

Response to Reviewers

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

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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 high-resolution 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 comment. We want to emphasize that the central purpose of these figures is the evaluation of MATCHA against observations, for which the model must be compared to the observations collocated across space and time. In Figs. 8, 9, and 12-15 the model dataset is sampled at the observation times and sites, and the figures show these collocated model-observation pairs. The in-situ records are temporally sparse and irregular over 2003–2019 and differ from site to site, so a time-mean domain-wide field would show a different statistic from the collocated values. Placing such a field behind the points would display spatial information that differs from what the collocated points represent, which we consider more likely to confuse the reader than to clarify.

For the boundary-layer height (Figs. 8 and 9) this is made more complex by its strong diurnal cycle, since the model is sampled at the radiosonde release times and an all-hours mean field would not be comparable to the time-specific soundings. We have therefore retained the collocated presentation for these evaluation figures. We also note that the spatial correspondence between MATCHA and the observations is already assessed quantitatively rather than only visually (in Tables 2-4). The correlation coefficient reported per variable and season in Tables 2 to 4 quantifies how well MATCHA reproduces the observed spatial pattern across the sites and thus can provide the spatial fidelity information evaluated directly against the observations.

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-and-limitations paragraph added to Sect. 4 (in response to Reviewer 2, Comment 1) are intended to serve exactly this purpose.

Major Comment 1.2

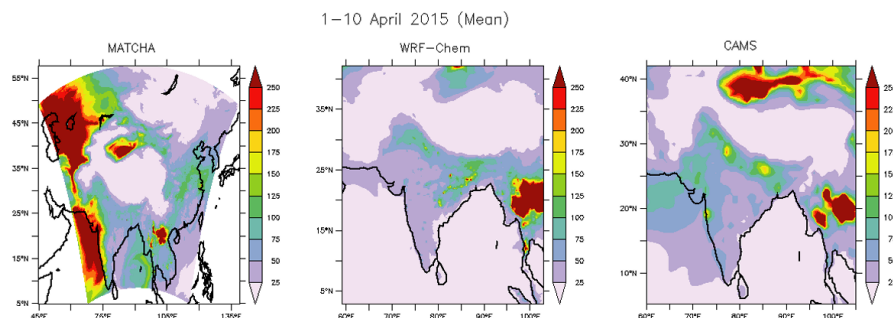


Figure: Mean distribution of PM_{2.5} ($\mu\text{g.m}^{-3}$) from MATCHA data (presented in this manuscript), from ‘a WRF-Chem simulation’ and CAMS reanalysis. Domains and physics/chemistry are not identical and comparison is for broad inferences.

Somehow on the western boundary of MATCHA fields, there seem anomalously high PM_{2.5} (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 PM₁₀ 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 $1000 \mu\text{g/m}^3$ 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 $2.5\ \mu m$ (Pino-Carmona et al., 2024) and is why the bias appears in $PM_{2.5}$ and not only PM_{10} . 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 $2.5\ \mu m$, 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.

