Authors' reply to referee comments RC1 of the paper egusphere-2025-2903 entitled "Simulating liquid water distribution at the pore scale in snow: water retention curves and effective transport properties" by Bouvet et al.

We thank very much Reviewer 1 for the comments. Please find below our point-by-point replies in blue color.

The physical properties of wet snow are less well understood than those of dry snow, with fewer measurement data and experimental results available. In this study, the authors reported the relationship between the microstructure of snow and the physical properties of wet snow based on simulations. They also compare the simulation results with existing experimental results and propose new equations for estimating these physical parameters. Their simulation approach is unique, and there is no doubt that their method is useful in situations where experimental results are lacking in the wet snow field. For these reasons, this paper makes a significant scientific contribution to the field of wet snow science and is worthy of publication in TC. The paper is well organized and easy for readers to understand.
On the other hand, the discussion in this paper is based on simulation results. Simulation results depend on conditions and parameters, so it is necessary to verify the accuracy of the simulation results based on experimental or observational results. Until the accuracy of the simulation is guaranteed, it is not possible to evaluate the true scientific contribution of the research. Therefore, I believe that it is necessary to add a discussion on the accuracy of the simulation to the paper before it is accepted for publication. I will list a few points I have noticed, including these points.

Major point

As shown in Equation (5), the pressure head of a liquid depends on the radius of the pore, and this is the basic equation used in the simulations in this study. In order to use Equation (5), it is necessary to calculate the radius of the pores in the snow. However, since the pores in the snow are interconnected, it is necessary to separate them in some way in order to determine their radii. Therefore, the distribution of radii may vary depending on the method used to separate the pores, which in turn may affect the simulation results. For this reason, the authors should add an explanation of the method used to separate the pores and discuss the impact of the pores separation method on the simulation results. Finally, based on comparisons of the measurement results of water retention curve, they need to discuss the accuracy of the simulation results, including the best method for separating each pore.

The model implemented in the software SatuDict is the Pore Morphology Method (PMM) (e.g., Hilpert and Miller, 2001; Silin and Patzek, 2006; Ahrenholz et al., 2008; Schulz et al., 2015; Berg et al., 2016; Liu et al., 2022; Arnold et al., 2023). The PMM does not require to separate the pores as in a Pore Network Model (PNM) (Vogel et al., 2005; Joekar-Niasar and Hassanizadeh, 2012; Xiong et al., 2016). The PMM uses a sphere with a radius r as a probe to detect the pore space that is accessible by the non-wetting phase (NWP), here the air. This radius is computed from the Young–Laplace equation: $r = 2\gamma\cos(\psi)/p_c$ where p_c is the capillary pressure, γ is the interfacial tension and ψ is the contact angle. Morphological operations, namely, erosion and /or dilation are used in the PMM (Hilpert and Miller, 2001). The algorithm of the PMM can be decomposed into several steps as follows:

- In drainage condition, the porous medium is initially saturated with the wetting phase (WP) ($p_c = 0$). The invading NWP is connected to the inlet, which is the NWP reservoir, and the WP can escape through to the outlet, the WP reservoir. (i) Then, p_c is increased incrementally, i.e. r is decreased incrementally. The solid phase is first dilated by a sphere with radius r (ii) All the pores connected to the NWP reservoir are labelled as NWP. (iii) The NWP is then dilated with the same sphere with radius r. The remaining pores are filled with the WP. The saturation can be then calculated. (iv) All the pores filled by the WP disconnected from the WP reservoir are considered as WP residual, and are no more considered in the next steps. All these steps are repeated by increasing the value of the pressure, i.e. decreasing the value of r. In the present case, the radius r has been decreased gradually with a step of 2 pixel size.

- In imbibition condition, the porous medium is initially saturated with the NWP. The invading WP is connected to the inlet, which is the WP reservoir, and the NWP can escape through the outlet, the NWP reservoir. (i) Then, p_c is decreased incrementally, i.e. r is increased incrementally. The solid phase is first dilated by a sphere with radius r. (ii) The NWP is then dilated with the same sphere with radius r. (iii) All the pores connected to the WP are now labelled as WP. The remaining pores are NWP. The saturation can then be calculated. (iv) All the pores filled by the NWP disconnected from the NWP reservoir are considered as NWP residual, and are no longer considered in the next steps. As for the drainage condition, all these steps are repeated for the next value of the pressure, i.e. the next value of r. In the present case, the radius r has been increased gradually with a step of 2 pixel size.

