Answer to reviewers

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We thank both reviewers for their constructive and relevant comments and suggestions. We have taken into account all the suggested points and we think that the revised version of the paper has gained considerably in clarity and accuracy. Our answers to the reviewers' comments (which are in italic) are shown in black regular font, the new additions or modifications in the revised paper are shown in blue font.

Anonymous Reviewer #2

Specific comments

1. *p3l25-27. Please split the line in two.*

   Thanks to Reviewer 2 for pointing this out. This has been fixed:

   The article is structured as follows. In Section 2, a description of the COSMO NWP model as well as the radar data used for the evaluation of the operator is given. In Section 3, the different steps of the polarimetric radar operator are extensively described and its assumptions are discussed in details.

2. *p4l14. Rutledge is probably meant here instead of Rudledge.*

   Yes, indeed, there was a typo in the bibliography file. This is now fixed.

3. *p5. Table 1 contains several typos: f instead of free, minus sign instead of empty sign and vice versa, some missing information. Please check it carefully*

   Yes, indeed, we are thankful to Reviewer 2 for noticing that. We have checked the table and made several corrections. The occurence of empty signs were removed and replaced with dash signs, every time the hydrometeor was considered in the microphysical scheme, but the specific parameter was not used in the parameterization. The $\emptyset$ is only used if the hydrometeor type is not considered by the microphysical scheme (hail in the one-moment scheme). Please check the new Table 1 in the revised version.

4. *p7. In the caption of Figure 1, five radars are mentioned whereas there are only three used in the study.*

   Yes, indeed the sentence was a bit clumsy. In fact there are currently five operational polarimetric C-band radars in Switzerland, which are all displayed in the Figure 1. However, two of them were installed only quite recently and as some of the studied events are already quite old (up to 2010), only the three "older" radars were used, which explains the caption. We have reformulated the sentence a bit to make this less confusing:

   An overview of the specifications of all radars used in this study is given in Table 2. The location of the Swiss operational radars used in the evaluation of the radar operator (Section 4.3) and their maximum considered range (100 km) are shown in Figure 1.

   And in the caption of Figure 1:

   Location of the Swiss operational radars. The three radars used in the context of this study are surrounded by black circles which indicate the maximum range of radar data (100 km) used for the evaluation of the radar operator (Section 4.3). Note that as they were installed only quite recently, no data from the Weissfluhgipfel and Plaine Morte radars were used in this study.

5. *p10l25-31. Why is it better to interpolate uncorrelated variables?*

   Thanks to Reviewer 2. for raising this point. After reflexion, we realized that our explanation could be confusing. What we wanted to say is that by computing radar observables after downscaling model variables (concentration and temperature), one is able to ensure the conservation of the mathematical relations between radar observables (which are clearly correlated and dependent) at the radar gate scale. Doing the opposite (i.e. computing radar observables at the model grid scale) and downscaling them later to the radar grid does not guarantee this conservation and leads to an artificial linearization of these relations, caused by the linear interpolation method.

   To illustrate this we designed a small idealized setup: a Gaussian field of rain mass concentrations (g of rain per m^3 of air) of size 128 x 128 pixels is generated randomly. Let's call this field Q. Two approaches are then compared.

   (a) The resolution of the field Q is decimated by reducing by two its resolution along both dimensions. The factor of decimation is then increased from 2 to 4, 8, 16 and 32. For a factor of 32, this implies that the resulting decimated field will be of size 4 x 4. The decimated field is then downscaled with bilinear interpolation to match the original resolution of 128 x 128. From this downscaled field of rain concentration, for every decimation factor, the radar observables Z_{H} and Z_{DR} are computed using the COSMO DSD and lookup tables used in the radar operator (at X-band).

   (b) Z_{H} and Z_{DR} are computed only once on the original undecimated field Q. The computed Z_{H} and Z_{DR} fields are then decimated and downscaled in a similar fashion as in approach 1.

