Responses to Referee #4

I would like to begin by thanking the reviewer for the time they've taken to read and constructively comment on the manuscript titled 'An adaptation of the CO_2 slicing technique for the Infrared Atmospheric Sounding Interferometer to obtain the height of tropospheric volcanic ash clouds' (amt-2018-447). We believe that these comments have helped to improve the content and clarity of the manuscript and we hope that you agree.

Below are responses to the comments made. The reviewer's comments are coloured in blue and are in bold font. Our responses are offset from these and in black. Text in italics are relevant passages from the revised text.

Specific Comments

Page 3 line 10: Add version of RTTOV.

This now reads:

'This has been simulated with the fast radiative transfer model RTTOV (version 9, Saunders et al. *1998) and replicates what would be observed with IASI given specified atmospheric conditions'*

Page 3 line 28: The expression "L_obs ν_1" should be replaced to "L_obs (ν_1)".

Done

Page 4 line 7: "w" is used for window channel in Eq. (3) but later it uses for weighting function.

The weighting function has been changed to k

Page 4 line 9: There are no explanation for L_cld (ν) in the text. Is it the same as L_obs (ν)?

Where it occurs $L_{cld}(\nu)$ has been replaced with $L_{obs}(\nu)$.

Section 4: In the approach of CO_2 slicing of this paper, contribution of meteorological clouds seems to be omitted in radiance calculations. If so, it should be mentioned in the text.

We've added an additional line to clarify:

'To do this, the CO_2 *slicing technique was first applied to 384 simulated ash spectra. These are 'ideal' test cases, which do not include other aerosols or aqueous cloud.'*

Page 6 line 5-6: Add reference for the atmospheric profiles.

A reference has been added for the MIPAS atmospheric profiles:

'These spectra include six different atmospheres: high latitude, mid-latitude day and night, tropical daytime and polar summer and winter (including atmospheric profiles created for MIPAS; Remedios et al. 2007)'

The reference for these profiles: https://www.atmos-chem-phys-discuss.net/7/9973/2007/

Page 6 line 6-7: Add the applied ash model of refractive index for ash optical properties. Is it Pollack andesite model?

An additional line has been included:

'The refractive index used in this study is from measurements made of ash from the Eyjafjallajökull eruption (Peters, 2010): the main eruption considered in this study. In the future different refractive indices could be used such as those in Prata et al. (2019).'

Page 6 line 13-14: The values or reference for the noise of the instrument should be added.

We've added this:

'(1) $L_{obs}v_1$-$L_{clr}v_1$ must be greater than the noise of the instrument at channel v_1 (CO_2 channel); within the CO_2 absorption band the noise of the IASI instruments is between 2.55×10^{-8} and 3.77×10^{-8} W/(cm^2.sr.cm^{-1}))'

Page 8 line 28-29: More explanation for the flagged pixel is required. Do you determine the flagged pixels by yourself? What channel and threshold value are used? If the flagged pixels were given from somewhere, the data source should be added.

More detail has been added to describe the method used to flag the ash pixels prior to the application of the CO_2 slicing and optimal estimation techniques:

'In this application of the retrieval, it has only been applied to pixels which are flagged as containing volcanic ash by a linear ash retrieval developed for IASI (Ventress et al. 2016; Sears et al. 2013): following the method developed for SO_2 by Walker et al. 2012). This method compares each IASI spectra against a covariance matrix formed from pixels which contain no volcanic ash thereby representing the spectral variability associated with interfering gas species or clouds, and also the instrument noise. A least squares fit is performed for three ash altitudes (400, 600 and 800 hPa) to retrieve a value for ash optical depth. A pixel is then flagged if it exceeds a threshold at any height. As SO_2 can, with caution, be used as a proxy for volcanic ash (Carn et al., 2009; Thomas and Prata, 2011) the retrieval has also been run for pixels flagged for SO_2 using the same approach (Walker et al. 2011, 2012; Carboni et al. 2012, 2016).'

