



Common Parameterizations Tend to Overestimate the Dry Deposition of Coarse and Larger Dust

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Abstract. Dust particles larger than 10 μm are increasingly recognized as important to the climate system, yet models tend to underestimate their atmospheric abundance. Although recent work has improved representations of dust emission processes, dry deposition remains comparatively unexplored. Here we derive a mass-conserving parameterization of the dust deposition velocity that is physically consistent from submicron through giant particle sizes. We calibrate the parameterization using laboratory measurements and compare it to commonly used formulations. We find that assuming spherical particles overestimates the deposition velocity for supermicron dust, while assuming Stokes-regime settling increasingly overestimates the deposition velocity for particles larger than 10 μm . Furthermore, the commonly used electric analogue formulation produces substantially larger deposition velocities than the mass-conserving formulation, particularly for particles larger than 10 μm , although the magnitude and, in some cases, sign of this discrepancy depend on atmospheric stability, friction velocity, reference height, and treatment of particle rebound. Taken together, commonly used assumptions can produce deposition velocities and fluxes up to a factor of 1.6 larger than more physically consistent formulations. A survey of dust schemes used in climate models participating in the Sixth Climate Model Intercomparison Project found that all used non-mass-conserving dry deposition formulations and Stokes theory for spherical-particle settling. These results suggest that commonly used model parameterizations tend to overestimate dust dry deposition, which may contribute to an underestimation of the abundance and lifetime of large dust particles.

1 Introduction

Wind-blown dust is one of the most abundant aerosols in Earth's atmosphere (Gliß et al., 2021), and affects weather and climate through a large number of mechanisms (Kok et al., 2023). The overwhelming majority of modeling studies aiming to improve understanding of dust in the climate system simulate particles with diameters of 10 μm or smaller, since it has long been assumed that larger particles are not transported long distances due to strong settling velocities. However, a number of studies have measured substantial concentrations of super-coarse and giant dust thousands of kilometers from likely source regions (Ryder et al., 2018; Weinzierl et al., 2017; Van Der Does et al., 2018), contributing to increasing recognition that super-coarse ($D_d > 10 \mu\text{m}$) and giant ($D_d > 62.5 \mu\text{m}$) dust particles are more abundant than previously thought. These large dust particles are also important to the climate system because they dominate the mass flux and thus nutrient transport, strongly modu-



late longwave radiation in the atmosphere, contain a large fraction of the surface area available for heterogeneous chemical reactions, and tend to have higher concentrations of ice nucleating particles (Adebisi et al., 2023).

Dry deposition (hereafter referred to only as deposition) is a key component of the dust cycle that influences the lifetime and burden of these aerosols in the atmosphere, so that model biases in deposition can hinder understanding of dust effects on climate (Farmer et al., 2021). Two aspects of commonly used dust dry deposition schemes may produce biases for supermicron dust particles. The first is the treatment of the particle settling velocity. Dust dry deposition parameterizations typically represent dust as spherical particles in the Stokes drag regime. However, particle asphericity (Huang et al., 2020) and departures from the Stokes drag regime at higher particle Reynolds numbers (Clift and Gauvin, 1971), can both substantially lower particle settling velocities relative to those for spherical particles in the Stokes regime (Bagheri and Bonadonna, 2016; Drakaki et al., 2022). Yet the subsequent influence on particle deposition has not been systematically evaluated in the literature. Second, dust deposition schemes typically use the electric analogue functional form of the deposition velocity, which does not conserve mass (Zhang et al., 2001). Previous work has suggested that employing a mass-conserving scheme does not significantly influence deposition velocities (Venkatram and Pleim, 1999), and that it can result in a reduction of the deposition velocity by as much as 20% for dust particles in the range of 2-10 μm (Sportisse, 2007). The differences in deposition velocity arising from these parameterization choices have not been thoroughly examined in the literature, particularly for dust particles larger than 10 μm .

Previous work has sought to improve representation of the processes of emission (Meng et al., 2022) and gravitational settling (Huang et al., 2020) of large dust particles in models. However, at least one recent study that incorporated such developments into a global simulation still implemented large empirical reductions in particle settling velocity to reproduce observed dust size distributions (Li et al., 2025), suggesting that current parameterizations of dry deposition, particularly for large particles, are incomplete. As such, the purpose of this manuscript is to quantify biases in the typical treatment of dust deposition, particularly for coarse and larger-sized particles, and to present a parameterization of dust dry deposition that is physically consistent from submicron through giant particle sizes. We limit our analysis to unvegetated and erodible surfaces, but this framework can also be applied to vegetated and wet surfaces if observational measurements are available to calibrate free parameters.

The remainder of this manuscript is structured as follows: In Section 2 we derive the mass-conserving deposition velocity and contrast this with that of the commonly used electric analogue. We include a description of the aerodynamic resistance and one parameterization of the quasi-laminar resistance. In Section 3 we calibrate two deposition velocity fitting parameters against laboratory measurements. In Section 4 we use these deposition velocity parameterizations to quantify how settling velocity and the functional form of the deposition velocity alter and bias dust deposition flux calculations. In Conclusions we summarize the work and its relevance to modeling coarse and larger dust particles, and discuss methods to implement more physically consistent deposition velocity parameterizations in models.

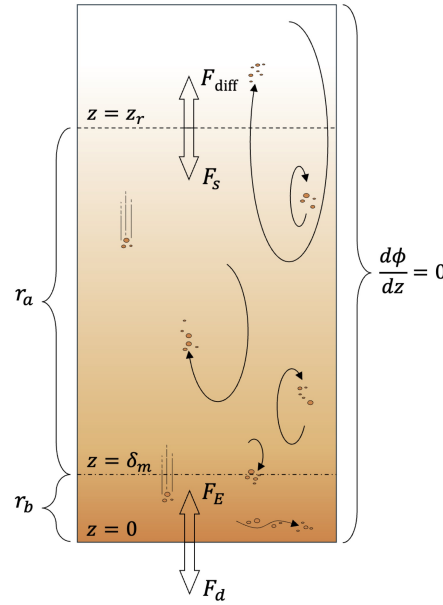


Figure 1. Schematic indicating the key processes controlling dust deposition. Shown is a representation of the surface layer (above $z = \delta_m$) overlying a quasi-laminar layer (below $z = \delta_m$). Key processes include gravitational settling (F_s), turbulent diffusion (F_{diff} , eddies in the surface layer), and molecular diffusion (near the surface). The net flux ϕ is constant with height, and at the reference height z_r is $F_{diff} + F_s$. At the surface ϕ is equal to the sum of the emitted (F_E) and deposition (F_d) fluxes. Particle transport between z_r and δ_m in the surface layer is characterized by the aerodynamic resistance r_a , whereas transport between δ_m and the surface is characterized by the quasi-laminar resistance (r_b).

2 Theoretical Basis for Deposition Velocity Parameterizations

Parameterizations of aerosol deposition typically employ a 2-layer model consisting of an upper surface layer overlying a shallow quasi-laminar layer. The boundary between the two layers δ_m represents the height below which mixing by molecular diffusion is greater than that by turbulent eddies. Within the surface layer the net flux ϕ is the sum of the diffusive F_{diff} and gravitational settling F_s fluxes, and at the surface ϕ is the sum of the emitted F_E and deposition F_d fluxes. In steady state the net flux is constant with height, so that the fluxes at some reference height z_r within the surface layer can be directly related to those at the surface. (Fig. 1). Here we describe the physical rationale underlying the mass-conserving 2-layer parameterization of the deposition velocity.

