Response to Anonymous Referee #2

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. In particular we have expanded our discussion of the optimal estimation scheme and why we believe the CO_2 slicing technique has performed better in the cases studied.

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.

Major Comments

1) Abstract and elsewhere: The statement in the abstract reads "Overall, the CO_2 slicing tool performs better than the optimal estimation scheme", which stopped me in my tracks! In common with the report of Referee #1, I was surprised by this – why indeed should the CO_2 slicing approach (which is basically a cut-down version of a full OE retrieval) outperform the OE approach? I feel that this should be explored in some more detail, because this (for me) is the main scientific issue in this manuscript. The authors suggest that the prior height constraint is responsible for the low ash height bias shown by the OE retrievals – to me, this suggests that the prior is clearly not appropriate in this case, or is being given far too much weight in the analysis.

> **Following here the answer to the same question posed by referee #1:**
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> 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.
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> 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.
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> We have also reworded the discussion of why the output of the two retrievals is different and improved the description of the a priori:
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> *'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.'*

2) Section 4.1, paragraph beginning "Figure 3 demonstrates. . .": I felt that this paragraph didn't really do justice to the description of Figure 3, and I think it would be good if the reader could be "guided" through the details of this Figure a little bit more. When you say ". . .the best performing channels. . .", do you mean CO_2 channels, reference channels, or both? When you say "As expected, this shifts from lower wavenumbers at lower pressures to higher wavenumbers closer to the surface", I found it very hard to interpret the intended meaning. Is "this" referring to the "best performing channels"? I really couldn't reconcile this sentence with what I was seeing in Figure 3.

The description of figure 3 was previously on **page 6, lines 24-34**.

We have expanded this paragraph to provide more detail on what is shown in figure 3. We now hopefully guide the reader through this better and demonstrate that the height of the ash layer affects the performance of the different channel combinations:

'Figure 3 demonstrates that the best performing channel pairs vary depending on the height of the plume. For plumes at lower pressures, the maximum pressure difference between the simulated and retrieved pressures is smaller at lower CO_2 *wavenumbers. For example, for the plumes simulated at 300 hPa, the maximum pressure difference was lowest (less than 20 hPa) for* CO_2 *channels between 700 and 710* cm^{-1}*. As the pressure of the ash layer is increased, values are no longer obtained at smaller wavenumbers. For example, for a plume at 500 hPa, solutions are no longer obtained for* CO_2 *channels which are less than 700* cm^{-1}*: the maximum pressure difference between the true and retrieved values is now smaller for slightly higher wavenumbers. For a plume at 800 hPa the maximum pressure difference is lowest (less than 60 hPa) for* CO_2 *channels between 715 and 720* cm^{-1}*. This observation reflects what is shown in figure 1b and c: that the channel's peak sensitivity shifts from higher in the atmosphere at lower wavenumbers to close to the surface as higher wavenumbers effecting the best performing channel combination. Notably, at 200 hPa there...'*

3) Section 5.2, page 10, 28-29: You suggest that "In future applications of the OE scheme, the CO_2 slicing results could be used as the a priori". I disagree very strongly with this statement! One CANNOT use as prior information a state which has already been influenced by the measurements themselves. You could use the CO_2-slicing solution as the first guess in the OE iterative process, but absolutely not as the prior constraint. There's an equivalent comment in Section 6 (line 16 on page 12).

The optimal estimation scheme used for comparison in this study uses a total of 105 channels as opposed to the entire spectra to improve computational efficiency. Of these only 14 are within the CO_2 band. The optimal estimation scheme only uses one channel which is also used by the CO_2 slicing scheme. If that channel were excluded from the optimal estimation retrieval, then the CO_2 slicing result could be used as an a priori as it is not based on the same measurements. This has hopefully been clarified with the addition of further description about the optimal estimation scheme (as described in response to your first comment) and an additional line has been included after the comment about using the CO_2 slicing heights as an a priori in section 6:

'In future applications of the OE scheme, the CO_2 *slicing results could be used as the a priori if the one* CO_2 *channel that the two retrievals have in common was removed from the optimal estimation scheme'*

Minor comments, grammar, typos, suggestions, etc.

1) Section 2, page 4, line 2: "dependant" in this context should, I think, be "dependent"?

Done

2) Section 3, page 5, line 16: Trivial I know, but EUMETSAT usually insist that the satellite name is "Metop" and not "MetOp"!

Done

3) Section 4.1, and elsewhere: I note that you use "mb" for pressure units – I suspect the journal would prefer "hPa".

This has been changed throughout.

4) Section 4.1, page 6, line 9: When you use the phrase "is greater than the CO_2 channel", in what sense is "greater than" meant in this context? Channel number, wavenumber? Best to be absolutely explicit for clarity.

