*

In Sect. 4, we added this,
*Isolating how much of the evaluated skill is attributable to the assimilation of MODIS AOD versus MOPITT CO is left to dedicated observing system experiments in a future work.*

2. *On the impact of BC deposition on snow and hydrology.* We fully agree this is an important aspect. The quantitative assessment the reviewer describes, i.e. the effect of LAP deposition on snow disappearance timing and the downstream runoff, evapotranspiration, and streamflow response, is the subject of a dedicated companion study currently in review (Mizukami et al., 2025) which is driven by this MATCHA dataset and uses a clean-snow versus LAP-deposited-snow experimental design coupled with the *mizuRoute* river model. We felt this analysis warranted a full paper rather than a condensed treatment here. We now cite this companion study in Sect. 2.1.4 and direct readers to it for the quantitative LAP-snow-hydrology results. In Sect. 2.1.4, we added this,
*The impact of LAPs deposition on the snowpack and the resulting hydrological response (timing of snow cover disappearance, runoff, evapotranspiration, and streamflow) over HMA river basins is assessed in a companion study using this MATCHA dataset (Mizukami et al., 2025).*

*Mizukami, N., Minallah, S., He, C., Roychoudhury, C., Cheng, W. Y. Y., and Kumar, R.: Hydrologic implications of aerosol deposition on snow in High Mountain Asia rivers, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2025-4586, 2025.*

**Major Comment 2.4**
Provide a high-level summary (e.g., Taylor diagrams or a summary table) of key performance metrics across variables, so readers can grasp overall performance, strengths and limitations, without browsing every figure.

We thank the reviewer for this helpful suggestion. We agree that a consolidated overview would help readers assess the overall performance of the dataset. We have added a new summary table (Table 5) at the beginning of Section 4, which condenses the seasonal metrics in Tables 2 to 4 into one row per variable, reporting the seasonal range of R and KGE, the dominant bias, and some comments. We opted for a summary table rather than a Taylor diagram because the normalization in a Taylor diagram removes bias information, which is necessary to characterize the average MATCHA performance (e.g. the positive $PM_{2.5}$/$PM_{10}$ biases and the negative surface CO bias). The table retains bias alongside correlation and KGE and therefore provides a better overview for this dataset.

**Minor Comment 2.1**
Line 20: "fine particulate matter: PM2.5/PM10" is confusing.

We thank the reviewer for pointing this out. We have rephrased L20 to "particulate matter ($PM_{2.5}$ and $PM_{10}$)" and removed the conflated wording.

**Minor Comment 2.2**
*Figure 1 is helpful but presentation could be improved: cluttered arrows, no clear visual hierarchy among key processes, and the meaning of different arrow colors is not explained.*

We thank the reviewer for this comment. We understand that the original Figure 1 had vague arrows and presentation. We have revised Figure 1 to improve clarity and defined the structure throughout the caption. In panel a), arrows now denote the two-way coupling between model components and the external forcings supplied to WRF-Chem. In panel c), we adopted a consistent color code, now defined in the caption as follows: blue for MODIS AOD and MOPITT

CO retrievals and model background ingested into GSI, while red for the analysis returned to WRF-Chem and the day-to-day re-initialization. Panel b) shows the ten tagged BC source regions with the model domain outlined. As this is a validation and data description paper, Figure 1 is intended as an overview of the framework since the finer details of the model, chemistry and assimilation configuration is given in Sect. 2. The revised caption reads as follows,

***Figure 1:*** *The MATCHA framework. (a) Schematic representation of the model setup in MATCHA. Within WRF-Chem (blue box), gas-phase chemistry and aerosols (MOZART-MOSAIC) are coupled to radiation (RRTMG), clouds (Morrison double-moment microphysics), and the land surface (CLM with the SNICAR snow-radiation module; green box), with grey arrows denoting the exchange of fields between components. External forcings (grey dashed box) comprise emission inputs as well as meteorological and chemical initial and boundary conditions. (b) the 10 tagged source regions for anthropogenic BC over the entire study domain. (c) the assimilation workflow used in MATCHA, where MODIS AOD and MOPITT CO profiles were assimilated every 3 hours into the WRF-Chem-CLM-SNICAR model for the 17 years of simulation period. The model advances through successive 3-hour windows daily. Blue arrows show MODIS AOD and MOPITT CO retrievals together with the model background state, ingested into the GSI data assimilation system; red arrows show the analysis returned to WRF-Chem and the re-initialization carrying the model state at the end of the day into the next day's 0 UTC cycle.*

### Minor Comment 2.3

*For sea salt and dust: show PM10 including these, or a plot of their contribution. For dust, clarify the relative contributions of local emissions versus lateral boundary transport, as long-range transport may matter here. Specify which dust emission scheme is used and discuss its potential impact.*

We thank the reviewer for this comment, which we address in three parts.

