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TELLUS

A note on aerosol sized particle deposition onto dense and tall canopies situated on gentle cosine hills

By GABRIEL G. KATUL[1,2,3]* and DAVIDE POGGI[3], [1]*Nicholas School of the Environment, Box 90328, Duke University, Durham, NC 27708-0328, USA;* [2]*Department of Civil and Environmental Engineering, Pratt School of Engineering, Duke University, Durham, NC 27708, USA;* [3]*Dipartimento di Idraulica, Trasporti ed Infrastrutture Civili, Politecnico di Torino, Torino, Italy*

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ABSTRACT

Micrometeorological measurements of aerosol sized dry particle deposition velocity (V_d) onto forested canopies have significantly advanced over the past two decades and now include both—airborne and stationary platforms. However, the interpretation of these V_d measurements still relies on stationary and planar homogeneous flow assumptions only appropriate to flat-terrain conditions. Simplified model calculations were used to examine how variations in hill height (H) introduce biases in V_d when assumptions appropriate to flat terrain are applied to periodic and gentle 2-D cosine topography covered with tall and dense forested canopies. It was shown that increasing H reduced the variability in V_d for all aerosol sized particle diameters (d_p) inside the canopy when the hill slope (H/L) remained constant (=0.1), where L is the cosine hill half-length. At the landscape scale, as may be monitored from airborne platforms, assumptions appropriate to flat-terrain appear accurate with increasing H for a constant and gentle H/L (= 0.1). Inside the canopy, variability in V_d tends to be larger than above the canopy for all H values and d_p classes.

1. Introduction

Dry deposition measurements of aerosol sized particles onto vegetated surfaces are drawing increased interest from a number of disciplines given the role that these particles play in global cycling of elements, acidification of some ecosystems, transport of microbial spores, deposition of ash and cinders from volcanic eruptions, trapping of fog water, crop spraying, and air pollution and human health to name a few (Stout et al., 1993; Petroff et al., 2008a; Pryor et al., 2008). Micrometeorological measurements of aerosol sized particle concentrations and fluxes to vegetated surfaces, whether collected at micrometeorological towers (Wesely and Hicks, 2000; Petroff et al., 2008a; Pryor et al., 2008; Grönholm et al., 2009; Rannik et al., 2009) or from airborne platforms (Hicks, 2008) have progressed dramatically over the past 10 yr. However, the interpretation of dry deposition velocity (V_d) measurements generated from such platforms still relies on stationary and planar homogeneous flow assumptions (Slinn, 1982; Hill et al., 1987; Hicks, 2008; Petroff et al., 2008b; Rannik et al., 2009). These two classes of measuring platforms sense different spatial domains: The airborne being commensurate with the landscape scale, while the tower-based platform being commensurate with local scales—usually on the order of the footprint contributing to the flux measurement height (Finnigan, 2000). Above a uniform canopy, these two measuring platforms provide comparable estimates of V_d for a flat terrain. When V_d is measured over non-flat terrain, even when the terrain is covered with a uniform canopy, linkages between deposition measurements at these two spatial scales remain a formidable research challenge. As a logical starting point, we ask how repeated gentle cosine hills perturb the 'flat-world' interpretation of V_d in a non-stratified atmospheric boundary layer at both—the local and landscape scales for tall and uniform distributed forested canopy. Naturally, this narrower scope has a number of deficiencies when conclusions drawn from this work are to be extrapolated to a particular site or a single terrain–canopy system. However, the choice of repeated gentle cosine hills and tall/uniform canopies does offer a number of advantages for deriving broad conclusions about the role of gentle terrain in modifying V_d. Two-dimensional cosine shaped hills guarantee symmetry in the topographic perturbations around their flat-terrain counterpart and all the resulting asymmetries in the flow statistics are outcomes of non-linear responses of the flow field to these symmetric topographic perturbations. Moreover, gentle topographic perturbations are dynamically interesting because the mean pressure gradient is not too large to 'over-ride' key

