Statement on the Revision of ⟨AMT 2017-182⟩ Based on the Referees' Report

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This statement concerns our revision of the ⟨AMT 2017-182⟩ paper, entitled "⟨*Fu-Liou Gu radiative transfer model used as ...*⟩", based on the referees' report.

Comments by Reviewer #1

> `Although the paper deals with lidar observations of cirrus extinction profiles, there is no information on the laser beam pointing (zenith or off zenith to avoid specular reflection) and no information about the receiver field of view which has an impact on the multiple scattering contribution. On the other side, the depolarization technique is explained (even the 45 deg calibration) although not used. Please re-write this section, update the instrument part to meet the requirements for this paper.`

The information about instrument depolarization channel was suppressed as not relevant for the paper, being the channel not used. On the contrary, we added a paragraph regarding measurement configuration and multiple scattering effects.

> Now, I come to my most important point: The authors use both, the Raman lidar method and the Klett retrieval to determine particle extinction profiles. And EARLINET members (experts in the field of Raman lidars) probably know that the optimum Klett solutions of the backscatter and the extinction profiles are obtained with the 'actual' lidar ratio (profile) from the Raman lidar observations. Ideally, Klett and Raman backscatter and extinction profiles coincide, ... but usually the available Klett codes cannot handle lidar ratio profiles. However, if you apply the method to such a rather rather thin cirrus as done in this paper, then we may have a problem. I would recommend to use a visible, very well developed cirrus cloud deck (not this subvisible cirrus with an optical depth 0f about 0.02). Is there a reason why this quite unusual cirrus is taken, and not a very normal one?

In the manuscript new version two more cases are reported and discussed, a thicker cirrus cloud and a case with biomass burning aerosol. Regarding the first part of the comment, we changed the text accordingly to make clear that the goal of this study it is to start a relevant discussion from a quantitative point of view, about the discrepancies of aerosol and cloud direct radiative effect calculated using the Raman technique or the simpler lidar elastic technique retrievals. Inconsistencies may arise also using a mixture of lidar techniques from multiple networks or within the same network. As example, what is the difference in retrieval if, we have data from an MPLNET permanent observation station vs. a more sophisticated (like those operating in the frame of EARLINET) instrument? This first work put the basis for a successive study where a much larger dataset will be analyzed to assess quantitatively how much the different techniques/data processing affect the retrieval of the optical and geometrical properties.

> Nevertheless, by just taking a climatological value for the dust lidar ratio of 45 sr and for the cirrus of 25 sr in the Klett retrievals, and in this way by completely ignoring the reality, i.e., the 'actual' Raman lidar observations of the lidar ratio . . .. it is not surprizing that you obtain different Klett and Raman extinction profiles. The true ones are, by the way, the Raman solutions. The Klett solutions are wrong. If your Klett code cannot handle lidar ratio profiles (from the Raman lidar observations), then you should at least take the dust layer optical depth from the Raman lidar observations to constrain the Klett solution. The Klett column backscatter times the used input lidar ratio must match the Raman solution for the dust optical depth. By playing around with the Klett solutions to find the best lidar ratio, you finally end up with the most appropriate column dust layer lidar ratio. After optimizing the Klett/Raman solution set you may continue with radiation calculations and show remaining differences in terms of TOA and SFC forcings. I am sure they are small.

Thanks for pointing it out but again, we think that we didn't state clearly enough the scope of our manuscript. We revised the text to avoid any possible confusion or misunderstanding. This study is preparatory for a future standardization of existing or future ground-based lidar network using different techniques as well space missions. The used metric for this evaluation is the net radiative effect calculation at TOA and SFC by the Fu-Liou-Gu radiative transfer model. The manuscript focuses on discrepancies between lidar techniques/data processing, not on the assumptions of the single retrieval of aerosol/cloud geometrical optical properties. Theoretically, the analysis can be performed on synthetic signals where all the geometrical, optical and microphysical cloud and aerosol properties are well known. In future work, a quantitative assessment of the differences will be evaluated on real cases taken from a climatological significant database

Comments by Reviewer #2

> 1) I am afraid that my main concern is the substance of the manuscript. I strongly support the idea of using radiation as an ultimate evaluation metric, but I feel that the manuscript was submitted too early and that the content is very much on the thin side. To make this manuscript useful, it would be good to address the following issues: a. The representativeness of cases: I agree it is not necessary to present overwhelming cases, but a synthesis from many cases is needed. This issue becomes even more crucial when the manuscript claims to be \in view of next and current lidar space mission", which is about a global scale and a longer time scale. I like grand statements like that to tell readers what the paper is about, but we also need to be careful not to oversell it. To be scientifically rigorous, I would think that the authors need to get the climatology of dust layer and cirrus clouds (either doing analyses on their own or taking information from the literature) to provide context of whether these two cases represent the majority of the observations, or they are actually outliers. Without that context, we really cannot say much from two cases. Once the climatology is available, then the authors can carefully select cases and think about a strategy how to best cover a wide range of dust/cirrus characteristics.

We would like to thank the reviewer for the meaningful comment. However, if from one side we agree that two cases are not enough (for this reason we added two more cases with an opaque cirrus clouds and a biomass burning event) on the other, we we were not trying to oversell our research but think that our manuscript lacks of clarity because the main goal is to evaluate the differences in term of net radiative effects among that the more sophisticated and simpler different lidar techniques. In theory, for the purpose of this manuscript, it can be used synthetic signals instead of real measurements, where the optical and geometrical aerosol and cloud properties are well known and quantify how the lidar technique/data processing affects the raidative transfer calculation, using FLG as metric. Our cases aims to show the existence of these not negligible differences arising from the diversity of lidar techniques/data processing, for the first time quantitatively. The statement that the reviewer is happy with the use of an RTM as the metric to assess the systematic effects in the retrieval of aerosol forcing using lidar is a strong encouragement for us to continue this work and assess the impact on much larger dataset.

> b. The methodology: The authors recognize the need of actual radiation measurements for their work, but unfortunately, they didn't go further to do it. For ice clouds, there is a BAMS paper http://journals.ametsoc.org/doi/pdf/10.1175/BAMS-88-2-191 talking about radiation closure. Although that paper focused on intercomparison of various retrieval methods and had a different purpose from the manuscript, it shows how sensitive shortwave/longwave fluxes and radiances are to ice cloud properties. Without comparing with radiation measurements, it is hard to know if the retrieval shown in the manuscript is good enough to be used to provide any recommendation. Additionally, the current form very much just reports numbers of \net radiative forcing" without any discussions. Note that there can be compensating errors from input variables in radiation calculations, so the resulting radiative effects should be discussed in more detail.

We agree that the microphysics parameterization of the cirrus cloud plays a fundamental role in calculating the net radiative effects of cirrus clouds and aerosol layers. For our calculations we used the empiric parameterization as found in Heymsfield et al., 2014. As stated in the paper mentioned in the comment, each parameterization shows pros and cons. However, as stated in the previous answer, our analysis can be carried out in principle on synthetic signal where the microphysics is fully known and still quantitatively describe the differences for the different retrievals. In fact, we are interested in the relative values between different lidar techniques/data processing. To reach this goal we use a RTM on the different retrieval and calculate the relative discrepancies (we applied the same parameterization for all the retrieved profiles). In future analysis we are going to take into consideration different parameterizations. Nevertheless we added some additional paragraphs where we clarify our choice and state how different parameterizations can affect the results citing properly the suggested BAMS paper.

> 2). The manuscript title is unnecessarily complicated and does not capture the key points. Essentially, this manuscript uses various input aerosol/cirrus properties (from retrieval) to compute radiative fluxes at TOA and at the surface, and then uses these fluxes to evaluate whether retrieval itself or the vertical resolution of profiles plays a more important role in the resulting fluxes. With this objective, radiative effect is the important component, not the choice of the radiative transfer code. Any decent radiative transfer code can do the work. I also don't think proxy is the right word to use. A title is supposed to be precise and to grab attention. For the sake of the authors, I will strongly recommend changing the current title to a simple yet effective one that truly reflects what has been discussed.

Agreed that the word "proxy" is misused and generates confusion. For this reason we changed completely the manuscript title into a simpler form:"Impact of the different lidar measurement techniques and data processing on evaluating cirrus cloud and aerosol direct radiative effects.". This new title version we think is simple and clear and really reflects what has been done in the paper.

