Reply to Z. Zhang,

The authors would like to thank Z. Zhang for its valuable comments and suggestions that lead to improve the paper. The different relevant questions made by Z. Zhang and also by the others reviewers led to rewrite almost integrally the section 4.3 concerning the heterogeneity impacts of aerosol above cloud retrieval. We hope that it is now clearer.

Please, find below answers to the comments

Major comments/suggestions: " From my perspective, the largest contribution of this paper is at it advances our understanding of how 3D effects influence the retrieval of polarimetric based remote sensing of above-cloud aerosols. However, there is almost no mention about above-cloud aerosols, e.g., their occurrence frequency, global distribution, climate importance, remote sensing methods to retrieve their properties. The background information on above-cloud aerosols is important for the readers to appreciate the importance of this paper. By now, there is a significant volume of literature on this topic, for example, Chand et al. (2009); Zhang et al. (2016);

We agree that aerosol above cloud retrieval is of main importance and that represents a significant part of our paper. However, it is not the unique topic of the paper. It is more generally focused on cloud heterogeneity effects on POLDER measurements and parameters that can be retrieved from them. Off course, many previous papers have already studied the cloud heterogeneity effect on optical thickness. The main differences here is that we focus on the POLDER instrument algorithm, which has a lower resolution but takes advantages on its multi-angularity. More original is the study of the cloud heterogeneity effects on polarized reflectances and on the parameters that can be retrieved from it. Aerosol above cloud optical thickness is one of them as well as effective radius, effective variance and cloud top pressure.

But, we agree than the importance and improving our knowledge of aerosols in cloudy scene is not enough presented in the introduction. To improve it, we add some sentences and references including the one given by the reviewer.
In the introduction section we add several paragraphs :
In addition, absorbing aerosol above clouds can generate a positive direct radiative forcing (i.e. warming), that is currently not well quantified, and modify the properties of the below cloud layer (Chand et al., 2009, Wilcox, 2010 and Costantino et Bréon, 2013).

and :
Concerning aerosols, spaceborne active instruments, such as the lidar CALIOP are dedicated tools to detect multi-layer situations and to retrieve Aerosol Above Cloud (AAC) properties (Young and Vaughan, 2009, Hu et al., 2007, Chand et al., 2008) and were used for climate studies (Zhang et al., 2016). Passive measurements, that allows a larger global coverage, can also be used. An operational algorithm was developed to retrieve AAC scenes from the polarization measurements provided by the POLDER instrument onboard PARASOL (Waquet et al., 2009, 2013a) and was used to provide global analysis of the aerosol above clouds properties (Waquet et al., 2013b). Further, Peers et al., (2015) combined total and polarized radiance measurements to retrieve the aerosol absorption above clouds. A color ratio technic was also developed to retrieve the AAC optical thickness and the corrected cloud optical thickness from total radiance measurements. This method was adapted to OMI UV measurements and MODIS multi-spectral measurements (Torres et al., 2012, Meyer et al., 2015).

And
Concerning Aerosol Above Cloud (AAC), intercomparisons of passive and active retrievals were performed for case studies (Jethva et al., 2013) and for global and multi-year data (Deaconu et al., 2017). The methods developed for passive instruments are however also based on 1D calculations and, so, generally restricted to homogeneous cloudy pixels, for which the 3D effects are minimized. In case of partial cloudy scenes, shadow, cloud enhancement of the clear areas by neighboring clouds can also

modify the retrieved aerosol properties. Errors on the retrieved aerosol properties are in general dependent of the cloud distribution, optical thickness and spatial resolution (Stap et al., 2016a; Stap et al., 2016b).

And added the sentence as:
Concerning AAC retrieval, to our knowledge, no study were conducted to assess errors due to cloud heterogeneity.

The impacts of the 3D effects on the POLDER above cloud AOT operational retrievals in case of fractional cloud were evaluated and presented in Section 5.

" In this study, the radiative transfer simulations are done at very high spatial resolution, 50 m. although the results are averaged to 7km to "mimic the radiometer measurements and applied the POLDER operational algorithm". Only retrievals at the 7km are presented and analyzed. The reason for the spatial average understandable. But the high-resolution radiative transfer and retrieval results (if any) should also be presented and analyzed for a couple of important reasons. First of all, the 3-D effects are highly dependent on the spatial scale. At small scale (e.g., 50m) the violation of independent pixel approximation (i.e., smoothing, illuminating and shadowing effects) is more important, while at coarser resolution (e.g., 7km) the plane-parallel bias is more important, as pointed out in many previous studies including Zhang et al. (2012). Therefore, the high-resolution results, in combination with the low-resolution results, are very important for us to gain a comprehensive understanding of the problem. Second, the high-resolution results are very relevant to air-borne instruments, such as RSP and HARP. These instruments have been employed in the recent ORACLES field campaign. These air-borne instruments have spatial resolution on the order of 100m. So the results in this paper are highly relevant. Therefore, I strongly suggest the authors add some results and discussion on the high-resolution radiative transfer and retrieval results.

