egusphere-2026-1343: “Modelling mineral dust emissions from proglacial valleys of the St. Elias Mountains, Canada”

Response to reviewers

Position indicators (lines) reflect positions in the revised manuscript.
Replies are given in blue. Changes to the manuscript are written in green.
***Bold** typeface is used to identify new additions within pre-existing lines in the manuscript.*

Referee #1

General Comments

This manuscript presents a modeling study that develops and evaluates a high-resolution WRF-Chem framework for simulating mineral dust emissions from proglacial valleys of the St. Elias Mountains, Canada. The manuscript is well structured, and the research method is based on a comprehensive suite of observations, including surface meteorological stations, optical particle counters, camera observations, and Doppler LiDAR measurements. The topic is interesting and important, especially because dust emissions from high-latitude proglacial valleys remain largely unresolved in current dust modeling efforts and are not represented in most regional or global dust inventories. The manuscript also contains substantial technical effort in modifying land-surface inputs and adapting the dust emission scheme for confined glaciofluvial deposits. In general, the manuscript demonstrates promising model skills in reproducing emission timing and some aspects of meteorology and vertical transport, with reasonable discussions of the simulation results. Therefore, I would recommend a major revision with more detailed discussion of model bias, parameter sensitivity, and the representativeness of the evaluation.

Thank you for reviewing this work and your detailed comments.

Major Comments:

A major issue with the manuscript is regarding the interpretation of the simulation bias in dust emission flux. As shown in the manuscript, the model successfully reproduced all observed emission events during the evaluation periods, but the simulated vertical dust flux at the DV grid point was only about 4% of the measured value. The manuscript attributes this mainly to underestimated surface winds, the aggregate disintegration behavior in the Shao (2004) scheme, and the overestimated soil moisture correction. While all of these are plausible, the discussion still remains somewhat qualitative and does not yet clearly establish which factor is most responsible for the large flux discrepancy. In particular, the results show that simulated fluxes are extremely sensitive to the prescribed soil texture, and that the comparison improves substantially when averaging over emissive grid cells of the delta rather than comparing only the DV grid point. This suggests that both parameter sensitivity and representativeness mismatch are central to the interpretation. Therefore, the discussion of modeling bias may benefit from a more detailed and more quantitative explanation.

Thank you for highlighting this. In response, we have reworked section 3.1.2 into a targeted quantitative breakdown of the factors causing the flux differences across the delta, followed by identifying the main causes of discrepancies in the point-scale comparison with measurements. This section is copied fully below.

L298: **"3.1.2. Vertical dust fluxes on the A'ąy Chù delta**

Friction velocity (u_*) and the vertical dust flux (F_d) (0.25 – 9.81 µm) were evaluated against measurements at DV during s01 and s02, as presented in Fig. 7. The underestimation of simulated surface winds (previous section) is further apparent in the u_* comparison, with a mean bias of –0.08 m s^{-1} at DV. Despite this, of 27 days of observed dust emission events on the A'ąy Chù delta during this period, all were simulated in WRF. Across both simulation periods, we measured a total vertical dust flux of 0.166 kg m^{-2} at DV, with a daily average of 5.9×10^{3} kg m^{-2} day^{-1}, notwithstanding observational gaps. In contrast, the closest grid point to DV simulated a total vertical dust flux of 6.2×10^{-3} kg m^{-2}, approximately 4% of that measured. In Fig. 7, simulated values of F_d at DV (soil class: *sand*) and F_d averaged over emissive grid cells of the delta (soil class: 56% *silt*; 44% *sand*) are illustrated separately to examine sediment texture sensitivity in the Shao (2004) scheme. Simulated F_d at DV was substantially underestimated (mean bias of –86 µg m^{-2} s^{-1}) however fluxes averaged across the delta compare more favourably (mean bias of +26 µg m^{-2} s^{-1}), notwithstanding u_* discrepancies. Below we highlight the causes of emission flux variability across the delta and the main factors underlying discrepancies at the point-scale comparison.