> 3). Following the comment above, it will be better to highlight why the Fu-Liou-Gu code works well for this study. My guess is that it has a rather sophisticated way to characterize optical properties for both aerosol and ice clouds, which is worth mentioning.

Agreed, we added a paragraph to describe in detail how the Fu-Liou-Gu radiative transfer model works and why it works good for reach the objective stated in the manuscript.

> 4) The misuse of radiative forcing. While some people loosely use radiative forcing and radiative effects and treat them like they are the same, they are, by definition, not the same. I believe what the authors did in the manuscript is calculating radiative effects, not forcing, although no description is ever given in the manuscript. Please clarify and describe it clearly.

We agree that the word "forcing" is often misused. Of course we calculate the net radiative effect of cirrus clouds and aerosol layers. We added a paragraph to describe the computation we performed and we substitute in the entire manuscript the word "forcing" with "effect".

> 5). Referencing could be better. For example, the first paragraph in Introduction should use some proper, more specific citations. And, Page 2, Line 4: Surely, Holben et al. (1998) is the standard citation for AERONET. But to demonstrate \Cloud and aerosol optical properties have been studied. . . \, papers using AERONET for studying cloud and aerosol should be added here. Also, it would be better to recognize and include studies using ARM or Cloudnet or ACTRiS observations. Same comments for satellite observations.

We agree and we changed accordingly the manuscript adding and acknowledging ARM, Cloudnet and ACTRIS work.

Comments by Reviewer #3

> General comments The main objective of this paper, entitled \Fu-Liou Gu radiative transfer model used as proxy to evaluate he impact of data processing and different lidar measurement techniques in view of next and current lidar space missions" is to quantify inconsistences in aerosol (one case in this study : dense dust aerosol event) and cloud (one case in this study : thin cirrus) radiative forcing at Top Of the Atmosphere and at surface due to two different ground lidar techniques (elastic and Raman lidar, i.e. the Multi-wavelengh System for Aerosols (MUSA) Lidar (Madonna et al., 2011)) and/or data processing (i.e. effect lidar measurement with different vertical resolution together with smoothing techniques). Vertical profiles of aerosols and cloud optical properties (i.e. extinction) are retrieved with classical algorithm (lidar ratio is set to 45 Sr for the aerosol event and to 25 Sr for the cirrus) and with the more accurate Raman lidar techniques. Then radiative forcing is computed with the help of Fu-Liou Gu radiative transfer. Sensitivity of radiative forcing to input parameters (extinction) is evaluated applying a Monte Carlo technique. Aerosol type is the number 17 in the radiative transfer model, and effective diameter of cirrus crystals is computed from Heymsfield et al. (2014) parametrisation. Finally, on the basis of this two study cases, authors conclude that radiative forcing is affected by the measurement and retrieval techniques as well as on the data processing constrainst/assumptions from 0.5% percent to 35% This paper address relevant scientific topics within the scope of AMT. Scientific methodologies and assumptions are valid but not always clearly outlined (see my specific comments). Description of experiments and calculations are rather complete. The overall presentation is rather structured and clear.

We thank the reviewer for the positive comments

> Nevertheless, I have two problems when I review this paper. Firstly, even if scientific methodology and calculation are interesting, scientific contribution of this work is not very novel. This paper is rather a sensitivity study of radiative forcing to vertical profiles of extinction retrieved by two different lidar techniques (classic and Raman lidar) but for only two specific two cases (an aerosol event and a thin cirrus). It is also obvious that vertical resolution of lidar measurement (and smoothing techniques) affects computed radiative forcing. I don't understand why these only two cases are representative of the numerous atmospheric conditions. I have the feeling that this paper presents early results and do not reach the scientific level of AMT. Maybe authors could go further in their investigations by, for example, analysing typical atmospheric conditions and/or more extreme atmospheric conditions (cirrus with large optical depth, with different effective radius, altitude, different aerosols, etc. . .).

We agree that it is already known that different lidar techniques and data processing produce different results, but in literature a discussion on the uncertainty/impact due to the use of different lidar techniques to validate the radative forcing inferred from satellite platform or modeling measurements is indeed missing. As metric we used the Fu-Liou-Gu radiative transfer model net radiative effect at the Top of the Atmosphere (for satellite based measurements) and at surface (for ground based measurements). Even if in literature many studies are based on case studies, we agree that the presented case are not enough. For this reason we added two more cases: one including a biomass burning event and another a thick cirrus cloud.

> Secondly, there is no coherency between the work and results presented in this paper and the title that do not reflect the contents of this paper. Fist off all, the title talk about \next and current lidar space missions". When I read this title and introduction, I expected that authors investigate also the sensitivity of radiative forcing due to the difficulty (spatial and temporal averaging scale) of retrievals of extinctions with CALIOP/CALIPSO or with CATS or with EarthCARE. However, authors refer this fact in the introduction but not in their computations and analyses. Moreover, EarthCARE lidar is a high spectral resolution lidar, witch is not exactly the same technique as the Raman technique. Next, I do not understand why authors make emphasis on the Fu- Liou Gu radiative transfer model. Certainly, this model is a good model. But why this model is considered by the authors as a proxy? Why it is stressed in the title like that?

We agree that the title can generate confusion and the manuscript lacks of clarity in this sense. For this reason we specified it in the title and changed the text accordingly. The rationale behind the title is that we would like to raise awareness on how much the different lidar techniques/data processing affect the retrieval of the optical and geometrical properties of the aerosol and cloud layers, bearing in mind that also several space missions are going on and other are ready to be launched using these techniques/data processing. We changed completely the title into:"Impact of the different lidar measurement techniques and data processing on evaluating cirrus cloud and aerosol direct radiative effects."

> Specific comments Page 1, line 17 (and further in the text) : Please give the mathematic definition of the net radiative forcing. In general we talk about radiative forcing defined as the change in the net (down minus up) irradiance.

We provided in the text the definition of direct radiative effect accordingly. For this study we used the difference between the total sky (when cloud and/or aerosols are present) and the pristine sky (clear atmosphere)

> Page2, line 2-3 : references are not appropriate.

The provided references investigate how the sign in net radiative effect of cirrus clouds can change daytime. Then, the net forcing is still uncertain.

> Page2, line 3 : Cloud and aerosols have been also studied with POLDER/PARASOL.

References were added

> Page2, line 21 : Please give other references on the retrievals of aerosol and cloud properties with Raman lidar. By the way, what are the effects of multiple scattering with Raman lidar ? References ?

References were added. Multiple scattering is of course playing an important role mostly for clouds. However, investigating multiple scattering is beyond the scope of the manuscript as we start our analysis using the available products. As the answer given for another reviewer, we try to quantify only the technique/data processing discrepancy, not other effects. For the purpose of the manuscript, also synthetic signals can be used.

> Page2, line 26, eq 1 : This equation is not well written (exp)

Changed accordingly

> Page 3, line 2 : Please give other references.

Additional references are provided

> Page 4, line3 : Reference of Campbell et al., 2016 is not provided.

The reference is now provided

> Page 4, line 7 : You talk about CATS and EarthCARE. What about the high spectral resolution technique compared to Raman technique?

That's an interesting point. Unfortunately, in this first study we don't have co-located HSRL measurements to compare.

> Page 4 , line 18 : Heymsfield et al. (2014) is not appropriate.

Fixed

> Page 4, line 24 : Why aerosol type number 17. What are optical properties of this aerosol?

This type of aerosol is labeled as transported dust. However, we are interested in relative discrepancies, as we use for all the cases this aerosol type. We agree that the absolute value may be incorrect.

> Page 5, line 3 : MUSA seem a great lidar, with polarization measurement. Why do not use polarization information in this study ?

Actually all the information obtained from MUSA lidar observations, i.e. the geometrical and optical properties of aerosols and clouds at different wavelengths together with depolarization and ancillary information (e. g. back-trajectories) were used to identify aerosol type and cloud phase. While only the aerosol/cloud extinction profile is used as input for the FLG radiative transfer model.

> Page 5, line 2 : What is the crystal shape of the cirrus ? What is the effect of changing effective diameter on the computed radiative forcing ?

