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

S. Lolli[1,2, 1], F. Madonna[1], M. Rosoldi[1], J. R. Campbell[3], E. J Welton[4] J. R. Lewis[2], Y. Gu[5], G. Pappalardo[1]

[1] CNR-IMAA, Istituto di Metodologie Ambientali Tito Scalo (PZ), Italy

[2] NASA GSFC-JCET, Code 612, 20771 Greenbelt, MD, USA

[3]Naval Research Laboratory, Monterey, CA, USA

[4]NASA GSFC, Code 612, 20771 Greenbelt, MD, USA

[5]UCLA, University of California Los Angeles, Los Angeles, USA

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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[1] Corresponding author: simone.lolli@imaa.cnr.it

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

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

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 $\alpha_{\lambda_L}^{mol}(r)$ and $\alpha_{\lambda_R}^{mol}(r)$ 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

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

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, $\beta_{\lambda_L}^{par}(r)$ $\beta_{\lambda_0}^{par}(r)$, 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) **<u>Dense Dust Aerosol and Biomass Burning Events</u>**. 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 2^{nd} order Savitzky-Golay smoothing filter (Press et al., 1992; Iarlori et al., 2015).

2) **<u>Thin and Opaque Cirrus Clouds</u>**. 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

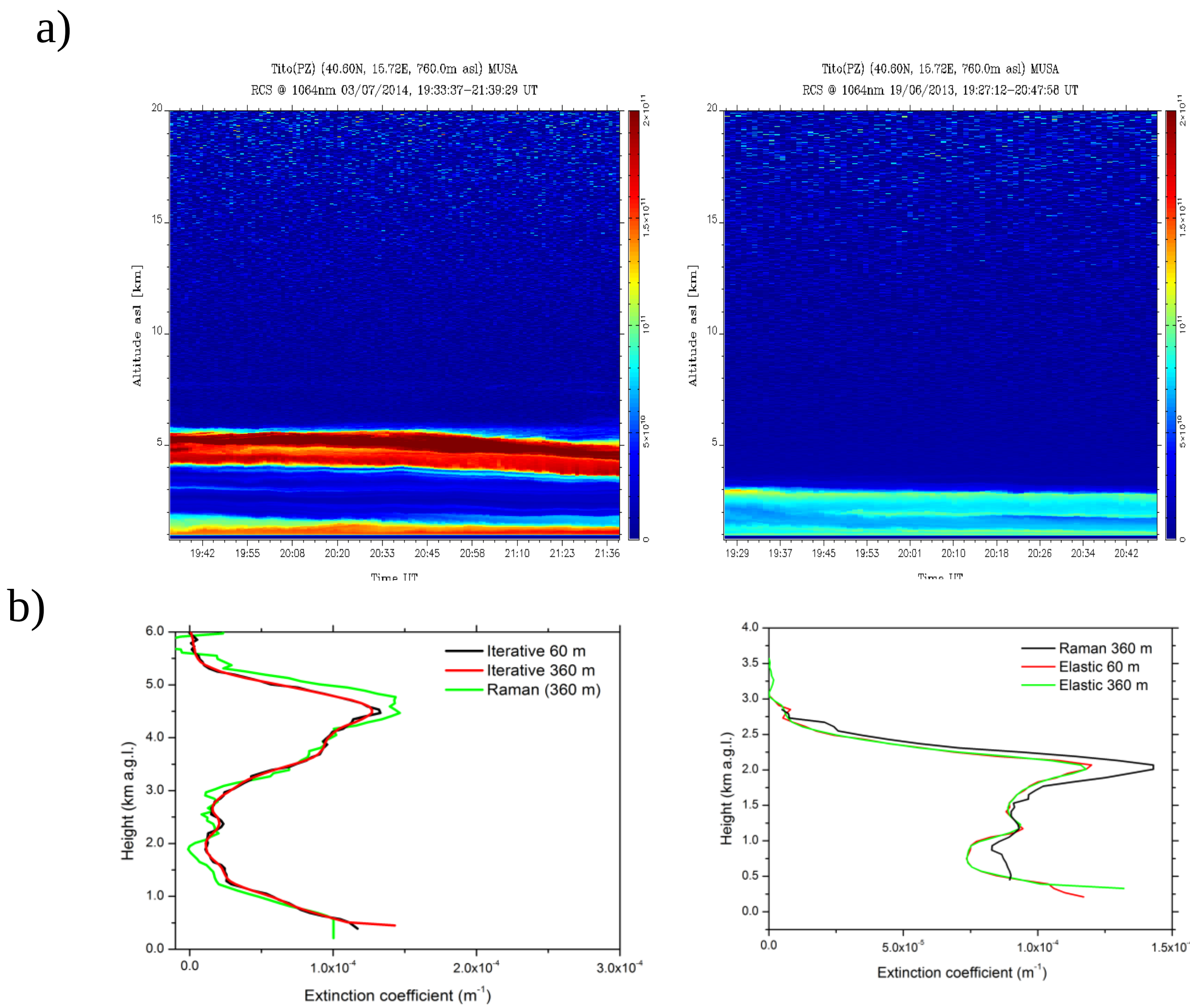

Figure 1 a): composite plot of the range corrected signal at 1064nm showing a well-defined dust layer at about 5 km a.s.l. (left panel) and for a biomass burning aerosol layer at about 2 km (right panel). b): aerosol lidar extinction profiles at 355nm retrieved with the Raman and the elastic lidar techniques 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.