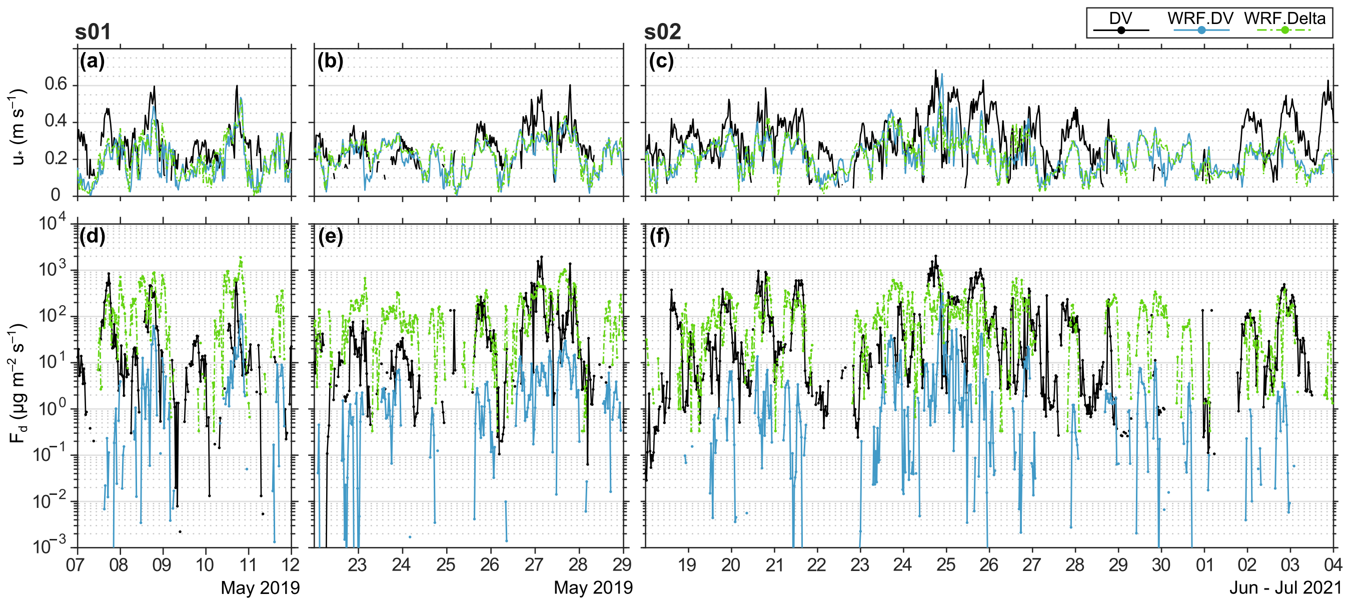

Figure 7. Comparison of measured (DV) and WRF-simulated variables: at the DV grid point (WRF.DV) and averaged over emissive grid cells of the A'ąy Chù delta (WRF.Delta). (a–c) Friction velocity (u_*). (d–f) Vertical dust flux (F_d) ($0.25 - 9.81$ µm).

The impact of soil moisture varied across the delta and influenced F_d substantially at low $u_* - u_{*t}$ values. Sediment texture heterogeneity, combined with simulated θ_v overestimates (Fig. 5.e–h) and the texture-dependent soil moisture corrections of Fécan, Marticorena and Bergametti (1999), also yielded moisture-induced spatial discrepancies in u_{*t}. Across all simulation periods (47 days) *fine* outwash deposits (sand) experienced moisture-induced heightening of u_{*t} for 45 days, despite the modified soil moistures used in dust emission parameterisation (Figure 2), while *very fine* deposits (silt) remained unaffected. For s01, with no rain and dry conditions, a soil moisture-induced u_{*t} modification of +0% to +40% was effected at DV (average +11%) under the modified emission scheme (Fig. 2), despite dry surface conditions being observed. Under this effect, u_{*t} ranged from 0.21 – 0.29 m s^{-1}. For very low values of $u_* - u_{*t}$ (<0.1 m s^{-1}) this can induce F_d reductions of 10^1-10^4 vs. dry soil u_{*t}: the source of the extremely low values for the DV comparison in Figure 7.d-f. While minor precipitation events did occur during s02 on the 21, 22 and 30 June, we note an average soil moisture correction of +16% was effected for the simulation duration.