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*Corresponding author.
e-mail: gaby@duke.edu
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turbulent processes inside the canopy such as the momentum flux gradient and yet not too small to be ignored (Finnigan and Belcher, 2004; Ross and Vosper, 2005). Finally, the two-dimensional representation of the hill system here amplifies the effects of hills on the deposition process along the longitudinal direction given the imposed homogeneity in the lateral direction. The compass of this work is to examine how variations in the cosine hill amplitude or height (H) introduce biases in V_{d} across a wide range of particle sizes when assumptions appropriate to flat terrain are applied to measurements sampled at these two spatial scales. The fact that particle size impacts the deposition through flow-dependent processes such as inertial impaction and turbophoresis makes the study of particle deposition quite different from gaseous compounds with no inertia. This comparison can provide practical rule-of-thumb guidelines to the now proliferating number of tower sites aimed at monitoring aerosol sized particle deposition rates onto forested ecosystems using micrometeorological techniques (e.g. Gallagher et al., 1997; Grönholm et al., 2009; Rannik et al., 2009).

2. Theory

The model formulation and assumptions are presented in Katul et al. (2010) and Katul and Poggi (2010) and are not repeated here. However, for completeness, the main budget equations are reviewed. In a stationary and non-stratified atmospheric boundary layer (ABL) flow on a gentle cosine hill covered with a uniform canopy, the conservation of fluid mass, mean momentum, and the mean concentration $\overline{c}$ of particles of size d_{p} are given by

$$\frac{\partial \overline{u}}{\partial x} + \frac{\partial \overline{w}}{\partial z} = 0, \tag{1a}$$

$$\overline{u}\frac{\partial \overline{u}}{\partial x} + \overline{w}\frac{\partial \overline{u}}{\partial z} = -\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x} - \left(\frac{\partial \overline{u'u'}}{\partial x} + \frac{\partial \overline{u'w'}}{\partial z}\right) - \frac{\overline{u}^2}{L_{\mathrm{c}}}\left[1 - H_{\mathrm{f}}(z, h_{\mathrm{c}})\right], \tag{1b}$$

$$\overbrace{\overline{u}(x,z)\frac{\partial \overline{c}(x,z)}{\partial x} + \overline{w}(x,z)\frac{\partial \overline{c}(x,z)}{\partial z}}^{\text{Mean Advective Terms}} = \underbrace{\frac{\partial}{\partial z}\left\{\left[D_{p,m} + D_{p,t}(x,z)\right]\frac{\partial \overline{c}(x,z)}{\partial z} + |V_{\mathrm{s}}|\,\overline{c}(x,z)\right\}}_{\text{Total Flux Gradient}} + \underbrace{\left(\frac{2a}{\pi}\right)\frac{\overline{c}(x,z)}{r_{\mathrm{b}}(x,z)}\left[1 - H_{\mathrm{f}}(z, h_{\mathrm{c}})\right]}_{\text{Vegetation Collection Mechanism}}, \tag{1c}$$

where x and z are the streamwise and cross-stream coordinates, respectively, referenced to an approximately surface normal coordinate system with $x = 0$ being the top of the cosine hill and $z = 0$ being the top of the canopy, $\overline{u}$ and $\overline{w}$ are the time averaged velocities in the x and z directions, respectively, u' and w' are the corresponding turbulent velocity fluctuations, respectively, such that $\overline{u'} = \overline{w'} = 0$, $\overline{u'w'}(x, z)$ and $\overline{u'u'}(x, z)$ are the momentum flux and longitudinal velocity variance respectively, $\overline{p}(x, z)$ is the mean static pressure perturbations induced by topography whose longitudinal variations are controlled by variations in the hill surface (Z_{s}), and $L_{\mathrm{c}} = (C_{\mathrm{d}}a)^{-1}$ is the adjustment length scale of the canopy with C_{d} being the canopy drag coefficient and a ($= LAI/h_{\mathrm{c}}$) is the leaf area density, LAI is the leaf area index (single sided foliage area per ground area), h_{c} is the mean canopy height, H_{f} is the Heaviside step function (=1 if $z > 0$ or zero otherwise), $D_{p,t}$ and $D_{p,m}$ are the particle turbulent and Brownian diffusivities, respectively, and V_{s} is the particle setting velocity. The factor π in eq. 1c adjusts for the single-side projected leaf area to total surface area of leaves (assuming the foliage needles to be cylinders). The leaf surface resistance ($= r_b$) is determined from a laminar boundary layer assumed to be 'pinned' to individual leaf elements whose micro-roughness is assumed small compared to the thickness of the viscous sublayer and can be expressed as (Hill et al., 1987; Seinfeld and Pandis, 1998):