Page 8 line 29-30: Add description of surface condition (temperature and emissivity) for the calculations of L_clr. Did you use the surface emissivity model in RTTOV?

We've added a few lines to explain this:

'*For the CO_2 slicing values for L_{clr} were obtained using the radiative transfer model RTTOV using the ECMWF atmospheric profile as an input and using the default ocean emissivity within RTTOV. The effect of surface emissivity is thought to be minimal as for the channels used the weighting functions peak above the surface, Fig. 1d.*'

Page 9, Sec 5.1.1: Detailed explanation for the determination of the a priori ash height in the optimal estimation scheme is needed in the text. It is the important point in the discussion for the results of comparison between OE and your CO_2 slicing.

We have expanded the discussion of the OE scheme within section 5.2 where the results of the OE and CO_2 slicing techniques are compared. Within this we give more detail on why the CO_2 slicing performs better in these cases and why the OE is affected by the a priori used.

Following here the answer to a similar question posed by referee #1:

In this study, we have compared the CO_2 slicing results against the height output from an optimal estimation scheme, the results of which have been published previously (Ventress *et al.* 2016). This optimal estimation technique uses 105 channels, 14 of which are within the CO_2 absorption band. The channels used were not selected for their ability to obtain the ash cloud height and the previous study acknowledged that this is something that could be improved. Where there is not sufficient information about the height within the channels then the output would tend to the prior. Changes could be made to the OE retrieval, such as the inclusion of further channels within the CO_2 absorption band and this might improve the results. In this case however, we are comparing our results against the previously published study.

To avoid misleading the reader, we have removed the statement saying that '*the CO_2 slicing technique performs better than the OE technique*' (previously **page 1, line 13**) as re-reading this, this might imply that the CO_2 slicing method performs better than *any* optimal estimation scheme rather than just the version chosen for comparison.

We have also reworded the discussion of why the output of the two retrievals is different and improved the description of the a priori:

'By contrast, the OE average heights are less variable: between 3 and 4.25 km throughout the period studied. Some example maps of the OE results are shown in Fig. 10 to 13. The different assumptions and limitations of the two techniques mean that it is not expected that the two retrievals will return the same or even similar values. The optimal estimation scheme uses only 105 channels between 680.75 and 1204.5 cm^{-1} (~8.3 - 14.6 µm) to improve computational efficiency. This includes 14 channels within the CO_2 absorption band, only one of which is in common with the CO_2 slicing. However, unlike the CO_2 slicing method presented here, the channels used by the optimal estimation scheme have not been optimised for retrieving the height of the ash layer. Ventress et al. (2016) noted that the optimal estimation retrieval could be further refined by altering the channels used. For example, channels with more height information could be selected. Similarly, Ventress et al. (2016) suggested that channels could be selected to minimise the effect of the underlying cloud layers following observations that the OE method can underestimate the cloud top height in cases of multiple cloud layers (Ventress et al. 2016). In the current application of the optimal estimation scheme, where there is not sufficient information about the height of the ash layer within the channels used, the retrieval height output will tend to the a priori height which in this case is around 3.5 km. This is potentially the reason for the persistently lower average height shown in Fig. 9 which suggests a strong dependence on the a priori.'

Figure 2: Label of the ordinate seems wrong. Add values of v_1 and v_2 in this calculation.

Figure 2 has been updated to show pressure on the y axis. We've added the following line to the caption to indicate which channels are used:

'In this example v_1 and v_2 are at 715 cm^{-1} and 725 cm^{-1} respectively.'

Figure 10-13: There are no discussions for the plots of ash mass (e). Add discussion if these plots are important.

These panels in figures 10-13 have been removed.

Table 3: What does the number of "step" in table 3 mean? Why step 2 does not exist?

This column in table 3 has been removed.

Figure A7: In the caption of Fig. A7, same sentences as those of Fig.6 is not necessarys

The caption has been edited and now reads:

'Same as figure 6 without a quality control applied.'