Throughout this manuscript we adopt the dust size classification from Adebiyi et al. (2023) with the addition of defining the accumulation mode as consisting of dust with submicron diameters (Table 1). Here we add an upper limit of $100 \mu\text{m}$ to the giant mode since we limit our analysis to particles up to this diameter.



Table 1. Definitions of particle size modes used in this manuscript. Dust having diameter less than $0.1 \mu\text{m}$ are not considered.

Mode	Diameter lower limit	Diameter upper limit
Accumulation	0.1	1
Fine	1	2.5
Coarse	2.5	10
Super-coarse	10	62.5
Giant	62.5	100

2.1 General Expression for the mass-conserving Deposition Velocity

We assume a stationary, horizontally homogeneous surface layer with an upward-positive flux. Let $c(z)$ be the mean particle concentration, ϕ the constant (net) vertical flux in air, w_s the gravitational settling velocity (approximately constant with height and defined as positive), $K_c(z)$ the scalar eddy diffusivity (which here refers to dust particles), and D_c the molecular diffusivity in the quasi-laminar layer.

Under steady state conditions, mass conservation in the surface layer is given by

$$\phi = -K_c(z) \frac{dc}{dz} - w_s c(z), \quad (1)$$

which can be rearranged and integrated from the height where molecular diffusion dominates over turbulent diffusion δ_m , to an arbitrary reference height z_r within the surface layer

$$\int_{c(\delta_m)}^{c(z_r)} \frac{dc}{\phi + w_s c(z)} = -r_a,$$

where the aerodynamic resistance $r_a(z_r)$ is defined as

$$r_a(z_r) = \int_{\delta_m}^{z_r} \frac{dz}{K_c(z)} \quad (2)$$

and is indicated schematically in Fig. 1. Evaluating the integral over concentration and rearranging yields

$$e^{-w_s r_a(z_r)} = \frac{\phi + w_s c(z_r)}{\phi + w_s c(\delta_m)}. \quad (3)$$

Mass conservation in the quasi-laminar layer is similarly given by

$$\phi = -D \frac{dc}{dz} - w_s c(z), \quad (4)$$

with D being the proportionality constant for Brownian diffusion, which is approximately constant across the layer. The quasi-laminar mass conservation expression (4) can be rearranged and integrated from the surface to δ_m to obtain

$$e^{-w_s r_b} = \frac{\phi + w_s c(\delta_m)}{\phi + w_s c(0)}, \quad (5)$$



where the quasi-laminar resistance r_b is defined as

$$r_b = \int_0^{\delta_m} \frac{dz}{D} \quad (6)$$

and is also indicated schematically in Fig. 1. Combining (3) and (5), assuming that $c(0) = 0$, and solving for $c(z_r)$ yields

$$c(z_r) = \frac{\phi}{w_s} (e^{-w_s R(z_r)} - 1), \quad (7)$$

90 where the combined resistance is $R(z_r) = r_a(z_r) + r_b$.

We define the deposition velocity $w_d(z_r)$ at the reference height z_r via the concentration at that height and the deposition flux

$$F_d = c(z_r)w_d(z_r).$$

Combining (7) with the above and solving for $w_d(z_r)$ gives the general form of the two-layer mass-conserving deposition
 95 velocity equation

$$w_d(z_r) = -\frac{F_d}{\phi} \frac{w_s}{1 - e^{-w_s R(z_r)}}. \quad (8)$$

In the absence of emission $\phi = -F_d$ and (8) is

$$w_d(z_r) = \frac{w_s}{1 - e^{-w_s R(z_r)}}. \quad (9)$$

This form of mass-conserving deposition velocity was first suggested by Venkatram and Pleim (1999). Formulations of the
 100 Aerodynamic r_a and quasi-laminar r_b resistances are presented in the subsequent section.

We note that Zhang and Shao (2014) derived a modified form of the mass-conserving deposition velocity. For a non-emitting surface, so that $\phi = -F_d$, they defined the deposition flux as $F_d = -c(\delta_m)/r_s$, where r_s is a surface resistance analogous to r_b . This allows one to solve $c(z_r)$ directly from (3),

$$w_d(z_r) = \frac{w_s}{1 - e^{-w_s r_a(z_r)}(1 - w_s r_s)}.$$

105 One can obtain a similar expression by assuming that $F_d = -c(0)/r_s$ and solving for $w_d(z_r)$ as described above. However, it is not clear if one should define the deposition flux as $-c/r_s$, since for a surface that is a perfect collector it leads to the nonphysical result $F_d \rightarrow -\infty$ as $r_s \rightarrow 0$. As such, we do not consider their formulation in this manuscript.

2.2 Resistance Formulation

We next review typical formulations of the aerodynamic and quasi-laminar resistances, retaining terms relevant for the deposition
 110 of coarse dust.

2.2.1 Aerodynamic Resistance

The particle diffusion coefficient K_c is defined as

$$K_c = \frac{\kappa z u_*}{\phi_c(\zeta)},$$



where u_* is friction velocity, ϕ_c is the similarity function for a passive scalar, κ is the Von Kármán constant, and the stability
 115 parameter $\zeta = z/L$. The Obukhov length L is given by

$$L = -\frac{u_*^3}{\kappa (g/\theta) w' \theta'_0}, \quad (10)$$

with θ and g taking on their typical definitions (Kaimal and Finnigan, 1994; Shao, 2008). One can relate ϕ_c to that for momen-
 tum ϕ_m via the trajectory crossing effect,

$$Sc_T(\zeta) = \phi_c(\zeta) / \phi_m(\zeta),$$

120 which is defined as

$$Sc_T(\zeta) = \sqrt{1 + \left(\frac{\beta w_s}{u_* \phi_w(\zeta)} \right)^2}$$

where β is typically taken to be unity, the vertical velocity similarity function is

$$\phi_w = \begin{cases} 1.25(1 + 0.2\zeta) & \text{for } \zeta > 0, \text{ stable conditions} \\ 1.25 & \text{for } \zeta = 0, \text{ neutral conditions} \\ 1.25(1 + 3|\zeta|)^{1/3} & \text{for } \zeta < 0, \text{ unstable conditions} \end{cases} \quad (11)$$

and the non-dimensional similarity function for momentum ϕ_m is

$$\phi_m = \begin{cases} 1 + 5\zeta & \text{for } \zeta > 0, \text{ stable conditions} \\ 1 & \text{for } \zeta = 0, \text{ neutral conditions} \\ (1 + 15|\zeta|)^{-1/4} & \text{for } \zeta < 0, \text{ unstable conditions} \end{cases} \quad (12)$$

The forms of the similarity functions in (11) and (12) are empirically determined (Businger et al., 1971), and slightly different
 values for these constants can be found in the literature (Högström, 1988).

The particle diffusivity coefficient is then

$$K_c = Sc_T^{-1}(\zeta) \frac{\kappa z u_*}{\phi_m(\zeta)},$$

130 and the surface layer resistance (2) can be written as

$$r_a(z_r) = \int_{\delta_m}^{z_r} \frac{\phi_m(\zeta)}{\kappa u_*} Sc_T(\zeta) d \ln z.$$

The integral in $r_a(z_r)$ is straightforward to evaluate for the neutral case $\zeta = 0$, and solutions exist for the stable and unstable
 cases, assuming that Sc_T is approximately constant with height (Freire et al., 2016). This assumption begins to breakdown in
 the Giant mode, where Sc_T can vary by as much as 10% from the surface to a height of 10 m for statically stable cases (not
 135 shown).