$$r_{\mathrm{b}}(x,z) = \left[\sqrt{-\overline{u'w'}(x,z)}\left(\theta Sc^{-2/3} + 10^{-3/St(x,z)}\right) + V_t(x,z)\right]^{-1}, \tag{2}$$

where $Sc = \nu/D_{m,p}$ is the Schmidt number and varies mainly with d_{p}, $St = V_{\mathrm{s}}[-\overline{u'w'}(x,z)]/(g\nu)$ is a turbulent Stokes number, and $V_t(x, z)$ is the turbo-phoretic velocity. The parameter $\theta = (\pi/2)(c_v/c_{\mathrm{d}})$, where c_v/c_{d} is the ratio of the viscous to form drag coefficient of the leaf. The factor π in θ is needed because it is the entire surface area not the projected area that contributes to Brownian diffusion, while the factor 1/2 is needed to account for the fact that c_v acts on the entire surface area while c_{d} acts only on the frontal area of the leaf surface. Within canopies, $c_v/c_p \approx 1/3$ is reasonable (Slinn, 1982; Petroff et al., 2008) though this ratio is expected to vary with a locally defined Reynolds number. For simplicity and to avoid the need to include a large number of 'leaf' specific parameters, we simply set $\theta = \frac{\pi}{2}\frac{c_v}{c_{\mathrm{d}}} \approx 0.5$. Turbo-phoresis fundamentally differs from classical turbulent diffusion ($D_{p,t}$) because it can impact particle transport in the absence of mean concentration gradients. The inertial impaction term ($=10^{-3/St}$) was developed for smooth surfaces and tested for smooth boundary layers (Slinn and Slinn, 1980; Aluko and Noll, 2006). Stomatal uptake, sedimentation, interception, rebound, and other phoretic processes are ignored. Once the mean particle concentration is solved for at each particle diameter, the spatial variation in deposition velocity can be computed from $\overline{c}(x, z)$ using

$$V_{\mathrm{d}}(x,z) = |V_{\mathrm{s}}| - [D_{p,m} + D_{p,t}(x,z)]\left(\frac{1}{\overline{c}(x,z)}\right)\frac{\partial \overline{c}(x,z)}{\partial z}. \tag{3}$$

Parametrizations of V_{s}, V_t, $D_{p,m}$, and $D_{p,t}$ as well as boundary conditions and numerical solution to these equations are described elsewhere (Katul et al., 2010). To keep the number of parameters to a tractable minimum, ground deposition was ignored thereby anchoring the entire deposition process onto vegetation. The model runs are based on two-dimensional repeated gentle cosine hills whose surface Z_s is given by

$$Z_s = \frac{H}{2}\left[\cos\left(\frac{\pi}{2}\frac{X}{L}\right) - 1\right] - h_c,$$

where X is the longitudinal distance, L and H are the hill half-length and hill height, respectively. The mean flow field model has been independently tested with gentle cosine hills covered with a rod canopy situated in a flume (Poggi et al., 2009) and the size-resolved mean particle continuity equation has been tested in a Scots pine forest using concentration profiles and two level fluxes (Katul et al., 2010). For a given friction velocity u_*, $\partial Z_s/\partial X$ impacts the spatial variations of $\overline{p}(x, z)$, which is the key forcing for the mean momentum balance. Throughout, we set $H/L = 0.1$ (gentle hill), $h_c/L_c = 0.75$, $C_d = 0.2$, and $a = LAI/h_c$ is assumed to be uniform across the entire hill with h_c and LAI set to 15 m and 4 m^2 m^{-2}, respectively. Moreover, the flat-world friction-velocity u_* was set to 0.5 m s^{-1}. Finally, in all model calculations, near-neutral conditions are assumed.

