Response to reviewer

Dust removal by snow is an important mechanism for dust wet deposition, which not only modifies atmospheric dust residence time but also helps the understanding of dust-snow interactions and dust-in-snow effects. Till now, it is still challenging to accurately estimate dust removal by snow. This study has developed a Euler-Lagrange numerical modeling framework to simulate and analyze snow particles motions and dust collection in turbulent boundary layers. It also proposes several equations for estimating dust removal by snow, which can be used for large-scale numerical models. Most of the manuscript is well written. I have some comments for further improvements of the manuscript.

Response: We sincerely thank the reviewers for taking the time to review our manuscript and for providing valuable and insightful comments. In response to your detailed and profound suggestions, we will undertake a comprehensive revision and supplementation of the manuscript to enhance the rigor of the research and the clarity of the presentation. Here, we provide detailed responses to each question and suggestion raised by the reviewers. All comments and suggestions have been carefully considered. In the following, the original comments from the reviewers will be presented in *italics*, and our responses are shown in **blue**.

Main comments:

1. *The results are derived based on several assumptions including spherical shape for snow particles and very small size (<20 nm) for dust particles. It is better to add a sentence to mention the assumptions before the description of the results in both Abstract and Conclusions. In addition, it might be better to also add some discussions on the impact of these assumptions on the applications of current results presented. In particular, the dust size is too small compared to commonly-used size range (the orders of 0.1-10 micrometer) in atmospheric models. I am wondering how the conclusions (e.g., optimal scavenging efficiency by snow particles in a diameter of 100–150 μm) and equations derived for dust collections can be applied in this range.*

   Response: Thank reviewer for the suggestion. We agree to add an explanation regarding the assumptions used in this study in both the abstract and discussion sections. 1、Regarding the Assumption of Snow Particle Shape (Spherical Particles)：This study employs the dimensionless parameter α to characterize the dynamic behavior of particles through the terminal settling velocity. The terminal settling velocity inherently integrates the effects of factors such as particle shape and density on drag. Therefore, even when considering non-spherical particles, their aerodynamic effects have been incorporated into the definition of this parameter through the core variable of terminal settling velocity. if changes in shape lead to variations in settling velocity, the value of α will adjust accordingly. The specific influence of complex shapes on the α threshold and related sensitivities is indeed an important issue requiring in-depth investigation. However, this involves specialized research on the coupling between microscopic particle shapes and flow fields, which extends beyond the core scope of this paper focusing on the macroscopic mechanisms of turbulence. Currently, our team is conducting specialized research on the values of α corresponding to different snow particle shapes, and the results of this research will be elaborated in subsequent work. 2、Regarding the Dust Particle Size Range. First, we need to clarify a typographical error in the manuscript: the particle size of the Aitken mode investigated in this study is actually d_p = 20–100 nm, not d_p < 20 nm. We sincerely apologize for any misunderstanding this error may have caused. Second, this study aims to reveal the influence of turbulent characteristics in the atmospheric boundary layer on the motion of snow particles in the air. It further explores the scavenging effect on dust particles caused by the relative motion between snow particles and air, and establishes the corresponding quantitative expression (Equation 22):

$$Sr = Vr \cdot T_d = V_t(0.97 + 19.85e^{-57.6D_p})e^{2.27e^{-11.02D_p}\cdot u_*}(\frac{h}{V_d}),$$

when calculating the scavenging efficiency of snow particles on dust, we substituted the dust concentration nn as a constant into the wet deposition model (Equation 25) for analysis.

$$Q = e_s n\pi(R+r)^2 Sr = e_s n\pi(R+r)^2 Vr \cdot T_d$$

We understand the reviewer's concern regarding the discrepancy between the particle size range in this study and the commonly used range in atmospheric models (approximately 0.1–10 μm). By substituting the dust concentration within this size range into the formula derived in this paper (Equation 25), the optimal snow particle size range for scavenging efficiency under the corresponding conditions can be obtained. Accordingly, we will add an explanation in the text on how to apply the conclusions and the wet deposition model to the common particle size range (0.1–10 μm) to deduce the optimal snow particle size range for scavenging efficiency.