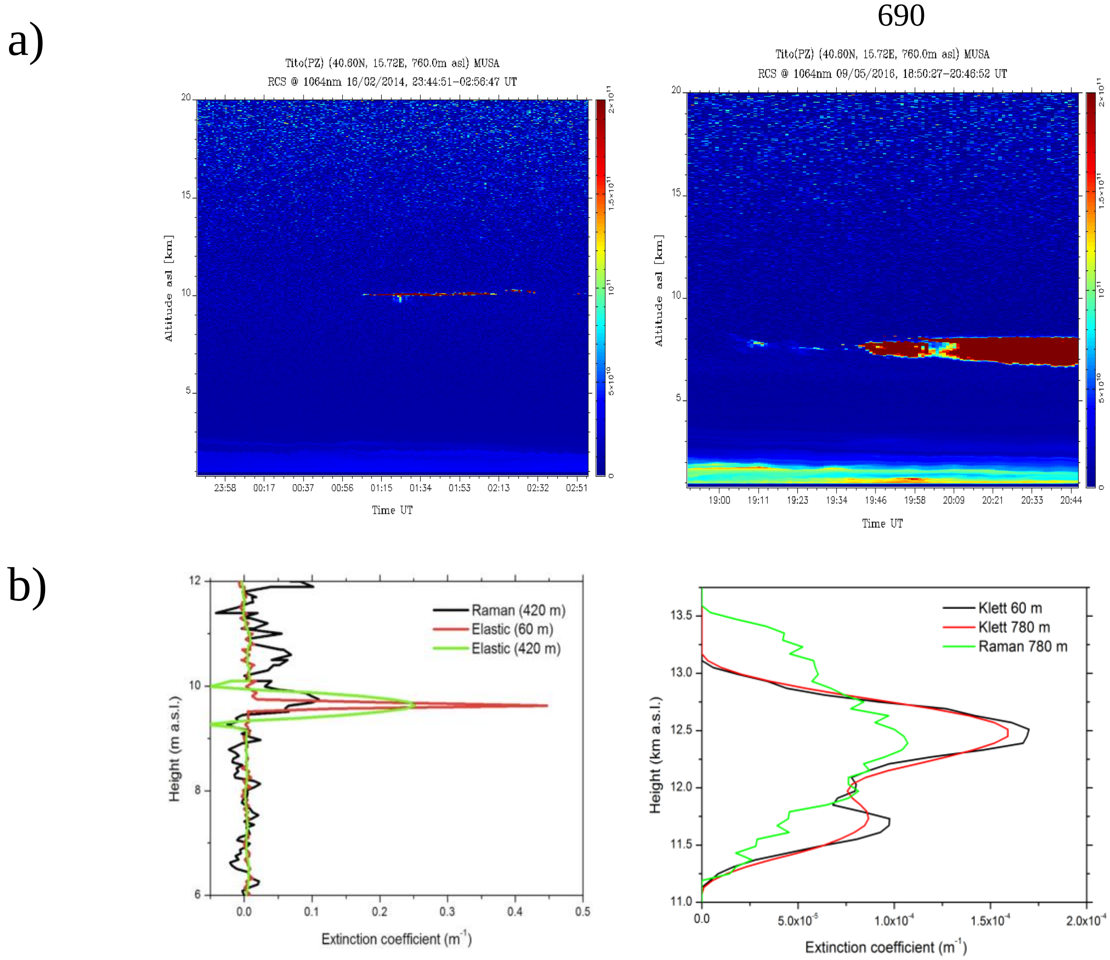

Figure 2: a) composite plot of the range corrected signal at 1064nm showing a thin cirrus cloud at about 10km (right panel) and an opaque cirrus cloud at about 12.5 km. b) left panel: lidar extinction profiles at 355nm from Raman and elastic channel respectively a cirrus cloud on 17 February 2014. The 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.