3. Results

A large number of model runs for varying H/h_c from 1 to 10 and d_p from 1nm to 100 μm were conducted. Increasing H nonlinearly impacts the amplitude of the mean pressure gradient driving the mean momentum balance and how V_d responds to these changes in H actually frames the study objective here. The runs were checked to ensure that (i) the canopy was sufficiently deep to absorb almost all the turbulent stress and (ii) the mean vertical velocity was not too large to impact the outer layer pressure (Ross and Vosper, 2005; Poggi et al. 2008). Hence, the flow field can be computed using the simplified model of Finnigan and Belcher (2004), hereafter referred to as FB04. The model results are contrasted with their flat-world counterparts, which were computed for identical parametrization but setting $H = 0$. These model results are summarized via two statistics

$$r(z) = \langle\psi\rangle = \int_{-2L}^{2L} \psi(x, z)\,\mathrm{d}x,$$

$$\sigma(z) = \left\langle(\psi(x, z) - \langle\psi\rangle)^2\right\rangle^{1/2}.$$

Here, $\psi(x, z)$ is a normalized flow variable (e.g. V_d across the hill normalized by its flat-world counterpart). The $r(z)$ represents expected departures of hill-averaged statistics across one hill wavelength from their flat-world counterpart (as a fraction), and σ represents the strength of this variability (or its dispersion around the flat-world counterpart). In terms of their connections to the measuring platforms, $r(z)$ matches the scales at which airborne sensing platforms provide measurements. An $r(z) = 1$ and a $\sigma(z) = 0$ indicate that flat-world approximations can be used to interpret spatially-averaged V_d. For $\bar{u}$ and $\overline{u'w'}$, $r(z)$ is unity throughout from the definition of background velocity in FB04. However, with increasing H, σ for $\bar{u}$ and $\overline{u'w'}$ decrease, especially inside the canopy due to increases in L (recall $H/L = 0.1$). The advection-distortion time scale of eddies scales as $L/\bar{U}_b$, where $\bar{U}_b$ is the background velocity. A longer advection distortion time scale implies that the flow is less impacted by advection and the relaxation time scale (i.e. ratio of turbulent kinetic energy to its dissipation rate) become the dominant time scales for the hill-induced perturbations (Belcher and Hunt, 1998). Hence, increasing H/h_c here is analogous to increasing L without any alterations to $\bar{U}_b$ thereby diminishing the effects of the horizontal gradients and rendering σ to zero for the two key flow statistics variables. For each pair of H/h_c and d_p, $r(z)$ and $\sigma(z)$ were computed for each run for the normalized deposition velocity. How r and σ vary with increasing H/h_c for a wide range of d_p are shown in Fig. 1. With increasing H/h_c, the difference between flat-world runs and hill-averaged deposition velocity diminished (recall that $H/L = 0.1$, $h_c = 15$ m and LAI = 4 m^2 m^{-2} are held constant). For all model runs, r varied appreciably with variations in d_p. For small particle sizes ($d_p < 100$ nm) and above the canopy, hill-averaged deposition velocity is overestimated by flat-world approximations and the converse is true for larger d_p except for very large d_p(∼100 μm) classes where the settling velocity becomes dominant. Inside the canopy, the hill disproportionately impacted deposition of particles in the diameter range 100 nm $< d_p <$ 100 μm when compared to their smaller sized counterparts (Fig. 1). This disproportional impact is not particularly pertinent to airborne platforms, but it can be important when interpreting multilevel tower measurements of V_d inside canopies situated on complex terrain. Figure 1 also shows how σ varies with increasing H/h_c and d_p. For all H/h_c and particle sizes, σ appears larger inside the canopy when compared to above the canopy. This finding can be problematic when interpreting multi-level particle flux measurements inside forested canopies at a single tower location as the variability is much larger at one height when compared to the other. The issue becomes compounded for $H/h_c > 1$ and for heavier particles (but V_d is still not controlled by V_s) with σ as large as 50%. Recall that σ represents a spatial standard deviation across the hill wavelength and need not represent 'extra' hill-induced variability at one particular tower location. However, in reality, fluctuations in mean wind direction may generate 'extra' spatial variability similar to σ given that such wind direction shifts are analogous to changing tower positions on complex topography.