The PMM has been used to simulate the quasi-static Water Retention Curves (WRC) of porous media (glass beads, sands,..) in drainage or imbibition conditions (Hilpert and Miller, 2001; Liu et al., 2022). In imbibition conditions, if step (iv) is ignored, the PMM also allows for the computation of Mercury Injection Capillary Pressure curves (MICP), which are a commonly used technique for measuring porosity and pore throat size distribution, for instance (Hilpert and Miller, 2001; Berg et al., 2016). As underlined in Hilpert and Miller (2001), the accuracy of the PMM may depend on the resolution and size of the 3D images and of the definition of the structural element. Finally, it is worth mentioning that the boundary conditions applied on the four sides of the 3D images that are not connected to the NWP or WP reservoirs may also play a role in the WRC curve simulations, even if this point has not been discussed in the literature, to the best of our knowledge. In Vogel et al. (2005), impervious boundary conditions are applied, whereas other conditions, such as symmetry, displaced fluid outlet, or invading fluid inlet, can also be applied (Berg et al., 2016). These boundary conditions may lead to different values of the NWP (air) residuals during the imbibition process, since these residuals can be trapped or not at the boundary. Depending on the boundary conditions, the maximum water saturation (θ_w^s) can range from 45% to 90% of the porosity. Despite such large differences, the values of $\alpha_{\rm vg}$ and $n_{\rm vg}$ in the van Genuchten (VG) model (van Genuchten, 1980) remain almost constant, with an effect only visible for $\alpha_{\rm vg}$, with differences around 10% of the value compared to the case $\theta_w^s = \phi$. This was also reported in the experiments of Likos et al. (2014) and Farooq et al. (2024), which showed that having θ_w^s smaller than ϕ generally implies greater $\alpha_{\rm vg}$ values, but has no significant impact on the $n_{\rm vg}$ values. The impact of the boundary conditions is less pronounced in drainage conditions, since the water residuals are mainly located at the junction between grains

In the present study, the PMM implemented in the SatudDict software was used to compute the WRCs of the 34 snow samples. We computed (i) a primary imbibition curve assuming that there is no air (NWP) residuals as in MICP experiments, thus $\theta_w^s = \phi$ in van Genuchten (VG) model, and then (ii) a primary drainage curve until to reach the water (WP) residuals (θ_w^r). In both cases, symmetric boundary conditions are applied on the four sides of the volumes.

Despite some limitations, the PMM appears as an appealing method to investigate two-phase flows in porous media in quasi-static conditions. Indeed, this method requires less computational time and computer memory compared to other two–phase flow simulation methods (lattice-Boltzmann methods, volume of fluids methods, phase fields models...) (Vogel et al., 2005; Ahrenholz et al., 2008; Bhatta et al., 2024) and provides similar results.

In the revised version, the description of the pore morphology method was substantially modified and includes all the above considerations (see introduction and Section 2.3)

Specific points

L27: I disagree because some studies evaluate results based on observations (e.g., runoff from snow cover) or comparisons with laboratory experiments. If they insist on their claim, they should point out the problems with past studies in more detail.

This sentence has been rephrased to specify the literature gap of estimating the hydraulic properties of snow for water flow, at the pore scale. The introduction of the revised version of the manuscript was substantially modified and provides now a more comprehensive state-of-the-art on studies and estimations of the effective properties of wet snow.

L117: If gravity is ignored, isn't it impossible to calculate the water retention curve? This is because gravity is included in equation (5).