The characteristic length scale of the quasi-laminar layer is the ratio of the dynamic viscosity of the air μ to the product of
 the friction velocity u_* and air density ρ ,

$$\delta = \frac{\mu}{\rho u_*}. \quad (13)$$



A typical assumption is that $\delta_m = O(1)\delta$ (Shao, 2008). However, since r_a tends to zero at the surface, the aerodynamic resistance is weakly sensitive to small variations in the lower bound of the integral in (2).

2.2.2 Quasi-laminar Resistance

Via (6) and (13) the quasi-laminar resistance is

$$r_b = \frac{S_m}{u_*},$$

where the Schmidt number $S_m = \mu/\rho D$. The diffusivity coefficient D is assumed to be constant over the depth of the quasi-laminar layer and is given by the Stokes-Einstein formula

$$D = C_c \frac{k_B T}{3\pi\mu D_p},$$

with Boltzmann's constant $k_b = 1.38065 \times 10^{-23}$ (J K⁻¹). The Cunningham slip correction factor C_c (Davies, 1945) is defined as

$$C_c = 1 + \frac{2\lambda}{D_p} \left[1.257 + 0.40 * \exp\left(-\frac{1.10D_p}{2\lambda}\right) \right]$$

which is a function of particle diameter D_p and the atmospheric mean free path λ

$$\lambda = \frac{k_b T}{(\pi\sqrt{2}d_m^2 P)},$$

where P is atmospheric pressure (Pa) and the molecular diameter of air molecules $d_m = 3.2 \times 10^{-10}$ (m). The slip correction factor C_c decreases sharply for increasing particle size in the submicron range, and is ~ 1 for $D_p > 30 \mu\text{m}$. This representation of D assumes a particle in the Stokes regime ($Re \ll 1$), which at standard temperature and pressure (STP) is approximately equivalent to $D_p \leq 10 \mu\text{m}$ (Drakaki et al., 2022). However, r_b rapidly approaches zero for larger diameter particles and thus the representation of D has a small effect on the deposition velocity for coarse and larger modes.

In practice, efficiencies representing deposition by surface elements or vegetation, as well as particle rebound effects, are included in the quasi-laminar resistance term. For example, via Slinn (1982),

$$r_b = \frac{1}{R_1 \epsilon_0 u_* (E_b + E_{IM} + E_{IN})}, \quad (14)$$

where E_b , E_{IM} , and E_{IN} represent collection efficiencies from molecular diffusion, impaction by roughness elements, and interception by vegetation, respectively. Here we consider $E_{IN} = 0$ since we are exclusively considering unvegetated surfaces. Adopting definitions from Zhang et al. (2001), $\epsilon_0 = 3$, the molecular diffusivity term $E_b = S_m^{-\gamma}$, and the impaction efficiency

$$E_{IM} = \left(\frac{S_t}{\alpha + S_t} \right)^2, \quad (15)$$

which is a dimensionless measure of the probability that a particle fails to follow airflow streamlines and collides with a surface element. The Stokes number is defined as $S_t = w_s u_*^2 \rho / g \mu$. The parameters γ and α are functions of the surface characteristics. Slight variations on these definitions exist in the literature (e.g. Pleim et al., 2022).

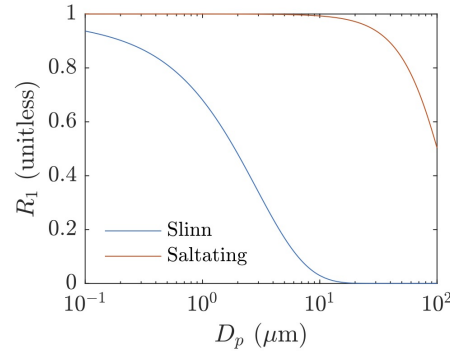


Figure 2. Plotted are parameterizations of the probability that a particle will stick to the surface upon impact R_1 as a function of particle diameter D_p using the formulation from (Slinn, 1982) and that consistent with parameterization of saltating particles Anderson and Haff (1991).

The term R_1 represents the probability that a particle incident upon the surface will stick rather than rebound off of it. One common parameterization $R_1 = \exp(-\sqrt{S_t})$ (Slinn, 1982), produces unphysical sticking probabilities that are effectively zero for coarse and larger size dust (Fig. 2). While other studies neglect this term due to uncertainty in defining the sticking probabilities (Pleim et al., 2022), we suggest that at least for smooth surfaces that can emit dust, R_1 should be consistent with that used for the probability of rebound for a saltating particle P_{reb} , which from Anderson and Haff (1991) is

$$P_{\text{reb}} = B[1 - \exp(-\gamma_r w_s)].$$

We take $B = 0.95$ and $\gamma_r = 1 \text{ s m}^{-1}$ (Kok et al., 2012), and then redefine the rebound as

$$R_1 = 1 - P_{\text{reb}} \quad (16)$$

This formulation produces more physically consistent sticking probabilities that are close to 1 for $D_p < 10 \text{ } \mu\text{m}$ and approach 0.5 at $D_p = 100 \text{ } \mu\text{m}$ (Fig. 2). We note however that including a parameterization of particle rebound within the quasi-laminar resistance can limit the influence of rebound effects on the deposition velocities for super-coarse and giant dust, since at these sizes $r_b \ll r_a$.

2.3 Basis of the Electric Analogue Deposition Velocity Parameterization

The classical electric analogue resistance model defines the net flux within the surface layer via a settling flux and an aerodynamic deposition velocity $1/r_a$ acting on a concentration gradient defined between the roughness length z_0 and reference height z_r ,

$$F_d = -w_s c(z_r) - \frac{1}{r_a} [c(z_r) - c(z_0)].$$

In the quasi-laminar layer the net flux is similarly defined

$$F_d = -w_s c(z_0) - \frac{1}{r_b} [c(z_0) - c(0)].$$



If $c(0) = 0$, equating the two fluxes yields an electric analogue deposition velocity,

$$w_d^e(z_r) = w_s + \frac{1}{r_a(z_r) + r_b + r_a(z_r)r_b w_s}, \quad (17)$$

where w_d^e is the electric analogue deposition velocity. As previously discussed, deposition parameterizations (e.g. Zhang et al., 2001) may incorporate a surface “sticking” term R_1 into the formulation of r_b that approaches zero for coarse size particles (Fig. 2). While such a term unrealistically implies that nearly all coarse particles rebound off the surface upon impact, this formulation has the desirable effect of forcing w_d^e to relax w_s as D_p approaches the giant mode. For w_d in (9), inclusion of a rebound term is not required for $w_d \rightarrow w_s$ at large D_p , which is another benefit of the mass-conserving formulation.

3 Calibration of the Mass-Conserving Deposition Velocity

For the remainder of this manuscript, and unless otherwise specified, we utilize the mass-conserving form of the deposition velocity for a non-emitting environment (9) with r_a as described in Section 2.2.1 and r_b given by (14). Here we estimate α and γ in the E_{IM} and E_b terms, respectively, by fitting w_d from (9) to laboratory measurements of the deposition velocity for three types of bare surfaces (sand, sandy loam, and sand and gravel) at different values of u_* (Zhang et al., 2014). These measurements were generated for approximately spherical fused silica particles having density of $2,200 \text{ kg m}^{-3}$ and diameters in the $1\text{--}40 \text{ }\mu\text{m}$ size range. As such, for the fitting procedure we calculated w_s following Clift and Gauvin (1971), which is valid for spherical particles within and outside the Stokes regime (Appendix A). We assume a temperature of 298 K, pressure of 1013 hPa, and statically neutral conditions, since these data were not provided.

