

Detecting the Passive Outgassing of CO₂ from Volcanoes Using MetOP-C IASI Spectra

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Abstract

This report looks at the possible ways of directly detecting passively outgassed volcanic CO₂ using data from the Meteorological Operational Polar Satellite-C (METOP-C) and its onboard Infrared Atmospheric Sounding Interferometer (IASI) instrument. Data from over Mauna Loa, Hawaii, and Mount Etna, Italy, has been analysed. 5 different methods were used with increasing complexity, the final method using a dot product calculation to compare the observed spectra with expected atmospheric spectra produced from the Reference Forward Model (RFM) and incorporating a background temperature gradient afterwards. This led to the conclusion that the other background atmospheric variables need to be more accurately filtered out using methods such as singular vector decomposition so that orbits with a larger proportion of cloud-covered IASI pixels can be inspected.

1 Introduction

Given that global warming is an increasingly prevalent issue, accurately monitoring the flux of gasses that reinforce its effects has become essential for providing climate model predictions. CO₂ gas in particular has many sources and sinks that have not yet been directly or accurately measured, including non-anthropogenic sources such as the passive outgassing of volcanoes. As of April 2026, the average concentration of CO₂ in the atmosphere

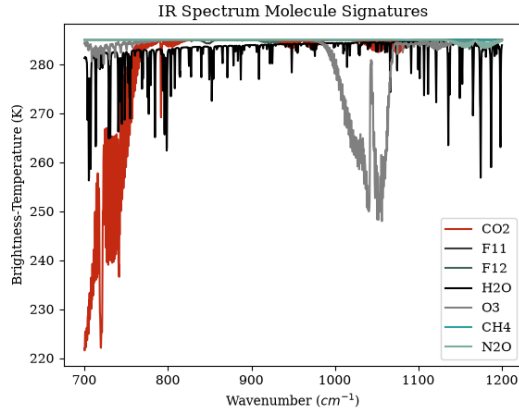
is 428.55 ppmv (Lan et al. 2026). This is a relatively high background concentration that complicates identification and quantification of localised volcanic changes. Previously, this has been overcome by using indirect methods, such as multiplying SO₂ emission rates (measured by ultra-violet spectroscopy) by a C/S mass ratio. However, this introduces multiple uncertainties from the measurements of each variable and misses out possible locations where a volcano does not emit a directly proportional volume of SO₂ to CO₂ (Werner et al. 2019). Alternatively, since the launch of the Meteorological Operational Polar (MetOp) series of three satellites from 2006, there is now the option of attempting to directly measure atmospheric CO₂ using the onboard Infrared Atmospheric Sounding Interferometer (IASI) instrument.

1.1 IASI

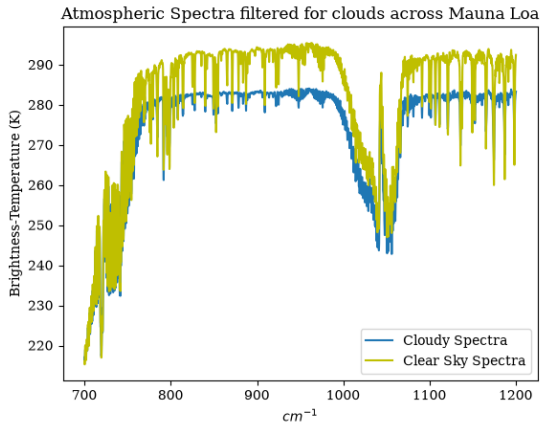
The IASI is a fourier transform spectrometer recording thermal infrared radiation (TIR) emitted by different components of the Earth across a spectral range of 645–2760 cm⁻¹ (EUMETSAT 2018). This is represented in wavenumber (cm⁻¹) which is the reciprocal of the wavelength (cm) detected. The CO₂ TIR signature is highlighted in red in Figure 1a, where brightness-temperature (K) is the temperature something appears to have based on the radiation it emits. Spectra can be filtered through multiple flags — including cloud percentage, land cover, and solar zenith angle — utilising code provided by the Earth Observation Data Group (EODG). Figure 1b

shows a standard IASI atmospheric spectra from Hawaii with a clear sky in comparison to one with clouds. As shown, clouds reduce the brightness-temperature of the spectra, but only do so minimally for the CO₂. The spatial data associated with the produced spectra are outlined in Figure 2.

Figure 1



(a) Brightness-temperature signatures that correspond to major TIR absorbers/emitters in the atmosphere in the range of 700–1200cm⁻¹. Highlighted in red is the CO₂ signature which shows a peak absorption around 700–850cm⁻¹



(b) Brightness-temperature spectra for 2 different pixels recorded by IASI over the ocean off the coast of Hawaii. The cloudy spectrum shows a considerable reduction in brightness-temperature.

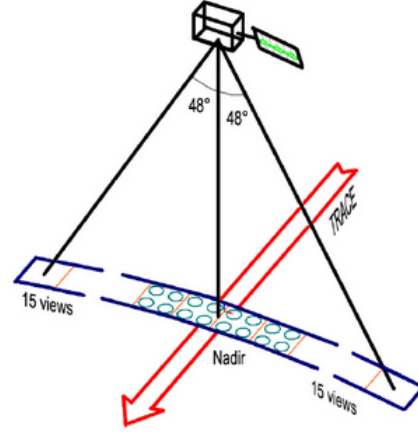


Figure 2: Spatial features of the IASI instrument. It has a swath width of ~ 2200 km and 4 footprints of 12 km diameter. Each footprint corresponds to 1 pixel. Image source: Clerbaux et al. (2009).