   Figure 1 shows the resulting Z_{H} - Z_{DR} relationships for both approaches, for a random generation of Q. However the conclusions that can be drawn are general and apply to any randomly generated field (with differences in the magnitude of the observed trends). It is evident that approach 1 (downscaling before computing the radar variables) seems preferable to approach 2 (computing radar variables and then downscaling). Indeed, the Z_{H} - Z_{DR} relationship of the original undecimated Q field is preserved no matter the decimation factor that is used. In contrary, when downscaling Z_{H} and Z_{DR}, the Z_{H} - Z_{DR} becomes more and more distorted, the larger the decimation factor. In fact it becomes more and more linear, which can be explained by the bilinear interpolation that is used.

   We hope that this example has made our point more clear. Note also that the explanation has been modified in the revised article.

   Secondly, computing radar observables after downscaling allows to preserve the mathematical relation between them. Indeed, radar variables are far from being independent. For example, in the liquid phase Z_{H} is closely co-fluctuating with Z_{DR}, in the form of a power-law that tends to stagnate at large reflectivities. Some tests were performed on random Gaussian fields of rain mass concentration. The results indicate that when computing the radar observables first and then downscaling them, this theoretical relation becomes more and more linear when the final downscaled resolution increases, which is quite unrealistic. In contrary, when computing the radar variables after downscaling the rain concentration field, the theoretical relationship is always preserved, regardless of the downscaling that is used.

6. *p10l29. The terms number concentration and mass concentration are both used in the text. Please specify whether you talk about the number or mass whenever the term concentration is used. Alternatively, use another term, like contents to refer to mass concentration.*

   Thanks. To solve this issue, we have removed all occurrences of the term "concentration" as a single word. It is now always explicitly referred to as "mass concentration" or "number concentration".

7. *p11l16. Has $Q_N^{(j)}$ been already defined?*

   No, indeed Reviewer 2 is right, we forgot to define it! We have now corrected this sentence in the text:

   [...] at every radar gate using the model variable $Q_M^{(j)}$, and, for the two-moments scheme, the prognostic number concentration $Q_N^{(j)}$ ($\mathcal{M}_0$) as well.