The pore morphology method is based on the use of the Young-Laplace equation, not Jurin's law. We apologise for this error in the original version of the manuscript. We modified Equation (5) with the Young-Laplace equation. It represents the difference of pressure at a curved interface, and is a function of the mean curvature and the surface tension only. Here, gravity and viscous forces are neglected compared to capillary forces. At the pore scale, surface forces usually play a much important role than gravity. For air and water, the Bond number, which measures the ratio between gravitational force and surface tension force, is defined as: $\mathrm{Bo} = (\rho_w - \rho_a) g l^2/\gamma$ where ρ_w and ρ_a are the water and the air density respectively, g is the gravity, γ the surface tension, and l a microscopic length as the pore size. This dimensionless number varies between 10^{-3} and 10^{-1} if the pore size l varies between 10^{-4} and 10^{-3} m respectively, as in snow. These estimations show that gravitational forces are negligible at the pore scale in comparison to capillary forces. Similarly, it can be shown (Auriault, 1987; Auriault et al., 2009) that within a porous media, the viscous stress (σ_v) at the pore scale is negligible in comparison to the fluid pressure (p) which is the order of the capillary pressure (p_c): $p \approx p_c \approx (L/l)\sigma_v$ where L is a macroscopic length, i.e. the size of the snowpack. If we assume that the pore size is $l = 10^{-3}$ m and $L = 0.1$ m, the capillary pressure is around 100 times larger than the viscous stress. This part has been included in the revised version of the manuscript (see section 2.3)

L126: Since cos12 is 0.97 and cos0 is 1, I don't think this will have a significant impact on the result. However, I think it would normally use 0 degrees, so what is the basis for using 12 degrees? Please provide the reference.
The contact angle between liquid water and ice close to the fusion temperature 0°C has been measured at 12° in Knight (1967). The reference has been added to the manuscript.

L131: As shown in L117, this model ignores the effects of gravity, so the simulation may not accurately reproduce the actual drainage process. How do they feel about this point?
As it has been shown previously, the viscous stress and the gravitational forces are negligible at the pore scale. The above estimations are valid for both drainage and imbibition conditions. So the WRC of snow can be obtained by considering only capillary forces at the pore scale. If the porous media present very large pores, typically the order of 1 cm, the Bond number will be the order of one, meaning that gravitational forces must be considered.

L249: Because nVG is said to depend on the distribution of pore sizes, the results of this study may be due to the method used to separate the pores. Therefore, this possibility needs to be discussed.
The pore morphology method (PMM) is used to compute the WRCs. The PMM method does not require to separate the pores, as in the case of a Pore Network Model. As mentioned above, a sphere of radius r is used as probe. In drainage or imbibition condition, the radius is decreased or increased with a step of 2 pixel size (see the detailed description of the method provided above).

L321: This argument is meaningless. This is because the data used for comparison are simulation results, so it is only natural that the results of this study are the most appropriate results.
We agree that the phrasing l.321 can be misleading. We modified this part accordingly to separate the evaluation of our regressions on our dataset, and the comparison with the other regressions of the literature.

L353 : As shown in Table 2, the parameter settings used in this study differ from those of Yamaguchi et al. (2012). For example, the αVG value in Yamaguchi et al. (2012) is two orders of magnitude larger than the value used in this study.

On the other hand, as shown in Figure 10, the calculated unsaturated hydraulic conductivity using the parameter settings in this study shows relatively good agreement with the results of Yamaguchi et al. (2012).

This result may suggest that the parameterization of the VG model may not have a significant influence on the unsaturated hydraulic conductivity.

I propose adding further discussion on which parameterization of αVG and nVG is more important in determining the unsaturated hydraulic conductivity. This discussion is considered useful for determining which parameterization requires higher accuracy.
There is two order of magnitude difference in the coefficient of the regressions for α_{vg} between Yamaguchi et al. (2012) and our regression because the exponent value is smaller in our case (-0.61 instead of -0.98, see Table 2). To avoid the fact that a large range of values for the two coefficients can describe almost the same WRC, we chose to simplify our new regression by keeping the multiplicator coefficient of Yamaguchi et al. (2012) (4.4×10^4) and only fitting the exponent coefficient. This is motivated by the fact that the first coefficient has more impact on the small ρ/d values, which correspond to most of the measured values of Yamaguchi et al. (2012), and the exponent has more impact on the

larger values of ρ/d, which correspond to most of our values from the numerical estimates. With this change, we obtain a new regression of $\alpha_{\rm vg}$ with an exponent of 0.95 $\pm$0.003 that is not so different from the one of Yamaguchi et al. (2012) of 0.98. This has been modified in the revised version in Sec. 3.1.3.