We know and agree that retrieval results and cloud heterogeneity effects are highly dependent on the spatial resolution. However, as explained in the previous answer, this paper focus on POLDER measurements which are made at a resolution of 6 km x 7 km. We agree that studies concerning heterogeneity effects are higher spatial resolution would be very valuable. However, we did not make the inversions from the high resolution cloud fields. It is not the scope of the paper and we thing that adding to much information will deserve the whole paper.

" This paper focuses on the polarimetric remote sensing technique. But it is somewhat disappointing that there is no discussion on the spectral methods for above-cloud aerosol retrievals (e.g., Jethva et al. 2013 and Meyer et al. 2015). As far as I understand, the radiative transfer and retrieval framework used in this study can be easily extended to the spectral method. I'd encourage the authors to take this opportunity to look into the 3-D effects on spectral based above-cloud aerosol retrievals. But I will leave this to the authors to decide whether they will do this in this study or future work. »

We add the mentioned reference about spectral method in the introduction, see above.

Concerning the method used here to assess cloud heterogeneity effects, for sure, it could be easily extended to above-cloud aerosol retrieval based on spectral method but again we think that is beyond the scope of our paper. It will maybe be done a future study (not yet planned).

" What is not clear from the current paper is how much the retrieval error is due to the 3D effects and how much is due to retrieval algorithm uncertainty.

You are right, it was not clear in the previous version of the manuscript, we did our best to clarify this point in the new version (see our point by point responses below).

For example, POLDER has a coarse angular resolution and it seems to me this is partly the reason why the above cloud AOD retrieval error is large in Table 3.

We do not agree. For the homogeneous cloud considered as infinite, the coarse resolution of POLDER is not an issue. The retrieved AOT from homogeneous cloud input is not significantly different comparing to the AOD input and can be considered as the benchmark value to assess the cloud heterogeneity effects. Retrieved AOT from heterogeneous clouds is then compared to the 1D retrieved AOT. Significant departures are observed for fractional clouds (3D input) in function of the solar zenith angle. As the same radiative transfer model is used for 1D and 3D cases, differences in AOT are then necessarily due to 3D effects that depend on the solar elevation.

To be clearer, we added the following sentence and paragraph in the manuscript :
We remind that the same input AOT is used in the 1D and 3D simulations (AOT of 0.15 at 865 nm).

And further….

As expected, the AOTs retrieved by the algorithm for homogenous clouds (1D input) are close to the input one, whatever the SZA value. The retrieved AOTs only slightly overestimate the input one (0.15) and are respectively equal to 0.18, 0.17, 0.17 for SZA of 20, 40 and 60°. This overestimation is likely due to the approximations used in the retrieval algorithm (e.g. interpolation of the LUTs). Comparing with the retrieved values from homogeneous cloud, significant departures are observed for fractional clouds (3D input) depending on the SZA. The AOTs retrieved at 865 nm are then equal to 0.119, 0.17 and 0.28 for SZA of 20, 40 and 60°, respectively. For a given solar zenith angle, the viewing geometries and the angular resolution are identical for the 1D and 3D inputs. The differences observed in AOT between the 1D and 3D calculations are then necessarily due to 3D effects.

Also, in the retrieval process based on the Waquet et al. (2013), how much a priori information is given to the retrieval algorithm? Does the retrieval algorithm know, for example, the single scattering albedo of the above-cloud aerosol at each wavelength? In reality, the algorithm certainly does NOT know the aerosol properties. Some discussions are needed to clarify how aerosols are treated in the Waquet et al. (2013) retrieval algorithm and justify the treatment.

You are right, our description of the aerosol above clouds algorithm was not enough detailed. Actually, Waquet et al. (2013) describes two algorithms: (1) a "research algorithm" that is an optimal estimate method that aims to retrieve a large number of aerosol and cloud parameters and (2) the so-called "operational algorithm" that retrieves the AOT and the Ångström exponent of aerosols above clouds at a global scale. The operational algorithm is the one considered in the present study. This algorithm is based on LUTs' calculations and do not use any a priori information on aerosol and cloud. However, the method uses assumptions on particles microphysics and the LUT is built for a limited set of aerosol and cloud models. The operational algorithm considers six fine mode spherical aerosol models (i.e. effective radius varying between 0.09 and 0.24 microns) and assumes a constant complex refractive index of 1.47+0.01i. The single scattering albedo (SSA) is then also prescribed since this parameter primarily depends on the particles size and on the imaginary part of the complex refractive index (e.g. SSA of 0.91 at 865 nm for mean radius of 0.149 microns and absorption of 0.01). As explained in Peers et al., 2015, polarization measurements are primarily sensitive to scattering processes and mainly provide the scattering AOT. In other words, with polarization measurements at 670 and 865 nm, we retrieve the scattering AOT and with an assumption for the SSA, we provide the total (extinction) AOT. Obviously, the choice of the level of absorption or the choice of the SSA impacts the retrieval of the scattering AOT. Errors due to the assumption made for the complex refractive index were estimated in Peers et al., (2015) and are around 20% for the AOT.