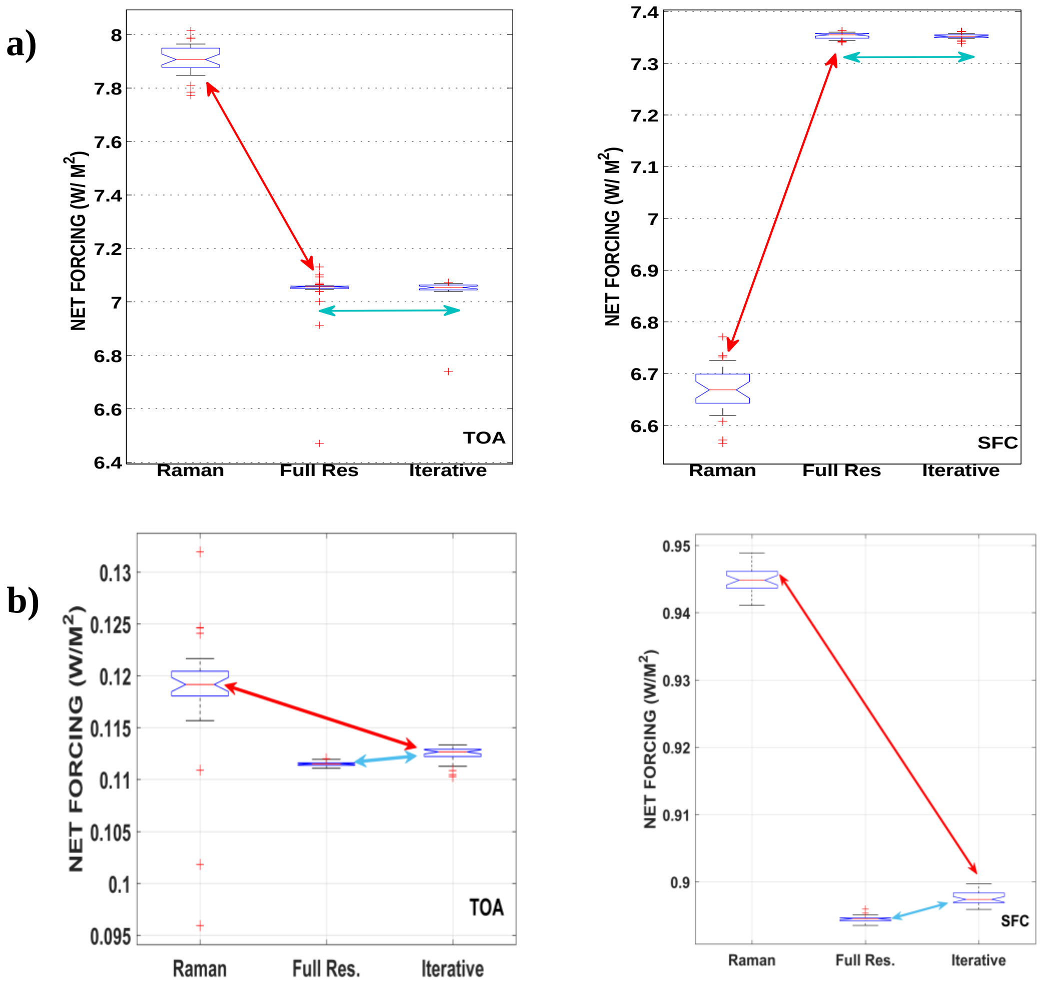

Figure 3. The direct radiative effect, for the dust aerosol case study (Figure 3a) on 03 July 2014 and biomass burning case on 19 June 2013(Figure 3b) represented as a distribution of values obtained with the MonteCarlo simulations by the boxplots, is calculated at TOA (left panel) and SFC (right panel) 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).