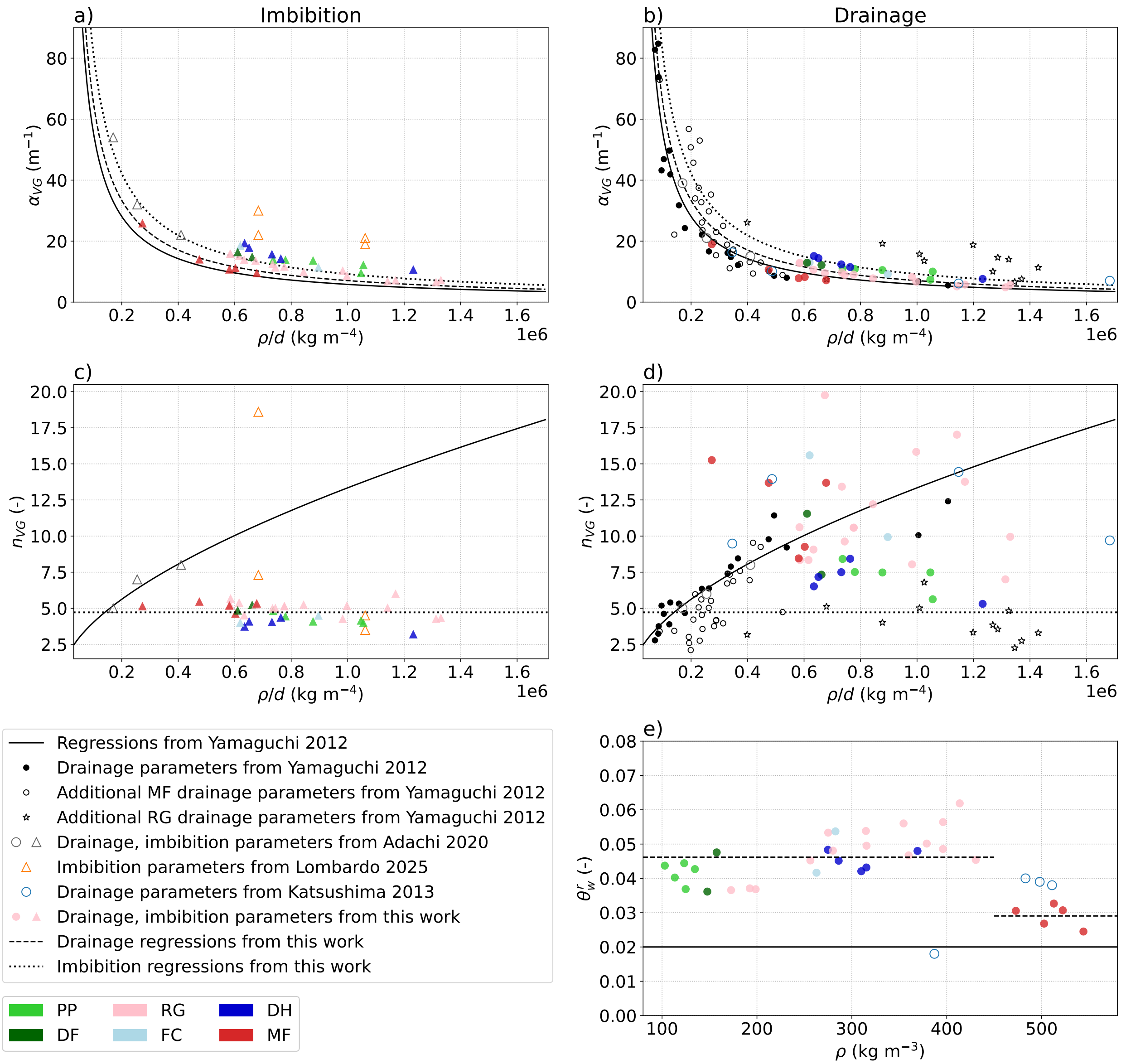

Figure 1. a) $\alpha_{\rm vg}$, b) $n_{\rm vg}$ and c) θ_w^r parameters of the VG model as a function of ρ/d or ρ for imbibition and drainage. The regressions of Yamaguchi et al. (2012) are shown by black lines, the values used to deduct those regressions are shown by black disks ("S-samples", composed of refrozen MF - see Yamaguchi et al. (2012)). The additional drainage measurements from Yamaguchi et al. (2012) are shown by circles (MF samples) and stars (RG samples). Measurements from Adachi et al. (2020) are shown by empty gray markers. Measurements from Lombardo et al. (2025) and Katsushima et al. (2013) are shown by empty orange triangles and blue circles. From this work, parameters from imbibition and drainage simulations are shown by colored disks and triangles, respectively, the colors showing the snow types. The proposed regressions based on our simulated data are shown by dashed and dotted lines (see Table 2).