The parameters α and γ were estimated by minimizing the sum of the squared residuals of the logarithm of the theoretical and measured deposition velocities. Uncertainties in the fitted parameters were estimated using a Monte Carlo procedure: the reported ranges in measurements of w_d for a given surface type and value of u_* were sampled via a uniform distribution. We then independently fit α and γ for each of the 2,000 Monte Carlo realizations. Fitting to the measurements yields $\alpha_m = 3.3$ (1.6, 9.9) and $\gamma_m = 0.35$ (0.27, 0.42), where the 95% confidence intervals are indicated in parentheses, and where the subscripts indicate that these parameters are fit to the mass-conserving form of the deposition velocity (9). We note that variability in α has strong effect on w_d when this parameter is at the lower end of the confidence interval, but has a weak influence when its value is at the upper end. Thus, this parameter is poorly constrained at its upper end, which results in the strongly skewed confidence interval.

When binned across three ranges of u_* the fitted deposition velocity (solid lines) generally captures the particle diameter dependency in the measurement medians (boxes), particularly when considering the measurement inner quartile ranges (IQR, error bars), which reflects both measurement uncertainty and the range of surface types (via z_0) and friction velocity values within each range of u_* (Fig. 3). The IQR of the theoretical curves (shading), which represents parameter uncertainty as well as the range of z_0 and u_* values within each bin, generally overlaps with the IQR for the measurements, with the exception of the diameter range of 7.5 to $17.5 \text{ }\mu\text{m}$ for $u_* > 0.4 \text{ m s}^{-1}$, where the measured values are below what is predicted by theory.

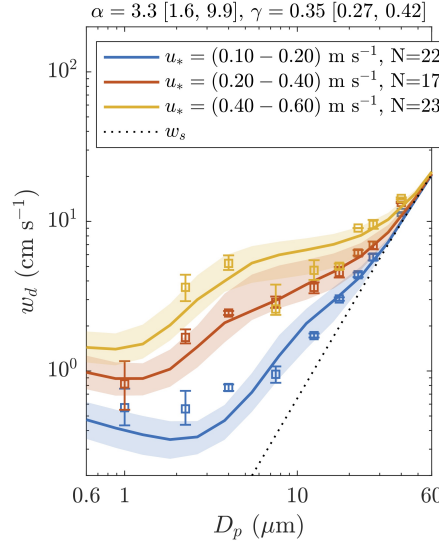


Figure 3. Plotted are measurements of deposition velocity (Zhang et al., 2014) (squares) and their uncertainties (error bars), together with the fitted mass-conserving deposition velocity w_d (solid lines), as a function of particle diameter and for three ranges of u_* . For each u_* bin, the squares represent the medians of the measurements within the bin, and the error bars denote their inner-quartile ranges, obtained from Monte Carlo perturbation of the reported measurement uncertainties. The solid lines represent the medians of the fitted theoretical deposition velocities, and the shaded regions represent their inner-quartile ranges, which is from a Monte Carlo perturbation of the fitting parameters α and γ .

4 Influence of Settling Velocity and Deposition Formulation

We next examine how treatment of the settling velocity and use of the electric analogue deposition velocity can affect estimates of the deposition velocity and thus flux. We assume that w_s is not a function of height since this term varies $O(0.1\%)$ over the depths considered here. Unless otherwise indicated, all calculations are completed for particle density $2,500 \text{ kg m}^{-3}$, $T = 299 \text{ K}$, $p = 1013 \text{ hPa}$, neutral static stability, roughness length $z_0 = 1 \text{ mm}$, and reference height $z_r = 10 \text{ m}$. Where relevant, we assume a particle aspect ratio of 1.7 and height to width ratio of 0.4 (Huang et al., 2020).

4.1 Influence of Settling Velocity

We investigate the influence of settling velocity w_s on the deposition velocity via four representations of w_s . A detailed formulation of each w_s considered here is presented in Appendix A. The key aspects relevant to this discussion are in Table 2.

The dimensionless particle Reynolds number $Re_p = w_s D_p \rho_a \mu^{-1}$, where D_p is the particle diameter and μ is the dynamic viscosity of air, reflects how air flows around a falling particle. For $Re_p \ll 1$ air flows smoothly around the particle, which is referred to as the Stokes Regime. For larger Re_p the flow can detach from the particle and form a wake in its path, commonly

Table 2. Key aspects of settling velocities considered in this study.

	Upper Size Limit	Shape
Stokes	Coarse	Spherical
Clift & Gauvin	Giant	Spherical
Huang 2020	Coarse	Aspherical
Triaxial ellipsoid	Giant	Aspherical

referred to as the intermediate regime. Importantly, $Re_p \propto D_p$ and at STP $Re_p \ll 1$ is approximately equivalent to $D_p < 10$
 230 μm (Drakaki et al., 2022).

The Stokes settling velocity is physically consistent for spherical particles and $Re_p \ll 1$, which corresponds to dust through
 the coarse mode, has a closed-form solution, and is the most commonly used settling velocity when modeling dust deposition
 processes. The Clift & Gauvin settling velocity (Clift and Gauvin, 1971) is valid beyond the Stokes regime, and thus provides a
 physically consistent settling velocity for spherical particles through the giant mode, although w_s must be solved numerically.
 235 We also consider two settling velocities that account for particle asphericity (Bagheri and Bonadonna, 2016), which are better
 approximations to the shape of dust particles than spheres (Huang et al., 2020). The first, which we refer to as Huang 2020, is
 a constant-factor correction to the Stokes settling velocity that accounts for the additional drag generated by triaxial ellipsoids
 as proposed by Bagheri and Bonadonna (2016), but assumes $Re_p \ll 1$, such that it has a closed form solution and is physically
 consistent through the coarse mode (Huang et al., 2020). The second is the full formulation given by (Bagheri and Bonadonna,
 240 2016), and is valid beyond the Stokes regime. This latter formulation of the settling velocity, which we refer to as triaxial
 ellipsoid, is assumed to be most physically consistent with the settling velocity of dust particles across all modes.

We calculated each settling velocity for $T = 299$ K and $p = 1013$ hPa, and for particle diameters of 0.1 to 100 μm (Fig. 4a).
 Firstly, all other velocities are slower than the Stokes settling velocity (blue), and these differences increase with increasing

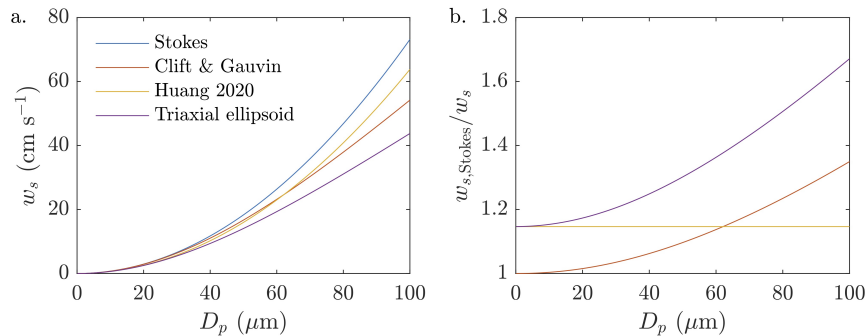


Figure 4. Shown in 4a are the four representations of the particle settling velocity w_s . In 4b are the ratios of the Stokes settling velocity to that from Clift & Gauvin (orange-red), Huang 2020 (yellow), and for randomly oriented triaxial ellipsoids (purple).

