#Response to referee #1 (A. Protat)

We would like to thank the referees for their helpful comments, especially about the description of the objectives and limitations of the method presented in this paper (abstract, introduction and section 2.1), and about the handling of the turbulence (section 4.4.2.). These comments will help to improve considerably the quality of the paper.

In this document, for each comment (black font), we display an answer (red font) as well as the intended changes to the manuscript (italic red font).

A. Protat (Referee)
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Review of “4D-VAR assimilation of disdrometer : : :” by Mercier et al.

The paper introduces a 4D-VAR assimilation technique that ingests disdrometer data at ground and vertical profiles of Doppler radar spectra to retrieve the DSD parameters and vertical air velocity. The framework presented in this paper is very promising and should allow for great progress in our understanding of rain microphysical processes. In its present form, the propagation model developed only allows for retrievals in light stratiform events. The major weakness of the paper is that there is essentially no validation of the results obtained with the technique. But there is not much the authors can do about that. The English is also not great and needs to be improved. Overall, given the great promise offered by such technique, I recommend publication provided that the following comments are addressed.

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Major comment

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The abstract and introduction need to be improved to clearly state that the objective of this paper is really to present a new and promising framework to better characterize rainfall microphysical processes.

It is important to clearly state that the current model is quite simplistic and does not include all important microphysical processes. Even in stratiform precipitation, there is horizontal advection, evaporation and coalescence / breakup.

Section 2, where the authors try to justify that they can neglect such processes, is not convincing.
They should rather explicitly say they are working with a simplified model as a first step, and then discuss how this model will be improved in the future, by either introducing parameterizations of those processes or more observations to constrain them. For instance there can be a lot of horizontal wind and vertical shear of horizontal wind in stratiform precipitation. Evaporation will be controlled by the low-level ambient humidity, which is not always high; therefore evaporation in most cases cannot be neglected.

Even the carefully chosen example, the vertical structure of the reflectivity field indicates that some neglected processes are actually active. It is also very important to state that you don't have independent data to validate the outputs, and that you will only discuss how realistic the outputs seem to be, leaving more validation work for other papers.

We mainly agree with your major comment. Abstract, introduction and section 2.1 should and will be rewritten in this way (see propositions below).
Nevertheless concerning the evaporation, I think that for the case study described in the article, it is definitely negligible. There are several reasons for this.
Even if it does not prove that the air is saturated everywhere, in-situ measurements show that it is at least saturated close to the ground during the entire event. Moreover, the radar reflectivity patterns show an increase of reflectivity when approaching the ground. While evaporation should make the reflectivity decrease, this increase is higher than what could be explained by attenuation effects alone (as it is discussed in section 5.1.).
Otherwise we have seen on warm rain events, with non-saturated ground atmosphere, that the evaporation effect on these patterns can be very clear, causing large decreases in reflectivity maps.
Lastly, I had also checked that for similar and more recent cases (long stratiform cold rain) vertical cross-sections of fine-scale Meteo France models show that the atmosphere was saturated at all levels in rain. So I would eventually let the paragraph about evaporation in section 2.1.2. as it is.

Here are the modifications proposed for the abstract. The new parts are in italic red, the deleted ones are struck through.

ABSTRACT

This paper presents a novel ~~approach~~ framework for retrieving the vertical raindrop size distribution (DSD) and vertical wind profiles during light rain events. This is also intended as a tool to better characterize rainfall microphysical processes. It consists in coupling K band Doppler spectra and ground disdrometer measurements (raindrop fluxes) in a 2-D numerical model propagating the DSD from the clouds to the ground level. The coupling is made via a 4-D-VAR data assimilation algorithm. As a first step, in this paper, the dynamical model and the geometry of the problem are quite simplistic. They do not allow to encompass the complexity implied by all rain microphysical processes (evaporation, coalescence break-up and horizontal air motion are not taken into account). In the end, the model is limited to the fall of droplets under gravity, modulated by the effects of vertical winds. The framework is thus illustrated with light, stratiform rain events.

