

NHESS-2019-321

Responses to reviews

The sensitivity of intense rainfall to aerosol particle loading - a comparison of bin-resolved microphysics modelling with observations of heavy precipitation from HyMeX IOP7a

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7 February, 2020

Note to the editor

We thank all of the reviewers, whose comments have led to significant improvements in the analysis and our manuscript. Each question and remark of the reviewer is answered below point by point.

Changes in the manuscript and the reply to the individual remarks of the reviewers are marked in red for easier notice.

We would like to point out, however, that our choice of NHESS as publication journal has motivated our focus on the study of the surface precipitation over a region, which is often affected by flash floods. Following the request of the reviewer we have added some more discussion on in-cloud processes, however the in-depth analysis of the cloud microphysics and their comparison with the available airborne probes will be published in another more appropriate journal.

Responses to reviewer #1's comments

Answers to Major comments

- This study is conducted based on rainfall characteristics at the ground only. This is a deliberate choice from the authors, who mention twice that in-cloud features will be presented in a future work. Following this idea, the paper neither discusses the quality of the simulated convective system macroscopic and microscopic characteristics (cloud height, anvil extension, cloud composition) nor investigates the rain formation processes (eg. Warm phase vs. mixed phase formation). This is especially lacking since the bin scheme is not expected to be used in operational NWP in the near future, but instead a very good tool for process studies and understanding. Thus, to me, the paper has more value as an introduction for a detailed cloud composition and processes study, despite being presented as a standalone paper. I can imagine a detailed study of the cloud composition and processes needs a paper by itself, so maybe the two parts could be made into a two-part paper (part 1 for model description and rainfall evaluation, part 2 for microphysics and processes)?

In order to provide the reader with a better description of the characteristics of the macroscopic cloud system (cloud height, vertical cloud composition) we added in chapter 4 two vertical cross sections indicating IWC and RWC as well as temperature and humidity conditions for the cloud system. This also clarifies several individual questions of both reviewers.

The inserted text:

The vertical structure of the simulated cloud and rain field is illustrated in Figs. 6a and b. Both figures show the same vertical cross section for the innermost domain reaching from the southern border (at $x=529$, $y=560$ km) to the northern limit (at $x=579$, $y=688$ km). Fig. 6a gives the ice water content (IWC), Fig. 6b the rainwater content RWC for values larger 0.1 g/m^3 . For the calculation of the RWC from the modelled drop size distribution only drop sizes larger $100 \mu\text{m}$ were considered. The illustration Fig.6b shows a quite continuous rain field during the intense rain episode at 8:20 h. Important RWC of $2\text{-}2.5 \text{ g/m}^3$ mainly forms close to the melting level. The 0°C levels varied due to the strong vertical motion over the complex terrain between altitudes from 3.3 and 3.7 km. We can also detect in Fig. 6b that raindrops appear in elevated layers up to -20°C . The IWC, however, reached much higher altitudes but the presences of ice values larger than 1 g/m^3 rarely exceeded a height of 8 km, which is in agreement with aircraft in-situ and cloud radar observations performed during the same time period. The illustration of the field of IWC indicates that the cloud system mainly developed to mid-tropospheric layers and convection did not exceed 7-8 km. Thus, the tropopause level could not be attained and consequently no anvil formation took place. Fig. 6a also includes two contour lines for relative humidity of 90% and 98%. The high humidity in the lower layers is caused by the southern flow from the nearby Mediterranean Sea. Relative humidity of 90% appears around 1000 m asl, 98% 200 to 300 m above. Cloud base height, i.e. the formation of cloud droplets is located at altitudes around 1200-1300 m.

The formation of the convective system was triggered by orographic lifting over the Cevennes Vivarais Mountains. The rapid cloud formation and intensification was in addition favoured by the high vapor loading in the lower atmospheric layers, arriving from the warm Mediterranean Sea and persisting for several hours.

- The paper sometimes stops short of providing or verifying an explanation for the presented results. We tried to justify all our conclusions.
- P6 I23-27: If the reach of the X-band radar is too short, why don't you use the French radar mosaic instead (especially since the radar is only used to check the large scale characteristics of the convective line)?