2. *Several equations are provided with values for parameters shown, such as Eqs. 16, 18, 19, 22, 27, 29. In these equations, it is suggested that the units for variables (and parameters) are provided as well, as the values can change if the units for the variables are changed. Please check the units throughout the manuscript to avoid such confusion.*

   Response: Thank reviewer for the suggestion. We fully agree that explicitly labeling the units of variables (and parameters) in all formulas throughout the paper is crucial for ensuring the clarity, reproducibility, and avoidance of misunderstandings in the results.

Specific comments:

1. *Line 10: quiescent atmosphere: not clear.*

   Response: Thank reviewer for the suggestion. We have revised the manuscript by replacing "quiescent atmosphere" with the more precise term "still-air condition."

2. *Lines 10-11: neglecting…, affecting…: not clear.*

   Response: Thank reviewer for the suggestion. The original sentence intended to convey that existing models affect the accurate estimation of wet deposition flux by neglecting the complex motion of snowfall particles induced by turbulence. We have revised it on lines 10–11 as follows: “Existing models only consider vertical scavenging under still-air conditions. However, they neglect the complex vertical and horizontal motion of snowfall particles induced by turbulence in the atmospheric boundary layer. Consequently, these models fail to accurately estimate wet deposition fluxes.”

3. *Line 20: "it" is not clear.*

   Response: Thank reviewer for the suggestion. In the original sentence, "its" refers to "horizontal collection." We have revised it on line 20 as follows: “…while under horizontal dominance, horizontal collection contributes more than 50%.”

4. *Line 26: also contributing: changed to “they also lead to”?*

   Response: Thank reviewer for the suggestion. We fully agree with your recommendation to change "also contributing to" to "they also lead to."

5. *Line 27: variations in dust concentrations: add “in the downstream regions” after it?*

   Response: Thank reviewer for the suggestion. We fully agree with your suggestion to add "in the downstream regions" after "variations in dust concentrations."

6. *Line 30: source aerosols?*

   Response: Thank reviewer for the suggestion. The original sentence intended to emphasize that "below-cloud scavenging," as a physical process, is one of the major pathways for removing aerosols emitted into the atmosphere (i.e., anthropogenic or natural primary and secondary aerosols). To avoid ambiguity, we have revised "source aerosols" to "atmospheric aerosols."

7. *Line 33: episodic?*

   Response: Thank reviewer for the suggestion. The original sentence in line 33 did not clearly connect the “continuously occurring microscale dynamic processes” with the “macroscale snowfall event described as sporadic.” To express this more precisely, we have revised the sentence as follows: “Snowfall particles capture airborne dust through dynamic processes such as Brownian diffusion and inertial impaction. These efficient scavenging mechanisms during precipitation events lead to high-flux dust deposition."

8. *Line 57: "(Langmuir, 1948)" changed to "Langmuir (1948)".*

   Response: Thank reviewer for the suggestion. In the revised manuscript, we have changed "(Langmuir, 1948)" to "Langmuir (1948)".

9. *Line 76: dynamical?*

   Response: Thank reviewer for the suggestion. In the manuscript, "dynamical" was used to emphasize that the terminal velocity is a key parameter directly related to the motion process of particles. To avoid potential ambiguity, we have revised it to the more commonly used "dynamic."

10. *Line 85: after "motions", add "trajectories"?*

    Response: Thank reviewer for the suggestion. Current models fundamentally neglect the complex three-dimensional motion trajectories of particles caused by turbulence, which is a key dynamic factor determining the scavenging of dust particles by snowflakes. We have added "trajectories" after "motions."

11. *Section 2: It is better to provide an overall description on how each method are used and combined to have results shown in Section 3. I am confused with that.*

    Response: Thank reviewer for the suggestion. The "Methods" section of the manuscript currently lacks logical continuity. While an overall framework is introduced at the beginning, it does not clearly outline the executable progression from the "numerical framework" to the "specific equations" and finally to the "final results." To address this, we will add an explanation of the overall research framework before Section 2.1.

12. *3 and 4: How about i and j?*

    Response: Thank reviewer for the suggestion. In the continuity equation of the manuscript, the index i appears repeatedly within a single term and should be treated as a summation dummy index.