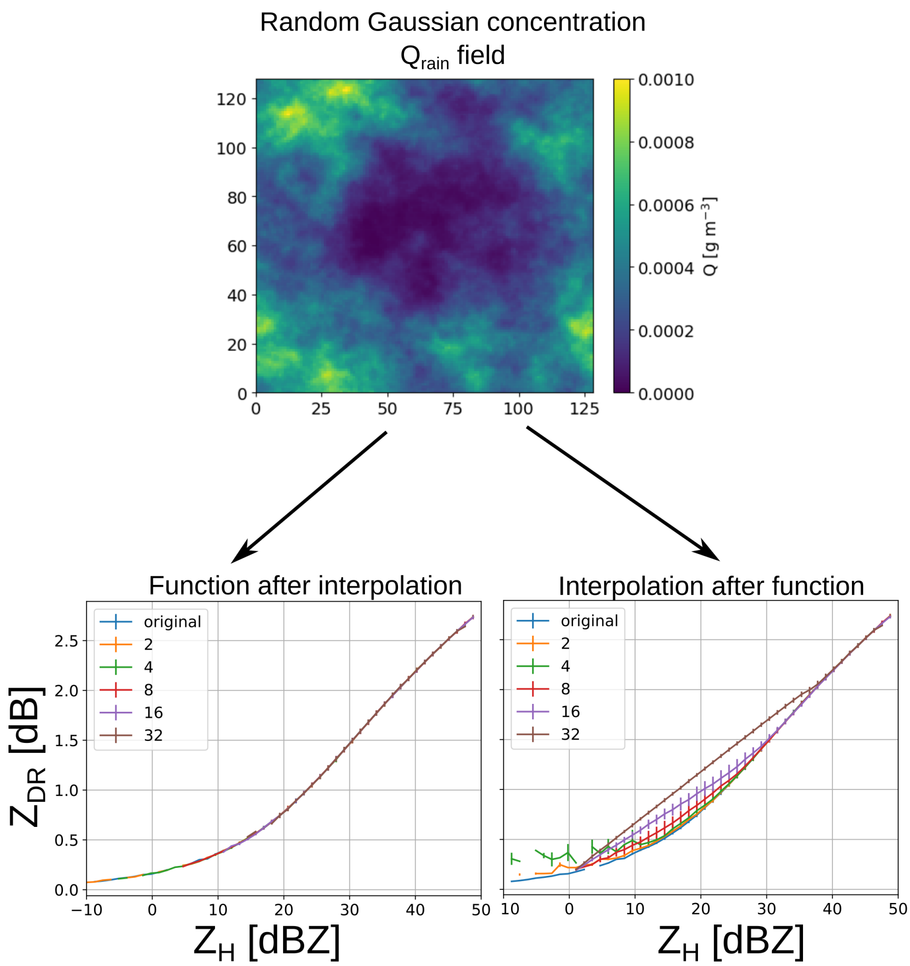

Figure 1: Example of random Q field (top) and Z_{H} - Z_{DR} relationships obtained by computing radar observables after downscaling (bottom-left) and before downscaling (bottom-right). The different lines correspond to the relationships obtained with different decimation factors.

8. *p11l19-20. I believe that the omission of the contribution of ice crystals in previous radar forward operators is somewhat overestimated by the authors. In particular, ice crystals are actually taken into account by Augros et al. (2016).*

   Yes, Reviewer 2 is right, sorry about that. We removed this sentence from the paper.

9. *p12l1-4. I do not understand how the PSDs of ice crystals are retrieved. May the authors provide more details? In particular, I am confused with the different moments that are used.*

   Yes, this part was really too short. We have added some details in the paper that we hope make it much more clear:

   Instead, a realistic PSD is retrieved with the double-moment normalization method of Lee et al. (2004). This formulation of the PSD requires to know two moments of the PSD as well as an appropriate normalized PSD function. Field et al. (2005) proposes best-fit relations between the moments of ice crystals PSDs as well as fits of generating functions for different pair of moments. Precisely, assuming moments 2 ($\mathcal{M}_2$) and 3 ($\mathcal{M}_3$) of the size distributions are known, Field et al. (2005) suggest to parameterize the PSD in the following way:

$$N^{\text{ice}}(D) = \mathcal{M}_2^4 \cdot \mathcal{M}_3^{-3} \phi_{23}(x), \qquad \text{with} \qquad x = D\left(\frac{\mathcal{M}_2}{\mathcal{M}_3}\right) \tag{4}$$

   with

$$\phi_{23}(x) = 490.6 \exp(-20.78x) + 17.46x^{0.6357} \exp(-3.290x) \tag{5}$$

Unfortunately, in the one-moment scheme of COSMO, only one single moment is known, which corresponds to $\mathcal{M}_3$, since the value of the b parameter in the mass-diameter power-law for ice crystals is equal to 3 (see Table 1). Fortunately Field et al. (2005), also provide best-fit relations relating $\mathcal{M}_2$ to other moments of the PSD. According to these relationships, $\mathcal{M}_3$ can be estimated from $\mathcal{M}_2$ with:

$$\mathcal{M}_3 \approx a(3, T_c)\mathcal{M}_2^{b(3,T_c)} \tag{6}$$

where $a(3, T_c)$ and $b(3, T_c)$ are polynomial functions of the in-cloud temperature (in $^\circ$ C) and the moment order (3 in this case).

Taking advantage of these results, it is possible to retrieve a PSD for ice crystals in the radar operator by (1) using the COSMO temperature to retrieve an estimate for $a(3, T_c)$ and $b(3, T_c)$, (2) inverting Equation 6 to get an estimate of $\mathcal{M}_2$, and (3) use Equations 4 and 5 to estimate the PSD of of ice crystals.

10. *p13. The math symbols ln and log are both used in the study. Do they have different meanings? If not, please use only one notation to avoid confusion.*

    Thank, we have replaced all occurences of "ln" by "log", to indicate the natural (Naperian) logarithm. If the common logarithm (base 10) is used it is written explicitly as $\log_{10}$. We hope this will clear it out.

11. *p13. In Equation 6, $z_j^{'}$ and $z_k^{'}$ are not used consistently*

    Unfortunately, we were not totally sure about what the Reviewer 2 refers to as an inconsistency. We have rephrased the description of Equation 6 to try to be more precise.

$$I\left[y\right](r_o, \theta_o, \phi_o) \approx \sum_{j=1,k=1}^{J,K} w_j' w_k' \; y(r_0,\; \theta_0 + z_j',\; \phi_0 + z_k') \cos\left(\theta_0 + z_k'\right) \tag{9}$$

where $w_i' = \sigma w_i$, $w_j' = \sigma w_j$ and $z_i' = \sigma z_i$, $z_j' = \sigma z_j$ with $\sigma = \frac{\Delta_{3\text{dB}}}{2\sqrt{2 \log 2}}$, where $\Delta_{3\text{dB}}$ is the 3 dB beamwidth of the antenna in degrees. w_i and z_i are respectively the weights and the roots of the Hermite polynomial of order J (for azimuthal integration) and w_i and z_i are the weights and roots of the Hermite polynomial of order K (for elevational integration).