1.2 Volcano Locations

During this work Mauna Loa and Mount Etna have been used as the main locations from which to measure spectra. These have been chosen due to the availability of clear sky spectra for them and that the latter two are island volcanoes. Using an island volcano gives the option of filtering out points retrieved from land so that there is a uniform background noise level and temperature across all of the spectra.

2 Methodology and Results

Primarily through each method the brightness-temperature spectra from the MetOP-C orbit on 17/01/2022 between 6-8am over the coordinate box of 159 – 152° W, 16–23° N, centring on Mauna Loa, Hawaii, has been used. This orbit had the largest number of clear sky pixels compared to any of the other orbits and volcano locations inspected. Although spectra from these orbits and locations have been analysed and will be included, graphs haven't been

consistently produced for each method.

Throughout all the methods, the Reference Forward Model (RFM) has been used to produce 2 files: a standard atmospheric file and an enhanced CO₂ atmospheric file with a perturbation of 1ppmv CO₂ added from 1–3 km in the troposphere. The RFM is a line-by-line radiative transfer model (Dudhia 2017).

NOAA’s Hysplit wind trajectories archive (Stein et al. 2015) (Rolph et al. 2017) has also been used as a reference for the wind direction and speed during each orbit. In theory this direction should match the direction of increased CO₂ plotted on the graphs produced. The forward wind trajectories starting from Mauna Loa have been plotted for altitudes of 3 km, 4.5 km and 5.5 km. The elevation of Mauna Loa is ~4.5 km.

The data used in the results figures are plotted over Mauna Loa on 17/01/2022 unless specified otherwise.

2.1 Method A

Initially, using the EODG python reader for IASI L1C.nat files, all IASI clear sky pixels located over the ocean and within the coordinate box were plotted. These pixels were then sorted into 20° sectors surrounding the volcano using 155.592°, W, 19.472°, N as the centre point for Mauna Loa. The mean of the brightness-temperature spectra between 700–1200 cm⁻¹ was then calculated for each sector and the difference was taken between that and the sector 180° opposite. This produced 9 spectra differences. In the case where a few of the differences were of similar magnitudes the pixels were reorganized into new sectors with a 10° offset from the first bearings. This produced another set of 9 spectra differences. Then, using the two RFM files, the difference was calculated between them to render a standard CO₂ increase, r , representing what spectra was ex-

pected to be seen. This was visually compared to the spectra differences to identify which segment pair was the upwind and downwind pairs. Figure ?? shows the 180° sector pair with the largest brightness-temperature difference value for 17/01/2022 is 60–80° and 240–260°, which clearly does not line up with the wind direction for the orbit shown in Figure 3. Having tested this method on other orbits and locations, this tends to be the general case. Therefore, noise is likely affecting the calculated differences, and more constraints need to be added. It would also be useful to see how different each sector mean spectrum was from a standard atmosphere spectrum on its own.

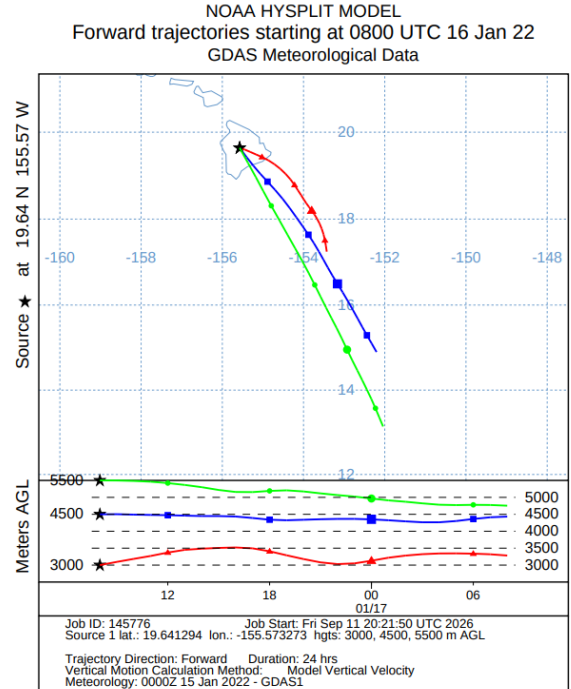
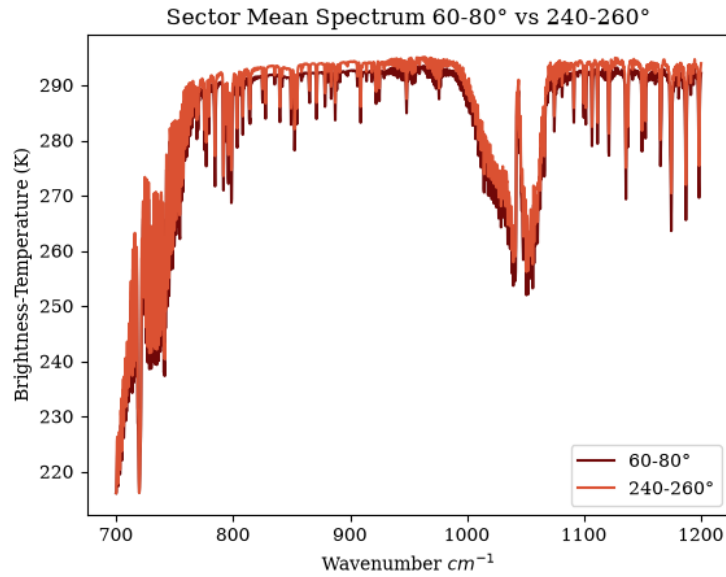
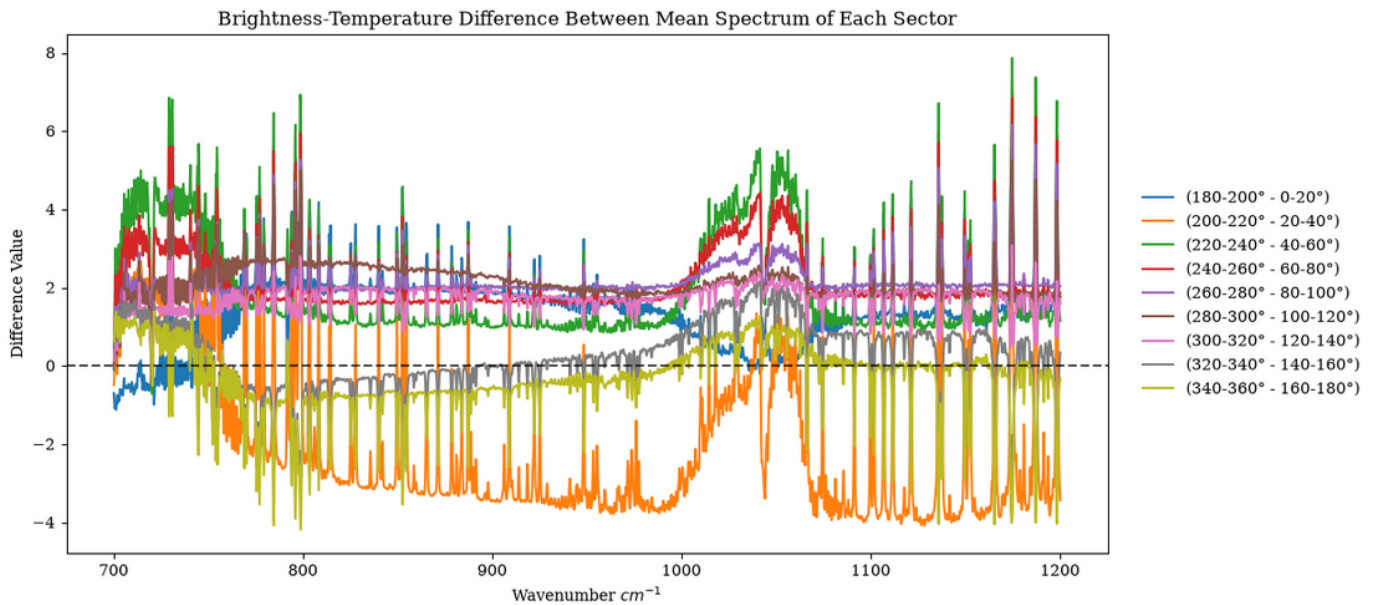