However, the way it is defined in the manuscript causes it to be mistakenly interpreted as a free index, leading to logical contradiction. In the momentum equation, i is correctly used as the free index and j as the summation (dummy) index, which is the standard and proper convention. Following the reviewer's recommendation, we have revised the equations to consistently use j as the summation dummy index and i as the free index. We have also added an explicit statement immediately after the equations to clarify their meanings: i is the free index (i = 1, 2, 3 corresponding to the x, y, z spatial directions), j is the summation dummy index.

13. *Line 106: Change "P" to "p"?*

Response: Thank reviewer for the suggestion. We have revised "P" to "p" as advised.

14. *Line 107: RANS/LES: full name?*

Response: Thank reviewer for the suggestion. Following your suggestion, we have supplemented the abbreviation at its first mention in the text (line 107) as follows: "Reynolds-Averaged Navier-Stokes (RANS) / Large-Eddy Simulation (LES)" instead of just "RANS/LES".

15. *Line 132: $<10^{-6}$: Supposing a certain falling velocity and a typical snow density, what is the snowfall rate equivalent to this value? I am wondering if the snowfall rate is at a similar magnitude as the realistic cases?*

Response: Thank reviewer for the suggestion. Regarding the reasonableness of the volume fraction $<10^{-6}$, our estimation based on snow particle density (ρ_p = 340 kg/m³) and settling velocity indicates that this volume fraction corresponds to a snowfall rate(snow water equivalent) of approximately 1 mm/h. This rate falls within the "Light" category in practical precipitation intensity classification.

The study in this paper only focuses on the case of low snowfall intensity, because in this case, the overall washing efficiency of falling snow on atmospheric dust is not high, and the influence of atmospheric turbulence on wet deposition is relatively prominent. Based on this consideration, in our numerical model, snowfall particles are considered as dilute phase substances and their reaction to air flow is not considered. According to the related research of two-phase flow, when the volume fraction of particulate matter is less than $<10^{-6}$ can be regarded as a dilute phase substance

(Balachandar and Eaton, 2010a). The volume fraction $<10^{-6}$ in the article meets the relevant requirements.

In the revised version, we will explain the related issues in detail to eliminate the confusion of readers.

16. *10-12: What are Ap and uf?*

Response: Thank reviewer for the suggestion. We will add definitions for A_p and u_f in the revised manuscript to enhance clarity, where A_p represents the projected area of the snow particle and u_f denotes the air velocity at the location of the particle.

17. *Line 144: escape: It is not clear to me.*

Response: Thank reviewer for the suggestion. In the manuscript, the "escape" boundary condition means that when a particle crosses this boundary, its trajectory calculation is terminated, and the particle is removed from the computational domain (without reflection, adsorption, or rebound). The subsequent motion of this particle is no longer considered. However, the data of the particle before its escape will be statistically analyzed. We have added clarifications accordingly in the revised manuscript.

18. *Line 147: diameter range: For easy reading, it is better to explicitly mention the diameter range here.*

Response: Thank reviewer for the suggestion. We agree that specifying the particle size range in the text will enhance readability.

19. *Lines 148-149: Changed to "we obtained xxx"*

Response: Thank reviewer for the suggestion. We have revised "friction velocities were obtained" to "we obtained the corresponding friction velocities."

20. *Table 1: and different* D_p *conditions.*

Response: Thank reviewer for the suggestion. We will supplement the explanation for different D_p conditions in the revised manuscript to ensure that the table headings more clearly reflect their content.

21. *Line 159: h=0.04m: what is h?*

Response: Thank reviewer for the suggestion. In this paper, h represents the reference height above ground. The selection of this value is intended to align with the reference height used in the experiments of Ishihara et al. (1999), ensuring that our simulation results are directly comparable with their experimental data.

22. *Line 162: velocity data are reintroduced?*

Response: Thank reviewer for the suggestion. This study employs a precursor simulation strategy based on the "recycling-rescaling" method: Within a developed empty wind-field computational domain, the three-dimensional instantaneous velocity field is continuously sampled in real time from a cross-sectional plane located at the streamwise center of the domain. The velocity data from this plane are then directly imposed onto the inlet boundary of the computational domain. This process is performed at every time step, thereby generating a physically realistic turbulent inflow condition for the computational domain. We have revised “velocity data are reintroduced” to “velocity data are directly imposed”.