The data from the nearby weather radars Bollène and Nîmes, available from the HyMEx data base, are not corrected for ground clutter and attenuation. As we don't have the competence to do these corrections, we excluded a further comparison with the model results. Corrected ARAMIS radar data (as a composite) only were available as surface rain. These data were used by the KED technique to determine (combined with rain gauges) the hourly rainfall, which we finally used for our comparison with modeled rain parameters. Thus, the radar based large scale characteristics are included and discussed for the precipitation field but not for radar reflectivity in the atmospheric levels above.

- P8 I6-10: The three simulations do not represent the precipitating system shift. Other studies of this case are mentioned in the paper (eg p3 I23, Hally et al 2014). How does that (or its consequence on the total rainfall amount slight mislocation) compare to others? This could hint at the influence of large scale conditions used for coupling.

Hally et al (2014) investigated the precipitation event on larger scales. Hourly rainfall, averaged over an area of 400x 400 km², was compared to observation. Individual changes in the evolution of the cloud system were not considered in their study.

- P8 l25-30 & p9 l1-5: Various studies of the impact of aerosols on clouds and precipitation show different effects. Sometimes an increase in aerosol concentrations leads to reduced precipitations, sometimes to “convective invigoration” instead. What processes (is the impact on droplets or ice crystals concentrations more important? More cloud droplets subjected to contact freezing with aerosols?) are important in this specific case (organized, long-lasting convection, with an orographic forcing), and are they different from what was found for isolated convective cells?

As both reviewers pointed out that hydrometeor formation by aerosol particles may be also important in elevated cloud layers due to “convective invigoration”, we will give a short explanation from our point of view (These considerations will not be part of the results presented in the paper, as considered out of scope).

Aerosol particles and especially water vapor are abundant in the lower atmospheric layers where the cloud forms. In our case of IOP7a the water vapor mixing ratio next to cloud base is about 10 g/kg. It is this water vapor in the lower 1000 m which is responsible for cloud formation and the subsequent cloud evolution over several kilometers in altitude. The convection (vertical motion) which is triggered by the strong heat release above cloud base, transports vapor, drops and aerosol particles to higher levels. Supersaturation gets strong in the first 3-4 km above cloud base and thus most nucleation of aerosol particles to drops takes place in this stage. Ice crystal formation may occur in our case from 4 km upward when temperature decreases below -3 to -5°C. The heterogeneous nucleation rates, however, are quite weak and ice particle formation by nucleation of non-activated particles remains low, even up to 6-7 km, when temperatures are higher than -15 to -20 °C. Ice formation occurs in this temperature range, but crystals form to a large extent by condensational freezing and Bigg freezing of already existing drops.

When rising to higher levels until -28°C (homogeneous nucleation will start for $T < -28^{\circ}\text{C}$) ice supersaturation can become more than 120 % and ice nucleation rate strongly increases. Invigoration of convection can arise at these altitudes (and also in higher levels for deeper cloud systems), when vertical momentum and water vapor are advected. But aerosol – hydrometeor interactions are only insignificantly affected for several reasons:

(1) the number concentration of the aerosol particles in the elevated levels is low compared to the cloud base environment

(2) the remaining interstitial concentration of particles (which can serve as CCN and INP) present in the rising updraft is also low as most of them were already consumed for drop formation in lower altitudes

(3) the pathway to form new droplets from non-activated aerosol is negligible due to the reduced kinetics of the water vapor diffusion for temperature $< -15^{\circ}\text{C}$. (i.e. the Köhler equilibrium fails)

(4) even if ice supersaturation is really high, we have to be aware that the supply with water vapor is quite low in these altitudes. In our case study of IOP7a water vapor mixing ratio is 1-2 g/kg at -20°C. From the new Fig. 6a we can see that maximum simulated (and also observed) IWC in this level can be well above 2 g/m³ which correspond to an ice mixing ratio of 3.6 g/kg. Thus, the environmental condition cannot be responsible for the high ice mass and also crystal concentration encountered in these elevated levels. Their presence is not a consequence of new ice nucleation and ice growth but due to advection

from the lower altitudes where droplets form and grow in a significant way and freeze in the elevated levels.

In summary, based on our actual knowledge on droplet activation and ice nucleation we cannot see a specific effect during convective invigoration on these processes.