We use Heymsfield et al., 2014 empirical parameterization. Again, as we are interested in relative values of the net radiative effect, the parameterization is not fundamental for our analysis because it is the same for the considered lidar techniques/data processing.

> Page 6, line 8 : This cirrus is very optically thin. What is the vertically optical depth ? Why do you choose such a small optical thickness? What is append if optical depth is large (1.5 to 3) ? What about the effect of multiple scattering? Do the retrieval algorithms (classic and Raman) take account of multiple scattering? For space mission lidar data, multiple scattering effects can be not negligible.

We added a case with an optically thicker cirrus cloud. For sure, the multiple scattering affects mainly the cirrus cloud net radiative effect calculations, as the multiple scattering is modifying the cloud atmospheric extinction profile. However, in this first study, the different techniques and data processing profiles are not corrected by multiple scattering effects, as we are interested in quantifying the relative differences. For the scope it can be used a synthetic cloud signal where multiple scattering effects are not present.

Comments by Reviewer #4

> This work deals with the use of different lidar techniques and configurations for studying radiative forcing of aerosol and clouds. In particular, authors analyze the use of backscatter and Raman lidar signals.Backscattering lidar needs the assumption of a constant extinction-to backscatter lidar ratio for the entire profile while combination of backscattering and Raman signals allow independent retrievals of aerosol and clouds extinction and backscattering profiles. Authors show that different lidar techniques and different data processing produce different results, and in this research advance in showing quantitatively how much are those discrepancies. The novelty of this work is then in quantifying the impact of each technique on radiative forcing calculations at TOA and SFC. Due to the large number of backscattering lidar, e.g. MPLNET network uses such systems and very few EARLINET instruments do have Raman lidar during daytime, the results of this analysis are of great interest for the scientific community and valuable for its publication in Atmospheric Measurement Techniques. Nevertheless, I agree with other reviewers that major revisions are needed as the publication suffers from hasty writing and more cases should be considered. Other concerns should be addressed before publication: 1.- I think that a single case thin cirrus cloud is not exhaustive for the analysis. I would rather extend the research at least for three cases: thin cirrus clouds (as already studied) with COD<0.03, Opaque cirrus clouds,with a COD in between 0.03 and 0.3 and thick cirrus cloud case, with a COD>0.3

Thanks for the meaningful comment. We added a thicker cirrus cloud in the analysis and a biomass burning aerosol event.

> It comes from the analyis that there is a different behavior between cirrus cloud and aerosols (cf. fig. 3 and fig. 4) It could be very intresting to add in the analysis cases where there is a simultaneous presence of a cirrus cloud on top of an aerosol layer, like dust or biomass-burning. In those cases it would be interesting to verify if technique or data processing are critical

We agree with the reviewer that a simultaneous presence of clouds and aerosol layers could be very interesting, but in our analysis is limited to single layer analysis to avoid any error compensation due to multiple mode.

> 3.- The description of lidar signals and the different ways of resolving the equations should be in a methodology section.

We added it accordingly

> 4.- Page 2, line 22: Traditional lidar Raman are expensive but the development of the rotational Raman techniques make it cheaper and improve signal-to-noise. Please include it in your discussion.

Even if we didn't go further in the analysis, we added a paragraph describing rotational Raman lidar adding also a reference: Veselovskii, I., Whiteman, D.N., Korenskiy, M., Suvorina, A., Pérez-Ramírez, D., (2015) Use of rotational Raman measurements in multiwavelength aerosol lidar for evaluation of particle backscattering and extinction. Atmospheric Measurement Techniques 8, 4111-4122.

> 5.- Page 2, line 23: The High Spectral Resolution Lidar and Dial techniques should be commented and cited.

Added accordingly to the text.

> 6.- The NASA Aerosol-Clouds-Ecosystems mission does plan to implement a multiwavelength HSRL system in the space allowing retrievals of aerosol microphysical parameters. Please include it in your discussion.

A short paragraph was added describing ACE and referenced (Whiteman, D.N., Pérez-Ramírez, D., Veselovskii, I., Colarco, P., Buchard, V. (2017) Simulations of spaceborne multiwavelength lidar measurements and retrievals of aerosol microphysics. Journal of Quantitative Spectroscopy and Radiative Transfer, submitted.)

> 7.- Radiative transfer codes do assume certain aerosol properties for each specie. The Fu-Liou-Gu model assumes OPAC aerosol module, which may differ from real measurements. Retrievals of aerosol microphysical properties can improve retrievals of radiative forcing if aerosol effective radius and single scattering albedo are introduced. Please discuss the use of an aerosol model

We agree with the referee. However, retrievals of aerosol microphysical properties require multi-wavelength lidar (e.g. Veselovskii et al., 2002, 2015), which are very sophisticated instrument sensitive to systematic and random errors in the optical data (Perez-Ramirez et al., 2013). Because we focus on lidar systems that can operate continuously in different networks, and our radiative forcing calculations do not vary much when changing effective radius and single scattering albedo.

> 8.- I agree with the previous referees that the current title does not macth approately with the goal of the manuscript. Please consider to change it.

Changed accordingly.

RELEVANT CHANGES TO MANUSCRIPT AMTD 2017-182

Title: it has been changed accordingly as suggested by the reviewers.

We specified in the manuscript introduction that the main goal of the paper is to assess how much change the aerosol/cloud direct radiative effects when different lidar techniques and data processing are considered (e.g. simpler elastic lidar networks versus more sophisticated networks, i.e. MPLNET vs. EARLINET)

As suggested by the reviewers, we analyzed and added two more cases: a biomass burning event, and an opaque cirrus cloud. For the biomass burning case, as there is not any available climatological value for lidar ratio at 355nm, we used an averaged value obtained from the Raman channel (S=63sr). This was also partially suggested by the Reviewer #1.

In the new abstract were added the results from the new cases. The discrepancies between lidar techniques/data processing were specified in W/m^2 instead of percentage. This choice is more consistent with IPCC guidelines.

Lines 45-70 We added a more exhaustive reference list of the different passive/active methods to retrieve aerosol and cloud optical and geometrical properties both from ground and from satellite.

Lines 156-186 We added two paragraphs explaining more in detail the radiative transfer model, adding formulas that show how the direct radiative effect is calculated. Also, we added few rows to explain the aerosol and cloud parameterizations that we used in the model.

Lines 194-200 We added a paragraph to describe how the multiple scattering is affecting the calculations and the assumptions we made.

Conclusions and figures were modified with the updated results from the new cases.

Impact of Varying Lidar Measurement and Data Processing Techniques in evaluating Cirrus Cloud and Aerosol Direct Radiative Effects.

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ABSTRACT

During the last two decades, ground-based lidar networks have drastically increased in scope and relevance, thanks primarily to the advent of lidar observations from space and need for validation. Lidar observations of aerosol and cloud geometrical and optical atmospheric properties are used to evaluate their direct radiative effects on climate. However, the retrievals are strongly dependent on the employed lidar instrument measurement technique and subsequent data processing methodologies. In this paper, we evaluate discrepancies between the use of Raman and elastic lidar measurement techniques and corresponding data processing methods for two aerosol layers in the free troposphere and for thin versus opaque cirrus clouds. The different lidar techniques are responsible of larger discrepancies in direct radiative effects for biomass burning (0.05 W/m^2 at surface and 0.007 W/m^2 at top of the atmosphere) and dust aerosol layers (0.7 W/m^2 at surface and 0.85 W/m^2 at top of the atmosphere).

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On the contrary, data processing is responsible for larger discrepancies on both thin (0.55 W/m^2 at surface and 2.7 W/m^2 at top of the atmosphere) and opaque (7.7 W/m^2 at surface and 11.8 W/m^2 at top of the atmosphere) cirrus clouds. Direct radiative effect discrepancies can be attributed to the larger variability of the lidar ratio for aerosols (20-150 sr) with respect to clouds (25-35 sr). For this reason, the influence of lidar technique applied plays a more fundamental role in aerosol monitoring because the lidar ratio must be retrieved with relatively high accuracy. On the contrary, for cirrus clouds, as the lidar ratio is much less variable, the data processing is of fundamental importance because different processing is modifying the extinction profile that translates into ice crystal creation/suppression ice crystals with consequent different direct radiative effect values.