~~The model is, up to now, limited to the fall of droplets under gravity, modulated by the effects of vertical winds. Since evaporation, coalescence/break-up and horizontal air motion are not taken into account, we limit the study to light, stratiform rain events in which these phenomena appear negligible.~~

We firstly use simulated data sets (data assimilation twin experiment) to show that the algorithm is able to retrieve the DSD profiles and vertical winds. It also demonstrates the ability of the algorithm to deal with the atmospheric turbulence (broadening of the Doppler spectra) and the instrumental noise. The method is then applied to a real case study which happened in the south-west of France during the autumn 2013. The data set collected during a long, quiet event (6h duration, rain rate between 2 and 7mmh-1) comes from an optical disdrometer and a 24GHz vertically pointing Doppler radar. We show that the algorithm is able to reproduce the observations and retrieve realistic DSD and vertical wind profiles, when

~~explain the observations and supplies DSD and vertical wind profiles realistic~~ compared to what could be expected for such a rain event.

A perspective for this study is to apply it to extended data sets for a ~~more thorough~~ validation with independent data, which cannot have been conducted with our available 2013 data. Other data sets would also help to parameterize more phenomena needed in the model (evaporation, coalescence/break-up) to apply the algorithm to convective rain and to evaluate the adequacy of the model's parameterization.

Here are the modifications proposed for the end of the introduction (page 12386, lines 17-28):

INTRODUCTION, P12386, lines 17-28

In this paper, we will focus on disdrometer and vertical-radar-reflectivity collocated observations. The data are merged through the use of a 4-D-VAR assimilation algorithm. The evolution in time and space of the DSD is based on a very simplified version of the Hu and Srivastava (1995) propagation model (~~see Eq. 1~~ see Eq. 3). It is actually limited to the fall of droplets, under gravity, solely modulated by the effect of vertical wind. The goal of this study is to develop a new mathematical framework in a simplified context. Once introduced, it will be tested by evaluating its performances, sensitivity and limits on both simulated data and real data (a calm stratiform real event of light rain). Notice that, even if simple, this model insures a resulting DSD in adequacy (through the model) with all the instruments (and their different scales). This aspect is not negligible when, as mentioned previously, you consider all the work done to establish consistent Z-R relationships.
Complexifications of this framework (encompassing evaporation, horizontal air motion, coalescence / break-up) as well as validation, both requiring more measurements, are deferred to future works allowed by extended data sets.
The paper is organized as follows. In Sect. 2, we present the simple model used and discuss the terms of the complete Hu and Srivastava (1995) propagation model, namely: wind, collision and evaporation terms.

~~Even though this model includes breakup, coalescence and evaporation along with both horizontal and vertical air motions, we work with a simplified version. In this work some hypotheses are made in order to do so. Thus the study is limited to a simple meteorological context (stratiform event of light rain) allowing a thorough validation of the approach. Some experiments are also done to underline the limits of this simple model.~~
~~The paper is organized as follows. In Sect. 2, we discuss each term of the Hu and Srivastava (1995) propagation model, namely: wind, collision and evaporation terms.~~
~~Then some model simplifications are retained considering some hypotheses.~~

Here are the modifications proposed for section 2 (page 12387, line 10 to page 12390, line 21) (We keep the equation numbers of the first version of the article. Since the equation order changes, the numbers will eventually evolve. It nevertheless seems more appropriate to stick to the older ones):

SECTION 2

2 Assimilation method

The aim of this work consists in retrieving information about the drop size distribution (DSD) vertical profiles by linking the measurements made by different instruments at different scales and heights. To carry out this relationship, we will use a dynamic model which propagates the DSD through space and time (mentioned below as "propagation model"). In this section, firstly, we ~~explicit~~ describe the corresponding partial differential equation (PDE) used. We as well introduce the associated discretization scheme, and the unknowns of our model. Then, we explain how the 4-D-VAR data assimilation algorithm combines the data available through the model to retrieve its unknowns. The second part of this section details this algorithm.

2.1 Propagation model

As explained before, this study develops a simple framework and so uses a very simple model presented in section 2.1.1. This simplistic model has the merit to add a spatio-temporal coherence to the DSD field. Since it only incorporates the effects of gravity and vertical wind it lacks the complexity to fully model rain.

In section 2.1.2., we introduce a complete PDE governing the evolution of the DSD (Hu and Srivastava, 1995). This propagation model is not in the purview of this article. It is solely used to discuss the different terms of the complete PDE (Eq. 1) and see how their inclusion or exclusion could affect the results. Finally, in section 2.1.3., we present the effective "simplistic" numerical model and the discretization underlying hypotheses.