- P9 & fig 7: The three simulations show very little differences below 70mm. Is there a physical explanation to the fact that aerosols only impact the occurrence of high precipitation?

We agree, there are very little differences in the relative occurrence of surface rain accumulation between 10 to 70 mm for all three scenarios. This may result from the overall similarity in the thermodynamic / dynamic evolution for the three cases. But we have to keep in mind the “relative” character of the frequency distribution of Fig.7 (now Fig.9), which probably does not allow concluding unambiguously that *aerosols only impact high rain accumulations*. All scenarios have spatial differences in surface rain coverage and intensity: the number of surface grid points with rain accumulation from 10 to 70 mm are in the *Remote* case 39210, but only 1720 in the *HymRef*. Consequently also total accumulated rain in the *Remote* case is significantly higher in the range from 10-70 mm. This becomes also clear when comparing the total mass of rainwater in Table 2. Subtracting results for Rain amount (>10mm) from Rain amount (>50 mm) gives 31.5 mm for *HymRef* but 38.2 mm for *Remote*.

Thus, Fig.7 (now Fig.9) only allows unambiguously the conclusion, that low aerosol concentration favors the formation of strong to very strong rain accumulation. The physical reason for this is the higher supersaturation that develops in a cleaner atmosphere. The higher the supersaturation, the more water and ice can form.

- P10 l11-18: The model resolution can explain some differences with the observations, eg. higher 5-min rainfall in the observations. However, there are differences between figs. 8 (observations) and 9 (models) that probably cannot be explained by the smoothing effect of the model resolution. The progressive increase and decrease in precipitation in the simulations, occurring over 20min to 1h, is more probably linked to differences in the convective system characteristics or dynamics **(1)**. Is this linked to convective cells dissipating slower in the model **(2)**? To convective cores being surrounded by larger regions of moderate precipitation in the model than in the observations **(3)**.

(1): Yes, it is to a certain extent right that the differences in local rain rate are due to the “differences in the convective system characteristics or dynamics”. From the X-band radar comparison we could detect that the observed convective cells are patchier and their orientation more often deviate from the main horizontal flow. The simulated convective cells are more steady state, especially over the ridge of Vivarais (between gauge 19 and 24 in Fig.3) where precipitation was strongest. But in addition this difference in dynamics is a consequence of non-resolved sub-grid effects given by our grid resolution of $dx=dy=500$ m.

(2): We compared in the region covered by the X-band radar (thus over the Cevennes mountains) the formation and dissipation of individual cells with the modeled ones and found that convective cells formed and dissipated on the same time scales.

(3): We also investigated the question if “this is linked to convective cores being surrounded by larger regions of moderate precipitation in the model than in the observations” by comparing modeled and observed X-band reflectivity. This comparison is illustrated by the frequency distribution in Fig. R1. We

can detect from this illustration, the model overestimates slightly the frequency of observed Z in the range from 27 to 37 dBZ, where moderate rain could be suspected. In the range from 19 to 27 dBZ, however, the model is strongly underestimating the weaker precipitation zones. From this comparison a clear statement concerning the reviewer's question is difficult, but we think this result indicates a reasonable agreement with the moderate precipitation zones ($Z > 27$ dBZ) and the overestimation of moderate precipitation by the model is quite weak and not the reason for the extended duration of rainfall after the transit of the main core.