For higher values of $u_* - u_{*t}$, sediment texture prescribed to the two-outwash classes present on the delta becomes the key control on variability, with differing sub-20 μm particle mass and variable dust production as a function of $u_* - u_{*t}$, following the aggregate disintegration scheme γ (Shao, 2001). Under ideal conditions at low $u_* - u_{*t}$, minimally-disturbed PSD definitions account for F_d discrepancies on the order of 10^1-10^2. For silt outwash, between minimally- and fully-disturbed PSDS, sub-20 μm particle mass only increase ~30% (supplementary Fig. S3), yielding limited influence on F_d as a function of $u_* - u_{*t}$. For sand outwash deposits as defined in this study (Table 4), sub-20 μm particle mass increased ~1800% for the same fixed u_* range as defined by γ, with 95% of the 9.75% ≤20 μm mass aggregated as saltation-sized particles, only released in the fully-disturbed PSD. The spatial differences in emission across the delta narrow with increasing $u_* - u_{*t}$.

Concerning the grid point comparison at DV, the identified soil moisture adjustments to u_{*t} are insufficient to account for persistent F_d underestimation during major dust events in high u_* conditions. During the peak emission in s02 (24 June 2021 18:00), observations provide u_* = 0.685 m s^{-1}, F_d = 2033 μg m^{-2} s^{-1}, while simulated u_* at DV was 0.301 m s^{-1} with F_d = 1.16 μg m^{-2} s^{-1}. A 1D implementation of S04 suggests bringing u_* in-line with observations would increase F_d by ~10^2, insufficient to match observations. The implemented $\kappa = 1$, representing a relatively resistant soil to disaggregation (Y. Shao *et al.*, 2011), may have been too low for these sand deposits and simulated saltation failed to release fine-grained materials as observed. However, field measurements of aggregate stability (κ) are limited and time-variant (Klose *et al.*, 2019), challenging the implementation of soil-specific coefficients in modelling efforts. The impact of underestimated u_* on simulated fluxes at DV is exacerbated by the aggregate disintegration efficacy in this scheme. Separately, we note that in applying stress partitioning correction for $u_*(r)$ instead of u_{*t} (Fig. 2), the aggregate disintegration mechanism applied over an extended range of u_*, for the *very coarse* and *coarse* outwash deposits subject to enhanced stress partitioning. Sediment textures were measured during 2022 (see supplementary 1), however with outwash deposits prone to rapid reworking by active sands and exposing finer sediment layers, fine sediment exposure may have been higher during 2019 and 2021 (Bellamy, King and Nadeau, 2026), and fine content may be underestimated in the average soil PSD."

Another major issue concerns the uncertainty associated with the customized land-surface characterization. The manuscript makes major improvements to land use, soil classes, albedo, roughness length, and the binary erodible source function, and this is clearly one of the strengths of the work. However, many of these choices are based on necessarily limited field observations or pragmatic assumptions, such as prescribing representative textures for several outwash classes and assigning the upper Kaskawulsh valley entirely as coarse material. Since these assumptions directly control emission strength, threshold friction velocity, and the spatial pattern of erodibility, it will be helpful to discuss more explicitly how uncertainty in these prescribed surface properties affects the robustness and transferability of the results. As shown in Fig.1, it seems like the whole St. Elias Mountains contain much larger areas with very similar landcover and topography as d01 and d02 simulated in this study. Thus, the extent to which this study can be confidently generalized to the whole area is worth to discuss.

This is a valid point. We have added a section to the discussion describing the importance of the prescribed variables and discussing uncertainties in land-surface characterisation for the domains considered here.

L466: **"4.1.2. Outwash deposit characterisation"**

"The mandatory overhaul of land-surface descriptions required the prescription of representative aerodynamic roughness lengths and sediment textures to mapped outwash deposit classes (Table 4), two key variables controlling the spatial pattern and strength of emissions. For the classes defined in this work, gravel-induced roughness across classes reduced u_* by a factor of 1-3.56 during emission parameterisation, while the assigned sediment textures had minimally-disturbed <20 μm particle counts of 0.9-48.2%. Both ranges can induce order-of-magnitude changes in the simulated dust emission flux; however, this captures the heterogeneity of deposits within glaciofluvial system we attempted to resolve (Maizels 1993). Within the A'ą̈y Chù valley, surface characteristics were well constrained with field observations and sediment sampling. Larger uncertainty exists in ascribing sediment characteristics within the Kaskawulsh and Alsek River systems. Surficial geological mapping, where available, is dated (Rampton and Paradis, 1982) and precedes major seasonal inundation experienced since a 2016 hydrological reorganization that enhanced river levels and likely extended deposits of erodible fine sediments (Bellamy, King and Nadeau, 2025). Considerable uncertainty subsequently remains in the characterisation of these surfaces and the final emission estimates presented. For studies modelling dust emissions from these active river systems, uncertainty in these prescribed surface properties is likely to remain persistent."

