Response to Reviewer 1

This study employs a Delayed Detached-Eddy Simulation (DDES) coupled with a Lagrangian particle tracking method to investigate the motion of snowfall particles within an atmospheric turbulent boundary layer. The authors analyze how turbulence influences the relative motion between snow particles and air, identifying a critical dimensionless parameter (α_d = 0.2). The results suggest that for (α_d < 0.2), horizontal relative motion dominates, significantly enhancing the swept volume and, consequently, the potential for dust wet deposition compared to gravitational settling alone.

The manuscript addresses an interesting and complex problem in atmospheric physics, the interplay between turbulence and precipitation scavenging. The use of DDES to resolve the turbulent wind field represents a sophisticated approach compared to standard RANS models often used in this field. The identification of the transition threshold at α_d = 0.2 offers a potentially valuable metric for parameterizing wet deposition in larger-scale models.

Please note that my evaluation focuses on the physical interpretation of the snowfall dynamic characteristics, the experimental design regarding particle physics, and the implications for dust wet deposition. As I am not a specialist in Computational Fluid Dynamics or hybrid RANS/LES modeling, I have not critically assessed the numerical implementation of the DDES model, the specific grid convergence strategies, or the stability of the solution. My comments regarding the methodology are restricted to its physical justification and consistency with atmospheric principles. While the trajectory analysis appears rigorous, I have concerns regarding the physical simplifications made for the snow particles, specifically the assumptions regarding particle shape and collection efficiency, which likely lead to an overestimation of the deposition flux. These issues should be addressed before publication.

Response: We sincerely thank the reviewer for taking the time to review our manuscript and for providing valuable and insightful comments. In response to the detailed and profound suggestions, we have comprehensively revised and supplemented the manuscript to enhance the rigor of the research and the clarity of its presentation. Here, we provide detailed responses to each of the questions and suggestions raised by the reviewer. All comments and suggestions have been carefully considered. Below, the reviewer’s original comments are presented in *italics*. Our responses are shown in blue, and the changes made in the revised manuscript are highlighted in yellow. The line numbers and page numbers of the revised words or sentences are highlighted in green.

In response to the reviewers' concerns about the physical assumptions in this paper, we provide the following detailed explanations: this study focuses on theoretical analysis, with the core research content being the effects of turbulent characteristics of the atmospheric boundary layer on the motion of snow particles in the air, and further explores the scavenging effect of dust particles caused by the relative motion between snow particles and air. To highlight the research focus on the impact of turbulence on snow particle motion and facilitate targeted analysis, we have made reasonable physical simplifications for the shape and collection efficiency of snow particles, which do not affect the scientificity and rationality of the core research conclusions.

The research results of this paper confirm that the turbulent characteristics of the atmospheric boundary layer have an important impact on the snowfall wet deposition process. This conclusion provides theoretical support for in-depth interpretation of the physical mechanism of snowfall wet deposition and for conducting more accurate wet deposition assessments in the future, which is of great academic significance.

It should be noted that the quantitative results of wet deposition amount obtained in this paper cannot be directly applied to the quantitative analysis of snowfall wet deposition in actual environments for the time being. To improve the universality of the research conclusions in this paper, we have specially introduced the dimensionless parameter α_d, which can comprehensively characterize the particle dynamic characteristics and the turbulent characteristics of the boundary layer. In the subsequent research plan, we will focus on exploring the intrinsic relationship between snow particle shape and the α_d parameter, and carry out special research on the collection efficiency of snow particles with different shapes and size, so as to gradually improve the research content, promote the better application of the research results of this paper in practical environments, and make up for the limitations of the current research.

In the revised version, we have provided a more explicit explanation of the premise assumptions of this work and the scope of application of the conclusions to avoid misunderstandings among readers.

Major comments

1. *In Section 3.3, the calculation of the dust collection amount assumes that "snow grains can fully collect all dust particles along their trajectories, i.e., the collection efficiency $e = 1$". This is a very strong assumption that likely leads to an overestimation of the removal rate. Collection efficiency can be governed by aerodynamic effects (Brownian diffusion, interception, and inertial impaction). For the Aitken mode dust mentioned in the text, flow streamlines around the falling snow particle may carry aerosols away from the collector surface, resulting in efficiency well below 1.0. Could the authors explicitly discuss the magnitude of uncertainty introduced by this assumption. The results should perhaps be framed as "maximum potential encounter volume" rather than actual "collection amount."*

   Response: Thank reviewer for the suggestion. We fully agree that the assumption of setting the collection efficiency to 1 may overestimate the actual scavenging efficiency. This simplification was indeed adopted to focus on the impact mechanism of turbulence on the relative motion between snow particles and dust particles. We have revised "actual collection amount" to "maximum potential collection amount" throughout the manuscript. Additionally, on page 19 (lines 419 to 428) of the revised manuscript, we have supplemented an explanation regarding the limitations of this idealized assumption, specifically noting that the actual capture efficiency is less than 1 due to aerodynamic effects. The details are as follows: "to investigate the influence mechanism of turbulence-induced relative motion between snow particles and dust on dust scavenging, we assume that a snow particle can completely collect all dust particles along its trajectory, i.e., the collection efficiency e_s=1. Under this idealized assumption, the total number of dust particles contained within the spatial volume swept by a snow particle during its settling process is defined as the maximum potential collection amount (Q) by the snow particle, as illustrated in Figure 16a. It should be noted that in the actual atmosphere, the actual collection efficiency of snow particles for dust is generally less than 1.0 due to aerodynamic effects (such as Brownian diffusion, interception, and inertial impaction). Therefore, the results calculated in this study represent the theoretical upper limit of the dust removal capacity. Correspondingly, its vertical and horizontal components represent the maximum potential vertical collection amount (Q_1) and the maximum potential horizontal collection amount (Q_2), respectively, which are used to evaluate the influence of turbulence on the dust removal capability in different directions."