One additional mineral dust model is also considered in this algorithm. One can note that the operational algorithm also uses a specific strategy to retrieve aerosol properties above clouds that depends on the aerosol type (see figure 4 in Waquet et al., 2013).
Finally, a recent global and multi-year comparison between POLDER AOT and CALIOP "depolarization method" AOT retrieved above clouds shows a fairly good agreement (Deaconu et al., 2017). This gives confidence in the operational method developed for POLDER since the depolarization method does not require any assumption in aerosol microphysics to retrieve the AOT.
In the new version of the manuscript, we will provide a better description of the POLDER operational algorithm (i.e. aerosol models, assumptions and retrieval uncertainties, retrieval strategy …) and we will refer to Waquet et al., (2013) for all technical details.

We add the following paragraph in the manuscript :

Waquet et al. (2013) describes two algorithms for Aerosol Above Clouds (AAC) retrieval using POLDER polarization measurements : (i) the research algorithm, that is an optimal estimation method that retrieves a large number of aerosol and cloud parameters, and (ii) the operational algorithm that allows to retrieve the AOT at 865 nm and the Ångström exponent of aerosol above clouds. The "operational algorithm" is the one considered in the present study. This is algorithm is based on LUTs' calculations performed with the successive order of scattering code that assumes a plane-parallel atmosphere (Lenoble et al., 2007). It uses assumptions on particles microphysics : six fine mode spherical aerosol models (i.e. effective radius varying between 0.09 and 0.24 microns) are considered and a constant complex refractive index of 1.47+0.01i is assumed. The errors due to the assumption made for the complex refractive index are around 20% on average for the AOT (Peers et al., 2015). Maximal relative error may reach 25% in case of extreme aerosol events (AOT > 0.6 at 550 nm). One additional non-spherical mineral dust model is also considered in the LUTs.

The operational algorithm uses a specific strategy to retrieve aerosol properties above clouds that depends on the aerosol type and also on the available viewing geometries (see figure 4 in Waquet et al., 2013). In case of fine mode particles, the retrieval is restricted to the use of observations acquired for scattering angles smaller than 130° where polarization measurements are highly sensitive to scattering by fine mode particles (such as biomass burning aerosol) and only weakly sensitive to cloud microphysics. In Figure 6, the dashed line show the increase of the polarized reflectances for scattering angles less than 130° when an aerosol layer is present above a cloud. However, non-spherical particles in the coarse mode such as mineral dust particles, cannot be handled with this method as they do not much polarize light. When dust particles are transported above clouds, they reduce the magnitude of the primary cloud bow. The operational algorithm includes thus the primary bow in order to retrieve the above cloud dust AOT. In this case, as the magnitude of the primary cloud bow primarily depends on the cloud droplet effective radius, it must be estimated or included in the retrieval process. Collocated cloud properties from MODIS at high resolution (1 km × 1 km) are used to characterize and to select the cloudy scenes within a POLDER pixel (6 km × 7 km at nadir) and the MODIS cloud products can then be used in the operational algorithm to estimate the droplets effective radius. As the magnitude of the primary cloud bow is only weakly impacted by the choice of the droplet effective variance, this parameter is assumed to be constant and equal to 0.06. Several filters are eventually applied to obtain a quality-assessed product. For instance, the retrievals are restricted to cloudy pixels associated with cloud optical thicknesses larger than 3.0, since the polarized radiation reflected by the cloud layer is then saturated and does not depend anymore on the cloud optical thickness. Criteria are also used to reject inhomogeneous and fractional cloudy pixels and to avoid cirrus cloud contamination. We refer to Sect. 3.4 in Waquet et al. (2013) for a detailed description of the operational algorithm.

Related to the last point, the AOD retrieval error could be put into a more meaningful context. For example, what is the relative error in AOD retrieval if the assumption of single-scattering albedo of aerosols is wrong in the retrieval algorithm?