Figure 3: The NOAA Hysplit data for the wind direction and speed beginning at approximately 24 hours before the end of the MetOp-C orbit on 17/01/2022.

Figure 4



(a) The mean brightness-temperature spectrum of sector 60–80° and sector 240–260° plotted together. These are the two spectra used to calculate the difference values for the red line plotted in (b).



(b) All the brightness-temperature sector pair differences for 17/01/2022 plotted together on one graph. Notably the difference values for 60–80° and 240–260° are not the largest at any particular point on the graph but their mean difference value has the largest magnitude compared to the other sector pairs.

2.2 Method B

A maximum radius of 280 km from the volcano for each pixel was introduced. The sorting of pixels into 20° sectors and calculating a sector mean spectrum was repeated but then a ‘residual’ spectrum, s_j , was calculated for each sector using the equation:

$$s_j = \langle s_{i+1} + s_{i-1} \rangle \quad (1)$$

where s_i is the average spectrum from the target sector and $\langle \dots \rangle$ denotes the average.

Then, the dot product between $\mathbf{r}$ and the residual spectra was taken according to the following equation to produce a value x for each sector:

$$x = \mathbf{r} \cdot (\mathbf{s}_i - s_j) \quad (2)$$

This was then repeated for the 10° offset sectors and their arrows were overlaid on the

same graph. In Figure 5 the magnitude of the dot product is represented by the size of the arrow using a logarithmic scale and whether the value was positive or negative was represented by the colour.

From Figure 5a it is obvious that an increase of CO₂ in the downwind direction has not been picked up and that there is some issue with the dot product calculation comparing the data to the RFM files. Figure 5b shows an example of a graph where all the IASI pixels have been replaced with the RFM standard atmosphere spectrum apart from one that has been replaced with the CO₂ perturbation spectrum. This synthetic data is ideally the pattern the graph with real data should be showing. From this it can be assumed the code itself is working properly. Likely the real data has too much noise for a simple model to pick up the small increase of CO₂ compared to a slightly varying background concentration.