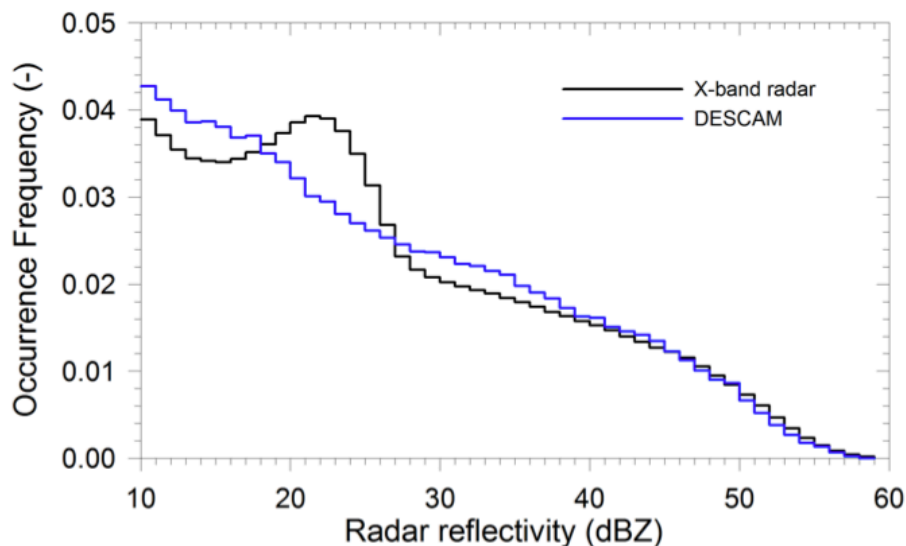


Figure R1. Probability density function of the X-band radar observations from 06:40 to 10:40 UTC and modeled with DESCAM over the same period every 20 min

- P11 I24+: To explain differences in rain size distributions between the model (at altitudes of 900-1000m) and observations (at 950m), the authors state that the cloud base may have been lower than simulated (1300 to 1400m). Are there no observations from the HyMeX campaign (Lidars? Cloud radars? Maybe MRRs?) to support this, even if they were not located at the same place?

Measurements coming from MRRs and from the airborne cloud radar confirm that precipitation was reaching until the surface, but don't give a hint on cloud base locations. In addition the low quality of the MRR data did unfortunately not allow a reliable retrieval of the RSD.

Lidars were not running during this IOP in the region of the Cevennes-Vivarais.

- The three simulations use realistic aerosol loadings (Table 2) coming from observations for this specific case (HymRef), the cleanest HyMeX case (HymLow) which still has high aerosol concentrations, and another set of observations to represent cleaner conditions (Remote). The total number concentration for these simulations is, as stated by the authors, lowest in the Remote case and highest in the HymRef case, and therefore conclusions are drawn throughout the paper about the impact of an increase / decrease in aerosol number concentration. However, if we look only at aerosol modes 2 and 3 (because the smallest aerosols from mode 1 with a diameter around 0.05 microns are much harder to activate into cloud droplets or ice crystals), the number concentrations are highest in the Remote simulation (which also has the largest diameters for these two modes) and lowest in the HymRef simulation, so maybe the conclusions based on aerosol number concentrations could be reversed? Simulations using the population from HymRef but modulated by the same factor

for the 3 modes would make this conclusion easier. Maybe this can be clarified in the current simulations, through an analysis of the activation of smaller aerosols in the three simulations (total number of activated aerosols, activation height or temperature or timing for the different modes...)?

Yes, there is a typo in our Table 2. The diameters of mode 2 and mode 3 for the *Remote case* are a factor 10 smaller than indicated, and used in the calculations. We apologize for this inaccuracy.

We added in the article Fig.2, which displays the size distribution with a linear ordinate for the number concentration to better illustrate the differences between the 3 scenarios.

- Comparisons of raindrop size distributions show that the number of small rain drops at the ground is not very well represented by DESCAM. Although the distance from cloud base changes the shape of the rain PSD, authors state that the decrease in small drops numbers with an increase in rain water content was not observed by disdrometers at lower altitudes. This calls for some more detailed analysis: how is the drop PSD changing with height in the model vs. observations (Micro Rain Radars were deployed during HyMeX and provide the rain PSD at different heights, polarimetric radars can also help assess the rain characteristics)?

Indeed, this calls for more detailed analysis, which will be subject of another article focusing on the microphysical structure of the cloud field. Starting here with this subject would automatically demand for more explanation on the processes in the layers above and so on ... and finally oversizing the paper.

As indicated before, rain PSD of Micro Rain Radars available during this event were not reliable or simply wrong (i.e. completely in contradiction to the disdrometer observations).

How can the use of polarimetric radars better assess rain characteristics? The PPI scans of the nearby weather radar all remained well below the melting level.

- Is this really possibly linked to the collisional break-up as suggested, or is this also possibly linked to overestimated collection rates, or errors in the sedimentation process?

Yes, we think that the treatment of breakup in the microphysics schemes starts to late, i.e. the large drops > 4mm can form, which leads, as you suggested to an overestimation of the collection rates with the small precipitation sizes.