The relative errors in AOT due to the assumption made for the complex refractive index (1.47-0.01i) were estimated in Peers et al., (2015). Synthetic simulations were generated with different assumptions for the complex refractive index. These synthetic simulations were used as an input to evaluate the algorithm (values of real part of refractive index of 1.42 and 1.54 instead of 1.47 and imaginary part of 0.03 instead of 0.01). The errors on the AOTs are around 20% on average. Maximal relative error may reach 25% in case of an extreme aerosol event (AOT > 0.6 at 550 nm).

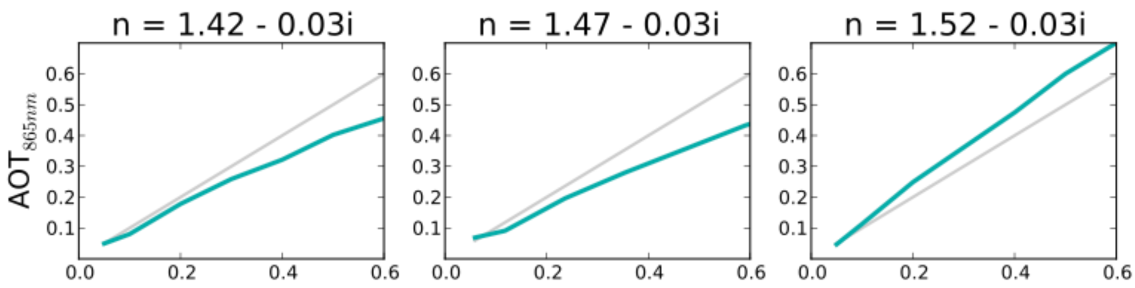

Figure 5 (from peers et al., 2015) *Sensitivity of the properties of ACA conditions with different aerosol models. total AOT at 865 nm, COT at 550 nm. Grey lines correspond to the properties of the actual modeled conditions and green lines to those retrieved by the algorithm. The aerosol model of the first column has a refractive index n equal to 1.42 − 0.03i, the second, n = 1.47 − 0.03i and the third, n = 1.52 − 0.03i. Aerosols have an effective radius of 0.1 μm and the effective radius of the cloud water droplets is 10 μm.*

As mentioned in the previous answer, we add this sentence :
Relative errors due to the assumption made for the complex refractive index are around 20% for the AOT, with a maximal error of 25% found in case of aerosols events associated with AOTs larger than 0.6 at 550 nm (Peers et al., 2015).

How is this error compared with the 3-D effects? Such comparison will help us understand the relative importance of 3-D effects in comparison with some other error sources in the retrieval.

The errors associated with the retrieval algorithm (i.e. assumptions in the particles microphysics and potential errors introduced by the use of LUTs and interpolation processes were already added in the manuscript:
The retrieved AOTs only slightly overestimate the input one (0.15) and are respectively equal to 0.18, 0.17, 0.17 for SZA of 20, 40 and 60°. This overestimation is likely due to the approximations used in the retrieval algorithm (e.g. interpolation of the LUTs).

and
The errors due to the assumption made for the complex refractive index are around 20% on average for the AOT (Peers et al., 2015). Maximal relative error may reach 25% in case of extreme aerosol events (AOT > 0.6 at 550 nm).

We also completed and rephrased the paragraph discussing the heterogeneity effects on the AAC retrieval.
For a SZA = 20°, the operational algorithm also successfully retrieves the input aerosol model for the homogeneous and fractional cloud. However, the AOT retrieved by the operational algorithm, under the 1D assumption, is underestimated with error between -35 and -40%. For a SZA of 20°, the range of scattering angles effectively used for the retrieval is between 100° and 130°. Polarized reflectances for SZA=20° are not shown but are similar to the ones shown in Figure 7 between 100° and 180°. Over the 100-130°, as shown in Figure 7, 3D polarized reflectances are lower than the 1D ones because of the plane-parallel biases, which explains why the AOT retrieved by the algorithm is

underestimated. However, as the differences are mainly due the plane-parallel bias, which is similar for the two wavelengths, the cloud heterogeneity effects do not affect the selection of the best aerosol model.

For SZA = 60°, the range of scattering angles used is between 60° and 130°. Between 60° and 90°, there is an increase of the forward scattering signal due to 3D effects, which is interpreted by the operational algorithm as an increase in the AOT. We note also that 3D effects bias the aerosol model for this case as a smaller value of Ångström exponent (corresponding to a larger effective radius) is retrieved for the fractional cloud. The retrieved AOT is thus higher (AOT of 0.28 comparing to 0.17) with a relative error up to 65%. For SZA=60°, the 3D effects consist in an increase of the polarized signal because of additional scattering in the clear sky parts. This increase is higher at 865 nm than at 670 nm. This leads to the selection by the algorithm of an erroneous model with a smaller Angström exponent.

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