We note that we do not attempt to generalise this study across the wider region, as dust emission activity is valley specific (terrain orientation vs. prevailing winds, hydrological system and bedload type), but simply report emission estimates from several of it's proglacial valleys. We present the approach as a tool for interrogating other regions.

Specific Comments:

(1) In the Abstract, the manuscript states that a total emission rate was estimated from erodible deposits across 47 simulation days. Since the manuscript also shows that the modeled dust flux is highly sensitive to soil texture, soil moisture, and point-versus-area comparison, it would be helpful to clarify in the abstract and conclusion that this value should be interpreted as a first-order estimate rather than a tightly constrained regional emission budget.

Done, modifications made:

L22: "A total emission rate of 1.0×10^4 kg km^{-2} day^{-1} was estimated from erodible deposits across 47 days of simulation, **providing a first-order estimate of emissions from these valleys during dusty periods.**"

L622: "This work provides **a first estimate** of mineral dust emissions for several proglacial valleys in the region, …"

(2) For the description of the erodible source function, the manuscript defines potential erodible areas as surfaces inundated during summer and exposed in autumn at least 5 times during 1984–2023. The basis for choosing "5 times" is not fully explained. It would be helpful to provide more justification for this threshold, or at least discuss how sensitive the mapped source area is to this criterion.

Further justification has been added to the text:

L137: "The criteria identified regularly reworked surfaces only but was sufficiently lenient to capture conditions following a major hydrological reorganisation in 2016 (Shugar *et al.*, 2017)."

(3) In Section 2.2.2, four outwash deposit classes are introduced with prescribed representative soil textures and aerodynamic roughness lengths. Since these parameters are central to the results, it might be helpful to summarize more explicitly in the main text how much of the simulated emission area falls into each of these four classes, rather than leaving the reader to infer their importance indirectly.

While these deposit classes are defined for all simulations, the emissive area of each class changes between simulations as land-surface datasets are updated and simulated meteorology differs. Hence, these values are not known apriori and are included in the Results. These areas are already given in Table 6 (section 3.2.1), alongside the total emissions from each class, such that readers can directly compare their importance. The relative contribution from each class is already reported in the main text (section 3.2.1). Discussion regarding the importance of these classes has been improved in response to the reviewer's second major comment (see section 4.1.2).

(4) For the albedo adjustment, the manuscript states that the albedo of the glaciofluvial deposits was set to 0.14 based on average noontime observations at the DV station, replacing the default barren-surface value of 0.38. Since albedo is likely to vary with sediment type, moisture state, and illumination conditions, it would be useful to briefly discuss whether this single value is expected to be representative for all deposit classes and all simulation periods.

Done, see below:

L164: "This adaptation improved outgoing radiative fluxes (supplementary 3), however replacing the single value does not improve on domain-wide albedo discrepancies due to variable surface moisture or deposit type."

(5) In the surface meteorology evaluation, the manuscript notes that the 24 h spin-up may have been insufficient for soil moisture adjustment, especially during s01. Soil moisture directly affects threshold friction velocity and emission onset. It would be useful to comment on whether a longer spin-up period was tested, or whether computational constraints prevented this.

Longer spin-up times were not tested as this initial rapid adjustment was only seen in one of the four simulations. Section 4.2.3 discusses this further, and how soil moisture remained overestimated for the duration of the simulations and is unlikely to be appropriately treated by lengthening spin-up times, suggesting pre-simulation modification of initial values instead. Accordingly, we did not modify the spin-up times.

(6) For the comparison of dust flux at DV versus the average over emissive grid cells on the delta, the manuscript shows a large difference between these two simulated quantities. The discussion would benefit from being more explicit about the representativeness issue: to what extent should the DV tower measurement be interpreted as a point-scale flux, and to what extent is it reasonable to compare it with a grid-cell or delta-averaged model flux?