Minor Comments

- p1,119-21: add references for the climatology of extreme events in the region and modelling difficulties.

We added reference to S n si et al., 1996; Romero et al., 2000; Delrieu et al., 2005; Silvestro et al., 2012; Rebor  et al., 2013

- p1,122-24: A lot more than just rain gauges and radars were available during the HyMeX campaign.

We wanted to introduce the main instruments exploited in this study. We modified the text in order to clarify that these types of instruments were not the only ones available during HyMeX.

- P2,124-27: The first stated objective is to show added value of a bin scheme vs. bulk schemes, however no result in the paper ever discuss the performance of bulk schemes. This should be moderated as there is no evidence of it in this paper → the first objective of the paper is to evaluate the performance of a 3D mesoscale model including a bin microphysics scheme in predicting heavy rainfall.

We agree. The objective of this paper is not to compare the bin vs. the bulk representation of the microphysics but to evaluate the performances of a bin model. We clarified this in the text.

- P4,l30-34: Please precise the aerosol concentration decrease in the first 3km (how many aerosols remain at 3km and above?)
The aerosol concentration decreases exponentially up to 3km height in a same way for all the different simulations. In HymRef, the concentration at 3 km is approx. 900 cm^{-3} . We clarified this in the manuscript.
- p5,l1-2: Please precise if soluble aerosols act as CCN only, or can also act as INPs (e.g. By immersion freezing)?
The aerosol particles are assumed to be ammonium sulfate that is 40 % soluble with molecular weight of 132 g/mole and 60 % of insoluble silicates. They can act as INPs too. We clarified the manuscript.
- P5,l7 & 13: some characters do not display correctly
We corrected that.
- P6,l1-2: this sentence is not necessary as the flight date and location were already mentioned before.
We deleted the sentence.
- P6,l18: figure 4 is used in the text before figure 3?
Figure 3a (now 4a) is used first - in the paragraph of the section 3. So we didn't change the order of the figures.
- p7,l29: text mentions precipitation over 10mm, while fig.4a shows reflectivity in dBZ.
We corrected the manuscript where the referencing where wrong. It was Fig. 3a (now Fig. 4a).
- P8,l13-15: Is the Taylor diagram necessary for only 3 simulations?
Even if only 3 simulations are performed, we preferred the Taylor diagram instead of a table because we thought it helps to compare the simulations with observations, especially to evaluate their performance.
- P9,l6-11: "considerable similarity" is exaggerated. For most precipitation accumulations, there is more difference between any simulation and observations, than between different simulations.
We modified the text.
- P10,l19-26: say at the beginning of the paragraph that we are now looking at fig. 10 (I initially thought that the comment was not fitting the figure because I was still looking at fig. 9 that does not show 5min precipitation over 6 or 7mm for Remote simulation)
We clarified the manuscript because in this paragraph, we compared the Figs 8 and 9 (now Figs 10 and 11).
- p11,l6-8: What fraction of observed DSD spectra is ignored?
The disdrometer of La Souche provided 70 spectra each with a 1 min sampling time. We excluded 9 spectra leading to RWC from 4.9 to 7.6 g/m^3 (and rain rates from 120 to 200 mm/h). This was included in the text

- P11,123: between 9000 and 1000m

Corrected

- p12,13-11: mass distributions from fig. 12 are very similar. Can the small differences be explained by the differences on rain water content (especially for Remote which has a higher mean RWC, but also for HymLow which has the same mean RWC but maybe more extreme values), or is there also a difference in distributions at the same given RWC for the 3 simulations ?

We know from this analysis and from previous studies that a cleaner atmosphere is able to develop larger cloud drop sizes and more liquid water. The objective of this illustration is to demonstrate that this size increase is also conserved in the mm size range.

Fig. 12 (now 14) responds to a large extent to the second part of the question (is there a difference in distributions at the same given RWC). HymRef and HymLow have the same mean RWC, but drops smaller than 2 mm are more frequent in HymRef than in HymLow and for drops larger than 2.5 mm vice versa. And these differences will certainly be conserved when we restrict the Remote RSD to lower values of RWC.

- P14,115: strange characters around “broken”

We corrected the text.

- Fig1: legend missing for the gray contours.

We clarified the manuscript.