Response to Anonymous Referee #1

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

The words "meteorological cloud" is used a lot. It is not obvious what that term means. Some explanation should be given to introduce it.

> To avoid confusion, we now use the words "aqueous clouds" and define this when it is mentioned in the introduction:
>
> *'Similar retrieval techniques exist to obtain the cloud height of aqueous clouds (i.e. water/ice clouds not associated with volcanic activity)'*

Line 12, page 3: "Assuming an atmosphere which is decreasing in temperature with height": This is not a realistic assumption since it is true only for the troposphere. There is some discussion on this in the last paragraph of section 2 but it should probably be moved here.

> This has been rephrased:
>
> *'In the Earth's troposphere where temperature is decreasing with height, the radiances measured by the instrument are proportional to the transparency of the atmosphere for each channel'.*

Do the simulated spectra cover the range of atmospheric conditions expected over the globe? The authors use six different atmospheres: high latitude, mid-latitude day and night, tropical daytime and polar summer and winter. What about tropical night, summer and winter in the tropics and mid-latitudes, etc?

> We believe that the six atmospheres chosen captured sufficient atmospheric variability to demonstrate the applicability of the method. From our results the method is weakest as the atmospheric lapse rate approach zero (polar summer). As the suggested atmospheres are far from isothermal, we do not believe much would be learned given the computational expense.

Lines 6-7, page 6: Need a reference(s) showing that those are appropriate values for ash cloud properties.

> In this study we have used a range simulated ash spectra. For the channel selection we use ash spectra representative of optically thick volcanic ash clouds (AODS: 5-15, ER: 5-10). We then test this on a

wider range of ash properties which represent thinner plumes before applying the technique to real ash scenes. We have expanded the first paragraph in section 4.1 to indicate why we chose these ranges and to emphasise that it is then tested on a wider range of properties including those more representative of thinner ash clouds:

'IASI has over 300 channels which fall within the CO_2 absorption band, and so, to ensure computational efficiency an appropriate subset of these channels must be selected. 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. 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 spectra were modelled using the refractive indices of samples of volcanic ash from the Eyjafjallajökull eruption in 2010 (Peter, 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). A range of ash properties were explored: cloud heights between 200 and 900 hPa (going slightly above the tropopause), ash effective radius between 5 and 10 µm, and ash optical depths between 5 and 15 (referenced at 550 nm). Typically, the effective radius is less than 8 µm for very fine ash (such as in a distal plume) and between 8 and 64 µm for fine ash (Marzano et al. 2018). The range of ash optical depths is highly variable. Ventress et al. (2016) and Balis et al. (2016) recorded ash optical depths of less than 1.2 from dispersed plumes from Eyjafjallajökull in 2010; however much higher values can be expected closer to the volcano or following large explosive eruptions. The effective radius and AOD explored here for the channel selection is in the upper range and above what might be expected: values which may only be true close to the volcanic vent. The spectrum of an optically thin plume is more difficult to differentiate from a clear spectrum commonly leading to the signal ($I_{obs}(v)$-$I_{clr}(v)$) to be within the instrument noise and subsequently will result in no retrieval. A decision was made to select the channels used using idealised optically thick cases, which may only be true close to the vent, for which the plume should be evident in the majority of the CO_2 channels. The selected channels are tested on a wider range of AODs and effective radius in section 4.2 including smaller values that are more representative of a disperse plume.'

How is the weighting function w = d(tau)/d(lnp) computed?

We compute the derivative of tau (output from RTTOV) with logarithm of pressure for the CO_2 channel using the IDL deriv routine. This gives weighting function profiles such as those seen in figure 1d.

The use of the weighting function (now k) to obtain a single pressure solution was originally mentioned on page 7, line 16. We've expanded this sentence to explain what this means and where the value for τ comes from:

'... where p_c is the pressure retrieved for channels v and k refers to the weighting function based on the derivative of atmospheric transmittance computed for each pressure level with RTTOV with respect to the log of atmospheric pressure ($d\tau[v,p]/d\ln p$).'

Fig. and Figure are both used. Choose one and be consistent.

We have followed the convention outlined by AMT in the Manuscript preparation guidelines. We have used Fig. where it appears in the running text and Figure at the start of a sentence.

It is surprising that a technique using just a few channels (CO_2 slicing) outperforms one that uses many more channels and retrieves several parameters self-consistently using radiative transfer simulations and iterative fits to spectra (OE). The authors suggest that this may be due to the OE retrievals being strongly influenced by the height a priori. This may be so. However, this suggests that the measurements do not have much information on ash height (otherwise, the prior should not strongly affect the retrievals). If that is the case, how does the CO_2 slicing obtain a better retrieval? A qualitative discussion of the difference between the two techniques is in order (not just that the results are different, but why they are different).

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.'*

Technical Comments

Line 7, page 2: which can result is -> which can result in

This has been corrected.