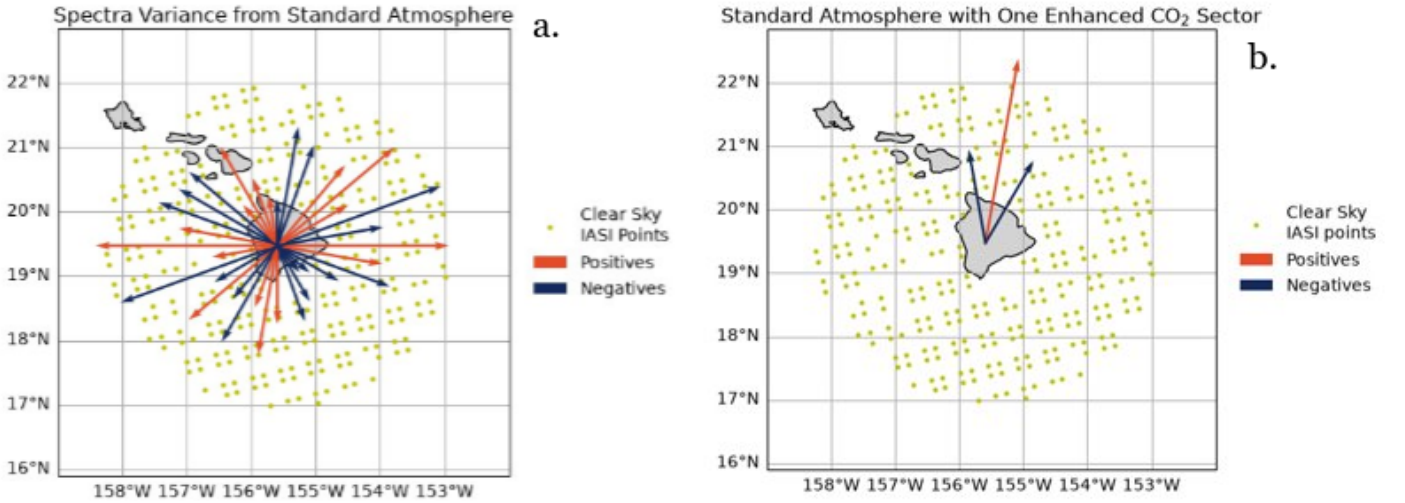


Figure 5: Graphs plotted using Method B. (a) is the real data whereas (b) is synthetic data (replacing the real spectra with the RFM spectra) demonstrating what a graph should look like if there was only a CO₂ increase in the sector 0–20°.

2.3 Method C

This iteration was the same as the last except for three parts. First, s_j was redefined as:

$$s_j = \langle \mathbf{s}_{i \neq j} \rangle \quad (3)$$

Then, a new constant, a , was calculated using the following equation:

$$a = \mathbf{r} - \hat{\mathbf{r}} \quad (4)$$

where $\hat{\mathbf{r}}$ = the mean value of all the elements of $\mathbf{r}$.

This was done to remove any constant differences between the spectra when the dot product with the residual spectra was taken later according to the equation:

$$x = a \cdot (\mathbf{s}_i - s_j) \quad (5)$$

The arrows calculated from this were plotted the same as before. With only clear sky

pixels this produced a similar graph to before, Figure 6a, but when cloud and land pixels were reintroduced, the negative arrows grouped on one side of the volcano and most of the positives within the other 180°. This is demonstrated in Figure 6b. Figure 6d is the cloudy and clear sky data plot for a different orbit on 02/02/2025, showing a small negative value in the centre of the positive side. The split in this graph is likely due to cloud pixels clustered in specific sections of the map. Figure 6c shows the synthetic data for Method C and that it differs from the synthetic data for Method B. This is to reduce the magnitude of the arrows not in the downwind sector, rather than only affect the arrows in the neighbouring sectors. This method was repeated for smaller wavenumber intervals in an attempt to reduce the noise incorporated in the calculations. The interval of 700–750cm⁻¹ was carried forward through the later methods.