2. *The study simplifies snowfall particles as spheres with a density of 340 kg/m3. While this simplifies the Lagrangian tracking, natural snow particles (dendrites, plates, aggregates) exhibit different drag coefficients and terminal velocities compared to spheres. This aerodynamic different directly affects the calculation of Vt and the critical parameter α_d. A discussion is needed on how non-spherical drag would alter the α_d threshold. Would complex shapes be more or less susceptible to the horizontal entrainment described in this study?*

   Response: Thank reviewer for the suggestion. The dimensionless parameter α_d we employed is essentially defined to characterize particle dynamics through the terminal settling velocity, which inherently integrates the influence of physical properties such as particle shape and density on drag. Thus, even when considering non-spherical particles, their aerodynamic effects are already incorporated into the definition of this parameter through the core variable of terminal settling velocity. If changes in shape alter the settling velocity, the value of α_d will adjust accordingly, thereby naturally accounting for the influence of particle shape within the existing framework.

   The specific effects of complex shapes on the α threshold and horizontal scavenging sensitivity are indeed important questions that warrant in-depth investigation. However, this involves specialized research on the coupling between microscopic particle morphology and flow fields, which extends beyond the core scope of this paper focusing on the macroscopic mechanisms of turbulence. Currently, our team is conducting dedicated studies on the α values corresponding to different snow particle shapes, and the relevant findings will be reported in subsequent work. Therefore, we have added a discussion on the impact of the assumptions on the results after the conclusion (lines 552 to 555) in the revised manuscript, as follows: "It should be noted that the actual shapes of snow particles are complex (such as dendritic, needle, plate, etc.), and differences in their shapes can lead to variations in terminal fall velocity, thereby affecting the threshold value of the dimensionless parameter α_d. Future work should conduct targeted studies on the α_d values corresponding to different snow particle shapes, in order to further expand the applicability of the model in real atmospheric environments."

3. *The manuscript defines the relative motion distance Sr as the product of the relative velocity and the*

suspension time Td. While this metric is useful for comparing cases, it is essentially a proxy for the "swept volume" or "effective path length." The text essentially equates longer suspension time in turbulence with higher deposition. However, if a particle is trapped in a vortex, it may be "sweeping" the same volume of air repeatedly (which has already been scavenged), rather than encountering fresh dust. Please clarify if the model accounts for the depletion of dust in the local trajectory of the snow particle, or if it assumes the dust concentration remains constant regardless of how many times the snow particle passes through a specific eddy.

Response: Thank reviewer for the suggestion. This study is grounded in the understanding of atmospheric boundary layer physical processes, where the probability of a single snow particle being continuously trapped within the same vortex is extremely low. The Stokes number of snow particles is typically several orders of magnitude larger than that of dust particles, and their greater inertia makes it difficult for them to be persistently captured by small-scale eddies. Therefore, it is reasonable for the model to assume that snow particles continuously encounter unswept air while moving through turbulence. Furthermore, the intense turbulent mixing within the boundary layer rapidly replenishes removed dust particles, maintaining a relatively constant local dust concentration. Consequently, based on the significant inertial disparity between snow and dust particles and the strong mixing effects in the boundary layer, we believe the scenario of "repetitive scavenging" raised by the reviewer is unlikely to occur in the physical processes examined in this study.

Specific comments:

1. *Some figure captions can be enhanced by defining the variables/parameters in the figure. For instance, Figure 17, the readers have to read through the manuscript to understand the meaning of Q, Q1, and Q2. And the meaning of the lines in Figure 8.*

   Response: Thank reviewer for the suggestion. We have supplemented and revised the captions of several figures throughout the manuscript. For example, in Figure 17 on page 20, it is now clearly indicated that Q denotes the total maximum potential collection amount, Q_1 represents the vertical maximum potential collection amount, and Q_2 refers to the horizontal maximum potential collection amount. Additionally, the meanings of the line styles in Figure 8 on page 12 have been specified: the black solid line represents the wind speed at the snow particle location, the green solid line indicates the particle velocity, and the blue solid line corresponds to the modulus of the difference between the wind speed at the particle position and the particle velocity.