1. Introduction

According to the International Panel for Climate Change (IPCC, 2014), the major sources of uncertainty relating to current climate studies include direct and indirect radiative effects caused by anthropogenic and natural aerosols. Further, current estimates of the global aerosol direct radiative effect remain subject to large relative uncertainties affecting even the actual sign (indicating either net cooling or heating of the earth-atmosphere system), which may change from positive to negative diurnally (e.g., Campbell et al., 2016, Lolli et al., 2017a). This depends on the so-called albedo effect (or the capability of aerosols of reflecting the incoming solar light) and whether or not it is outweighing the greenhouse effect (or the capability of trapping/absorbing outgoing longwave radiation; Campbell et al., 2016)

Studies on cloud and aerosol optical and geometrical properties largely increased in the last two decades through the increasing abundance of passive ground-based measurements (i.e., AErosol RObotic NETwork Network; AERONET Holben et al., 1998, Dubovik et al., 2000, Smirnov et al., 2005, Eck et al., 2014; the Atmospheric Radiation Measurement program, Campbell et al., 2002, Ferrare et al., 2006, Perez-Ramirez et al., 2014, McComiskey et al., 2016; Aerosols, Clouds and Trace gases Research Infrastructure, Asmi et al., 2013, Pappalardo et al., 2014) or using satellite sensors (i. e. MODerate resolution Infrared Spectroradiometer; MODIS, Tanré et al., 1997, King et al., 2003, Remer et al., 2005; i. e. Multi-angle Imaging Spectro-Radiometer; MISR, Diner et al., 1998, Di Girolamo et al., 2004, Kahn et al., 2009; i.e. Polarization and Anisotropy of Reflectances for Atmospheric science coupled with Observations from a Lidar; PARASOL, Tanré et al., 2011; NASA Aerosol-Cloud Ecosystem, Whiteman et al., 2017). Nevertheless, these measurements provide only an estimate of the columnar aerosol (or cloud) optical properties.

On the other hand, the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP; Winker et al., 2007), on board of the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite launched by the National Aeronautics and Space Administration (NASA) in 2006, is capable of estimating range-resolved aerosol and cloud physical properties. However, the sun-synchronous orbit limits spatial and temporal coverage (orbital revisit time period of 16 days) that make the datasets difficult to apply and interpret for specific forms of process study. The vertical structure of cloud and aerosol properties can also be retrieved through combined lidar and radar ground-based measurements as proposed in the frame of the CloudNet European Project

(Illingworth et al., 2015). Still, the radar technique proves capable of characterizing only the relatively extreme fraction of the aerosol size distribution (Madonna et al., 2010, Madonna et al., 2013).

Based on the progress in optical technologies in the late 1990's and the beginning of 2000's, federated ground networks of lidars were established [NASA Micro Pulse Lidar NETwork(MPLNET), Campbell et al., 2002, Welton et al., 2002, Lolli et al., 2013; European Aerosol Research LIdar NETwork, (EARLINET) Pappalardo et al., 2014, Asian Dust NETwork (ADNET), Sugimoto et al., 2010, Latin American Lidar NETwork (LALINET), Antuña-Marrero et al., 2015, Lolli et al., 2015], the bulk of which are based on single or dual-channel elastic and Raman lidar instruments. The Eulerian viewpoint of ground-based lidars is providing important contextual measurements relative to satellite profiling, like from CALIOP (Winker et al., 2007).

The emerging prominence of ground-based lidar, however, strengthens the necessity for further studies of optical and geometrical aerosols and clouds properties resolved from multi-spectral lidar techniques, as claimed by several papers (Pappalardo et al., 2004, Mona et al., 2006, Wang et al., 2012, Pani et al., 2016, Lolli et al., 2013, Campbell et al., 2016, Lolli et al., 2017). Multi-spectral and Raman lidars can retrieve aerosol and cloud properties with much better accuracy without many fundamental assumptions, (e.g., Grund and Eloranta, 1991; Ansmann et al., 1992; Goldsmith et al. 1998, Mona et al., 2012, Pappalardo et al., 2014), thought with greater operational expenses. In contrast, elastic-scattering lidar instruments require such assumptions and careful consideration of measurement strategies to constrain the lidar equation (Eq. 1), defined as

$$P_r(r) = K\frac{\beta(r)}{r^2}exp^{-2\int_0^r \alpha(r')dr'}$$

(1)

where $P_r(r)$ is the received power at a range r, K is the so-called lidar constant (instrument dependent, function of detector quantum and optical efficiencies, telescope diameter, instrument overlap function, etc.), followed by the two unknown variables, $\beta(r)$ the total backscattering coefficient and $\alpha(r)$ the total extinction coefficient.

A classical method to solving Eq. (1) for single-channel elastic-backscatter lidars (Fernald, 1984) is based on the assumption of the columnar-averaged value of the ratio between the two unknown coefficients, typically indicated by S and called "lidar ratio". The method, due to the large variability of S (i.e., 20-150 sr for aerosols; Ackermann, 1998) translates into large uncertainties associated with the retrieval of α and β (Lolli et al., 2013).

Through a greater spectral complexity, it is possible to retrieve α and β with multi-spectra lidars without relying too heavily on fundamental assumptions. For instance, the combined detection of the elastic-backscattered radiation and inelastic backscattering from the Raman roto-vibrational spectrum of nitrogen (or oxygen), using the Raman lidar technique, permits solving Eq. (1) by substitution of *a through* the analytical solution of Eq. [2] as

$$\alpha_{\lambda_L}^{par}(r) = \frac{{}^{d}\!/_{dr}\left\{\ln\left[n_R(r)/P_r(r)r^2\right]\right\} - \alpha_{\lambda_L}^{mol}(r) - \alpha_{\lambda_R}^{mol}(r)}{1+\left({}^{\lambda_L}\!/_{\lambda_R}\right)^{å}} \quad , \qquad (2)$$

where λ_L is the elastic wavelength while λ_R is the wavelength of the Raman scattering, $\alpha_{\lambda_L}^{par}(r)$ represents the particle (aerosols or clouds) extinction coefficient at elastic wavelength at range r while $\alpha^{mol}_{\lambda_L}(r)$ and $\alpha^{mol}_{\lambda_R}(r)$ are the molecular extinction coefficients at wavelengths λ_L and λ_R respectively, $P_r(r)r^2$ is the detected range corrected Raman signal from range r, while $n_R(r)$ represents the number density of range-resolved scatters. The wavelength dependence of the particle extinction coefficient is described by the Ångström coefficient, å, defined from the relation

$$\frac{\alpha^{par}_{\lambda_L}(r)}{\alpha^{par}_{\lambda_R}(r)} = \left(\frac{\lambda_R}{\lambda_L}\right)^{å} \quad (3)$$

Eq. (2) allows for independently retrieving vertically-resolved optical coefficients with only very limited *a-priori* assumptions (the Ångström coefficient should be estimated or assumed, but this estimate or assumption, involving a ratio, typically amounts to less than 5% of total error; Ansmann and Müller, 2005). The particle backscattering coefficient, $\beta^{par}_{\lambda_L}(r)$ $\beta^{par}_{\lambda_0}(r)$, can be derived directly from the ratio of the Raman signal at λ_R and the elastic signal at λ_L.

However, the Raman technique exhibits instabilities in retrieving the particle extinction coefficient (Ansmann et al., 1992, Wandinger et al, 1995), and in order to reduce the random uncertainty affecting the retrieval, a smoothing of the profile is required. In turn, smoothing decreases the effective vertical resolution (Pappalardo et al., 2004, Iarlori et al., 2015) of the aerosol extinction coefficient profile.

In summary, employing different lidar techniques and/or processing algorithms lead to differences of the retrieved vertically-resolved aerosol optical properties, affecting the apparent significance, position and the geometry of observed aerosol and cloud layers.

The impact of these differences on various end-user applications has never been extensively evaluated. Since lidar-derived optical properties obtained from different instrument techniques are being more and more frequently used to assess the direct radiative effects of clouds and aerosols (e.g., Campbell et al., 2016, Lolli et al., 2017a), corresponding uncertainties in determining direct radiative effects, which may help reconcile inconsistencies in studies carried out at the global scale based on different lidar techniques, are compulsory, especially now that several new space missions with lidar on board have been launched (Cloud-Aerosol Transport System; CATS, McGill et al., 2015) or are scheduled very soon (European Space Agency Earth Care mission; Illingworth et al., 2015).