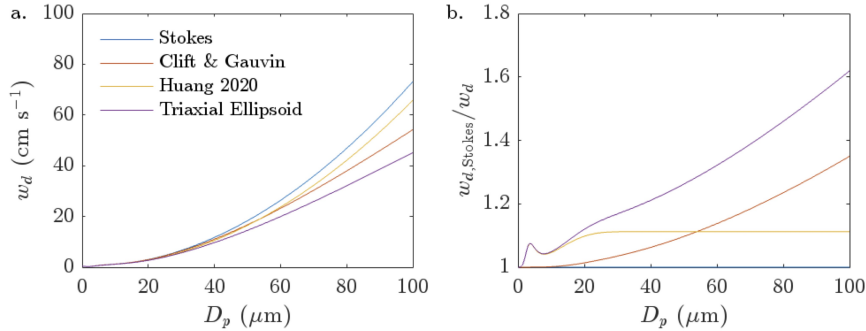


Figure 5. Shown in 5a are deposition velocities for different formulations of the particle settling velocity w_s . In 5b are ratios of deposition velocity calculated using the Stokes settling velocity to that calculated using settling velocities given by Clift & Gauvin (orange-red), Huang 2020 (yellow), and for randomly oriented triaxial ellipsoids (purple).

particle size. The Stokes and Clift & Gauvin settling velocities agree closely in the Stokes regime (i.e., coarse and smaller
 245 modes), as do the Huang 2020 and triaxial ellipsoid settling velocities (Fig. 4b). In the super-coarse and giant modes the influence of particle size on drag is non-negligible, such that the Clift & Gauvin and triaxial ellipsoid settling velocities increasingly diverge with larger particle sizes from the Stokes and Huang 2020 velocities, respectively (Fig. 4b). Near the giant particle size limit, $D_p = 63 \mu\text{m}$, the Stokes settling velocity is larger than that for the triaxial ellipsoid by a factor of 1.4, while the Clift & Gauvin and Huang 2020 settling velocities are equal (Fig. 4b). Thus, at this diameter, the discrepancy
 250 between the Stokes and triaxial ellipsoid velocities is equally due to the effects of particle asphericity and size, where the latter's influence is via Re_p .

We also calculated the mass-conserving deposition velocity using these four representations of w_s for $u_* = 0.2 \text{ m s}^{-1}$, which all show a similar shape of w_d as a function of particle size (Fig. 5a). Deposition velocities for all settling velocities are similar in the accumulation mode, where molecular diffusion dominates deposition. In the fine and coarse modes the spherical and
 255 aspherical deposition velocities diverge; the Huang 2020 and triaxial ellipsoid settling velocities are 5% smaller than that for the spherical cases at $D_p = 2 \mu\text{m}$ (Fig. 5b) since the smaller settling velocities generate weaker values of S_t and thus E_{IM} , indicating decreased inertial impaction by roughness elements, which then results in larger quasi-laminar resistances. This effect weakens as diameter approaches the super coarse mode, where r_b has a smaller influence on w_d . In the super coarse and giant modes $w_d \rightarrow w_s$, so that differences in the deposition velocities mirror those for the settling velocity (Fig. 4). Thus, using
 260 the Stokes settling velocity can overestimate the deposition velocity, and by association deposition flux, by a factor of 1.35 at the upper end of the super coarse mode, and 1.62 at the upper end of the particle diameters considered here, relative to deposition velocities calculated with the more physically consistent triaxial ellipsoid settling velocity. Similar results were obtained for the electric analogue deposition velocity parameterization (17), and statically unstable and stable cases (not shown).

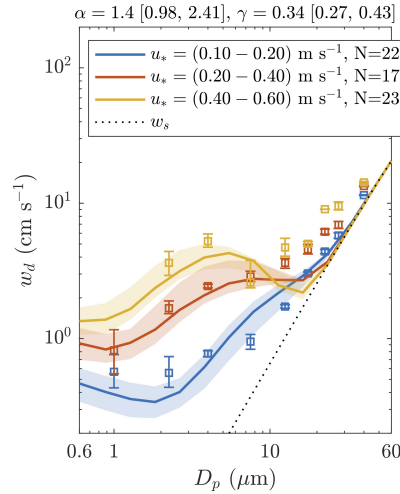


Figure 6. Description is identical to Figure 3 except that the laboratory measurements are fit to w_d^e (17), and using the formulation $R_1 = e^{-\sqrt{S_t}}$ (Slinn, 1982).

4.2 Contrasting the Electric Analogue and Mass-Conserving Deposition Velocities

We calculate the electric analogue deposition velocity w_d^e (17), using $R_1 = e^{-\sqrt{S_t}}$ (Fig. 2) and the triaxial ellipsoid settling velocity (Fig. 4a). We obtain electric analogue quasi-laminar resistance coefficients $\alpha_e = 1.4(0.98, 2.41)$ and $\gamma_e = 0.34(0.27, 0.43)$ by fitting this scheme to the measurements from Zhang et al. (2014) in a manner identical to that done for the mass-conserving deposition velocity. Results show reasonable agreement with observations in the accumulation and fine modes for all ranges of u_* , but the influence of the unphysical parameterization of R_1 (Fig. 2) causes $w_d^e \rightarrow w_s$ at smaller D_p than is suggested by the measurements, since in the Slinn formulation $R_1 \rightarrow 0$ at progressively smaller D_p as u_* increases (Fig. 6).

The Monte Carlo ensembles (shading) and their medians (solid lines) of the fitted w_d and w_d^e , for $u_* = 0.3$ and statically neutral conditions ($1/L = 0$), at $z_r = 10$ m, show that both parameterizations share the same general dependency on particle diameter and relax to w_s near the midpoint of the super-coarse mode (Fig. 7a). However, the ratio w_d^e/w_d for $u_* = 0.1, 0.2, 0.3$, and 0.4 reveals disagreement in the fine, coarse and super-coarse modes that is dependent on the value of friction velocity (Fig. 7b). In the accumulation mode $w_s \approx 0$, $r_b \gg r_a$ and r_b is strongly controlled by molecular diffusion (Pleim et al., 2022). Thus, in this mode differences in deposition velocity formulation and fitting coefficients have small impact on the velocities. The ratios have their maximum values in the fine and coarse modes, with the magnitude (1.14 to 1.23) and diameter (2 to 6 μm) of the maximum values increasing for decreasing u_* . At $u_* = 0.4 \text{ m s}^{-1}$ the ratio is less than one in the coarse and super-coarse modes, reaching a minimum of 0.84 at 16 μm . Qualitatively similar results are obtained for statically stable and unstable conditions (not shown).