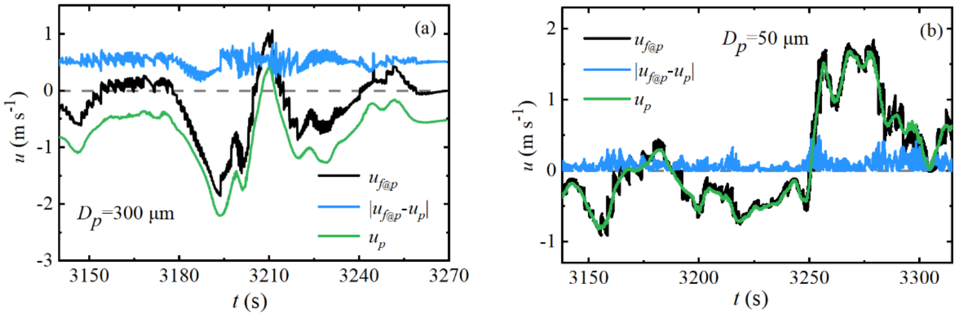

Figure 8. Temporal variations of snowfall particle velocity (the green solid line), wind field velocity at the snowfall particle location (the black solid line), and modulus of the difference between the wind speed at the particle location and the snow particle velocity (the blue solid line) under u*=0.75 m s^{-1}.

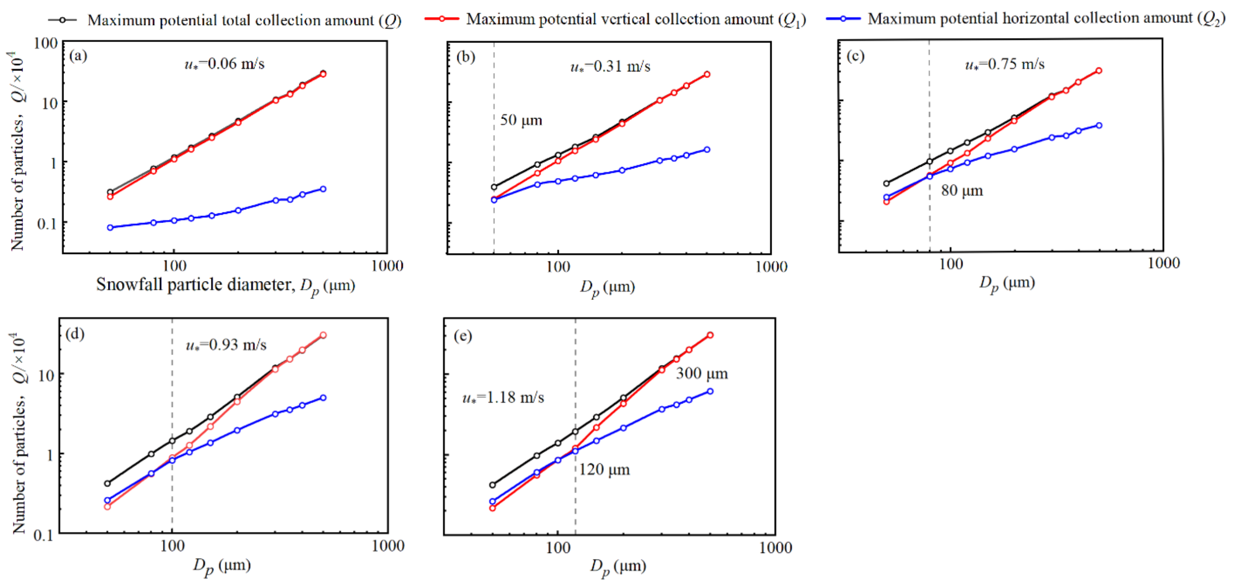

Figure 17. Maximum potential collection amount of dust by snowfall particles in various directions as a function of D_p for different u_* (the vertical dashed line in the figure represents the boundary between vertically dominated and horizontally dominated snow particle collection mechanisms, and the corresponding particle size is defined as the critical diameter).

2. *Line 71: the statement here should be softened, as the two research categories described do not fully encompass all possible approaches. Additional types of studies may exist.*

Response: Thank reviewer for the suggestion. We have softened the statement in line 72 to 77 of the revised manuscript and revised it to the following:“Currently, relevant research can primarily be divided into two type. The first type uses field-collected snow sample data to establish relationships between precipitation, snowfall particle size distribution, and ground-level aerosol mass concentration, thereby evaluating the scavenging efficiency of snowfall on aerosol. The second type focuses on the collision scavenging mechanisms between a single snowflakes (or snow crystals) falling at terminal velocity V_D and aerosol particles, investigated through laboratory simulations or direct observations (Pruppacher et al. 1998). It should be noted that while these two approaches are widely represented in current literature, they do not exhaust all possible research approaches.”

3. *Line 148: Add a comma before “and.”*

Response: Thank reviewer for the suggestion. We have made modifications in line 167.

4. *Figure 6: What do in panel (b) mean?*

Response: Thank reviewer for the suggestion. Thank you for pointing out the lack of clarity in Figure 6*b*. Figure 6*b* aims to illustrate the following key findings: the simulated turbulence intensity profile generally aligns with the lower bound of the range suggested by the ASCE 7-III standard (which allows turbulence intensity values to vary within ±20% of a specified baseline value [Kozmar, 2011]), with a maximum observed relative error of 16% in the near-ground region. Furthermore, the overall profile lies between the upper limits specified by the Chinese national standard and the ASCE 7-III standard. This demonstrates that the simulation results effectively reproduce the wind field characteristics of a real atmospheric boundary layer.