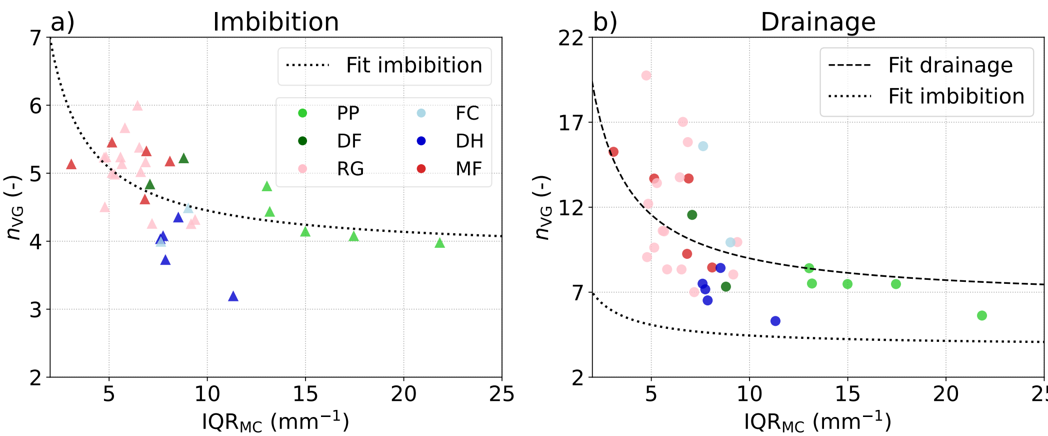

Figure 2. n_{vg} parameter as a function of the interquartile range $\mathrm{IQR}_{\mathrm{MC}}$ obtained for the mean curvature distribution computed on each 3D dry snow image. Regressions for imbibition and drainage are shown with dotted and dashed lines.

Regarding the unsaturated hydraulic conductivity, as the log scale makes it somewhat hard to see in Fig. 10 (corresponding to Fig. 11 in the revised version), we now provide the mean absolute error (MAE) values to compare quantitatively the VGM model using the estimates of the shape parameters from this study and from Yamaguchi et al. (2012) against the estimated regressions based our numerical results (Table 2). For the melt forms samples, a slight improvement is found using our regressions, with MAE values around 10% for Yamaguchi et al. (2012) and around 9% for our model. This similarities can be related to the fact that, on one hand, the regression of Yamaguchi et al. (2012) provides slightly better estimates of α_{vg} for this snow type, compared to our regression (Fig. 1.a); on the other hand, n_{vg} values are better estimates from our regression (Fig. 1.c and Fig. 2). For the other snow types, the VGM model using our shape parameter estimates provides better predictions of unsaturated hydraulic conductivity, showing MAE values around 17% compared to the VGM model using the estimates of Yamaguchi et al. (2012), showing MAEs around 22%. Indeed, for all the snow types excluding melt forms, both shape parameters α_{vg} and n_{vg} are overall better estimated using our regression (as optimized to best match our numerical simulations). We recently improved the n_{vg} parameterization by using the interquartile range (IQR) of the distribution, which is more suited to the shape of our distributions than the previously used standard deviation (see Fig. 2).

Hence, our results tend to show that both parameters α_{vg} and n_{vg} have an impact on the quality of the prediction of the hydraulic conductivity. However, in agreement with the reviewer comment, we point out that the VGM model based on the shape parameter estimates of Yamaguchi et al. (2012), which only required the knowledge of density and grain size, allows overall for fair estimates of the unsaturated hydraulic conductivity, with MAEs ranging from 10 to 22%, when compared to the simulations on our five samples. All the above considerations were included in the revised manuscript (Sec. 3.2.1).

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