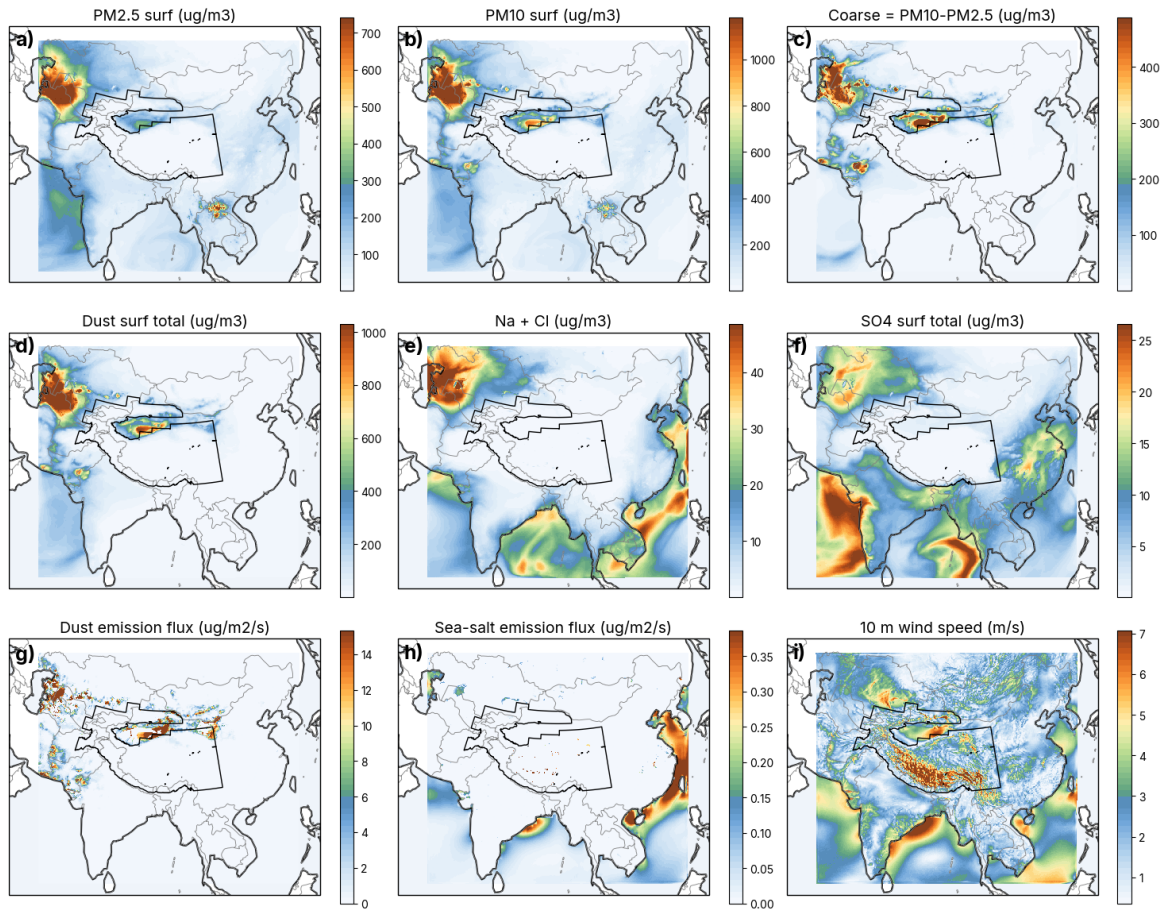


Figure R1: Mean surface concentrations over the western domain for 1 to 10 April 2015 from MATCHA: (a) PM2.5, (b) PM10, (c) coarse fraction (PM10 minus PM2.5), (d) dust, (e-h) sea salt, sulfate, nitrate, and ammonium, and (i) 10 m wind speed. The enhancement along the western boundary is carried almost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