We have revised the relevant description on the page 10 (lines 244 to 248) of the revised manuscript, which now reads: "As shown in Figure 6b, the simulated turbulence intensity profile largely aligns with the lower bound of the range recommended by the ASCE 7-III standard (which permits variations within ±20% of the baseline value [Kozmar, 2011]), with a maximum relative error of 16% in the near-ground region. Overall, the profile lies between the upper limits specified by the Chinese national standard and the ASCE 7-III standard. Thus, the simulation results effectively reproduce the wind field characteristics of a real atmospheric boundary layer."

5. *Equations 18 and 19. Please elaborate on why this particular functional form was chosen. A brief justification or reference would help readers better understand the reasoning behind these expressions.*

Response: Thank reviewer for the suggestion. The model takes the friction velocity u_* (the fundamental driving force for particle transport) as the core independent variable. Equation (18) first constructs the dimensionless ratio Vr/Vt to eliminate the dominant influence of gravitational settling, thereby placing particles of different sizes on a unified dynamic comparison baseline. It employs an exponential function form dependent on particle diameter D_p (e.g., e^(-k*Dp*)) to characterize the nonlinear decay behavior of particle inertia with increasing particle size: for smaller particles with lower Stokes numbers, motion is dominated by turbulent disturbances, making them highly sensitive to changes in u_*, and the relevant parameters decay rapidly with increasing D_p; for larger particles with higher Stokes numbers, inertial effects become dominant, leading to a significantly reduced sensitivity to changes in u_* and a much slower decay rate. This transition corresponds physically to the variation in Stokes number, while the exponential function naturally captures this nonlinear dynamic process mathematically. Thus, the model integrates u_* as the dynamic input, the dimensionless ratio as a unified benchmark, and the exponential function to represent the particle inertia effect, forming a complete physical chain that spans from external driving and dynamic balance to particle response—combining clear dynamic mechanisms with concise mathematical expression.

In Equation (19), the standard deviation of the relative velocity fluctuations Vr' is expressed as a linear function of the friction velocity u_*, which primarily originates from the scaling laws of boundary-layer turbulence and the response mechanisms of particle dynamics. In near-surface turbulence, the root mean square of velocity fluctuations is generally proportional to u_* The linear form $Vr' = \mathrm{c0} + \mathrm{k(Dp)}\cdot u_*$ intuitively captures the quasi-linear response of particle fluctuations to changes in turbulent intensity. We have added supplementary explanations for Equation (19) on page 13 (lines 297 to 306): "The model employs an exponential function of the form e^(-kD_p), which decays with particle diameter, to capture the nonlinear modulation of particles inertia on turbulence response as particles size increases, thereby accurately describing the particles size distribution characteristics transitioning from "turbulence-following" to "inertia-dominated" behaviour.

As shown in Figure 10a, the dimensionless mean relative velocity (Vr/V_t) increases exponentially with u_*, and the growth rate decreases significantly with increasing particles size. This trend indicates that small particles are highly sensitive to changes in turbulence, while large particles, dominated by inertial effects, exhibit a significantly weakened response to variations in u_*. To eliminate the influence of gravitational settling, the model first introduces a dimensionless relative velocity (Vr/V_t), placing particles of different sizes on a unified benchmark for dynamic comparison. On this basis, an exponential function e^(bu_*) dependent on u_* is adopted to describe the variation in the mean relative velocity."; and Equation (21) on pages 14 (lines 318 to 321) of the revised manuscript: "In turbulent boundary layers, the root mean square of velocity fluctuations is typically proportional to the friction velocity, reflecting the fundamental principle that turbulent fluctuation energy originates from surface shear stress. Therefore, a linear function of the form $Vr'=c_0+k(D_p)\cdot u_*$ is adopted to intuitively capture the response of particle velocity fluctuations to changes in turbulence intensity."

6. *Equation 20, Please check whether a bar is missing over the variable on the righthand side of the equation?*

   Response: Thank reviewer for the suggestion. We have added a bar above Equation (23).

7. *In Figure 14(a) and the y-axis label, the word "Verticle" is misspelled. It should be corrected to "Vertical."*

   Response: Thank reviewer for the suggestion. We have corrected "Verticle" to "Vertical" in the y-axis label in Figure 14(a) from on page 18 of the revised manuscript.

Response to reviewer 2

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 have undertaken 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*. Our responses are shown in blue, and the changes made in the revised manuscript are highlighted in yellow. The line numbers and page numbers of the revised words or sentences are highlighted in green.