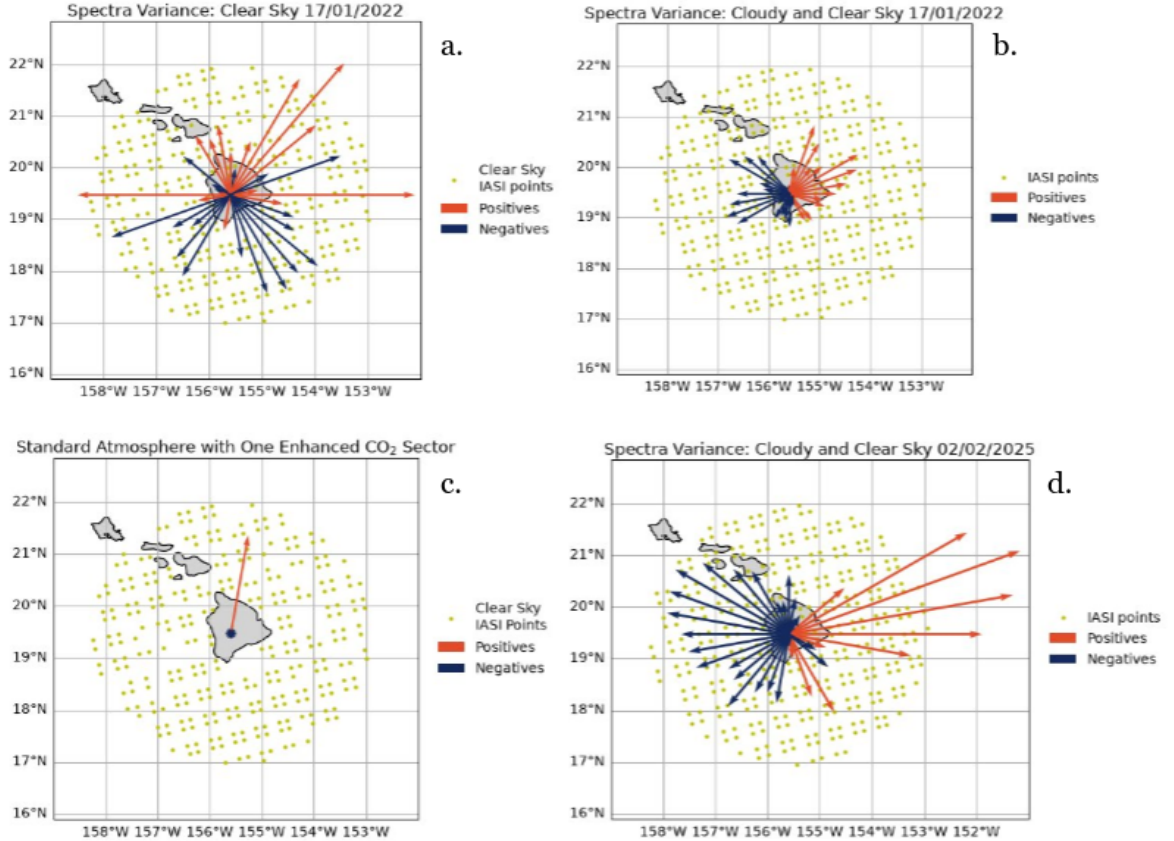


Figure 6: Graphs plotted using Method C. No land pixels have been filtered out. (a) and (b) are both on 17/01/2022 but (a) has cloud pixels filtered out of the calculations. (c) is synthetic data (replacing the real spectra with the RFM spectra) demonstrating what a graph should look like if there was only a CO₂ increase in the sector 0–20°. (d) is real data plotted from 02/02/2025 with no cloud filtering. Cloud is known to be located in only the centre-east part of the area.

Figure 7 shows Method C applied to an orbit over Mount Etna which produces the same pattern. When the cloud pixels are removed in Figure 7b this pattern rotates counter-clockwise slightly and the arrows reduce in magnitude. The most positive arrows are in a westerly direction across Sicily, likely influenced by the land pixels used.

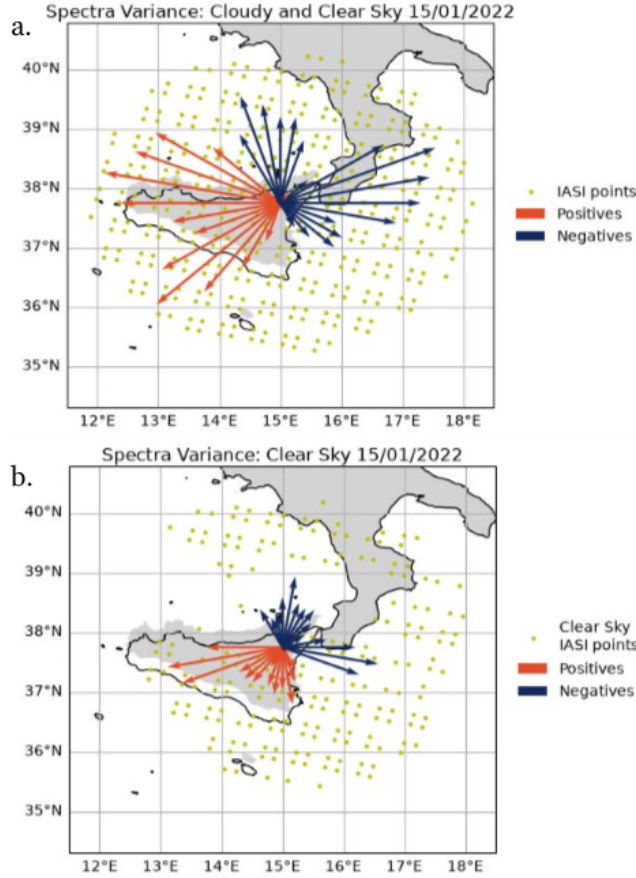


Figure 7: Graphs plotted using Method C over Mount Etna on 15/01/2022. No land pixels have been filtered out. (a) and (b) use the same initial set of data but (b) has the cloud pixels filtered out.

2.4 Method D

To understand which IASI pixels were influencing the arrows the most the next attempt was to calculate a residual spectrum for individual pixels within each sector. This meant that the difference from the spectrum of each pixel in a sector had the mean of the spectra from all the pixels outside of its own sector taken off it. This is demonstrated visually by Figure 8. Each pixel's residual then had a dot product calculated for it with the a_v value. The 10° offset pixel reorganisation was not carried out in this method due to time constraints and that theoretically it would be visible on the first graph produced as to whether it would be necessary to calculate. The dot products were plotted on a map with a colour gradient changing depending on how positive and negative the values were. Land and cloudy pixels were initially kept but later filtered out.

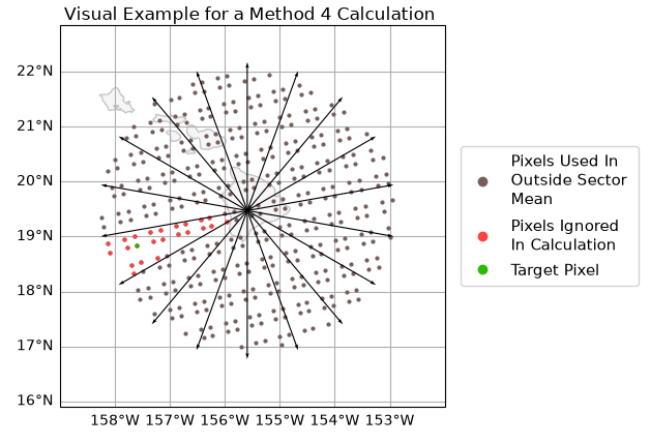


Figure 8: An example showing which IASI pixels were used in a residual spectrum calculation for method D.

Figure 10a shows the same data as Figure 6b but plotted in this new way. The colour split from the arrows is visible as well as the positive influence of the land pixels. There is a general negative to positive gradient across the map. This suggested the atmospheric temperature gradient picked up by the IASI was likely influencing the spectra too much. As shown in Figure 9 the signature for atmospheric temperature increase is quite similar to the CO₂ increase signature – as expected for the TIR spectrum. The temperature though was assumed to be a constant across the area analysed and therefore when the differences were calculated should not have interfered with the dot product. Figure 10c removes the positive land pixels. The most positive pixels then are mainly clustered together on the right-hand side of the island. When cloud pixels are filtered out again in Figure 10b it is obvious those pixels were cloudy as not only do they disappear but the overall graph pattern changes. It is now a graph of alternate, parallel, positive and negative stripes along the axis from ~ 255

to 75° , rather than a smooth linear change.

