Response to Referee #1

For referee comment no.2

Thank you for carefully checking the manuscript and providing useful suggestions to improve the paper. The replies to the referee comments are given below. The referee comments are in blue with our responses in black. The sentences in the manuscript are between the quotation marks, with the modifications in red.

The manuscript has improved after the first revision. However, I have a few comments / suggestions which relates to aspects which were not addressed properly or to some unclear expressions or misspelling. I refer mainly to my previous comments as the other reviewers may comment on their points. In bold, the text from the manuscript.

I suggest the publication of this manuscript after addressing all the points raised by Reviewers after the second revision.

General statement:

I was wondering why a common smoothing range was not used for both lidar and ceilometer. Thus, 12 bins smoothing for lidar and 9 bins smoothing for ceilometer would have given the same effective resolution of 90m.

In our current data processing program, we used odd number of bins as the sliding window for the vertical smoothing. In our future data analysis, we will improve the program so that we can used both odd and even number of bins. In this manuscript we mainly consider the layer mean values, thus we think the current vertical smoothing don't have significant impacts on the results.

Line 25: changed should be change

The correction has been done.

"

> this decrease with time could be linked to the particle aging and related changes in the smoke particle shape properties.

"

Lines 27-29: sentence is not clear:

A complete ceilometer data processing for a Vaisala CL51 is presented, including the water vapor correction for high latitude for the first time, from sensor provided attenuated backscatter coefficient to particle mass concentration.

Maybe:

A complete ceilometer data processing for a Vaisala CL51 is presented (including the water vapor correction for high latitude for the first time) and the estimation of the particle mass concentration from sensor provided attenuated backscatter coefficient.

Please revise and state what is performed 'for the first time'.

Thank you for the suggestion. We made modifications for the clarity:

"

> A complete ceilometer data processing for a Vaisala CL51 is presented from sensor provided attenuated backscatter coefficient to particle mass concentration (including the water vapor correction for high latitude for the first time).

"

Lines 98-111: references

Please add:

Tsaknakis et (2011) for ceilometer capacity of measuring smoke layers and dust layers (Atmos. Meas. Tech., 4, 1261–1273, 2011, www.atmos-meas-tech.net/4/1261/2011/)

Cazorla et al (2017) for near real time monitoring of a dust outbreak (Atmos. Chem. Phys., 17, 11861–11876, 2017, https://doi.org/10.5194/acp-17-11861-2017)

Adam et al (2016) for operational ceilometer network for pollution events monitoring (EPJ Web of Conferences, 119, 27007, 2016, ILRC 27, DOI: 10.1051/epjconf/201611927007,)

Dionisi et al (2018) for ceilometer estimates of mass concentration (Atmos. Meas. Tech., 11, 6013– 6042, 2018, https://doi.org/10.5194/amt-11-6013-2018).

Thank you for the suggestion, we made modifications in the introduction as:

“

> Ceilometer measurements have been used in several aerosol studies even though the instruments were originally designed to measure cloud heights. From an Arctic station, Mielonen et al. (2013) reported ceilometer observations of biomass burning plume heights from the 2010 Russian wildfires in northern Finland. Tsaknakis et al. (2011) present an inter-comparison of lidar and ceilometer measurements under different atmospheric conditions (urban air pollution, biomass burning and Saharan dust event), showing good agreements in determining the mixing layer height and the attenuated backscatter coefficient. Cazorla et al. (2017) present the implementation of procedures to manage the Iberian Ceilometer Network (ICENET) for monitoring aerosol characterization for near real time, which has been tested during a dust outbreak. Ceilometer measurements of the German Weather Service (DWD) network (http://www.dwd.de/ceilomap, last access: 20 July 2021) were employed to follow the progression of the volcanic ash layer (Emeis et al., 2011), and to visualise the dispersion and temporal development of the North American smoke plumes (Trickl et al., 2015). Vaughan et al. (2018) showed how a dense network of lidars and ceilometers in UK tracked the evolution of Canadian forest fire smoke. Adam et al. (2016) demonstrated that the operational ceilometer network of the Met Office can also provide valuable information for monitoring pollution events. Huff et al. (2021) demonstrated that ceilometers in the Unified Ceilometer Network (UCN, https://alg.umbc.edu/ucn/, last access: 20 July 2021) can verify and track smoke plume transport from a prescribed fire, in Maryland. Calibrated ceilometer profiles were also used as a tool to evaluate the aerosol forecasts by the European Centre for Medium-Range Weather Forecasts (ECMWF) Integrated Forecasting System aerosol module (IFS-AER) (Flentje et al., 2021). Dionisi et al. (2018) proposed a model-assisted methodology to retrieve key aerosol properties (such as extinction coefficient, surface area, and volume) from ceilometer measurements, under continental conditions; the good performances of that approach suggest that ceilometers can provide quantitative information for operational air quality and meteorological monitoring. ~~However, ceilometer studies in the literature often only provide information of layer heights and locations, mainly in terms of attenuated backscatter.~~ In order to analyse to what extent the existing ceilometer infrastructure could do in case of smoke monitoring, we performed a comparison study using an advanced Raman lidar, a ceilometer, and model data.