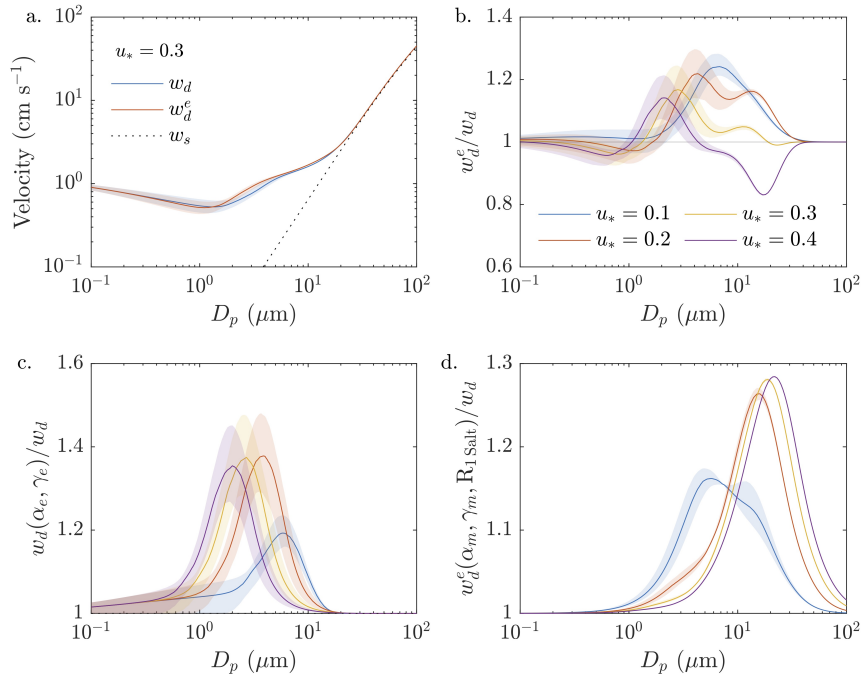


Figure 7. Plotted in 7a are the mass-conserving w_d (light blue) and electric analogue w_d^e (orange-red) deposition velocities calculated for the triaxial ellipsoid settling velocity (black-dotted), as a function of particle diameter D_p . In 7b is the ratio of these two deposition velocities over the same particle size range for four values of friction velocity. Panel c shows the ratio of the mass-conserving deposition velocity calculated using the fitting coefficients α_e and γ_e , which were derived by fitting w_d^e to laboratory measurements (Fig. 6), to w_d . In 7d is the ratio of w_d^e calculated using α_m , γ_m , and R_1 for saltating particles (16), to w_d . In all plots the shaded region represents the IQR of the deposition velocities obtained from Monte Carlo perturbation of the fitting parameters α and γ .

The differences in w_d and w_d^e implied in Figure 7 are both related to the differences in the fitting parameters α and γ , and the functional form of the deposition velocities themselves. We quantify the influence of the fitting parameters by examining the ratio of w_d calculated using α_e and γ_e , with that calculated using α_m and γ_m , for the same range of u_* (Fig. 7c). In the
 285 accumulation mode molecular diffusion dominates the deposition velocity (Pleim et al., 2022), and differences in γ have small influence on r_b since the Schmidt number is also small here. The Schmidt number increases with increasing particle diameter, so that a relatively small decrease in γ produces a large reduction in r_b and thus larger deposition velocity in the fine and coarse modes. However, in these modes impaction becomes the dominant mechanism for deposition. At these sizes the smaller value of α_e produces larger values of the impaction efficiency (15), with differences that grow in magnitude for increasing D_p . In
 290 the super-coarse modes and giant modes the fitting coefficients have a vanishingly small influence on the deposition velocity since aerodynamic resistance and then gravitational settling dominate deposition processes.

We evaluate how the functional form of the electric analogue deposition velocity results in differences when compared to the mass-conserving form by examining the ratio w_d^e/w_d , but where we calculate w_d^e using α_m and γ_m , and the rebound

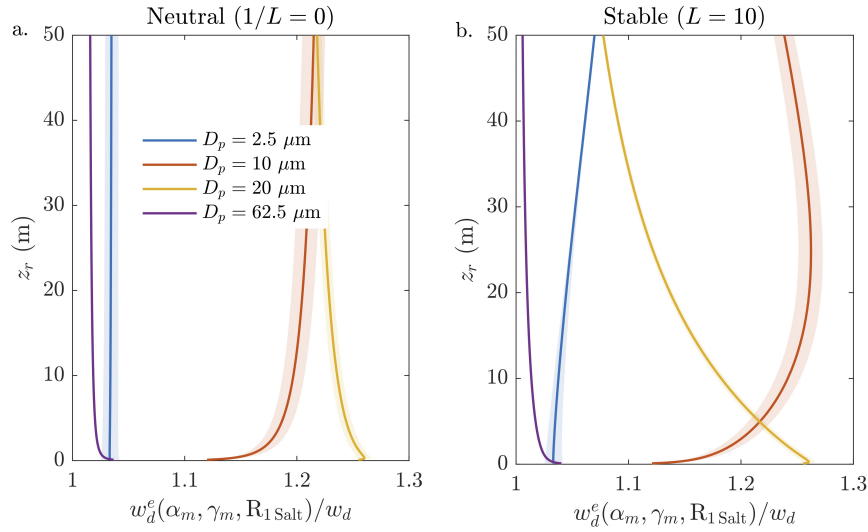


Figure 8. Plotted are the ratios of w_d^e to w_d , as a function of z_r and for $u_* = 0.2 \text{ m s}^{-1}$, statically neutral 8a and stable 8b environments, and at 4 particle diameters. In both panels w_d^e is calculated using α_m , γ_m , and rebound R_1 consistent with saltating particles (16), so that the ratios only reflect the different functional forms of the deposition velocity. Solid lines represent the median ratios and the shaded regions represent their IQR as determined from Monte Carlo perturbation of the fitting parameters.

parameterization R_1 for saltating particles (16). In the accumulation mode both deposition velocities are approximately $R(z)^{-1}$ and thus the ratios are near unity (Fig. 7d). However, in the fine through giant modes $w_d^e > w_d$. In the super-coarse and giant modes $w_d \rightarrow w_s$ but $w_d^e \rightarrow w_s + (w_s r_a r_b)^{-1}$, so that w_d^e relaxes to w_s more slowly than w_d , resulting in the large ratios seen in these modes that diminish as D_p approaches $100 \mu\text{m}$. In the fine and coarse modes the deposition velocities do not reduce to a simple form since the resistances and settling velocities have values of the same order magnitude, and thus there is not a straightforward way to explain why $w_d^e > w_d$ in this range.

Another potential complication associated with not using a mass-conserving deposition velocity is biases associated with choice of reference height. From the definition of the deposition velocity $w_d(z_r) = F_d/c(z_r)$, and for $F_e = 0$, via (9) the mass-conserving dust concentration is

$$c(z) = -\frac{\phi}{w_s} \left(1 - e^{-w_s R(z)}\right). \quad (18)$$

This concentration profile is consistent with the mass-conserving equations (1) and (4). Then, the mass-conserving deposition flux $F_d = -\phi$, which is constant with height in a constant flux layer. The deposition flux for the electric analogue case, $F_d^e = c(z)w_d^e(z_r)$, is not constant with height and thus violates the criteria of a constant flux layer, meaning that the calculated deposition flux is a function of the choice of reference height.

