Manuscript Review: W-band Radar Observations for Fog Forecast Improvement: an Analysis of Model and Forward Operator Errors

Thanks to all of the reviewers who kindly gave their time to analyse the article and returned some relevant comments to help clarify the research for future readers. We hope to respond to your queries below.

Reviewer 3

Comment: I find the simulations with the forward operator quite confused. First a Gamma modified PSD is introduced; this has 4 free parameters (the authors do not mention any correlation between parameters). They then introduce other 2 parameters C and X (I do not know really why?). For some reason then they study the variability of a profile with alpha, nu and N_0 but they forget completely Lambda (i.e. the characteristic fog size). Why?

Response: The idea here was just to clarify all parameters in the modified gamma distribution as it is used in ICE-3. Indeed, the formulation of N with C and x is unnecessary here, as for liquid cloud droplets x = 0. For lambda, it would also be possible to modify this parameterisation to investigate the uncertainty in this parameter, however as it is already a function of the mass of droplets, α and ν, it had been indirectly modified through changes in the ν parameter already.

Change: Several paragraphs have been added in section 4.1 (detailed below) to clarify the work done here and to summarise previous works.

Equation (7) was removed and equation (6) has been adapted to make sense without mention of these parameters.

Comment: Fig.4: all units in the y-axis are wrong. Not sure how useful is Fig.4 , particularly the bottom panel. If N_0 changes then there is just an amplification (not sure the figure is actually right, it looks like the maximum of the blue line is different from the orange one). Similarly simulating reflectivities changing N_0 is trivial and should not be plotted (Fig 5, right panel), doubling N_0 just add 3 dB.

Response: It seems that some additional explanation was needed before introducing the figures for a better understanding. Indeed, the maxima of this modified gamma distribution will change when the concentration number is changed in order to keep the liquid water content the same, so this figure is correct.

The increase in reflectivity would indeed be 3dB per doubling of the droplets *if the original distribution was doubled.* However, this is not what this work shows. In fact, it shows that increasing the number concentration *reduces* the values of reflectivity, because there are more small droplets but fewer large droplets. This is because the LWC is conserved in the modified gamma distribution. In our opinion, (old figure 5b, new figure 6b) is necessary to compare to (old figure 5a, new Figure 6a) to show the magnitude of the changes in reflectivity when the two parameters are changed.

Change: Thanks for noting the axis unit error- figures have been remade correcting for the errors in the scale and units on the y-axis. These figures were also remade using a logarithmic scale so that the changes in the distribution shape and the absolute values can be clearly seen.

Inserted paragraph before figures of distributions: ‘The advantages of using the modified gamma distribution are that the shape and median diameter of the distribution are modified with the liquid water content of the cloud. For example, when using the modified gamma distribution with a total concentration of 30 cm^{-3}, the median diameter will be greater than for a total concentration of 300 cm^{-3}, as illustrated in figure 5. This is because the same amount of water must be divided among fewer droplets.’

Comment: On the other hand the change of alpha nu and Lambda should be better investigated accounting for the possible relationship between the different parameters (It is not enough to change only one parameter at a time).

Response: This was a point raised in some way by all three reviewers and so more research was done into previous studies looking at this.

Indeed, it seems that varying α and ν together with the quoted uncertainties probably gives an overestimation of the total uncertainty. The main effect that increasing both parameters have, is to narrow the size distribution spectra. Going back to the literature, most studies investigating these parameters fixed α at one or three and looked at the optimal values of ν (Geoffroy et al., 2010; Mazoyer, 2016). Where α is lower, ν is typically higher. For continental clouds in ICE-3, a value of α = 1 is used, so it was decided to recompute our results fixing this value here.

Regarding the varying of ν with N, the most honest answer here is that there is not enough in the literature to define rigorous bounds for the variance of one with the other in the context of fog (Geoffroy et al, 2010). It is a very interesting point, and one for which more research could be conducted with a new experimental dataset that will soon be available from the SOFOG3D campaign). We agree with the reviewer that it is important to make the reader aware of the current limitation that we hope could be surpassed when extra in-situ measurements are available.

Attempts have been made to find optimal values of the ν parameter during fog conditions. In the thesis of Marie Mazoyer, this was investigated in the context of optimising the gamma distribution shape to represent observed fog droplet size distributions. She looked at the droplet size distributions for 24 fog cases, and attempted to optimise the gamma distribution fit for the first, second and fifth moments. The plots in figure 3 below show that the standard deviation of errors between the idealised distribution and the observed distribution for the first and second moment are both reduced for increasing ν. However, for the fifth moment, an increase in the ν coefficient resulted in increased errors. For simulations of radar reflectivity, the sixth moment of the distribution would be important to model (as radar reflectivity is proportional to the r^6 where the Rayleigh approximation is valid), as well as the third moment of the distribution for making retrievals of LWC. It could therefore be interesting to repeat this study and optimise for the third and sixth moments. From this, a better estimation of the mean value and standard deviation of values of ν, for the specific use of using radar reflectivity to make retrievals of LWC, could be performed.