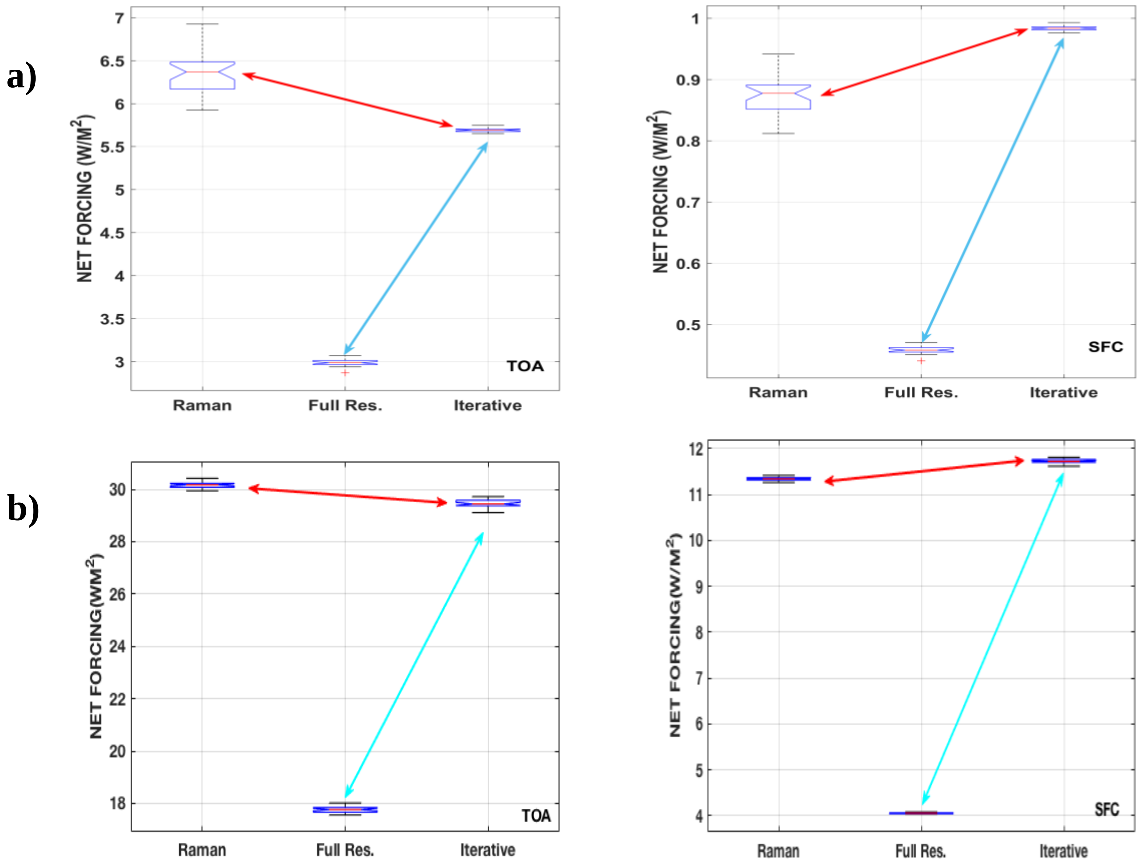

Figure 4 Same as Figure 3 but for two cirrus cloud cases (Fig. 4a, 17 Feb 2014, Fig 4b, 09 May 2016). The net radiative effect is calculated at TOA (left panel) and SFC (right panel) respectively. As it is clearly visible, in both cases the larger discrepancy in radiative effect is related mostly to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