12. *p16l3-4. The authors write that the T-matrix method is also used for solid hydrometeors (snow, graupel and hail). If it was also used for ice crystals, it should be added to the list of solid hydrometeors in parenthesis.*

    Indeed, the T-matrix method was used for ice crystals as well. We have added this info in the parenthesis according to your suggestion.

    This method was also used for the solid hydrometeors (snow, graupel, hail and ice crystals), at the expense of some adjustments, that will be described later on.

13. *p17. Please check Equation 11 which contains some typos: unexpected use of d, use of 1 instead of l, etc.*

    In accordance with the remarks of Reviewer 1 and 2, this equation has been significantly changed.

$$o : g_o(o, D) = \mathcal{N}\left(0, \sigma_o(D)\right) \tag{15}$$

$$\frac{1}{a_r} : g_{1/a_r}(1/a_r, D) = \frac{(\frac{1}{a_r} - 1)^{\Lambda_{a_r}(D)-1} \text{exp}\left(-\frac{\frac{1}{a_r}-1}{M(D)}\right)}{M(D)^{\Lambda_{a_r}(D)}\Gamma(\Lambda_{a_r}(D))} b \tag{16}$$

14. *p18l6 and p19l2. Please check the meaning of whereas. I think while applies better in these contexts.*

    We have replaced both occurences of "whereas" by "while"

15. *p19. How come ZDR is always above 1 dB in Figure 6?*

Thanks to Reviewer 2 for raising this important point. The plot label was indeed wrong because ZDR was in linear units (dimensionless Z_h/Z_v) instead of dB, so this explains the strange values. This has been fixed in the revised version, and ZDR is now plotted in dB as indicated in the label.

16. *p22. I do not understand Equations 19 and 20. Why introduce f_{wet}^{ms} and f_{wet}^{mg} if they are both equal to $Q^r/(Q^r + Q^s + Q^g)$?*

We are not sure to understand the Reviewer's point here. In the text, it is written that:

$$f_{\mathrm{wet}}^{ms} = \frac{Q^r Q^s}{Q^s\left(Q^s + Q^g\right) + Q^r Q^s} \tag{28}$$

$$f_{\mathrm{wet}}^{mg} = \frac{Q^r Q^g}{Q^g\left(Q^s + Q^g\right) + Q^r Q^g} \tag{29}$$

So they are not equal to $Q^r/(Q^r + Q^s + Q^g)$ and are not equal to each other either. Could you please clarify this point if still needed?

17. *p24. Please check Equation 29. I suspect m is actually m^m. Also, are terminal velocities missing?*

Indeed, Reviewer 2. is right. Thanks for pointing this out. We have now fixed the equation:

$$\kappa = \frac{Q^m}{\int\limits_{D_{\mathrm{min}}}^{D_{\mathrm{max}}} m^m(D) N^m(D) dD} \tag{41}$$

Terminal velocities are indeed missing from this equation, which depends only on the concentration (in kg m^{-3}) of the melting hydrometeor (we force the concentration of the adjusted PSD to match the concentrations of melting hydrometeors derived from Equations 23 and 24). There is no precipitation intensity involved, so no terminal velocity is needed.