~~*2.1.1 Complete propagation model*~~

2.1.1 Simplistic propagation model

The DSD, noted N, is the number of raindrops by unit of volume and diameter (unit: m-4). It is a function of time, position and diameter. In the framework presented here, we will work in an air column, and so limit the study to a time-height-diameter space, so that N=N(t,z,D). Then, the PDE, modelling the vertical evolution of DSD, has the form:

(Eq. 3)

The first term of Eq. (3) represents the instantaneous variation of N. The second term is the vertical advection of droplets: w is the vertical wind (component of the 3D-wind ***W*** *along the vertical axis u_z), v is the terminal velocity of droplets under gravity. In this study, the parameter v is supposed to depend only on the diameter D, according to the Atlas et al. (1973) relation:*

(Eq.2)

with D in m and v in ms-1. This relation was fitted to be in good agreement with Gunn and Kinzer (1949) measurements (which are often used as a reference) in the diameter range [0.6–5.8 mm] (Atlas et al., 1973).

Eq. 3 can be considered as a simplified version of the model proposed for instance in Hu and Srivastava, 1995. We will now present this complete model and discuss its different terms.
~~*The PDE governing the evolution of N during the fall of droplets has the form (Hu and Srivastava, 1995):*~~

~~*Eq.1*~~

~~*The first term of Eq. (1) represents the instantaneous variation of N. The second term is the spatial advection of droplets:* ***W*** *is the 3-D wind field and v is the terminal velocity of droplets under gravity (which acts along the downward vertical axis* $\mathbf{u}_z$*). In this study, the parameter v is supposed to depend only on the diameter D, according to the Atlas et al. (1973) relation:*~~

~~*Eq.2*~~

~~*with D in m and v in ms-1. This relation appears to be in good agreement with Gunn and Kinzer (1949) measurements (which are often used as a reference) in the diameter range [0.6–5.8 mm] (Atlas et al., 1973).*~~

2.1.2 Complete propagation model Hu and Srivastava (1995) and discussion of its different terms

In the Hu and Srivastava (1995) study, N depends on time, 3 coordinates of space, and diameter (N=N(t,x,y,z,D)), and obey the PDE :

(Eq.1)

We recognize the two first terms of Eq. (3) with the difference that we have 3D-wind ***W*** *advection here. The third term of Eq. (1) represents the evaporation. τ is the net rate of change of droplets masses (unit kgs-1) and dD/dm is the derivative of the diameter-mass relation for spheric drops (unit mkg-1). The last term I represents the collision effects (drop mass changes not due to evaporation).*

~~*In this section, we successively analyze the different terms of Eq. (1). We explain why, in this study, the model can be reduced to only the vertical advection of drops under gravity and vertical wind. This allows us to put aside the effects of evaporation, horizontal wind, and collisions in the propagation model.*~~

3-D wind W

The vertical wind is considered to add an offset to the terminal velocity of drops. Besides, the knowledge of the real droplet vertical speed is critical to have information about the DSD from the return power spectra of a vertically pointing Doppler radar. This question has been widely treated in the literature (Lhermitte, 1988; Giangrande et al., 2012; Tridon et al., 2013) and it shows that we have to take the vertical wind into account to properly deal with Doppler radar data.

The horizontal wind is the main force which makes the droplets move in the horizontal plane. However, with only one ~~a~~ vertically-pointing radar and colocalized ground point measurements of the DSD, it is not possible to record the horizontal variability of the DSD.

Consequently, as mentioned above, we limit the study to a (z,t) plane.

~~*we suppose that N, as a function of the diameter (this dependency will be implicit later), varies only with time and height (we limit the study to a (z, t) plane).*~~

This ~~assumption~~ simplification is consistent if the horizontal air motions are weak or if the DSD is homogeneous in the horizontal plane. (Of course the DSD can be inhomogeneous with height). To limit the errors caused by this simplification, we will only treat quiet, stratiform *light rain events (see the case study analysis in Sect. 3.3), and we will study the ability of the algorithm to reproduce the observations.*

~~To ensure that this restriction is physically consistent, we will only treat quiet, stratiform light rain events (see the case study analysis in Sect. 3.3).~~

Evaporation (3rd term of Eq. 1)

The evaporation is mathematically modeled as a term of advection along the mass of droplets coordinate. The advection speed (parameter \tau of Eq. 1) depends on the drop diameter, and on several meteorological variables, including pressure, temperature and, mainly, humidity. Seifert (2008) proposes a parameterization of this term. According to this parameterization and for long cold stratiform rain events similar to the one treated in this study (see Sect. 3.3), we verified (not shown) that evaporation can be neglected.