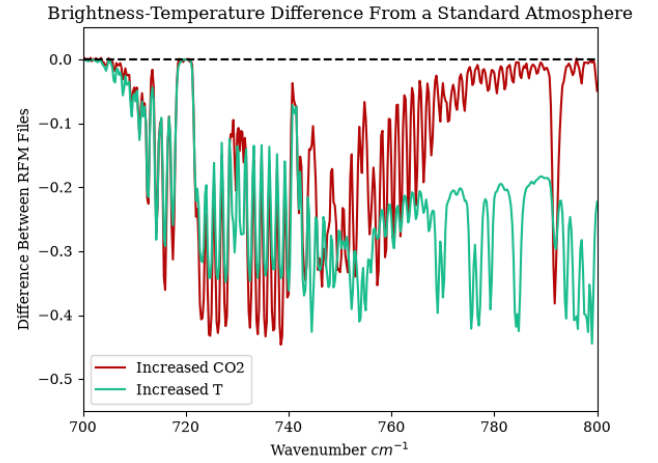


Figure 9: Shape of the atmospheric temperature (T) increase signature in the thermal infrared $700\text{--}800\text{cm}^{-1}$ range plotted along with the CO₂ increase signature. These are produced from standard atmosphere RFM files with a 1K increase from 1–3km and a 1ppmv CO₂ increase from 1–3km.

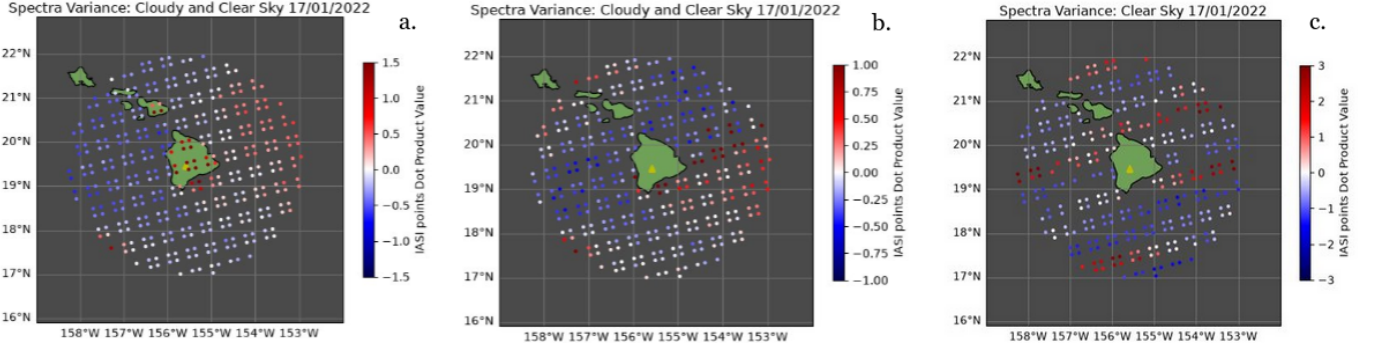


Figure 10: Set of graphs plotted using Method D. (a) is all the data, (b) has just the land pixels removed and (c) has both cloud and land pixels removed. The colour bar scale has been altered to best represent the values for each plot.

2.5 Method E

2.5.1 First Temperature Gradient

Going back to method C, a temperature function was added to each sector's dot product

depending on the bearing of the most negative arrow (dot product). At first this was a linear gradient across the area using the following equation:

$$G = Fd \cos(b) \quad (6)$$

Where G = temperature gradient function,
 F = arbitrary scaling factor,
 d = scaled distance, b = adjusted bearing (rad).

The scaled distance was calculated from the distance of the pixel divided by the radius. The mean distance from centre of all pixels in a sector was 185.72km for a radius of 280km, which was used when adding the temperature function to the sector means.

The adjusted bearing was calculated from the bearing of the pixel minus the bearing of the most negative arrow. For each sector average this used the central bearing of each sector.

The values from this equation were then added to the dot product, essentially adding a positive value to negative dot products and

vice versa to minimise the temperature gradient difference.

At the same time, a graph from method D was also recalculated to include the temperature function and plotted with the colour gradient adjusted to highlight any particularly positive pixels. To begin with, land pixels only were filtered out due to them showing up with the largest positive values. Both Figure 11a and 11c use the linear background temperature gradient and show the clouds overwhelmingly ignore it. Figure 11c, had all the pixels been for clear sky, shows an ideal result that the project was aiming to find. Figures 11b and 11d show the result after cloud pixels have been removed. The linear temperature gradient running parallel to the stripes does visibly affect 11b but shows only a minor change to 11d.