18. *p24l13-19. I do not understand how propagation effects (attenuation, in particular) are taken into account when the number of quadrature points is increased in the melting layer only.*

Indeed there were some missing indications in the text. Some trades-off are required to be able to use such a simple oversampling scheme. In fact, in the melting layer integration scheme, the order of attenuation correction and integration are reversed, i.e. attenuation correction is done only at the end, after all variables have been integrated over the antenna diagram. This allows to get an estimation of k_h, even when not all sub-beams are used at a certain range (by integrating it only over the available sub-beams). Of course, this is a somewhat strong simplification but it is the only way to perform a local oversampling, which is the only computationally feasible way to simulate the melting layer effect. We have added some additional information in the revised version:

Unfortunately, some trades-off are required to run such a simple oversampling scheme. Because the number of quadrature points is not constant at every radar gate (as not all sub-beams cover the whole radar beam trajectory), the order of attenuation computation and integration have to be reversed, i.e. attenuation computation is done only at the very end, once all radar variables (including k_h and k_v) have been integrated over the antenna diagram. This is a somewhat unrealistic simplification but it is the only way to perform a local oversampling, which is the only computationally feasible way to simulate the melting layer effect with volumetric integration. The effect of this approximation was investigated for the strong convective event of the 13 August 2015 (with $J = 5, K = 7$ and an oversampling factor of 10). The results indicate an overestimation of the final Z_{H} by an average of 0.58 dBZ, with respect to the normal integration scheme. This bias is caused by the underestimation of the attenuation effect. For Z_{DR} however, the bias is negligible (0.03 dB), which is likely due to the fact that this simplification affects Z_{H} and Z_{v} to a similar extent.

19. *p28. Please check Equation 39. A parenthesis is not balanced, the function is not Gaussian, etc.*

We thank Reviewer 2 for this correction, this equation was indeed wrong. It has been fixed in the text, both in terms of parenthesis, index of convolution and missing square in the Gaussian (it was right in the code, since we were using the appropriate function from the *numpy* and *scipy* python libraries).

$$S^{\mathrm{corr}}[i] = \sum_{j=0}^{N_{\mathrm{FFT}}} S[i-j] \frac{1}{\sigma_{t+\alpha}\sqrt{2\pi}} \exp\left[-\frac{(v_{\mathrm{rad,bins}}[j])^2}{2\sigma_{t+\alpha}^2}\right] \tag{52}$$

where $\sigma_{t+\alpha} = \sigma_t + \sigma_\alpha$

20. *p28. Please check Equation 40 which is wrong, given the definition of k_H in Appendix C.*

    Thanks for pointing this out. This has been fixed in the paper. Please read all the response to Specific comment 8 of Reviewer 1, which is directly related. The new section is:

    In reality, attenuation will cause a decrease in observed radar reflectivities at all velocity bins within the spectrum. To take into account this effect, the path integrated attenuation in linear units at a given radar gate (k_h in Equations C2) is distributed uniformly throughout the spectrum.

$$S(r_g,\phi_g,\theta_g)^{\mathrm{att}}[i] = S(r_g,\phi_g,\theta_g)[i] \cdot \exp\left(-2\int_{r=0}^{r_g} k_h(r,\theta_g,\phi_g)\ dr\right) \tag{53}$$

21. *p28l15. What is gamma?*

    The attenuation computation in the Doppler spectrum was wrong (see Specific comment 8 of Reviewer 1). This was fixed in the revised version, so there is no γ anymore in this part of the paper.

22. *p32l29-31. Is μ_{rain} changed in the radar forward operator only, or in the COSMO simulations as well?*

    It has been changed in the COSMO simulations as well. We have added a sentence to make it more clear.

    Note that the COSMO model has been run twice, once with $\mu^{\mathrm{rain}} = 0.5$ and once with $\mu^{\mathrm{rain}} = 2$.

23. *. p34l27. I do not understand why it is argued that GPM tends to underestimate larger reflectivities to explain why larger reflectivities are present more frequently in the simulations. Attenuation is taken into account in the simulations, isnt it? Please elaborate.*

    Yes attenuation is taken into account, though for GPM, which is a spaceborne radar, its effect is quite small. We were just stating that previous comparison by Speirs et al. (2017) have shown that GPM tends to be negatively biased in complex terrain in terms of estimated precipitation intensities at the ground when compared with rain gauge and the operational C-band QPE. So, the results we observe in Figure 20 (there are less observations of high reflectivities than simulated values), are not surprising.

    We have slightly rephrased the corresponding sentence:

    Note that similar observations in terms of underestimation of surface rainfall intensities by GPM with respect to the Swiss operational rain gauge and radar precipitation products have been reported by Speirs et al. (2017).

24. *p46l9-11. The reference is incomplete.*

    We have fixed this reference.