”

Line 128-129:

This study reports, for the first time, a quantitative comparison study for Raman lidar and ceilometer observations of smoke particles.

It is not clear what quantitative comparison for smoke particles means. Do you refer to smoke mass concentration? Please state it. Tsaknakis et al showed comparisons for attenuated backscatter from Raman lidar and Vaisala ceilometer. Mass concentration comparison between model and ceilometer (derived) is shown by Dionisi et al. No specific case of smoke only is discussed though.

Thank you for the comment, we made modifications for the clarity:

“

> This study reports, for the first time, a quantitative comparison study of mass concentration estimates of smoke particles, for Raman lidar and ceilometer observations ~~of smoke particles~~.

”

Lines 131-132

E-profile is the good example of monitoring smoke, dust and other aerosol layers. I don't know how many papers are published. E.g. Vaughan et al, 2019.

E-profile provide the near-real time quicklook of attenuated backscatter, which is good way for monitoring smoke plume location. But mass retrievals are likely even more valuable as they provide information on the mass load of the plume which is important information for example for aviation. We made modifications for the clarity:
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> Moreover, we demonstrate the usefulness of a Vaisala ceilometer to monitor smoke (in terms of quantitative information on the aerosol load) in the troposphere; the potential for mass concentration retrieval from ceilometer observations is also discussed.

"

Line 162:

When talking about radiosonde sounding, please cite Weigner et al 2019 (Atmos. Meas. Tech., 12, 471–490, 2019, https://doi.org/10.5194/amt-12-471-2019)

We have added the reference.
"

> Aiming at the observations of water vapor profiles, the most used and well-established measurement method is radiosonde sounding (Wiegner et al., 2019).

"

Line 165: GDAS1

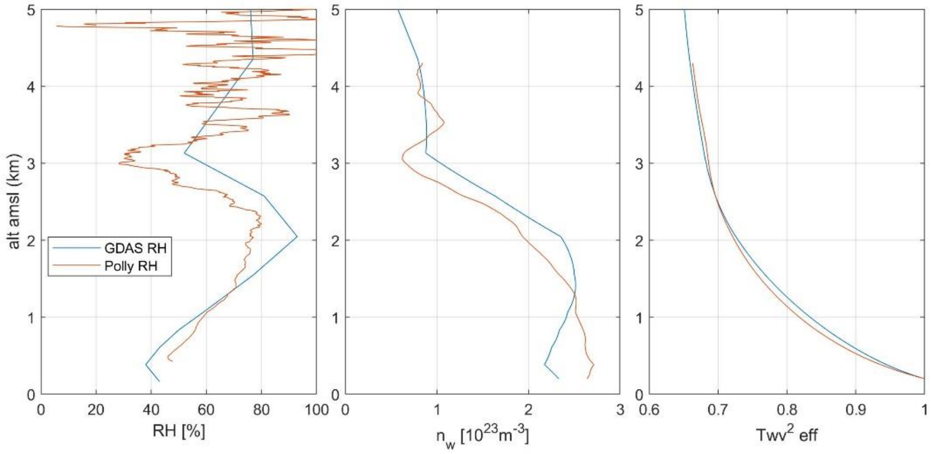
It is not discussed the uncertainty of the water vapor transmission was assumed, using GDAS1 for obtaining the water vapor number concentration. Figure 1 shows the uncertainty in the backscatter coefficients but we don't know what the input uncertainty in water vapor transmission was. The use of RH derived from Raman water vapor channel was no mentioned (as PollyXT provided it). From RH one derives AH and then number density (e.g. Bedoya-Velasquez et al 2021 (Atmospheric Research 250 (2021) 105379). However, Bedoya- Velasquez uses MWR to get T and RH.