Figure 2 presents the effects of H/h_c on V_d more explicitly by focusing on three heights: $z/h_c = -0.5,\ 0,\ 0.5$. In a flat-world interpretation, these heights represent the within canopy system, canopy–atmosphere interface, and the transition from the canopy sublayer to the atmospheric surface layer. From Fig. 2, increasing H/h_c leads to $r \rightarrow 1$, though for particles whose V_d is controlled by inertial impaction term, this approach

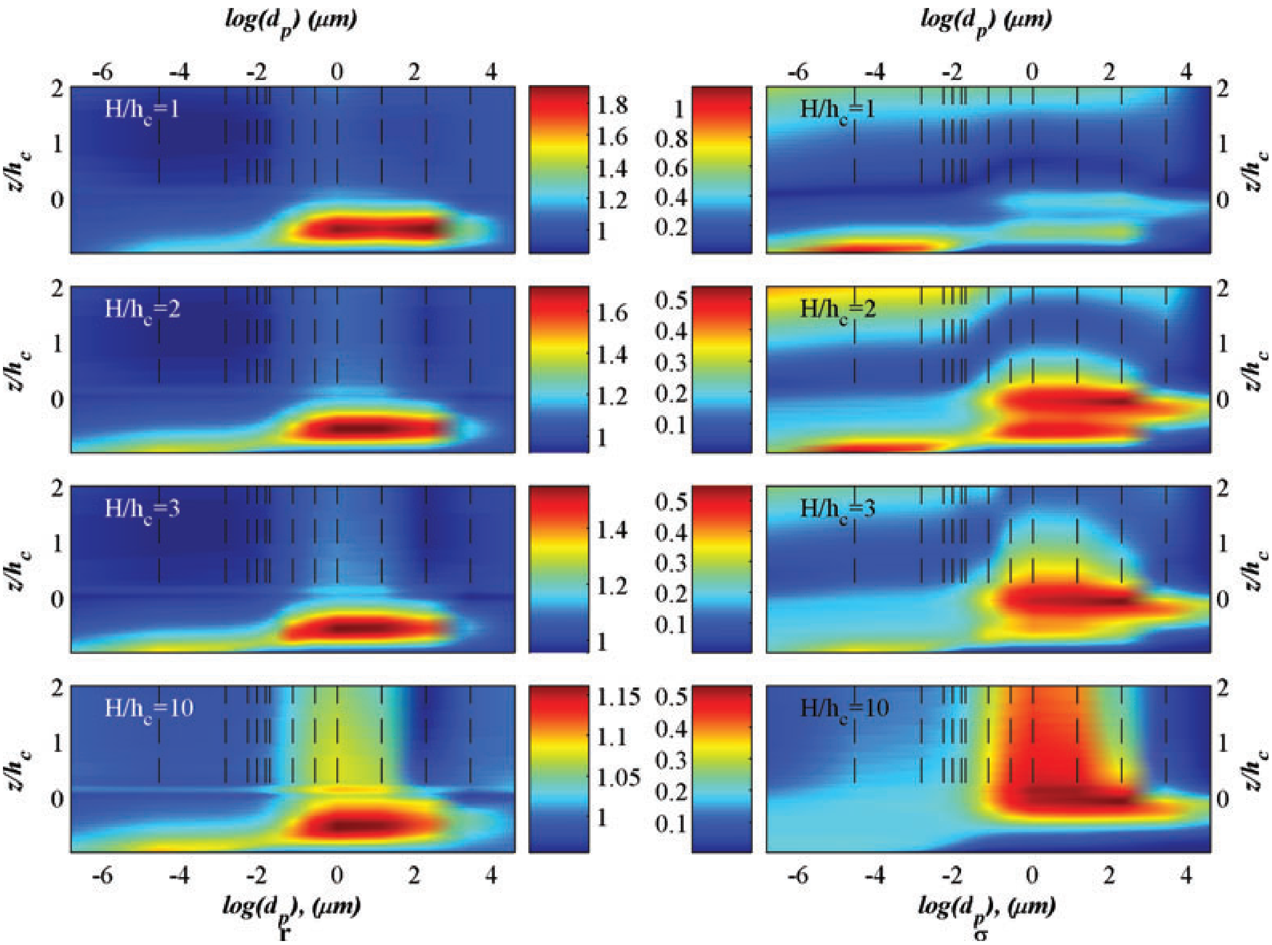

Fig. 1. The variation of the hill-averaged deposition velocity normalized by the flat-world deposition velocity (r) as a function of z/h_c,H/h_c and d_p (left-hand panels), where $z/h_c = 0$ defines the canopy top. An $r = 1$ indicates that the flat-terrain and hill-averaged V_d are identical. The standard deviation around the hill-averaged deposition velocity, normalized by the flat-terrain deposition velocity ($=\sigma$) are also shown (right-hand panels). The dashed vertical lines indicate the sizes used in the model calculations. Note that the range of values represented by the colour-bars differs across H/h_c runs.