The objective of this paper is to evaluate the relative differences between the aerosol/cloud direct radiative effects both at surface (SFC) and at the top-of the-atmosphere (TOA) retrieved using the aerosol/cloud optical properties estimated using a more sophisticated versus simpler lidar technique (i.e., Raman vs. elastic lidar). To reach this goal, we use the Fu-Liou-Gu (FLG; Fu and Liou, 1992, Fu and Liou, 1993, Gu et al., 2003, Gu et al., 2011, Lolli et al, 2017b) radiative transfer model to calculate the difference in net direct radiative effect for aerosols and clouds at TOA and SFC for profiles derived from both elastic and combined Raman/elastic lidar techniques.

2. Method

2.1 Fu-Liou-Gu radiative Transfer Model

To calculate aerosol and cloud direct radiative effects, we use the one-dimensional FLG radiative transfer model, developed in the early 1990's. The original code has recently been adapted to retrieve cloud and aerosol direct radiative effects using the aerosol and cloud vertical profile of lidar extinction as input. There exist several parameterizations that provide the vertical profile of cloud microphysics using lidar-retrieved cloud extinction profile, each one with pros and cons, as showed in Comstock et al., (2007). For the purpose of this study and also considering authors past experience (Campbell et al., 2016, Lolli et al., 2017a), we parameterize cirrus clouds through the Heymsfield et al., (2014) empirical relationship conceived expressly for lidar measurements. Here, the cirrus cloud ice crystal average diameter is directly proportional to the absolute atmospheric temperature (obtained through a radiosonde, regularly launched at measurement site, or numerical reanalysis dataset). Cirrus cloud optical depth and crystal size profiles are used to calculate the single scattering albedo (SSA), phase function and asymmetry factor (AF) at each level.

Similarly, FLG calculates the direct radiative effect of aerosols as a function of the partial contribution of each aerosol species to the total optical depth at each altitude level. FLG uses a lookup table (LUT) with single scattering properties for eighteen different types of aerosols coming from the OPAC (Optical Properties of Aerosol and Clouds) database (d'Almeida et al., 1991; Tegen and Lacis, 1996; Hess et al., 1998). Among all the aerosol species, for the first of the cases discussed in Section 2.2 we assume that the dust layer is constituted by pure dust advected from Saharan region (aerosol type 17 in FLG), while in the second case we assume pure biomass burning aerosol (aerosol type 11 in FLG). Nevertheless, if the measured aerosol atmospheric profiles do not match exactly the two-selected aerosol types this does not affect the results interpretation because we are interested in evaluating the relative discrepancies among the different lidar techniques/data processing. Therefore, what is most relevant in the approach is the application of the same parameterization to each of the different techniques/data processing.

The aerosol/cloud direct radiative effect is calculated subtracting from the FLG total sky run (where aerosols or clouds are present) the FLG run with a pristine atmosphere (control), as reported in Eq. 4:

$$DRE = FLG^{TotalSky} - FLG^{Pristine} \quad (4)$$

2.2 Analysis of direct radiative effect

For the analysis in this study, we analyzed lidar data collected with the MUlti-wavelength System for Aerosols (MUSA) Lidar (Madonna et al., 2011), deployed at Consiglio Nazionale delle Ricerche (CNR), Istituto di Metodologie per l'Analisi Ambientale (IMAA) Atmospheric Observatory (CIAO) in Potenza, Italy (40.60N, 15.72E, 760m a.s.l.). MUSA is a mobile multi-wavelength lidar system based on a Nd:YAG laser source equipped with second and third harmonic generators and on a Cassegrain telescope with a primary mirror of 300mm diameter. MUSA full angle field-of-view (FOV) is large enough (about 1.5 mrad) to add important multiple scattering (MS) contributions to the retrieved extinction profile. However, for the purpose of this study we are interested in evaluating the relative discrepancies between different lidar techniques/data processing, and therefore, at this stage, do not correct for any MS contributions since we assume that this effect impacts equally both techniques and subsequent data processing.

The three laser beams at 1064, 532 and 355nm are simultaneously and coaxially transmitted into the atmosphere in biaxial configuration. The receiving system has 3 channels for the detection of the radiation elastically backscattered from the atmosphere and 2 channels for the detection of the Raman radiation backscattered by the atmospheric N_2 molecules at 607 and 387 nm. The elastic channel at 532 nm is split into parallel and perpendicular polarization components by means of a polarizer beamsplitter cube. The backscattered radiation at all the wavelengths is acquired both in analog and photon counting mode. The typical vertical resolution of the raw profiles is 3.75 m with a temporal resolution of 1 min. The system is compact and transportable. It has operated since 2009, and it is one of the reference systems used for the intercomparison of lidar systems within EARLINET (Pappalardo et al., 2014; Wandinger et al., 2016) Quality Assurance program. In this paper, the data analysis has been carried out considering four observation scenarios at night, as the Raman channel signal shows a much higher signal-to-noise ratio during nighttime:

1) **Dense Dust Aerosol and Biomass Burning Events**. The aerosol extinction profiles are retrieved using the UV (355nm) channel. For each case, the extinction profile is retrieved both with the Raman technique (Ansmann et al., 1990, Whiteman et al., 1992, Veselovskii et al., 2015) and estimated using the sole elastic channel, applying an iterative algorithm (Di Girolamo et al., 1999) with an assigned lidar ratio (S=45 sr for dust case, Mona et al., 2006 and S=63 sr for biomass burning, retrieved averaging the lidar ratio from MUSA Raman channel). Both the Raman and elastic lidar signals have been smoothed by performing a binning of 16 range gates, resulting in a vertical resolution of 60 m. For the

Raman channel retrieval, the extinction profile has been calculated using the sliding linear fit technique, with a bin number resulting in an effective vertical resolution of 360 m (Pappalardo et al., 2004). For the elastic channel retrieval, the estimated extinction profile has been first calculated with the signal full vertical resolution of 60 m and then smoothed to the same effective vertical resolution as the Raman extinction profile (360m), using a 2nd order Savitzky-Golay smoothing filter (Press et al., 1992; Iarlori et al., 2015).

2) **Thin and Opaque Cirrus Clouds**. Like aerosols, cirrus cloud extinction profiles are retrieved using the UV (355nm) channel with the Raman technique. The elastic channel retrieval for thin cirrus cloud is obtained applying the same iterative algorithm followed for dust and biomass burning. Although, for the opaque cirrus cloud, due to convergence problems of the iterative method for higher cloud optical depths, we used the MPLNET Level 1.5 cloud product algorithm (Lewis et al., 2016) based on a Klett inversion (Klett, 1985). For both cases (iterative and MPLNET), we assumed a fix lidar ratio value of 25*sr* (Campbell et al., 2016, Lolli et al., 2017a). The Raman extinction profile has been calculated with an effective vertical resolution of 420 m (thin cirrus cloud) and 780 m (opaque cirrus cloud), respectively. The iterative (thin cirrus) and MPLNET Level 1.5 cloud algorithm (opaque cirrus; Lewis et al., 2016) extinction profiles are calculated with the original signal vertical resolution of 60 m and smoothed at a resolution of 420 m (thin cirrus) and 780 m (opaque cirrus), respectively, using the Savitzky-Golay filter to match Raman channel spatial resolution.

3) The thermodynamic profile of the atmosphere, needed to calculate the direct radiative effect, is estimated using a standard thermodynamic profile (USS976) mid-latitude model. Emissivity and albedo values are taken from the MODIS Bidirectional Reflectance Distribution Function (BRDF)/Albedo algorithm product (Strahler et al., 1999), with a spatial resolution of 0.1 degrees averaged over a 16-day temporal window (Campbell et al., 2016). As each measured cloud and aerosol extinction profile comes with a relative uncertainty per range bin, the sensitivity of FLG to the input parameters is evaluated applying a Monte Carlo technique. Each extinction profile is replicated 30 times (i.e. a number statistically meaningful), running the MonteCarlo code on the original profile random uncertainty. Likewise, for each replicated extinction profile, the Monte Carlo technique gives a value of surface albedo and profile temperature, based on their respective uncertainties. The direct radiative effect parameters derived for each profile are then represented with a boxplot. It is possible then to quantify the effect of the smoothing calculating the uncertainty from the mean and the standard deviation of the values of net forcing.