Collisions (4th term of Eq. 1)

Collisions between drops can lead to coalescence (two drops producing one drop) or break-up (two drops producing at least two drops). Coalescence/break-up phenomena are generally assumed to be an important factor governing the DSD temporal evolution (Mcfarquhar, 2010; Prat et al., 2012), even if some studies reconsider this assumption (Villermaux and Bossa, 2009; Villermaux and Eloi, 2011). The phenomena have been widely investigated. Numerous parameterizations have been proposed. Among them, some characterize the ability of 2 drops to coalesce, depending on the energy involved in the collision (Low and List, 1982b; Brazier-Smith et al., 1972 or Straub et al., 2010). Others are more interested by the distribution of resulting drops in case of break-up. (The resulting distributions can be based on laboratory experiments: Low and List, 1982a, b, or on numerical fluid dynamics models: Schlottke et al., 2010; Beheng, 2010.) Since our first objective is to retrieve DSD profiles using data assimilation, we restrict ourselves to a simple framework, and we do not take into account the collisions between drops. Moreover, among the wide litterature mentionned above, many authors show that the coalescence/break-up processes are ~~negligible~~ less critical for low rain rates (List et al., 1987; Prat and Barros, 2007a; Barthes and Mallet, 2013). Thus, this paper will focus only on a light rain event ~~(see Sect. 3.3).~~ in order to limit the errors caused by this simplification. And as for the horizontal wind exclusion, we will study the ability of the algorithm to reproduce the observations despite this simplification.

2.1.3 Numerical model (discretization)

~~2.1.3 Simplified propagation model~~

~~According to the previous discussion, the PDE modelling the vertical evolution of DSD, with its dependencies on time t, height z and diameter D, has finally the form:~~

~~(Eq.3)~~

*~~with w the vertical wind (component of **W** along $\mathbf{u}_z$).~~*

The simplified PDE used in this study (Eq. 3) is discretized ~~This PDE is discretized~~ on a (time/height/diameter) Arakawa C-grid (Arakawa and Lamb, 1977), meaning that N is evaluated at the grid-box centers while w is evaluated at the grid-box faces.

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Technical comments

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Overall, the English is too casual and really needs to be improved. I assume the paper will be edited later, but below I provide some suggestions (not exhaustive, by far).

1. P. 12384, line 2: “(DSD) and vertical wind profiles: : :”

Ok.

2. P. 12384, lines 9-10: about “ : : : in which these phenomena appear negligible”. I don’t think this statement is true and should be reworded. You don’t really have to say such things if you change the pitch of the abstract and introduction as suggested in the major comment.

Ok.

The abstract will be modified as suggested in your major comment.

3. P. 12384, lines 18-19: suggest “the algorithm is able to reproduce the observations and retrieve realistic DSD and vertical wind profiles, when compared to what : : :”

Ok.

4. P. 12386, line 2: “either” instead of “whether”

Ok.

5. P. 12387, line 15: “describe” instead of “explicit”

Ok.

6. P. 12390, line 5: “interested in” instead of “interested by”

Ok.

7. and line 15: “the simplified PDE modelling : : :”

Included in the general revision of section 2.1.

8. P. 12392, line 1: replace “is often supposed to be gamma” with “is well approximated by a gamma distribution (and provide references)”

Ok.

We add a reference to McFarquhar 2010.

9. also lines 22-23: “vertical wind profile”, “variational” instead of “variationnal”, and I would remove “coarsely”.

Ok for “variational”. There is also the penalization term in the cost function, which is less critical than the observation term but is nevertheless important. So I do not want to simply remove “coarsely”.

We propose to replace “coarsely” by “basically”.

10. P. 12393, line 13: replace “which are able to explain the observations” with “which minimize the cost function”.

Ok.