to unity in r is much more gradual. Above the canopy, departures from unity in r are on the order of H/L, and hence, are not large. The sizes in which σ is experiencing most sensitivity to variations in H/h_c are particle sizes where V_d is dominated by inertial impaction and turbo-phoresis, which is again not surprising. For large V_s, $V_d \approx V_s$ and the spatial variability in V_d becomes negligible so that $r \rightarrow 1$ and $\sigma \rightarrow 0$.

4. Conclusions

At the local scale, we found that increasing H while maintaining a constant hill slope tends to reduce variability in V_d for all particle sizes. This reduction is primarily connected with increasing L (constant hill slope) and the lengthening of the advection–distortion time scale that then dampens advective spatial gradients. At the landscape scale, assumptions appropriate to flat-terrain tend to be more reasonable again above the canopy when H increases while maintaining a constant hill slope (H/L). The excursions from flat-terrain are on the order or less than H/L (above the canopy). Moreover, inside the canopy, the variability in deposition velocities tends to be larger than above the canopy for all H values and all particle diameters. However, the variability can be extreme inside the canopy for particle diameters whose deposition velocity is regulated by turbo-phoresis and inertial impaction.

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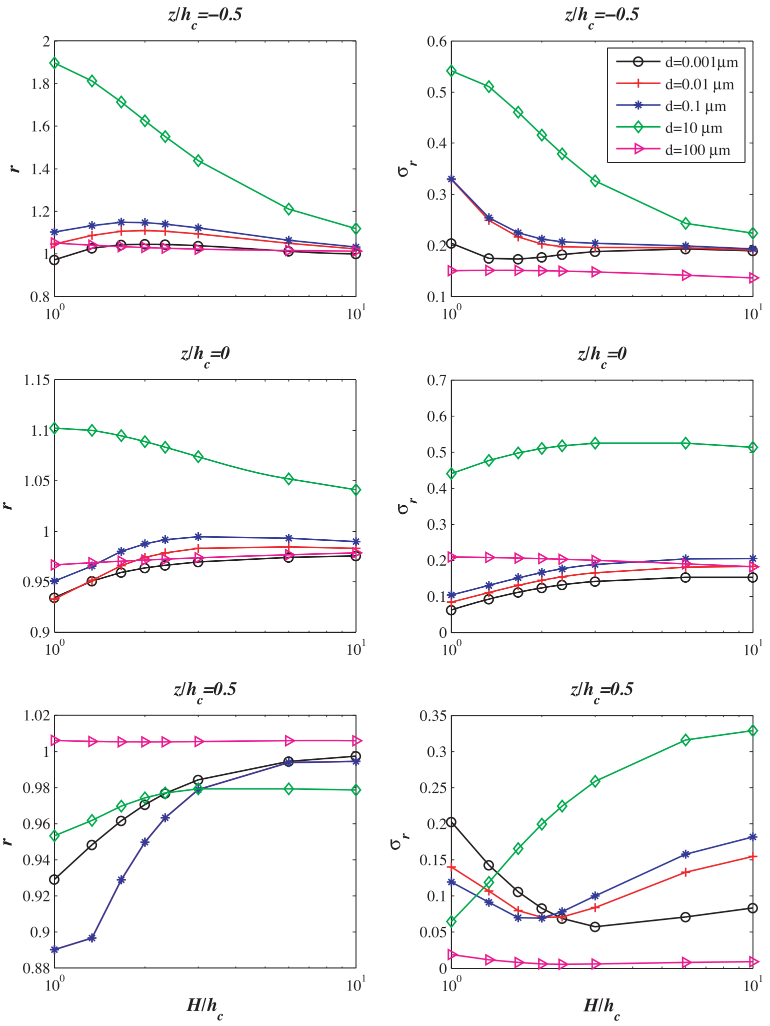

Fig. 2. The variation in r (left-hand panels) and σ (right-hand panels) for $z/h_c = -0.5$, 0, 0.5 and for the five particle diameter classes (d_p).

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