3. Results

3.1 Dust and Biomass Burning Event

The analyzed dust event is retrieved from measurements taken on 3 July 2014 at CIAO. Figure 1 shows both the range-corrected composite signal at 1064nm (Fig. 1a, left panel), and the lidar aerosol extinction profiles at 355nm (Fig. 1b, left panel) obtained using the Raman technique with an effective resolution of 360m and estimated using the elastic lidar technique at two different resolutions (60m and 360m) using a fixed S value obtained analyzing climatological data (S=45sr; Mona et al., 2006). It can be immediately recognized that the Raman extinction profile is noisier with respect to those obtained with the iterative method. All the profiles, calculated with an integration time of 121 minutes, in the time window from 19:34UT to 21:40UT, show no significant aerosol loading above 5.5 km.

Figure 3a shows the difference between the estimation of the direct radiative effect using the two considered lidar techniques and data processing at TOA (Fig 3a, left panel) and at SFC (Fig. 3a right panel).The most important contribution to this difference in FLG calculations for this case is related to the adopted lidar technique (red arrows in Fig. 3a, left and right panels) and not to the effective vertical resolution determined by the smoothing (blue arrows in Fig. 3a, left and right panels). This characteristic is invariant switching from TOA (Fig. 3a right panel) to SFC (Fig. 3a left panel) and it is mainly the result of the assumption of a fixed lidar ratio to estimate the aerosol extinction profile using the elastic technique.

For the dust case, the net direct radiative effect determined with the two different lidar techniques differs by 0.7 W/m^2 (5%) at SFC and 0.85 W/m^2 (6%) at TOA. In absolute value, those net total forcing values are larger than the uncertainty on average estimated direct effect by IPCC (mean -0.5 W/m^2, range -0.9 to -0.1). The contribution due to smoothing is negligible in comparison.

The analyzed biomass burning case study is retrieved from measurements taken on 19 June 2013 at CIAO integrating the signal temporally from 19:27UT to 20:48 UT. The extinction profiles used as input into the FLG radiative transfer model was retrieved in the same way as for the dust case, but being unavailable a climatological lidar ratio value at 355nm, we used S=63 sr, obtained averaging the retrieved Raman channel lidar ratio in the biomass burning layer. In Figure 1b (right panel) are the extinction profiles obtained from both the Raman and iterative methods (full resolution and smoothed over 360m window). Figure 3b shows the difference in biomass burning direct radiative effects with respect to the different lidar techniques and data processing. Similar to the dust case event, the bigger differences are found to be related to the different lidar techniques both at SFC (0.05 W/m^2 or 5%; red arrows, Fig. 3b right panel) and at TOA (0.007 W/m^2 or 5%; Fig. 3b left panel).

The analysis shows how the mixing of different lidar techniques in a specific study or in the routine operations of an aerosol network at regional or global scale must take into account of the uncertainties related to the assumptions that are behind the retrieval of the optical properties. This is important not only to provide a complete assessment of the total uncertainty budget for each lidar product but also to enable a physically consistent use of the lidar data in the estimation of the direct radiative effect and, likely, for many other user-oriented applications based on lidar data.

3.2 Cirrus cloud

Similar to Fig.1, Fig. 2a and 2b shows the composite range-corrected signal and three extinction profiles retrieved from lidar measurements of cirrus cloud obtained with Raman channel with a vertical resolution of 420m (thin cirrus, Fig 2a,b left panel) and 780m (opaque cirrus, Fig 2a,b right panel) and with the elastic channel at two vertical resolutions (60m and 420m iterative method for thin cirrus cloud; 60m and 780m

MPLNET Level 1.5 cloud product algorithm for opaque cirrus cloud) using a lidar ratio of 25sr. The obtained cloud extinction profiles with the different lidar techniques and data processing techniques are averaged over 42 minutes, in the time window from 01:29UT to 02:13UT on 17 February 2014 (thin cirrus) and from 19:40UT to 20:44UT in 09 May 2016 (opaque cirrus), respectively.

Figure 4a depicts the results obtained for cirrus cloud measurements taken on 17 February 2014. Here we have a completely different situation with respect to the aerosol cases. That is, the discrepancies between the Raman and elastic lidar techniques (red arrows in Fig. 4a, left and right panels) are much smaller than the discrepancies due to the effective vertical resolution of the aerosol extinction coefficient profile both at TOA and SFC (blue arrows in Fig. 4a, left and right panels). This is related to the typically much stronger extinction for clouds than for aerosols. In the considered cirrus cloud case, the direct radiative effect determined with the two different lidar techniques differs of about 0.5 W/m^2 (9%) at TOA and 0.11 W/m^2 (10%) at SFC, while the effect of smoothing on a window of 420 m provides an additional difference of 2.7 W/m^2 (47%) at the TOA and of about 0.55 W/m^2 (53%) at SFC.

Results from the opaque cirrus cloud (Fig. 4b, left and right panels) exhibit a similar behavior to the thin cirrus cloud, with signal smoothing being outweighing lidar technique (blue arrow). The order of magnitude is similar to the thin cirrus cloud, with a difference at TOA between techniques of 0.8 W/m^2 (3%) and 0.38 W/m^2 (3%) at SFC. In contrast, the difference in data processing is of 11.8 W/m^2 (39%) at TOA and 7.7 W/m^2 (64%) at SFC. The results are evidence of the critical need to study cirrus clouds using high-resolution profiles of the optical properties to provide an accurate estimation of the cloud direct radiative effect.

4. Conclusions and future perspectives

We applied the adapted Fu-Liou-Gu (FLG) radiative transfer model to quantitatively evaluate how much the lidar technique and/or data processing influence the net direct radiative effect exerted by two different upper atmospheric aerosol layers (dust and biomass burning) and a thin and opaque cirrus cloud layer, both at top-of-the-atmosphere (TOA) and surface (SFC). The evaluation has been made using the aerosol/cloud extinction atmospheric profile as inputs into FLG radiative transfer model retrieved using the Raman/elastic technique and estimated by lidar elastic measurements only (iterative method for aerosol layers and thin cirrus cloud; MPLNET Level 1.5 cloud algorithm for opaque cirrus cloud). Because the Raman measurement retrieval is unstable due to the derivative of the signal at the numerator (see Eq. 2), a smoothing of the range-corrected signal is necessary to reduce the associated random uncertainty. The same processing treatment has been applied also to the elastic measurement signals.

The results show that the difference in direct radiative effect between the techniques and data processing/smoothing applied is mostly unvaried at TOA and SFC. For the dust and biomass burning episodes, the data processing/smoothing does not play a major role, but instead the lidar measurement technique is more important with respect to the final result. This can be explained by the large variability of the lidar ratio (i.e., the unknown extinction-to-backscatter ratio used to constrain the single-solution lidar equation) compared to the assumed value. The opposite is true for cirrus clouds, where the applied data processing/smoothing play a fundamental role in determining sensitivities in the final results. This is due to the smoothing effect on the observed sharp structures that strongly alters the vertical structure and the extinction of the cloud.

Summarizing, we found that for the aerosol cases, the main difference both at TOA and SFC is driven by the different lidar technique and not the data processing with a difference on dust direct radiative effect of 0.7 W/m^2 (5%) at SFC and 0.85 W/m^2 (6%) at TOA. Similarly, for biomass burning we found a discrepancy 0.05 W/m^2 (5%) at SFC and 0.007 W/m^2 (5%) at TOA. On the contrary, for the cirrus clouds, the data smoothing is producing larger differences with respect to the lidar technique. On the contrary, using a different data processing/smoothing implies a larger difference in cirrus cloud direct radiative effect. A discrepancy of 0.55 W/m^2 (53%) is found at SFC while about 2.7 W/m^2 (47%) at TOA for the thin cirrus cloud. Similarly, for the opaque cirrus the discrepancies produced by data processing/smoothing is larger with respect to the different lidar technique. At SFC we have a difference of 7.7 W/m^2 (64%) and 11.8 W/m^2 at TOA (39%). A possible explanation of this different behavior is that the FLG radiative transfer model calculations are strongly dependent on the optical depth of the examined atmospheric layer. At coarse resolution (cloud) the smoothing is producing changes in the extinction profile that translates into creation/suppression of ice crystals that have a strong influence on direct radiative effect. At finer resolution, as in the case of aerosol case studies, the smoothing is just producing fluctuations that do not influence the total radiative effect. In this case, the lidar technique is making a big difference, as an assumed wrong value for lidar ratio (*S*) that has a much larger variability with respect to the clouds, will amplify or suppress the aerosol peak that will translate into a higher/lower radiative effect.