We describe the height dependency implicit in w_d^e by examining the ratio w_d^e/w_d as a function of z_r for $u_* = 0.2$ and under a statically neutral (Fig. 8a) and stable (Fig. 8b) surface layer. Here we calculate w_d^e using the same fitting parameters and rebound as those specified for w_d , so that the differences only reflect the influence of the different functional forms of the deposition

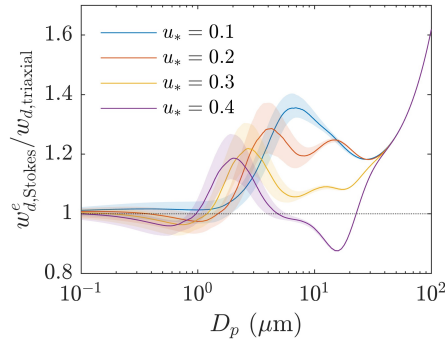


Figure 9. Shown are ratios of the deposition velocities as a function of particle size calculated via the commonly used electric analogue formulation and Stokes settling velocity $w_{d,Stokes}^e$, to that calculated using the mass-conserving formulation and triaxial ellipsoid settling velocity $w_{d,triaxial}$, for four values of the friction velocity, a neutrally stable surface layer, and a reference height of 10 m. Solid lines represent the median ratios and the shaded regions represent their IQR, obtained from Monte Carlo perturbation of the fitting parameters α and γ .

velocity. Since r_b and w_s are not functions of height, these ratios only change with r_a which increases with height, with the rate of change increasing for increasing stability. As previously noted, in the accumulation mode both deposition velocities approximately reduce to $R^{-1}(z_r)$, and resistance at these sizes is dominated by r_b so that there is no height dependency in w_d . At the giant mode threshold ($62.5 \mu\text{m}$) the ratio slightly declines with height since $r_a(z)$ is small close to the surface, and
 315 since gravitational settling is approximately constant with height (see discussion for Fig. 7d). In the coarse and super coarse modes these ratios slightly increase with height ($2.5 \mu\text{m}$), increase more strongly with height ($10 \mu\text{m}$), and decrease with height ($20 \mu\text{m}$), where the magnitudes of these variations increase for the stable environment. As noted for Figure 7d, differences in these modes are difficult to explain since the resistances and settling velocity are of similar magnitude. Analysis of this ratio for an unstable case showed similar height dependency as in the neutral case (not shown).

320 4.3 Combined Effects of Typical Assumptions on Dust Deposition

We lastly describe how the combined use of the Stokes settling velocity, the electric analogue formulation of the deposition velocity, and the Slinn formulation of particle rebound, $w_{d,Stokes}^e$, results in larger deposition velocities when compared to the more physically consistent mass-conserving form of the deposition velocity, with the settling velocity given by that for the triaxial ellipsoid and rebound consistent with that for saltating particles, $w_{d,triaxial}$. We calculate both deposition velocities for
 325 a statically neutral surface layer at a reference height of 10 m, and for four values of friction velocity (Fig. 9).

The shape of the ratio $w_{d,Stokes}^e / w_{d,triaxial}$ closely mirrors that in Fig. 7b in the accumulation through coarse modes, and the ratio for the triaxial ellipsoid settling velocity in Fig. 5b in the super coarse and giant modes. In the fine mode $w_{d,Stokes}^e$ generates deposition velocities that are up to 9% (for $u_* = 0.1 \text{ m s}^{-1}$) to 18% (for $u_* = 0.4 \text{ m s}^{-1}$) larger than those given by $w_{d,triaxial}$. In the coarse mode these numbers increase to 16% (for $u_* = 0.4 \text{ m s}^{-1}$) to 35% (for $u_* = 0.1 \text{ m s}^{-1}$). Above
 330 $D_p = 40 \mu\text{m}$ there is no influence of u_* on the deposition velocities so that at 62.5 and the $100 \mu\text{m}$ $w_{d,Stokes}^e$ is 33% and 62%



larger than the more physically consistent $w_{d, \text{triaxial}}$, respectively. Qualitatively similar results were obtained for the stable and unstable cases (not shown).

5 Conclusions

In this manuscript we examined differences between a mass-conserving formulation of the deposition velocity that accounts for particle asphericity, and the commonly used electric analogue formulation for spherical particles in the Stokes regime. We first reviewed the theory underlying the mass-conserving and electric analogue formulations (Sec 2). We presented a parameterization for the rebound parameter that is consistent for saltating particles at the surface, and that is more physically consistent than existing parameters (Fig. 2). We calibrated the mass-conserving and electric analogue deposition velocities against laboratory measurements (Sec 3), and used the calibrated formulations to quantify how the treatment of particle gravitational settling (Fig. 5) and mass conservation affects estimates of the deposition velocity (Figs. 7), and by extension, the deposition flux (Sec 4).

When compared to the more physically consistent mass-conserving deposition velocity for aspherical particles, commonly used formulations produce broadly similar deposition velocities in the accumulation mode, where gravitational settling is weak and deposition is primarily controlled by molecular diffusion (Pleim et al., 2022). This agreement is consistent with the particle-size range for which deposition velocity parameterizations had been developed, and likely led to the assumption that use of the mass-conserving form of the deposition velocity has negligible effect on the resultant deposition fluxes (Venkatram and Pleim, 1999). However, these deposition velocities diverge in larger modes, as differences related to parameters controlling the impaction efficiency (fine and coarse mode), the formulation of the deposition velocity parameterization (coarse and super-coarse modes), and finally the influence of gravitational settling (super-coarse and giant modes) become increasingly important (Fig. 9). Furthermore, the magnitude of these discrepancies varies with layer stability, friction velocity, and reference height (Fig. 8), making them difficult to characterize. Thus, commonly used deposition velocity parameterizations can produce deposition fluxes that yield substantial and condition-dependent differences when compared to a more physically consistent parameterization.

How relevant is this comparison in terms of current dust modeling? To address this question we attempted to identify the deposition schemes used in models participating in the Sixth Climate Model Intercomparison Project (CMIP6) that were previously examined for their representation of the dust cycle (Zhao et al., 2022). For the 8 models for which we were able to identify the dry dust deposition scheme used, none employed a mass-conserving formulation, with 6 using the electric analogue formulation described here (17), and 2 utilizing formulations that were not electric analogues but were also not mass-conserving (Table 3). All models parameterized the settling velocity using Stokes settling theory. However, the deposition scheme proposed by Zender et al. (2003) also included a time-invariant correction factor that accounts for finite particle Reynolds number effects, although it is not clear whether this correction was applied in the CMIP6 simulations. We also note that at least one model (GISS ModelE) has since been updated with a mass-conserving scheme (Clifton et al., 2024).

If the comparisons in Fig. 9 are representative of the range of overestimation of the particle deposition velocity in these models, our results suggest that the simulated lifetime and burden of super-coarse and giant dust is likely underestimated.



Table 3. List of CMIP6 models evaluated by Zhao et al. (2022) for which the authors were able to identify the dust dry deposition scheme used in the simulations.

Model Name	Parameterization	Reference
CESM	Electric analogue	Liu et al. (2012)
CanAM5	Electric analogue	Peng et al. (2012)
GISS ModelE	Not mass-conserving	Walcek et al. (1986)
HadGEM3	Electric analogue	Woodward (2001)
MIROC	Not mass-conserving	Takemura et al. (2000)
MRI	Electric analogue	Yumimoto et al. (2017)
NorESM	Electric analogue	Zender et al. (2003)
UKESM	Electric analogue	Woodward (2001)

Fortunately, it may be relatively straightforward to implement the mass-conserving formulation of the deposition velocity in models since this only represents a rearrangement of existing variables already calculated in deposition schemes (e.g., r_a, r_b, w_s). For finite volume models, which represent dust as a mean concentration c_m over a discrete layer in the atmosphere, mass conservation can be achieved by calculating a subgrid scale concentration profile that follows the form of Eq (18), and that conserves the grid scale mean,

$$c(z_r) = c_m z_{\text{top}} \frac{1 - e^{-w_s R(z_r)}}{\int_0^{z_{\text{top}}} [1 - e^{-w_s R(z)}] dz},$$

where z_{top} is the geometric thickness of the lowest model layer, and where we assume that w_s is approximately constant over this depth. Then the mass-conserving deposition flux is

$$F_d = \frac{z_{\text{top}} c_m w_s}{\int_0^{z_{\text{top}}} [1 - e^{-w_s R(z)}] dz}, \quad (19)$$

which is independent of z_r . Furthermore, it is possible to obtain the coefficients α and γ in Eq 9 for other surface types (e.g. Zhang et al., 2001), using existing compilations of dry deposition velocity measurements (e.g. Farmer et al., 2021).

