Response to Reviewers

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

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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 µg/m^3 in winter, 29 µg/m^3 in spring, 17 µg/m^3 in summer, and 68 µg/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 µg/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.