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 have added a clarification regarding the assumption of spherical snow particles in the abstract of the revised manuscript, as follows: "This study employs the Eulerian-Lagrangian numerical method, simplifying snow particles as spherical particles, to simulate and analyze the dynamic characteristics of snow particles and collection in a turbulent boundary layer." This revision can be found on page 1, line 13 of the revised manuscript. Furthermore, we have added a statement of this assumption in the conclusions section on page 24 of the revised manuscript, before the discussion of the results, as follows: " In this study, we investigated the motion of snowfall particles in a turbulent boundary layer using the Eulerian-Lagrangian method, under the assumption that particles are spherical "; following the conclusions, we have added a discussion on the impact of this assumption on the results,"It should be noted that the actual shapes of snow particles are complex (such as dendritic, needle, plate, etc.), and differences in their shapes can lead to variations in terminal fall velocity, thereby affecting the threshold value of the dimensionless parameter α_d. Future work should conduct targeted studies on the α_d values corresponding to different snow particle shapes, in order to further expand the applicability of the model in real atmospheric environments." This revision can be found on page 25, lines 552 to 555 of the revised manuscript. 1、Regarding the Assumption of Snow Particle Shape (Spherical Particles)：This study employs the dimensionless parameter α_d 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_d will adjust accordingly. The specific influence of complex shapes on the α_d 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_d 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 27):

$$Sr = Vr \cdot T_d = V_t (0.97 + 19.85 e^{-57.6 D_p}) e^{2.27 e^{-11.02 D_p} \cdot u_*} (\frac{H_0}{V_d}),$$

when calculating the scavenging efficiency of snow particles on dust, we substituted the dust concentration *n* as a constant into the wet deposition model (Equation 35) for analysis.

$$Q_{N_1(D_p)} = e_s n \pi (R + r)^2 \left(Vr \cdot T_d\right) N_1$$

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 35), 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. To this end, we have added an explanation in the final part of Section 3.4 (lines 509 to 512) of the revised manuscript on how to apply the conclusions and the wet deposition model presented in this paper to the common particle size range (0.1–10 μm) to derive the snow particle size range corresponding to the optimal scavenging efficiency. The details are as follows: “It should be noted that the conclusions in Section 3.4 above are based on the assumption that the dust particle size falls within the Aitken nucleus mode of 20–100 nm. For the commonly observed atmospheric particle size range of 0.1–10 μm, the dust concentration corresponding to that specific particle size can be substituted into the wet deposition model established in this paper (Equation 35) to derive the optimal scavenged snow particle size under such conditions.”

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 have clearly indicated the units of variables and parameters in all formulas throughout the revised manuscript. For example: In the revised manuscript, on page 12, lines 268 to 270, we have added units for the variables in Equation 17 (16); on page 14, line 309, we have added units for the variables in Equations 19 and 20 (18, 19); on page 17, lines 369 to 370, we have added units for the variables in Equation 28 (22); on page 22, line 469, we have added units for the parameters in Equation 33 (27); and on page 23, line 493, we have added units for the variables in Equation 35 (29).

Specific comments:

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

   Response: Thank reviewer for the suggestion. We have replaced "quiescent atmosphere" with "still-air condition" in lines 10 and 86 of the revised manuscript.

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 in lines 9 to 11 as follows: “Existing models only consider vertical scavenging under still-air conditions, neglecting turbulence-induced complex vertical and horizontal motions of snowfall particles in the actual atmosphere boundary layer, which leads to inaccurate estimation of wet deposition flux.”

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 in lines 20 to 21 as follows: "for $\alpha_d \geqslant 1$, vertical collection for over 75% of the total; when horizontal dominance, horizontal collection contributes over 50%"

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

Response: Thank reviewer for the suggestion. We have revised "also contributing to" to "they also lead to" in line 26 of the revised manuscript as follows: "…and they also lead to respiratory and cardiovascular diseases."

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

Response: Thank reviewer for the suggestion. We have added "in the downstream regions" after "variations in dust concentrations" in line 27 of the revised manuscript, as follows: "Variations in dust concentration in the downstream regions are primarily governed by the removal rate via atmospheric wet deposition."

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" in line 30 of the revised manuscript.

7. *Line 33: episodic?*

Response: Thank reviewer for the suggestion. The original sentence in line 32 to 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 in line 33 of the revised manuscript as follows: "These 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. We have revised "(Langmuir, 1948)" to "Langmuir (1948)" in line 58 of the revised manuscript.

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" in line 78 of the revised manuscript.

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

    Response: Thank reviewer for the suggestion. Existing 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 snow. We have added "trajectories" after "motions" in line 87 on page 3 of the revised manuscript.

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". We have added an explanation of the overall research framework before Section 2.1 on page 4 (lines 101 to 107), as follows: “This study aims to quantitatively assess the influence of turbulence on the efficiency of snow particles in scavenging atmospheric dust. To achieve this, based on the assumptions and governing equations presented in Section 2.1, we first employ an OpenFOAM solver to simulate and generate a statistically stationary neutral atmospheric boundary layer turbulent wind field. Subsequently, a particle tracking module is developed based on the OpenFOAM Lagrangian particle tracking library. This module reads the pre-computed turbulent wind field as the background flow and solves the equation of motion for snow particles (Section 2.2) to track their trajectories and behaviour within the turbulent wind field. Finally, in Section 3, the impact of turbulence on the scavenging efficiency of snow particles is quantitatively analysed."

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. We have revised Equations 3-8 on pages 4 to 5 of the revised manuscript as follows: we now consistently use j as the summation dummy index and i as the free index. Their meanings are clearly stated in lines 115 to 117, as follows: "where u_i represents the velocity component in the i-direction (with i =1,2,3 corresponding to the x, y, z directions); x_i represents the spatial coordinate component (with i=1,2,3 also corresponding to the x, y, z directions); and j is the summation index, indicating summation over all spatial directions (j=1,2,3)."