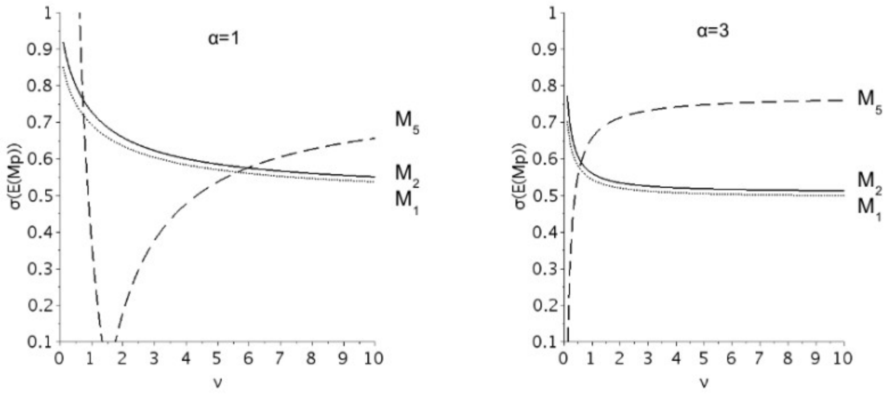

Figure 3: Errors between observed and predicted by assuming modified gamma distribution with α set to 1(left) and three (right) for the first, second and fifth moment of the distribution. Figure taken from Mazoyer (2016).

In a study which aimed to minimise first, second, fifth and sixth moments of the cloud droplet distribution errors, Geoffroy (2010) found that the optimal value of ν for α = 1 could be estimated from the LWC. This parametrisation gave optimised values of ν = 6.8-11.1 for typical values of LWC inside a fog layer. This agreed well with the work of Miles (2000). In their study, a mean value of 8.7 was found for the ν parameter, with a standard deviation of 6.3. The uncertainty from simulated reflectivity resulting from the uncertainty of this parameter was therefore calculated with values one standard deviation above and below the mean values. T

Change: Section 4.1 rewritten. Lines 325-369:

In the pair of equations, N(D) is the droplet number concentration where D is the droplet diameter. Coefficients a and b determine the mass-diameter relationship of the droplets, which, when applied to cloud droplets are well known due to their spherical nature, and are set at 524 and 3 respectively. α and ν are fixed coefficients referred to as the shape parameters and are set to 1 and 3 respectively in ICE-3 for cloud liquid droplet over land. N_0 is the total droplet concentration and is set to 300 in ICE-3 for liquid cloud over land. M is the liquid water content of the grid point in $kg.m^{-3}$.

The advantages of using this modified gamma distribution are that the shape and median diameter of the distribution are modified with the liquid water content and number concentration of the cloud. For example, when using the modified gamma distribution with a total concentration of $30cm^{-3}$, the median diameter will be greater than for a total concentration of $300cm^{-3}$, as illustrated in figure 5.

As all parameters of the modified gamma distribution except for the liquid water content are held constant in ICE-3, when radar simulations are made for cloud with a droplet size distribution which the parameters do not accurately describe, errors are likely to be made in the calculation of radar reflectivity. In order to assess this uncertainty, simulations were made on an AROME model profile in fog conditions, for which the size distribution parameters were perturbed. These perturbations would need to reflect potential variabilities seen in (continental liquid water) fog and low liquid cloud.

Microphysical observations have been investigated on fog events in previous works(Mazoyer et al., 2019; Podzimek et al, 1997) which tend to show lower droplet concentrations than is prescribed for continental clouds in the ICE3 microphysical scheme (of $300cm^{-3)}$). From the works of Mazoyer (2016), which looked at median droplet concentrations for continental fog events, and Zhao (2019), which investigated the microphysics of continental boundary layer clouds, reasonable lower and upper bounds of the N_0 parameter of 30 and 300cm^{-3} were decided. Figure 5 shows the difference in cloud droplet distribution shapes when these two values are used.

As the α and ν parameters both affect the width of the size distribution (as may be seen in figure 5), it has been a common approach (Mazoyer, 2016; Geoffroy et al. 2010) to fix α and to optimise the value of ν. The most frequently used values are α = 1 (Liu et al, 2000) and α = 3 (Seifert et al, 2001). For this work, it was decided to use α = 1 which was shown by Mazoyer (2016) to best represent fog droplet size distributions and also for consistency with the ICE-3 value.

From previous studies examining the value of ν where α = 1 (Geoffroy, 2010; Miles, 2000) it was decided that a range of ν = 6.8 to 11.1 should be used. The modified gamma distribution with these values is shown in figure 5. Though there may be correlations between the LWC and the value of N and ν, a parameterisation for the values of ν and N_0 for fog in the context of cloud radar has yet to be performed. For this reason, the parameters ν and N_0 are treated as varying randomly for the purpose of investigating the uncertainty in simulated reflectivity.

Comment: Line 405-410: I am not convinced that some of the big differences we see in Fig.6 can be attributed to non sphericity. Where is the freezing level in this scene? Also instead of ``isotropic particles'' use ``spherical particles''.

Response: I think the placement of figures in the article made this a little confusing- indeed it was not my intention to suggest the differences in figure 6 arise from non sphericity, it is just that the figure which is commented upon in the previous section appears with the text where the sphericity is discussed. However, I will say that it was verified that the fog in this case was below the freezing level in both observations and simulations.

Changes: ‘isotropic’ changed to ‘spherical’

Figure has also been masked where large differences between simulation and observation occur due to precipitation.

Comment: Fig8: not sure about the cluster of points above 500 m. Is that fog? If so why you are cutting the plots at 1km?

Response: The clusters at around 700-800m are indeed clouds. The plots were cut at 1km as in winter above 1km we more commonly see ice in clouds and it was not the objective of this paper to examine the ice clouds. However, even if this work focuses on fog, low clouds have a significant impact on the fog life cycle with potential stratus lowering. It is thus important to validate our methodology also for the low liquid clouds.

Comment: Tab1: Range for HATPRO (0 to 10 km) ==> it does not make any sense to specify a range for a radiometer

Change: Agreed. This has been removed.

Comment: Fig1, caption: I do not see 11:00 UTC but 10:20 UTC in the plots.

Change: Thanks for the correction. Caption changed as advised.