23. *Line 202: What is k?*

Response: Thank reviewer for the suggestion. In line 202 of the manuscript, k is an index at the grid level, used to distinguish computational grids of different densities. N_k denotes the total number of nodes in the k-th level grid. We will explicitly define the meaning of k in the revised manuscript.

24. *Line 215: Please explain how turbulence intensity is defined.*

Response: Thank reviewer for the suggestion. In this study, turbulence intensity (I) is defined as the ratio of the root-mean-square of the fluctuating velocity (σ) to the mean wind speed. The specific formula is as follows:

$$I_u(y) = \frac{\sigma_u(y)}{\overline{U}(y)} \times 100\%,$$

where, $I_u(y)$: Streamwise turbulence intensity (%) at height y; $\sigma u(y)$: Standard deviation of the streamwise velocity component (m s^{-1}); $\overline{U}(y)$: Time-averaged streamwise velocity (m s^{-1}).

25. *Figure 5: At which moment?*

Response: Thank reviewer for the suggestion. We will add the time information to the caption of Figure 5 in the revised manuscript.

26. *Line 229: larger-diameter: lease add the range of diameters explicitly to make it clear.*

Response: Thank reviewer for the suggestion. We will specify the particle size range on line 229 of the revised manuscript to facilitate reader understanding.

27. *Line 239: Please clarify whether this function is suitable for snow particles.*

Response: Thank reviewer for the suggestion. The applicability of the terminal settling velocity formula (Carrier, 1953) in this study is based on the following two points: First, This formula has been adopted as the standard for calculating the terminal velocity of snow particles in research on blowing snow and atmospheric deposition. For example, the key reference cited in this study, Huang and Shi (2017), explicitly uses this formula to calculate the settling velocity of snow particles (see Equation (3)). Second, The physical essence of this formula is consistent with that of the spherical particle terminal velocity formula derived from force balance. By comparing it with the general formula, it can be seen that coefficients A and B in the Carrier formula essentially represent a parametric fitting of the relationship between the drag coefficient (CD) and the Reynolds number with respect to air viscosity (νa) and snow particle density (ρp). This fitting provides convenient and accurate computational results within the typical size range of snow particles (tens to hundreds of micrometers).

28. *Figure 7: Please check if there are identical results (trajectories) for u*=0.75 m/s and D_p=500 μm in Fig. a and Fig.b.*

Response: Thank reviewer for the suggestion. Upon verification, the label " D_p =500 μm" in Figure (b) is indeed a typographical error. Figure 7b actually displays the trajectory of snow particles with a diameter D_p =100 μm under different friction wind speeds. We have implemented two important revisions to Figure 7: Correcting the label in Figure (b) to " D_p =100 μm"; Adding clear diameter labels to each representative trajectory in Figure 7a.

29. *Lines 247-249: Please also add the information in Fig.8 for easy viewing. Please also explain what "mag" is in Fig.8.*

Response: Thank reviewer for the suggestion. We have revised Figure 8 accordingly by supplementing necessary information and clarifying in the caption that "mag" denotes the magnitude of the relative velocity.

30. *Figure 9: Please check if there are identical results (PDF) for u*=0.75 m/s and Dp=500 μm in Fig. a and Fig.b. Probably use same color (e.g., black) for this case to facilitate the comparison.*

Response: Thank reviewer for the suggestion. We will conduct a thorough review of Figure 9(a) and (b) in the manuscript and, in the revised figures, use consistent coloring to facilitate the most intuitive comparison.

31. *Line 280: fitting parameters: For easy understanding, could you also write down the equation and indicate what a and b mean?*

Response: Thank reviewer for the suggestion. We will add relevant information in the revised manuscript to make the data analysis and interpretation clearer and more complete.

32. *Line 282: fitting parameters: For easy understanding, could you also write down the equation and indicate what b1 means?*

Response: Thank reviewer for the suggestion. We will further list the equation in the revised manuscript and clarify the meaning of b1.

33. *Liness 290-291: ra and rs: It is better to use individual lines for these equations.*

Response: Thank reviewer for the suggestion. We fully agree that presenting the equations on separate lines will help readers better understand them.