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

    Response: Thank reviewer for the suggestion. We have revised "P" to "p" in line 117 of the revised manuscript.

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

    Response: Thank reviewer for the suggestion. We have spelled out "RANS/LES" in full as "Reynolds-Averaged Navier-Stokes (RANS) / Large-Eddy Simulation (LES)" when this method is first mentioned in line 119 of the revised manuscript.

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.

We have provided a detailed explanation of the related issues on page 5 (lines 144 to 147) of the manuscript to eliminate the confusion of readers, as follows: “Snowfall particles are treated as a dilute phase with a volume fraction $\varphi_V < 10^{-6}$, corresponding to a light snow event in terms of snow water equivalent rate. Under such light snow conditions, the disturbance of particle trajectories by turbulence becomes more significant, exerting a critical influence on the particle settlement distribution. considering only the one-way coupling of the fluid on the particles.”

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

    Response: Thank reviewer for the suggestion. We have supplemented the definitions of A_p and u_f in lines 152 to 153 of the revised manuscript as follows: “ρ is the air density, $A_p=\pi D_p^2/4$ is the projected cross-sectional area of the spherical particle, and u_f is the air velocity.”

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 supplementary explanation on page 6 (lines

159 to 162) of the revised manuscript as follows: "For all other boundaries, the condition is set to Escape: when a particle crosses such a boundary, its trajectory calculation is immediately terminated, and the particle is removed from the computational domain (neither reflected, trapped, nor rebounded), with no further tracking of its subsequent motion. It should be noted that the motion data generated by the particle prior to escape are still included in the statistical analysis."

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 have specified the particle size range in lines 165 to 166 of the revised manuscript.

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" in line 167 of the revised manuscript.

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

    Response: Thank reviewer for the suggestion. We have added an explanation of the different D_p conditions in the Table 1 in the revised manuscript, as follows: "Table 1: The particle Reynolds number (Re_p) of snowfall for various particle sizes under different friction velocity (u_*) conditions."

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. We have added a supplementary explanation in line 179 of the revised manuscript.

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" in lines 182 to 183 of the manuscript, as follows: "Velocity data from this cross-section are collected in real-time and directly imposed at the inlet as the turbulent velocity boundary condition (inflow)."

23. *Line 202: What is k?*

Response: Thank reviewer for the suggestion. 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 have clarified the definition of k in lines 227 to 228 of the revised manuscript.

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

Response: Thank reviewer for the suggestion. In this study, turbulence intensity 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:

$$I_u = \frac{\sigma_u}{\bar{u}} \times 100\%,$$

where, I_u is the streamwise turbulence intensity (%) at a certain height, σ_u is the standard deviation of the streamwise velocity component (m s^{-1}), and $\bar{u}$ is the time-averaged streamwise velocity (m s^{-1}). We have supplemented the definitions in lines 193 to 196 of the revised manuscript.

25. *Figure 5: At which moment?*

Response: Thank reviewer for the suggestion. We have added the time information in the caption of Figure 5 on page 11 of 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 have specified the particle size range in line 255 of the revised manuscript.

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 (C_D) and the Reynolds number with respect to air viscosity (ν_a) and snow particle density (ρ_p). This fitting provides convenient and accurate computational results within the typical size range of snow particles (tens to hundreds of micrometers). We have added an applicability statement in lines 265 to 266 of the revised manuscript, as follows: "…which has been validated for snow particles within the typical size range (Huang and Shi 2017)"

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. 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 revised Figure 7 on page 12 of the revised manuscript: the label in Figure 7b has been corrected to D_p =100 μm, as follows: "

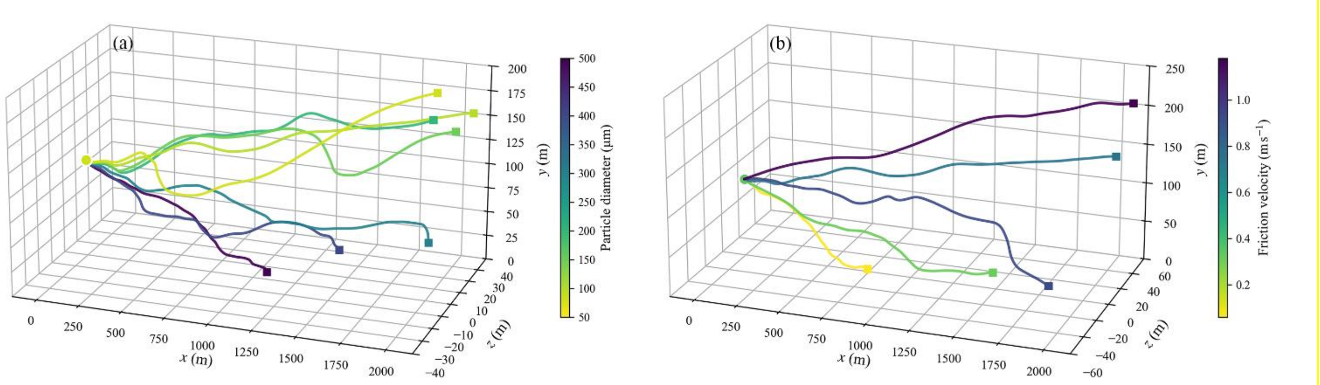

Figure 7. Random motion trajectories of (a) snowfall particles with different diameters at u_*=0.75 m/s and (b) snowfall particles (D_p=100 μm) under different u_* conditions."