Please add for reference Bedoya-Velasquez et al 2021 (Atmospheric Research 250 (2021) 105379) for water vapor correction.

Thank you for the comment. In this study, we used GDAS T and RH to derive absolute humidity and then the water vapor number density n_w, as the Raman lidar RH measurements were only available at night-time, and no nearby radiosonde measurements were available. Nevertheless, we have compared GDAS RH profiles with Raman lidar RH profiles, good agreements were found.
In the following figure we show for the case in Fig. 1 of the manuscript:

left: the RHs from GDAS (blue, at 21h UTC) and measured by PollyXT (orange, 20-22h UTC),
middle: derived water vapor number density n_w from RH of GDAS or PollyXT, separately.
right: calculated squared effective water vapor transmissions using RH of GDAS or PollyXT.

Note that we used GDAS temperature profile for the calculations.



We add in the manuscript:

"

The uncertainties range due to wrong assumptions of $\lambda_0 \pm 2$ nm is given by the horizontal lines in Fig. 1. The uncertainties in backscatter coefficients of the analytical solution were also shown by dashed lines. Bedoya-Velásquez et al. (2021) applied a water vapor correction method on the CL51 ceilometer measurements, based on the one proposed by Wiegner and Gasteiger (2015). They have also studied the sensitivity of the aerosol retrievals to the use of modelled temperature and absolute humidity from HYSPLIT to correct water vapor absorption, instead of the co-located Microwave radiometer measurements: it leads to errors in the pre-processed range-corrected signals up to 9 %, and in particle backscatter coefficients up to 2.2 %. Thus, an extra uncertainty should be considered as GDAS data were used for the water vapor correction. We cannot quantify the error in GDAS temperature. Nevertheless, Polly^{XT} measured relative humidity (RH) were applied for the comparison, and good agreements were found. The relative difference on the squared effective water vapor transmissions using RH profiles of GDAS or Polly^{XT} is less than 2 % for the case in Fig. 1. The input uncertainty in water vapor transmissions due to the use of modelled input was not taken into account in this study, as there was no means to quantify the value. As the water vapor contribution cannot be neglected at Kuopio during summer, the water vapor corrections have been applied to CL51 data in this study.

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Line 273:

In Haarig it is 82 ± 27. Please correct (also in Table 2).

Thank you for pointing it out. We used lidar ratio values from table 3 of Haarig et al. which were obtained from the BERTHA measurements. But now we changed to values from table 1 of Haarig et al. which were mean values with all three lidars. We corrected the values in text and in tables:

"

A value of 82 sr for LR, as measured at 1064 nm (82 ± 27 sr in Haarig et al., 2018), was assumed as being appropriate for use at 910 nm in this study.

"

in Table 1:

	Lidar ratio (sr)			PDR (%)		Ångström exponent			R_{eff} (µm)
	355	532	1064	355	532	EAE 355/532	BAE 355/532	BAE 532/1064	
Haarig et al. (2018)	45 ± 5	68 ± 9	82 ± 27	2 ± 4	3 ± 2	0.9 ± 0.5	2.1 ± 0.6	0.8 ± 0.3	0.17 ± 0.06

in Table 2:

	Parameter	Wavelength	Value	References
Method #2	Lidar ratio (sr)	355	47 ± 5	This study
		1064	82 ± 27	Haarig et al. (2018)
		910	82 ± 27*	Haarig et al. (2018)

Line 287:

If you assume that the pollen is well mixed in PBL, please mention it.

Thank you for the comments. We made modifications for the clarity:
“

Our in situ pollen measurements (more information about pollen instruments can be found in Bohlmann et al., 2021) shows high pine pollen loading at the ground (highest 2 h pollen concentrations were ~ 3000 m^{-3} on 5 June and ~ 7000 m^{-3} on 6 June). The pollen particles were well mixed in the boundary layer (below 2 km), causing strong backscattering together with high depolarization ratio at 532 nm with a clear diurnal cycle.

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Lines 405-406

I wonder if the large difference at 14-16h UTC can be due to an inaccurate estimate of the water vapor transmission term in ceilometer retrieval. Usually, the water vapor amount is higher during day time.

Thank you for the idea! We looked into this as you are right that typically the water vapor amount is higher during daytime. But water vapor transmission can be ignored at PollyXT wavelengths and retrievals based on PollyXT observations also showed large differences when compared with the model profiles. Therefore, we think that the reason for the discrepancies originates from somewhere else than the water vapor transmission.