With this study, we wish to draw attention in speculating how much derived aerosol and cloud radiative effect behaviors are dependent on lidar measurement and retrieval techniques as well as on the data processing constraints/assumptions. This dependence looks relevant for existing and future space missions involving lidar instrument, as well as for the GAW Atmospheric LIdar Observation Network (GALION; Hoff et al., 2008) project, which has as main objective to federate all the existing ground-based lidar networks to provide atmospheric measurement profiles of the aerosol and cloud optical and microphysical properties with sufficient coverage, accuracy and resolution. For future work, it is imperative on the community to continue understanding and refining what are the limits of the each lidar technique along with the related retrieval algorithms adopted in each ground-based network. FLG or any other well-established radiative transfer model then can be used as diagnostic tool to assure data quality through continued intercomparisons with real observation both at ground (using flux measurements), in situ (aircraft measurements) and at TOA (using satellite-based measurements).

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Figures

a)

b)

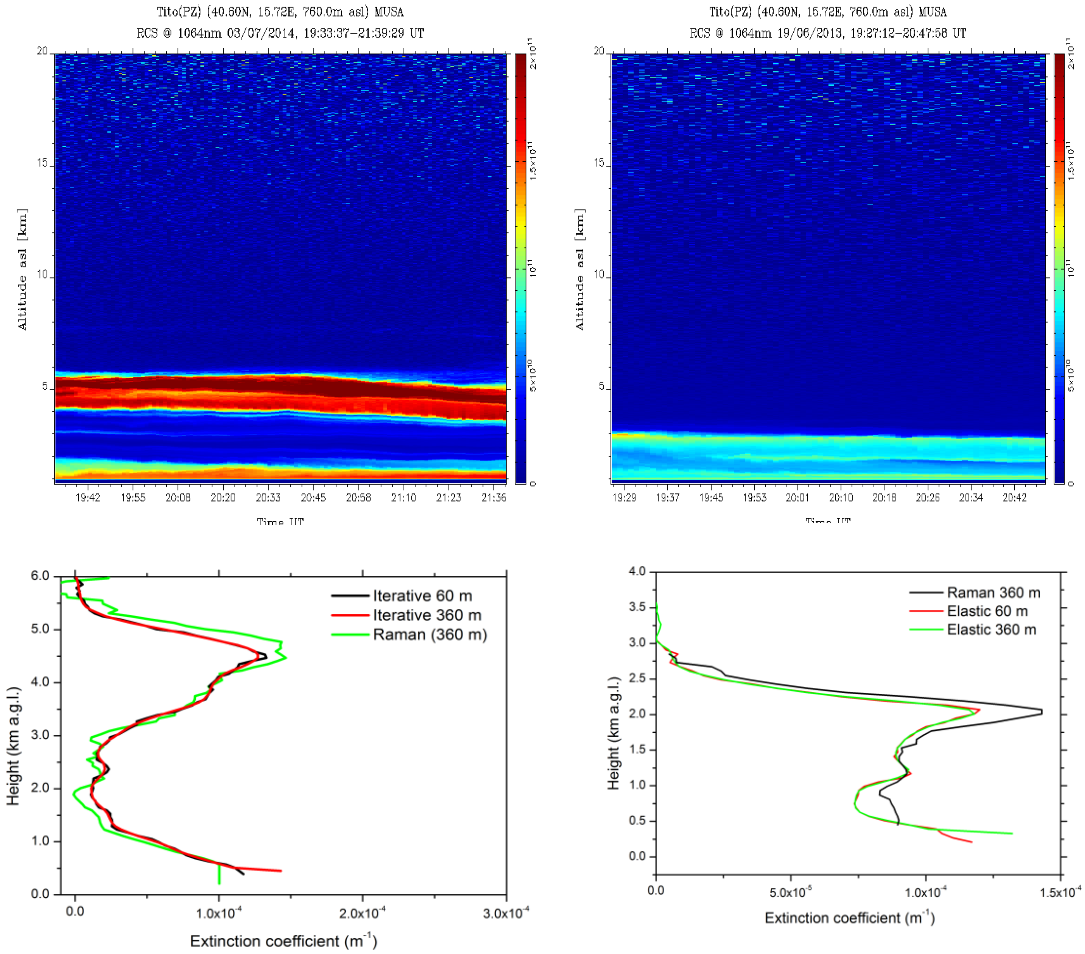

Figure 1 a): composite plot of the range corrected signal at 1064nm showing a well-defined dust layer at about 5 km a.s.l. (left panel) and for a biomass burning aerosol layer at about 2 km (right panel). b): aerosol lidar extinction profiles at 355nm retrieved with the Raman and the elastic lidar techniques with different spatial resolutions (60m and 360m) for dust outbreak on 3 July 2014 (left panel) and for biomass burning on 19 June 2013 (right panel). The iterative method used a fixed lidar ratio value of S=45sr, determined by climatological measurements (Mona et al., 2006) for the dust aerosol layer. For the biomass burning we used the averaged value of S=63sr obtained from MUSA Raman lidar.

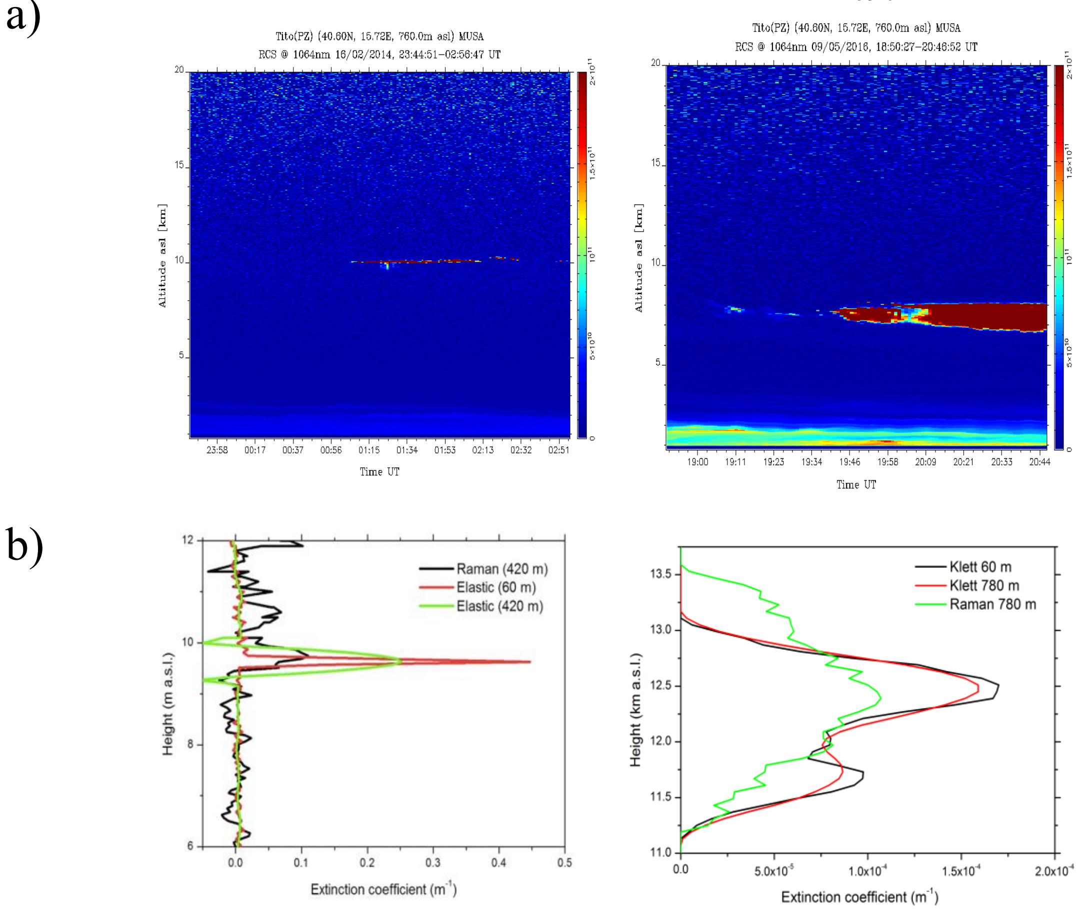

Figure 2: a) composite plot of the range corrected signal at 1064nm showing a thin cirrus cloud at about 10km (right panel) and an opaque cirrus cloud at about 12.5 km. b) left panel: lidar extinction profiles at 355nm from Raman and elastic channel respectively a cirrus cloud on 17 February 2014. The iterative method at the two different resolutions (60m and 420m) used a fixed S value (*25sr*), determined by climatological measurement. Figure 2a, b) right panels: same as Figure 2a, b) left panels but for a cirrus cloud detected on 09 May 2016. The Raman is retrieved over a 780m spatial window while the elastic channel is retrieved using MPLNET algorithm (Lewis et al., 2016) with *S=25sr* at 60m and 780m respectively.