This was referring to wavenumber which has now been stated:

'The CO_2 *slicing method was first applied using every channel combination between 660 and 800* cm^{-1}*, where the reference channel (*v_2*) wavenumber is greater than the* CO_2 *channel (*v_1*) wavenumber.'*

5) Section 4.2, page 6, line 16: When you say "The top two lines show. . .", I suggest using the word "rows" instead of "lines".

Done

6) Section 4.2, page 6, lines 26 and 29: You use the phrase "less channels" a couple of times. It should be "fewer channels".

Done

7) Section 4.2, page 7, lines 16-19: It's not made clear in the text why you make the distinction between using narrower ranges for the channel selection work (ash optical depths ranging between 5 and 15, ash effective radius between 5 and 10 microns) than for the simulated retrieval work (ash optical depths ranging between 0.5 and 15, ash effective radius between 1 and 10 microns). It would be good for you to be explicit as to exactly why you didn't use "spectra representative of thinner ash clouds" for the channel selection.

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

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.'

8) Section 5, page 8, line 31: "planck" should have upper-case "P".

Done

9) Section 5, page 9, line 33: You say that you have defined the tropopause "as the height at which the temperature profile inverts and has a positive gradient", but it's confusing that the tropopause dashed lines in Figures 6(a-f) have obviously not used this definition!

This has been rewritten to avoid confusion. When applying the CO_2 slicing technique to simulated data to select the channels and then test the applicability of the technique, the procedure was allowed to return values above the tropopause to test how successfully it performed. As the method was shown to perform poorly when the temperature gradient is stable, for the application to real ash scenes, it was only allowed to retrieve up to the tropopause as defined by the WMO. Figure 6 shows the tropopause (dashed line) as defined by the WMO.

The rewritten passage:

'Another point to note is that, in section 4, the maximum height that could be retrieved was defined as the height at which the temperature profile inverts and has a positive gradient. This is slightly above the tropopause which is defined by the World Meteorological Organisation (WMO) as the point at which the lapse rate is less than 2°C/km, and remains lower than this for at least 2 km. This was done to demonstrate how the CO_2 slicing method performs above the troposphere where the atmospheric temperature does not vary significantly: the atmospheric lapse rate here approaches zero. Figure 6 demonstrates that the CO_2 slicing method performs poorly in these cases and so in the application to real data the CO_2 slicing method is only allowed to retrieve values up to the tropopause as defined by the WMO.'

10) Section 5, page 9, lines 1-2: When you say "Figure 6 demonstrated that the CO_2 slicing method performs poorly where the temperature profile steepens significantly", can you clarify exactly what "steepens" means in this context – when dealing with (negative) vertical gradients, it's very easy for the reader to become confused with words such as "steepens"!

This has been rephrased to improve clarity:

'This was done to demonstrate how the CO_2 slicing method performs above the troposphere where the atmospheric temperature does not vary significantly: the atmospheric lapse rate here approaches zero.'

11) Section 5.2, page 10, lines 31-32: You say that "Ventress et al. (2016) identified that in some cases the retrieval assumed a lower altitude and a higher ash optical depth in order to fit the spectra". Lower/higher than what? Just needs to be a little clearer.

We have expanded this sentence:

'Ventress et al. (2016) identified that in some cases the retrieval underestimated the altitude of the plume and obtained a high ash optical depth in order to fit the measured spectra, when in reality the ash layer might have a lower optical depth and higher altitude.'

12) Figure 4: What is the x-axis here? The y-axis is labelled simply as "Wavenumber". Presumably they should both be the same as for Figure 3?

The x axis was also wavenumber. The axes have now been labelled CO_2 wavenumber (x axis) and reference wavenumber (y axis).

13) Figures 10-13: Where does the retrieved ash mass come from – the OE retrievals? In any case, it's not clear to me exactly why these mass column loadings have been included in the paper, as I don't believe they are ever referred to. What do they add to the paper?

The ash mass can be calculated from the ash optical depth and effective radius obtained with the optimal estimation scheme (assuming an ash density). The maps of these are included for reference.

We have included an additional line within the manuscript which makes reference to these plots:

'Some example maps of the OE heights are shown in Fig. 10 to 13b, alongside the ash mass (panel c) calculated from the OE retrievals of AOD and effective radius, assuming an ash density. The maps of ash mass show that in general the ash mass falls with transportation away from the vent.'

As we do not refer to panel (e) of figures 10-13 within the paper we have decided to remove these.

14) Table 3: Needs units! Presumably the "Channel Ranges" etc. refer to wavenumbers (cm^-1)? Are the "Peak Sensitivity Ranges" in mb/hPa?

We've added units to the table. The channel ranges/reference channel are in wavenumber (cm^{-1}) and the peak sensitivity was in (hPa).