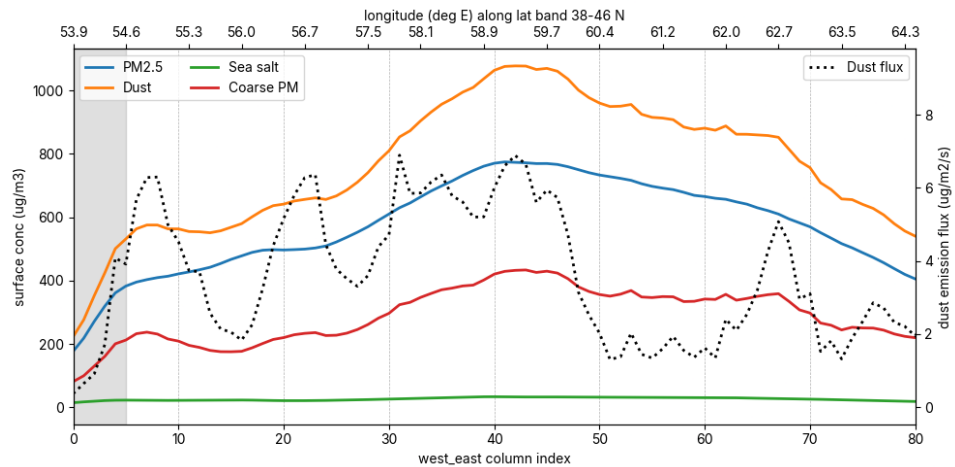


Figure R2: West-to-east transects across the northwestern domain, averaged over 1 to 10 April 2015: surface dust and PM_{2.5} concentrations (solid lines, left axis) and simulated dust emission flux (dotted line, right axis). Grey shading marks the lateral boundary. Concentrations peak about 470 km inland 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 PM₁₀ 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>.

Binouk, 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).*

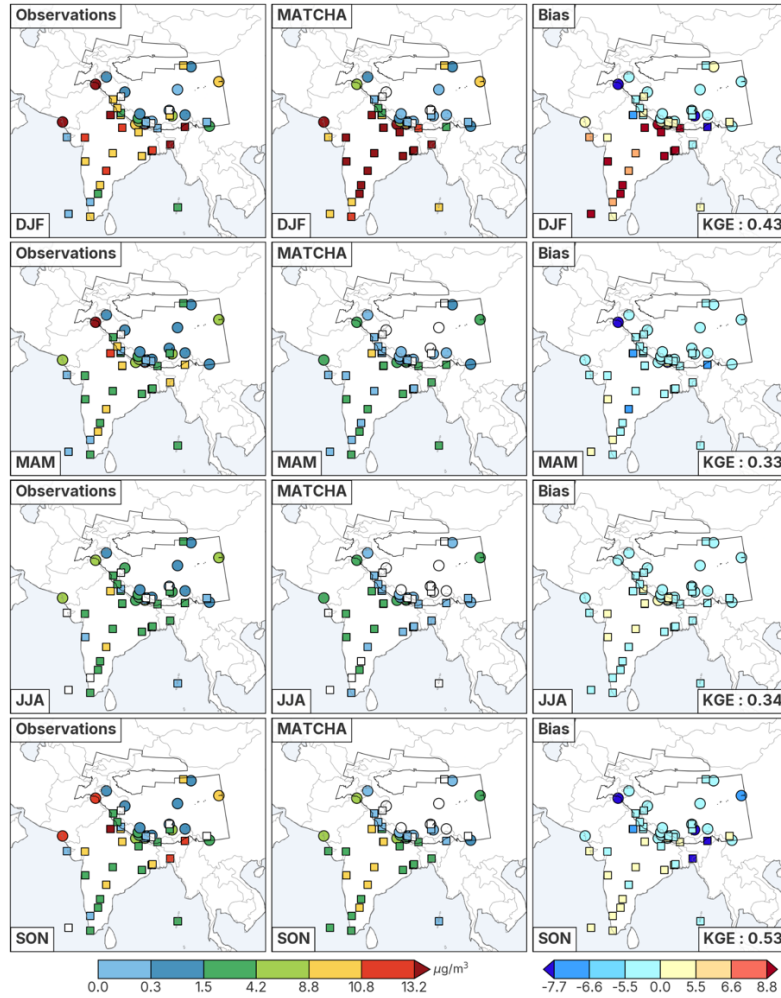
Sun, H., Su, F., Yao, T., He, Z., Tang, G., Huang, J., Zheng, B., Meng, F., Ou, T., and Chen, D.: General overestimation of ERA5 precipitation in flow simulations for High Mountain Asia basins, Environmental Research Communications, 3, 121003, <https://doi.org/10.1088/2515-7620/ac40f0>, 2021.

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 $\mu\text{g m}^{-3}$.

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 $\mu\text{g m}^{-3}$ 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 PM₁₀. 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.