11. Also line 20, weird statement: “provide an admissible answer”, what do you mean ? Penalization terms are generally used to smooth out the solution, avoid multi-minima, help convergence, filter noise etc : : :

The main goal of these terms is to constrain the solution where (and when) there are no observations available. Without them, the algorithm could produce high frequency unphysical oscillations of the DSD inside the observation windows, or could produce extremely high unphysical values of winds close to the ground (where there are no Doppler spectra).
So yes, the (mathematical) goal is to smooth out the solution (and by the way it avoids multi-minima), but the background justification of these terms is to provide an admissible answer, meaning a solution physically consistent, in the areas without observations.

The detailed significance of these terms is given in section 2.2.4., so we delete this vague “admissible answer” concept and just refer to section 2.2.4.

12. P. 12395, line 6: “radar returned power as a function of the Doppler velocity, the so-called Doppler spectrum (Giangrande : : :”)

Ok.

13. P. 12398, line 18: “manufacturer” instead of “maker”

Ok.

14. P. 12399, line 1-2: suggest replacing with “apply a minimum diameter threshold of 0.4 mm)”. We have no idea why you choose such a threshold, so you also need to explain why.

Ok.
We add (P12399, line2):
“0.4mm corresponds to a value over which we are sure that the instrument avoids false detections (Delahaye et al. 2006) and can be compared to other instruments (Krajewski et al. 2006).”

15. Also line 14, suggest replacing “regular” with “sustained”.

Ok.

16. Also line 27, I don’t understand what the “fall height of the drops is”. You show on that plot that drops fall from a higher height than that (melting layer is much higher). Do you actually mean “top of the retrieval domain” here?

Yes. Fall height of the model drops…
Replaced by “top of the retrieval domain” in the article.

17. P. 12400, lines 2-3, winds are “light” not “low”. The sentence needs to be revised.

Ok.
The sentence will also be split in 2 parts (about wind and humidity).

18. Also line 7: “for” instead of “fo”

Ok.

19. P. 12402, line 8: replace with “to get winds within +- 2ms-1”

Ok.

20. P. 12406, line 20: replace “control” with “assess” ?

Ok.

21. P. 12407, line 20: “subsection” instead of “paragraph”

Ok.

22. P. 12408, lines 1-2: sentence needs to be revised, “does less good” does not mean anything (performs less accurately, or produces less accurate results).

Ok.

“it does less good” replaced by “the algorithm performs less accurately”.

23. P. 12409, lines 13-14, and throughout the document: you need to be careful with the word “significant” because you have no way to test the statistical significance of your results. Use “ little” in this case, and please check other locations.

Ok, by “not significant” we indeed only meant “very little”.

“there is no significant bias” replaced by “only a very little bias”.

Also changed in the text for :

P12403, l6 : “significant” -> “large”.
P12405, l16 : “significantly” -> “highly”.
P12406, l8 : “significantly” -> “sharply”.
P12408, l9 : “significantly” -> “much more”
P12409, l20 : “significant” -> “” (deleted)
P12410, l5 : “significantly” -> “”(deleted)
P12410, l23 : “significantly” -> “deeply”
P12413, l4 : “significantly” -> “”(deleted)

24. P. 12410, line 9, add “assumed negligible in our propagation model” after the word “phenomena” and replace “phenomena” with “processes”.

Ok.

25. Also line 10-11, this sentence is extremely vague and is not based on an actual result proving it. You need to avoid such speculative statements.

It is based on the results presented in the previous paragraph (mainly those from Table 3). A “compromise solution merging the different data available” is here a solution with no bias and point-to-point differences (MAE or MAPE) small compared to the observed values.

Modified in the text in “Anyway, the assimilation algorithm appears able to merge the different data available to produce a solution making a compromise between the observations available (low biases and MAE / MAPE for the three first moments of the spectra and for disdrometer data, see Table 3)”.

26. Also line 20: what do you mean by “followed” ? “well reproduced” ?

Yes, it is not reproduced at all by the algorithm because the observations of the disdrometer are not consistent with the radar ones. The algorithm reproduces the radar observations because the spectral energies are higher than the disdrometer drop counts for this range of diameters.

“followed” replaced by “reproduced”.

27. P. 12411, line 25: “on average”

Ok.

28. P.12413, line 17: “we showed that the proposed technique is able to : : :”

Ok.

29. P. 12414, line 7: “For this purpose, we plan to use dual-frequency wind profilers :”

Ok.