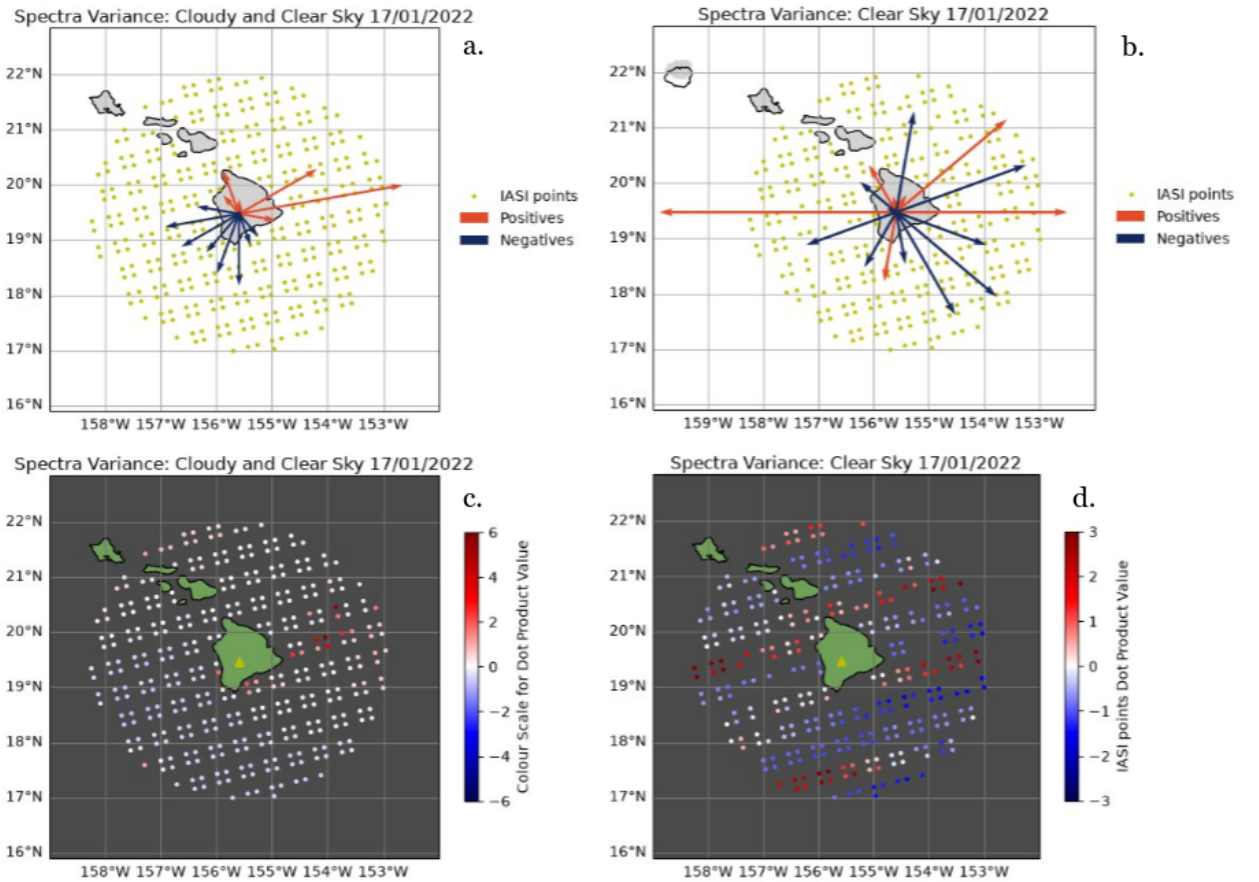


Figure 11: Graphs plotted using the linear temperature gradient from Method E. Land pixels have been filtered out. (a) and (c) both include cloud pixels which are highlighted clearly in red in (c). (b) and (d) both have the cloud pixels filtered out.

2.5.2 Second Temperature Gradient

The second temperature gradient built on the first equation but instead of trying to minimise a smooth positive to negative gradient over the entire circle it aimed to minimise a pattern of parallel stripes of positive and negative values that is only apparent when cloud pixels are filtered out. The scaled distance and adjusted bearing were calculated the same and used in the below equation:

$$G = F \sin(dn\pi \cos(b) - 1) \quad (7)$$

where n = half the number of visible stripes and -1 was used to alter the position of the stripes across the circle.

Figure 12 uses this second temperature gradient and is the final result produced still

using the 17/01/2022 orbit. With the land and cloud pixels removed, there were ~ 290 IASI pixels used in the calculations. There is no clear pattern across the graph and no obvious CO_2 increase in the downwind section.

Figure 13 also uses Method E Equation 7 but with the parameters slightly adjusted to better match the pattern during the 18/01/2022 orbit a day later. In the calculations ~ 220 IASI pixels were used. Unfortunately, it can be seen in Figure 13c that the wind direction did not stay consistent in one direction, though there are positive pixels in the same general South-West direction. This is not particularly conclusive though due to positive values also appearing North of the islands as well.

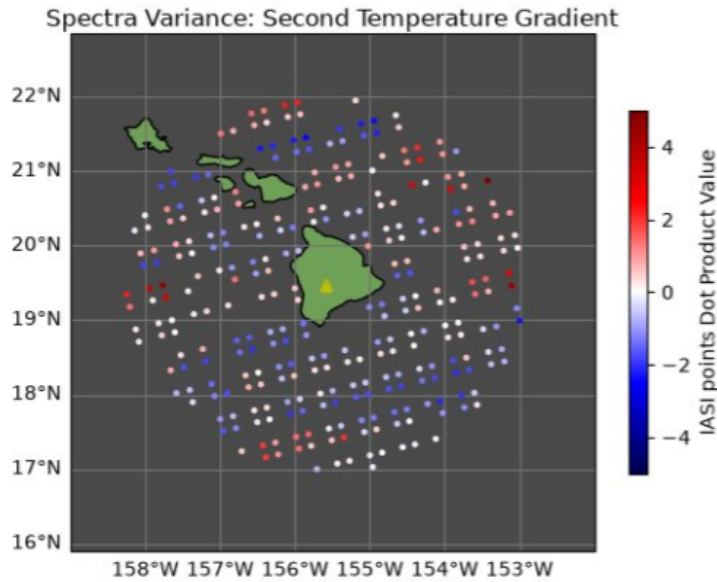


Figure 12: Graph produced with the Method E gradient using Equation 7 where $\text{SF} = 1.2$ and $n = 4$.