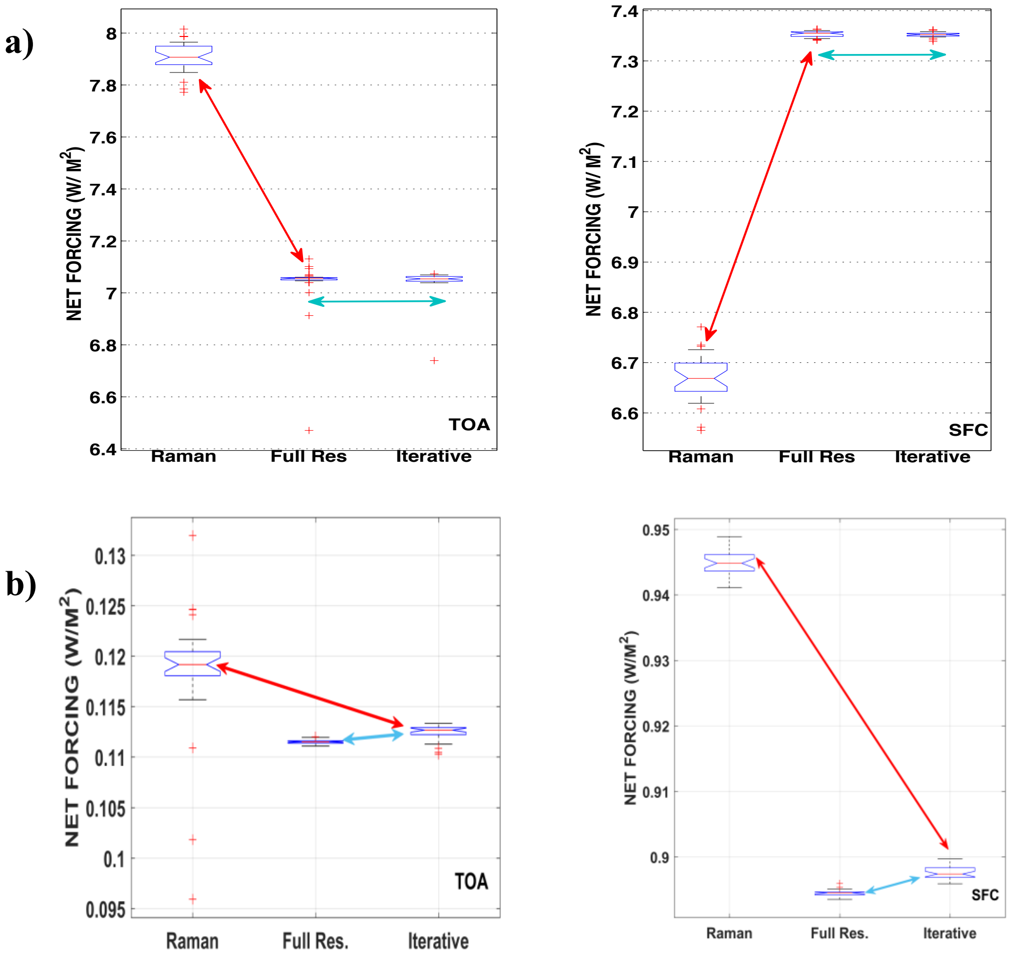

Figure 3. The direct radiative effect, for the dust aerosol case study (Figure 3a) on 03 July 2014 and biomass burning case on 19 June 2013(Figure 3b) represented as a distribution of values obtained with the MonteCarlo simulations by the boxplots, is calculated at TOA (left panel) and SFC (right panel) respectively. As it is clearly visible, the larger discrepancy in forcing is related mostly to the lidar measurements technique (red arrows), not on the data processing constraints/assumptions (blue arrows).

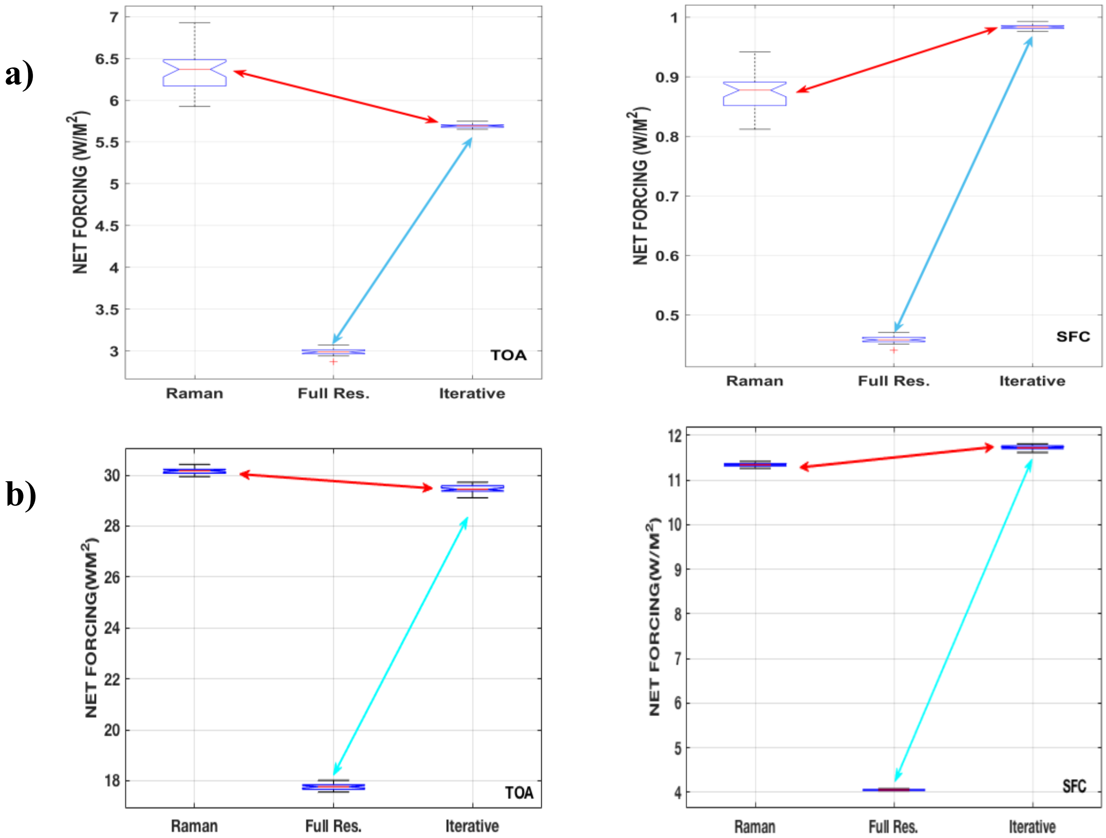

Figure 4 Same as Figure 3 but for two cirrus cloud cases (Fig. 4a, 17 Feb 2014, Fig 4b, 09 May 2016). The net radiative effect is calculated at TOA (left panel) and SFC (right panel) respectively. As it is clearly visible, in both cases the larger discrepancy in radiative effect is related mostly to the data processing (blue arrows), not on lidar technique (red arrows).