This comment has been resolved by corrections made in response to the first major comment from the reviewer. The comparison is now much more thorough and focuses on comparing the point-scale flux.

(7) The manuscript uses camera observations to qualitatively evaluate dust activity in adjacent valleys. The limitations of the method should perhaps be emphasized a bit more clearly. Since camera-based emission logs depend on visibility conditions, viewing angle, and plume contrast, it would be helpful to briefly comment on whether weak or short-lived events may have been missed in the qualitative record.

Limitations have been noted more explicitly in the manuscript:

L259: "As the approach required the visual identification of suspended dust, weaker events may be absent from camera-based emission logs."

(8) Figure 2 contains many symbols and terms that are not easy to follow on first reading. It may help to simplify the presentation slightly or to ensure that all modified parameters are clearly highlighted in the figure caption, so that readers can more easily identify what was changed relative to the standard implementation.

The caption has been updated to highlight the modified parameters:

L198: "Figure 2. Overview of the modified Shao (2004) scheme in WRF-Chem developed in this work. **Modifications were applied to the drag partition parameterisation ($\lambda_r, u_*(r)$), further detailed in section 2.2.3**."

Referee #2:

This manuscript discusses the development and evaluation of high-resolution WRF-Chem modeling approaches to simulate mineral dust emissions from proglacial valleys in the St. Elias Mountains, Canada, across three different time periods and seasons. The land-surface input datasets were updated and the Shao (2004) dust emission scheme was modified to better represent surface erodibility. The model results were evaluated using field data from meteorological stations, Doppler LiDAR, and cameras. The model successfully captured dust emission dynamics, demonstrating seasonal and diurnal variability and dependence on soil type. The model underpredicted surface wind speeds and vertical dust flux, while overpredicting soil moisture. These studies could be used to improve our understanding of high-latitude dust emissions and their response to climate change.

Specific comments:

Note to editor: The specific comments from referee 2 were received during the rapid access review, and manuscript modifications were performed prior to the open discussion. The responses and manuscript changes are repeated below:

Figure 9c and d: The contour plot of wind direction is difficult to understand in the way it is presented.

Difficulty in interpreting the plots is understandable given the concentration of information, however filled contour plots are a frequently used way to illustrate diurnal wind speeds and directions. The alternative would be a wind vector plot i.e. quiver plot, which we attempted below. The method is not ideal for illustrating horizontal wind speed and direction, plotting u and v component on an x,y plane is likely to lead to misinterpretation. In lieu of further precision of issues with the original contour plot, the figure remains unmodified in the manuscript.

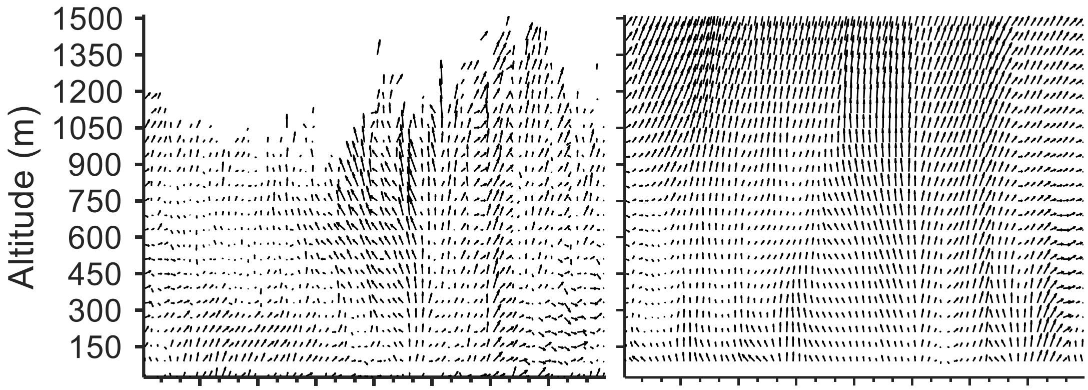

Figure 10: What is causing the high dust concentration in LiDAR data around 1-1.5 km on May 24?

This signal was previously attributed to previously emitted dust returning to the LiDAR following a wind direction shift. Upon further review, we have evaluated it to be low-lying cloud that was not caught during cloud screening procedures. We have updated the LiDAR cloud-screening, eliminating this higher altitude signal. Figures 9 and 10 have been updated.