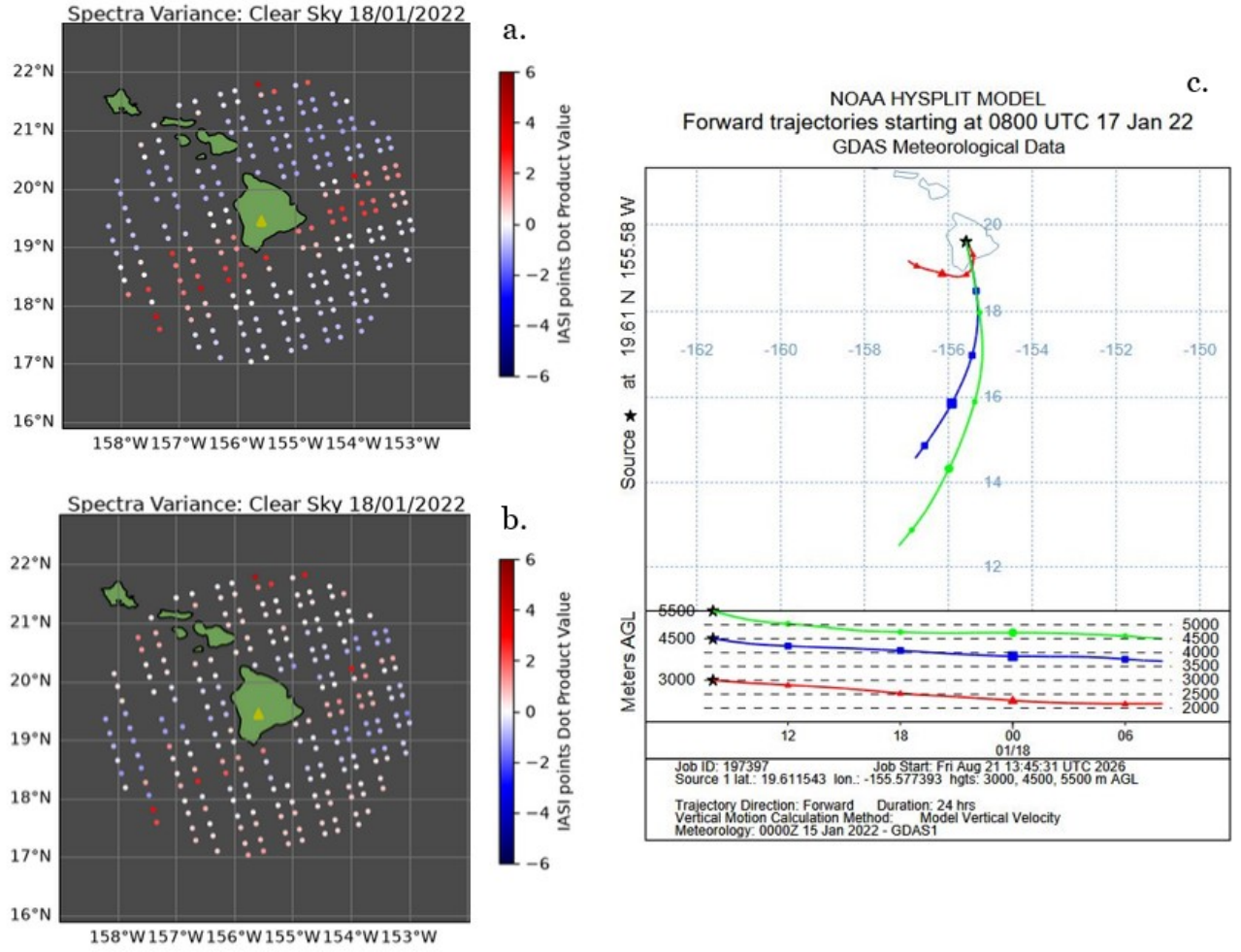


Figure 13: Graphs produced with the Method E gradient using Equation 7 for the orbit over Mauna Loa on 18/01/2022 6–8am. (a) shows the plot before the gradient function is applied, (b) shows the results after. $SF = 1.2$, $n = 1.8$ and -0.6 (instead of -1) were used in the function. (c) is the NOAA HYSPLIT data starting from 24 hours before the end of the orbit.

3 Discussion and Interpretation

Using the most developed method (Method E) more orbits and locations ideally need to be analysed than just the 17/01/2022 6–8am orbit over Mauna Loa. This particular orbit occurred after a period of inconsistent wind directions. Although for the few hours during

the orbit the wind was southward and carried air to the edge of the radius used, this still likely affected the concentration of the background CO_2 present and thus the magnitude of the CO_2 increase comparatively. To effectively analyse other orbits, cloud pixels need to be included so that orbits where the downwind CO_2 direction is at least partially obscured by cloud can be inspected. The problem with this is

that applying a filter to remove only the cloud influenced part of the spectrum would be complex and would need to account for the varying properties they exhibit. One possible way to do this would be singular vector decomposition so that the background noise can be isolated.

4 Conclusion

The orbit over Mauna Loa on 17/01/2022 shows no discernable CO₂ increase in a particular area. The orbit on 18/01/2022 vaguely shows a CO₂ increase in the general downwind direction but due to the inconsistent wind trajectories and the positively valued pixels North of the islands it is still an inconclusive result. Ultimately, directly detecting the CO₂ passively outgassed from volcanoes is not going to be as simple a process as initially hoped. The variability in background factors that influence the TIR spectra recorded by IASI, specifically cloud influence, need to be more tightly constrained. Then, the current method, or singular vector decomposition, needs to be applied to different orbits with consistent wind directions.

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