Line 10, page 3: need reference for RTTOV

This has been added:

'This has been simulated with the fast radiative transfer model RTTOV (version 9, Saunders et al. 1998) …'

Line28, page 4: remove "That"

Done

Line 30, page 4: "The second" -> "The third"

The original passage read: *'(2) the two channels used in Eq. 1 are sufficiently close that the difference in emissivity between them is negligible; (3) in cases where there are multiple layers of cloud, the lower level clouds are ignored. The second is particularly important to consider when the channel pairs are selected.'*

The channel pairs selected must have a negligible emissivity difference – this is referring to the second stated assumption. This paragraph has been restructured to avoid confusion:

'The CO_2 slicing method makes a number of assumptions: (1) the cloud is infinitesimally thin; (2) in cases where there are multiple layers of cloud, the lower level clouds are ignored; (3) the two channels used in Eq. 1 are sufficiently close that the difference in emissivity between them is negligible: this is particularly important to consider when the channel pairs are selected. Multiple cloud layers have previously been identified as a source of error in the CO_2 slicing retrieval …'

Line 8, page 5: dependant -> dependent

Done

Line 1, page 9: demonstrated -> demonstrates

Done

Line 23, page 9: including the CO_2 slicing technique -> including those obtained using the CO_2 slicing technique

This has been reworded:

'CALIOP and other LiDAR instruments are commonly used as a tool for the validation of cloud heights, including previous studies with the CO_2 *slicing technique'*

Figure 3 caption: lines of the plot -> rows of the plot

Changed.

Figure 6 caption: The plots show the true (simulated) pressure plotted against the CO_2 slicing retrieved value for the six different atmospheres. -> Panels (a)-(f) show the true (simulated) pressure plotted against the CO_2 slicing retrieved value for the six different atmospheres.

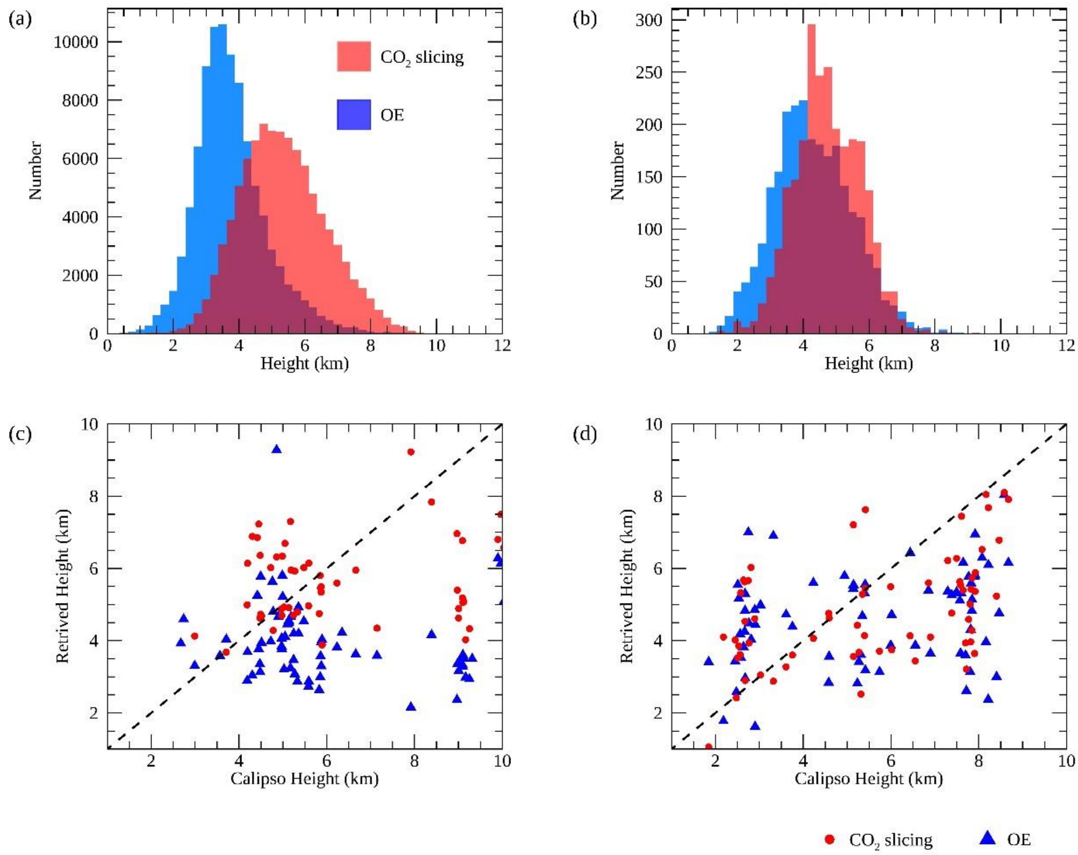
Changed

Figure 8 caption: The authors should note that the maroon distribution represents CALIOP retrievals

Panels (a) and (b) of figure 8 show the distribution of the CO_2 slicing (red/maroon) and optimal estimation (blue) heights obtained for the Eyjafjallajökull and Grímsvötn eruptions respectively. This is for all the pixels to which the retrieval was applied. Neither shows the distribution of heights obtained from CALIOP.

Panels (c) and (d) show scatterplots comparing the heights obtained with CALIOP (x axis) with those retrieved by the two IASI retrievals (CO2 slicing in red and OE in blue) again for both eruptions.

We've expanded the figure caption to make this easier to understand and added a legend for panels (c) and (d):



‘(a) Distribution of the CO_2 slicing and optimal estimation retrieved ash heights for all pixels from the Eyjafjallajökull eruption. (b) Same as (a) for the Grímsvötn eruption. (c) Comparison of the CALIOP heights with those obtained with the CO_2 slicing and optimal estimation techniques for a subset of pixels (where measurements fell within 50 km and 2 hours of each other) from the Eyjafjallajökull eruption. (d) Same as (c) for the Grímsvötn eruption. Related statistics can be seen in table 5.’