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 incorporated the information for Figure 8 into the text in lines 283 to 287 of the revised manuscript. Additionally, we have supplemented the necessary information in Figure 8 and clarified the meaning of each line in the figure caption, as follows: "

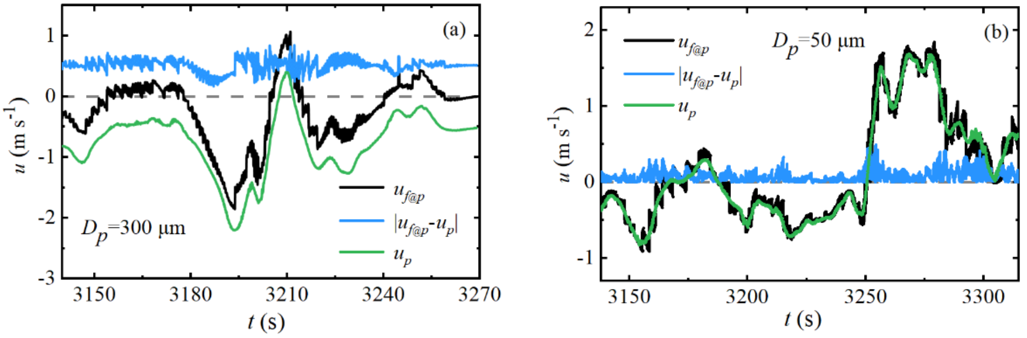

Figure 8. Temporal variations of snowfall particle velocity (the green solid line), wind field velocity at the snowfall particle location (the black solid line), and modulus of the difference between the wind speed at the particle location and the snow particle velocity (the blue solid line) under u_*=0.75 m s^{-1}."

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 have conducted a thorough verification of Figures 9a and 9b in the revised manuscript, made further revisions, and used the same color coding to facilitate the most intuitive comparison. The details are as follows: "

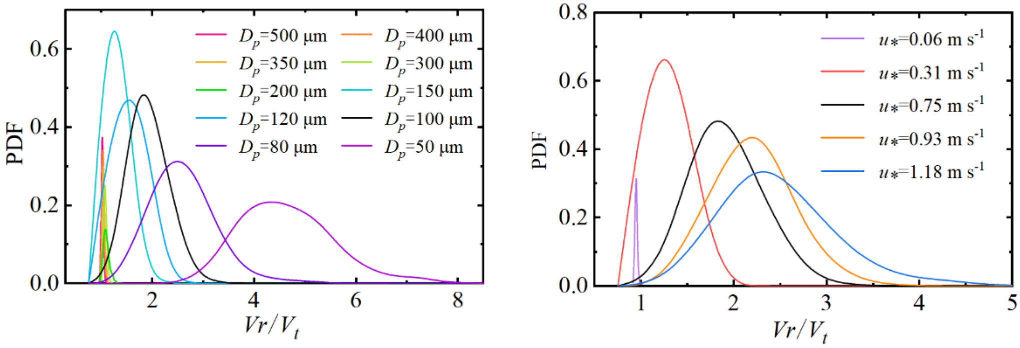

Figure 9. Probability distribution of Vr/V_t for (a) snowfall particles with Different diameter at u_*=0.75 m s^{-1} and (b) snowfall particles with D_p=100 μm under different friction velocities."

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 have supplemented the information on page 14 (lines 308 to 313) of the revised manuscript, as follows: "

The variation of the mean relative velocity of snowfall particles with friction velocity and particle diameter can be expressed by Eq. (19):

$$Vr = V_t \cdot a e^{b \cdot u_*}, \qquad (19)$$

where parameters *a* and *b* are function of the snow particle diameter (D_p, mm), with their specific forms obtained through fitting:

$$a = (0.97 + 19.85 e^{-57.6 D_p}), b = 2.27 e^{-11.02 D_p}, \qquad (20)$$

as illustrated in Fig.10b, both parameters *a* and *b* decrease in a negative exponential manner with increasing snow particle diameter, further confirming the modulating effect of particle inertia on the turbulent response."

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 have listed the equation and explained the meaning of b_1 on page 14 (lines 321 to 326) of the revised manuscript, as follows:

The variation of Vr' with friction velocity and snowfall particle diameter can be expressed by Eq. (21):

$$Vr' = 0.003 + b_1 \cdot u_*, \tag{21}$$

where the intercept of the linear function is independent of snowfall particle diameter, and the parameter b_1 exhibits negative exponential growth with increasing particle diameter (D_p, mm).

$$b_1 = 0.17 - 0.05e^{-3.25D_p}. \tag{22}$$

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

Response: Thank reviewer for the suggestion. We have presented Equation (25) and Equation (26) on separate lines in lines 340 to 343 of the revised manuscript.