Lastly, implementing a settling velocity appropriate outside the Stokes drag regime is also relatively straightforward (Appendix A), and is appropriate in the super-coarse and giant modes, whereas the scaling factor described in Huang et al. (2020) can correct for asphericity in the fine and coarse modes (Fig. 5).

Code and data availability. All code used to generate the figures in this study is available at https://github.com/amatoevan/Dry_Deposition/. Laboratory measurements of the dry deposition flux of dust are available via Zhang et al. (2014).



380 Appendix A: Models of the Settling Velocity

Here we describe four representations of the particle settling velocity w_s . In steady state buoyancy, and particle drag forces are in balance,

$$\frac{1}{2}C_d A_p \rho_a w_s^2 = \rho_p V_p g - \rho_a V_p g, \quad (\text{A1})$$

where g is gravitational acceleration, V_p is particle volume, and A_p is particle area. The drag coefficient C_d is a function of the dimensionless particle Reynolds number Re_p

$$Re_p = \frac{w_s D_p \rho_a}{\mu}, \quad (\text{A2})$$

where D_p is the diameter of the particle and μ is the dynamic viscosity of air, which can be approximated as

$$\mu = \mu_0 \frac{T_0 + S}{T + S} \left(\frac{T}{T_0} \right)^{3/2},$$

where T is air temperature (K), $\mu_0 = 1.812 \times 10^{-5} \text{ kg m}^{-1} \text{ s}^{-1}$ is the viscosity at the reference temperature $T_0 = 288.15$, and the Sutherland constant $S = 120 \text{ K}$ (Mallios et al., 2020, and references therein).

A1 Spherical Particles in the Stokes Regime

In the Stokes regime ($Re_p \ll 1$), which at STP is approximately equivalent to $D_p < 10 \text{ } \mu\text{m}$ (Drakaki et al., 2022), the drag coefficient is given by

$$C_{d,\text{Stokes}} = \frac{24}{C_c Re_p}, \quad (\text{A3})$$

where the Cunningham slip correction factor C_c (Davies, 1945) is defined as

$$C_c = 1 + \frac{2\lambda}{D_p} \left[1.257 + 0.40 * \exp \left(-\frac{1.10 D_p}{2\lambda} \right) \right]$$

and is a function of particle diameter D_p and the atmospheric mean free path λ ,

$$\lambda = \frac{k_b T}{(\pi \sqrt{2} d_m^2 P)},$$

with the Boltzmann's constant $k_b = 1.38065 \times 10^{-23} \text{ (J K}^{-1}\text{)}$, P is atmospheric pressure (Pa), and the molecular diameter of air molecules $d_m = 3.2 \times 10^{-10} \text{ (m)}$. The slip correction factor C_c decreases sharply for increasing particle size in the submicron range, and is ~ 1 for $D_p > 30 \text{ } \mu\text{m}$. Thus, although some studies specifically only apply this correction factor when $Re \leq 0.1$, we find that this criteria for application has negligible effect on the settling velocity of coarse dust.

An expression for particle settling velocity in the Stokes regime $w_{s,\text{Stokes}}$ can be obtained by substituting the expressions for the Reynolds number (A2) and drag coefficient (A3) in the force balance in (A1)

$$w_{s,\text{Stokes}} = C_c \frac{g D_p^2 (\rho_p - \rho_a)}{18\mu}. \quad (\text{A4})$$



A2 Spherical Particles Outside the Stokes Regime

A more general form of the drag coefficient described by Clift and Gauvin (1971) can be used to calculate the settling velocity at high Reynolds number, and is thus appropriate for calculating the settling velocity of larger particles,

$$C_{d,CG} = \frac{24}{Re} (1 + 0.15Re^{0.687}) + \frac{0.42}{1 + 42500/Re^{1.16}}. \quad (A5)$$

410 The force balance in (A1) can then be transformed by substituting $C_{d,CG}$ for C_d , using (A2) to replace w_s in the resultant expression and including the slip-correction factor to obtain

$$\left[\frac{24}{Re} (1 + 0.15Re^{0.687}) + \frac{0.42}{1 + 42500/Re^{1.16}} \right] Re^2 = C_c \frac{4gD_p^3(\rho_p - \rho_a)\rho_a}{3\mu^2}, \quad (A6)$$

which can be solved numerically for a given D_p . This value of Re_p can, in-turn, be used to calculate w_s via (A2).

A3 Triaxial Ellipsoids

415 It is well-known that dust particles are aspherical, whose shapes are better represented by prolate spheroids than spheres (e.g., Huang et al., 2020), which can have substantially slower settling velocities (Ginoux, 2003). A thorough treatment of this problem can be found in Mallios et al. (2020), who show that the largest reductions in settling velocity (30 – 70%) due to particle asphericity are for $1 < D_p < 100 \mu\text{m}$. We employ an empirically derived estimate of the drag coefficient for randomly oriented triaxial ellipsoids using the formulation provided in Bagheri and Bonadonna (2016).

420 Here, the drag coefficient $C_{d,\text{ellipsoid}}$ is

$$C_{d,\text{ellipsoid}} = \frac{24k_S}{Re_p} \left[1 + 0.125 \left(Re \frac{k_N}{k_S} \right)^{2/3} \right] + \frac{0.46k_N}{\left(1 + \frac{5330k_S}{k_N Re} \right)}, \quad (A7)$$

where

$$a_2 = 0.45 + 10/\exp(2.5\log\rho' + 30)$$

$$b_2 = 1 - 37/\exp(3\log\rho' + 100)$$

425 $k_N = 10^{a_2[-\log(F_N)]^{b_2}}$

$$k_S = 0.5 \left(F_S^{1/3} + F_S^{-1/3} \right)$$

$$F_S = fe^{1.3}$$

$$F_N = f^2e$$

430 f is particle's height-to-width ratio (HWR), ρ' is the particle to fluid ratio, and e is the ratio of the particle aspect ratio (AR) to HWR.

The resulting settling velocity is found using the same procedure as described for the high Reynolds number case (A6). Although for coarse prolate spheroids orientation does not significantly alter the settling velocity (Bagheri and Bonadonna,



2016), orientation may have a larger impact on reducing the settling velocity of coarse dust modeled as a triaxial ellipsoid, although such effects are neglected in this study.

435 We note that Huang et al. (2020) presented an approximation to the above formulation of the settling velocity, calculating a correction factor that can be applied to the Stokes regime settling velocity and estimated from measurements of AR and HWR. For their values $AR = 1.7$ and $HWR = 0.4$, this correction factor $\gamma = 0.872$, implying that within the Stokes regime triaxial ellipsoids have settling velocities 87.2% of those for spherical particles.

Author contributions. A.T.E. conceived of and designed the study, and wrote the manuscript. J.F.K. and M.C. helped develop the theory and
440 edited the manuscript draft.

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