34. *Line 299: It is better to use individual lines for these equations.*

Response: Thank reviewer for the suggestion. We fully agree that presenting the equations on separate lines will help readers better understand them.

35. *Line 310: dimensionless settling time: Please explicitly mention what this means for easy understanding.*

Response: Thank reviewer for the suggestion. We fully agree that clearly defining the "dimensionless settling time" is crucial for readers to understand the results in Figure 13. In the relevant section of the revised manuscript, we will add a clear definition and physical explanation of the "dimensionless settling time." This dimensionless parameter is used to eliminate scale effects, enabling universal comparative analysis across different u_* conditions.

36. *22: =Vr=?*

Response: Thank reviewer for the suggestion. We have removed the redundant "=Vr=" in the revised manuscript.

37. *Line 323: Use a new paragraph for easy reading.*

Response: Thank reviewer for the suggestion. We fully agree with using a new paragraph to improve readability.

38. *Line 330: add a space before "due".*

Response: Thank reviewer for the suggestion. We will add a space before "due" in the revised manuscript.

39. *Line 352: I think the concentrations may be too small.*

Response: Thank reviewer for the suggestion. The description of the particle size range for Aitken mode particles in the manuscript was incorrect and has now been corrected: the particle size range for Aitken mode particles is dp = 20~100 nm. This value was not subjectively determined but was established based on actual observational data of atmospheric aerosols in the Beijing region. Studies indicate that under clean to moderately polluted conditions, the number concentration of Aitken mode aerosols typically falls within the order of 10^4 cm^{-3}. We have corrected the error in the revised manuscript and will provide further elaboration on the relevant justifications to enhance the clarity and persuasiveness of the discussion.

40. *Line 352: Dp<20 nm: Actually, such small dust particles are poorly studied and known. Please clarify whether it is reliable or meaningful to have this assumption.*

Response: Thank reviewer for the suggestion. The typical particle size range of the Aitken mode in the manuscript is 20–100 nm. Particles smaller than 20 nm are generally referred to as the "Nucleation mode." The concentration value we cited and assumed ($n = 1.5\times10^4$ cm^{-3}) specifically targets Aitken mode particles in the size range of 20–100 nm. We have revised this statement in the manuscript accordingly.

41. *Figure 17 captions: Please explain what Q1 and Q2 are. Please also what dash means indeed.*

Response: Thank reviewer for the suggestion. We will specify the definitions of Q1 and Q2 in Figure 17 of the revised manuscript and clarify the meaning of the dashed line.

42. *Line 377: (Q1+Q2)/Q is not equal to 100%?*

Response: Thank reviewer for the suggestion. In this study, $Q_1 + Q_2 = Q$, and therefore $(Q_1 + Q_2) / Q = 100\%$. In the figure, the vertical coordinate values corresponding to the black dots (Q_1/Q) and blue dots (Q_2/Q) for the same horizontal coordinate sum to 100%. The statement in the manuscript that " Q_2 accounts for the smallest proportion of the total collection, approximately 50%" refers to the fact that under $\alpha d < 0.2$, the minimum value of Q_2/ Q is about 50%, while the maximum value of Q_1/ Q is also about 50%. For cases where $\alpha d \geq 1$, Q_1/ Q exceeds 75%, while Q_2/ Q is less than 25%.

We will revise the wording in the updated manuscript to make it more precise and avoid any potential misunderstandings.

43. *26: I am not wondering how Q_{u*} and Q_0 are related to Q_1 and Q_2.*

Response: Thank reviewer for the suggestion. We will unify the notation in the revised manuscript to enhance reader comprehension. Here, we clarify the definitions and relationships of key symbols in the text: Q_0 represents the total collection of snow particles dominated solely by gravitational settling, where $Q_0 = Q_1$ and $Q_2 = 0$； Q_{u*} represents the total collection of snow particles under the friction velocity, i.e., the Q mentioned in the manuscript, where $Q = Q_{u*} = Q_1 + Q_2$.

44. *Line 389: add "As shown in Fig. 19," before "the".*

Response: Thank reviewer for the suggestion. We have inserted "As shown in Fig. 19," before "the" in line 389 of the revised manuscript.