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

Response: Thank reviewer for the suggestion. We have presented Equation (27) on a separate line in line 353 of the revised manuscript.

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

Response: Thank reviewer for the suggestion. We have supplemented a clear definition and physical explanation of the "dimensionless settling time" in lines 354 to 355 on page 16 of the revised manuscript. This dimensionless parameter is used to eliminate scale effects and facilitate universal comparative analysis under different u_* conditions. The details are as follows: "As shown in Figure 13, the dimensionless setting time ($T_d \cdot u_*/H$), defined to eliminate scale effects (where H is the boundary layer height) …"

36. *22: =Vr=?*

Response: Thank reviewer for the suggestion. We have removed the redundant "=Vr=" in Equation (28) of the revised manuscript.

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

    Response: Thank reviewer for the suggestion. We have started a new paragraph in line 382 of the revised manuscript to improve readability.

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

    Response: Thank reviewer for the suggestion. We have added a space before "due" in line 389 of 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 have shown that under heavily polluted conditions, the number concentration of Aitken mode aerosols is often on the order of 10^4 cm^{-3} (Liu et al. 2016). We have corrected the error in line 411 of the revised manuscript and provided further explanation of the relevant basis in lines 413 to 414, as follows: "This concentration value is based on observational data from the Beijing region, where the number concentration of Aitken mode dusts is typically on the order of 10^4 cm^{-3} under heavily polluted conditions(Liu et al., 2016)."

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." We have corrected this description in line 411 of the revised manuscript.

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

Response: Thank reviewer for the suggestion. We have explained the definitions of Q_1 and Q_2 in Figure 17 of the revised manuscript and clarified the specific meaning of the dashed line, as follows: “

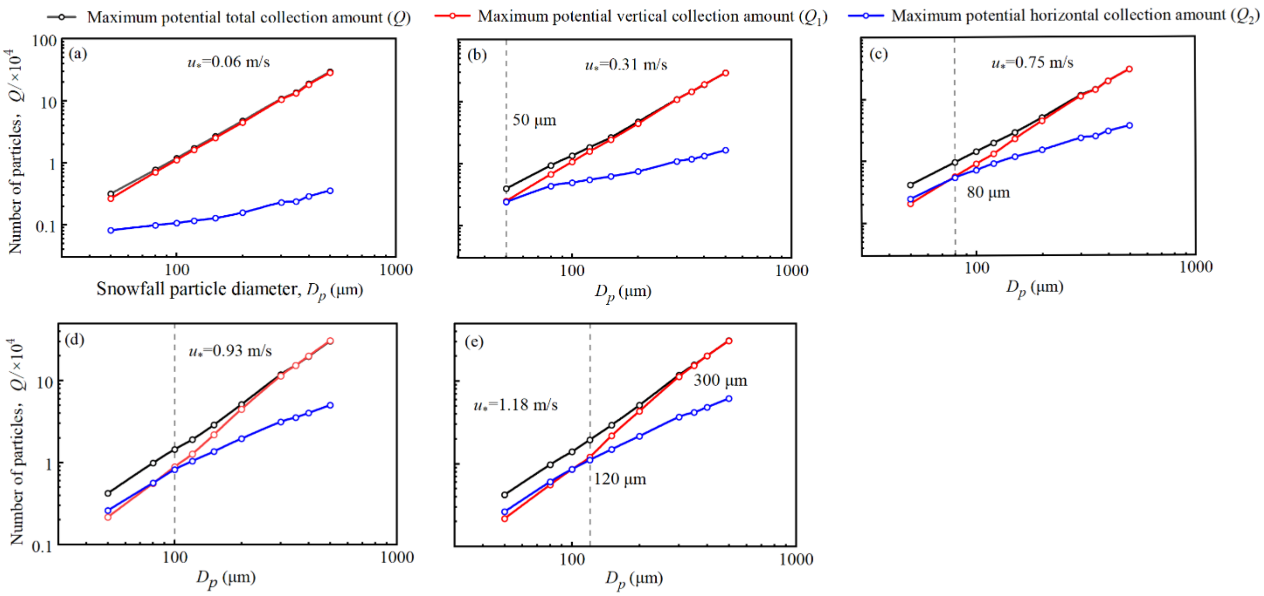

Figure 17. Maximum potential collection amount of dust by snowfall particles in various directions as a function of D_p for different u_* (the vertical dashed line in the figure represents the boundary between vertically dominated and horizontally dominated snow particle collection mechanisms, and the corresponding particle size is defined as the critical diameter). ”

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 have revised this statement on page 20 (lines 443 to 447) of the revised manuscript, as follows: “As shown in Figure 18, snowfall particles with $\alpha_d \geqslant 1$, Q_1 accounts for over 75% of the maximum potential total collection (with the corresponding Q_2 proportion being less than 25%). In contrast, for snowfall particles with $\alpha_d < 0.2$, the horizontal collection capability significantly strengthens with increasing u_*; the minimum proportion of Q_2 in the maximum potential total collection is approximately 50% (at which point the maximum proportion of Q_1 is also around 50%."

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 have standardized the symbols in Equation (32) of the revised manuscript to facilitate 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 added "As shown in Fig. 19," before "the" in line 462 of the revised manuscript.