1. We have touched upon the contribution of sea salt and dust to PM10 in its evaluation within the text. Fig. 14 shows the adjusted $PM_{10}$ field after sea salt and dust are removed, and Table 4 reports both the total and the adjusted domain-mean statistics for every season. The difference between the two gives the sea salt plus dust contribution to the $PM_{10}$ bias directly: 141 $\mu g/m^3$ in winter, 29 $\mu g/m^3$ in spring, 17 $\mu g/m^3$ in summer, and 68 $\mu g/m^3$ in fall. These two species therefore account for most of the positive $PM_{10}$ bias in winter (69%) and fall (92%) and a smaller contribution in summer. We have added the total (unadjusted) seasonal $PM_{10}$ maps as an appendix figure (Fig. A5) to Fig. 14 and we now mention the contribution numbers in Sect. 3.3.2.

   *When expressed as the difference between the total and adjusted domain-mean bias (Table 4), sea salt and dust together contribute 141, 29, 17, and 68 $\mu g/m^3$ to the PM10 bias in winter, spring, summer, and fall. The seasonal maps for total (unadjusted) $PM_{10}$ are shown in Fig. A5 for comparison with the adjusted fields in Fig. 14. The contrast is most visible over India in summer and eastern China in winter, where sea salt and dust account for most of the positive bias.*

2. We agree that long-range transport from the Arabian, Thar, and Central Asian deserts contributes to columnar dust loading over HMA, and that contribution can enter MATCHA through the boundary conditions. However, that dust is not tagged as a tracer in MATCHA (only BC is tagged), so a quantitative split of the two pathways (local vs boundary) is not available. Our diagnostics in response to Reviewer 1 (Major Comment 1.2) show that the dominant dust signal over the western domain is locally generated: along west-to-east transects, dust and PM2.5 rise from the boundary to a maximum roughly 400 to 470 km inland near 59° E, the concentration profile follows the simulated dust emission flux (R of 0.7), and the relaxation-zone columns carry weak emission and lower concentration than the interior. Lateral inflow would produce the opposite signature, a maximum at the boundary decaying inward. Long-range transport from the Arabian, Thar, and Central Asian deserts does contribute to columnar dust over HMA via the boundary conditions, but local emission dominates the surface PM bias. This clarification has been added as a separate bullet to Sect. 3.3.2.

   *Over the arid desert regions along the western edge of the domain, MATCHA overestimates surface dust and, in turn, $PM_{2.5}$ and $PM_{10}$ (Fig. A5). The GOCART dust emission scheme (Ginoux et al., 2001) used in the model setup of MATCHA combines a high prescribed erodibility over these regions with a low soil-moisture-dependent threshold, producing strong emission even under moderate winds, a behavior linked to dust and PM overestimation in WRF-Chem over the arid regions of southwest Asia (Parajuli et al., 2019). The emitted mass is also redistributed from the GOCART size sections onto the MOSAIC bins in a way that places an excessive fraction below 2.5 μm, so the overestimation also affects $PM_{2.5}$ and not only $PM_{10}$ (Pino-Carmona et al., 2024). Dust reaches the domain both through emissions generated within* *the domain and through the CAMS-EAC4 chemical boundary conditions (Table 1), which carry long-range transport from sources such as the Arabian and Thar deserts. Dust is not tagged as a tracer in MATCHA, so the two pathways cannot be partitioned quantitatively. The enhancement over the western source regions, however, is generated within the domain rather than advected through the lateral boundaries, as the concentration maximum sits several hundred kilometres inland and is co-located with the simulated emission flux. Surface dust and PM magnitudes over these western source regions should therefore be read as an upper bound.*

3. MATCHA uses the GOCART dust emission scheme coupled to the MOSAIC aerosol module (WRF-Chem `dust_opt = 13`), with the Ginoux et al. (2001) source function. We have added this to Table 1 and named it in the text. Its potential impact on the results is threefold, 1) the emission flux scales with 10 m wind speed, so the positive wind bias inflates the dust flux as it does for sea salt, 2) GOCART tends to over-emit over the sparsely vegetated dry soils along the Central Asian and Caspian margins (Parajuli et al., 2019), and 3) the remapping of GOCART-emitted dust onto the MOSAIC size bins places a disproportionate fraction of the mass in the fine bins, raising PM2.5 and the fine portion of PM10 (Pino-Carmona et al., 2024). We now discuss these explicitly. We have added this text in the aforementioned bullet in Section 3.3.2.

The references are mentioned below,

Ginoux, P., Chin, M., Tegen, I., Prospero, J. M., Holben, B., Dubovik, O., and Lin, S.-J.: Sources and distributions of dust aerosols simulated with the GOCART model, Journal of Geophysical Research: Atmospheres, 106, 20255–20273, https://doi.org/10.1029/2000JD000053, 2001.

Parajuli, S. P., Stenchikov, G. L., Ukhov, A., and Kim, H.: Dust emission modeling using a new high-resolution dust source function in WRF-Chem with implications for air quality, Journal of Geophysical Research: Atmospheres, 124, 10109–10133, https://doi.org/10.1029/2019JD030248, 2019.

Pino-Carmona, M., Ruiz-Arias, J. A., Fernández-Carvelo, S., Bravo-Aranda, J. A., and Alados-Arboledas, L.: Intercomparison of WRF-Chem aerosol schemes during a dry Saharan dust outbreak in Southern Iberian Peninsula, Atmospheric Environment, 339, 120872, https://doi.org/10.1016/j.atmosenv.2024.120872, 2024.