AO18: Satellite tracking of volcanic eruption plumes using ash and SO_2

Candidate number: 782932
Supervisors: Dr E. Carboni, Dr R. Grainger, Dr G. Thomas
Word Count: 5946

Abstract

The aim of this project was to study, using satellite images, both ash and SO_2 emitted from volcanoes during eruptions, particularly to investigate whether the ash and SO_2 in volcanic plumes are always collocated. If not, the aim was to see whether there is a predictable separation pattern which could be used to provide a useful service to aviation companies. The most important goal was to determine under what circumstances SO_2 can be used as a proxy for ash following a volcanic eruption. The eruptions of Puyehue in June 2011 and Eyjafjallajökull in April and May 2010 were studied in detail, and the locations of ash and SO_2 determined using data from the IASI and AATSR satellite sensors respectively.

1 Introduction

1.1 Motivation for the project

Volcanic ash can have a potentially catastrophic effect on aircraft engines including, in 1989, an aircraft losing power to all four of its engines mid-flight [1]. The most dangerous consequence of a jet aircraft flying through an ash cloud is that if fine ash particles enter an engine, they will melt due to the high operating temperatures (the melting point of volcanic ash is $\sim 1100\,\mathrm{K}$, while typical operating temperatures for aircraft engines are $\sim 1400\,\mathrm{K}$ [2]). They then adhere to the moving parts of the turbine, causing it to jam. Other damaging effects include the sandblasting of the windscreen causing visibility problems for the pilot, and interference with the plane's communication systems due to the charged nature of the ash particles [3]. Between the years 1970 and 2000, over 90 aircraft sustained damage as a direct result of flying through clouds of volcanic ash [4]. Although more recently the number of encounters has decreased due to improving ash detection systems, this is still a major problem which needs to be addressed, and a reliable way of predicting the presence (or not) and path of ash from any eruption would be of great benefit.

Although the negative effects are not as serious as those from ash, sulfur dioxide (SO_2), which is also emitted in large amounts from volcanoes, can also have a detrimental effect on aircraft, leading to degradation of parts and hence costly repairs [2, 5]. The sulfuric acid produced (see below) can also aid erosion of the airframe.

In addition to the potential loss of life and assets, the financial implications of any accident are severe, as is the cost associated with any prolonged closure of airspace or airports as a result of a volcanic eruption – being able to accurately predict ash cloud movements could therefore bring financial benefits to airlines. According to the International Air Transport Association, during the eruption of Eyjafjallajökull in Iceland in 2010, the closure of airspace over much of Europe caused a loss to the airline industry of an estimated £1.1 billion [6].

As well as inconveniences to air travel, SO_2 has a negative effect on the environment, mainly through the following reactions [7]:

$$\begin{aligned} SO_2 + OH + M &\rightarrow HSO_3 + M \qquad (1)\\ HSO_3 + O_2 &\rightarrow HO_2 + SO_3 \qquad (2)\\ SO_3 + H_2O + M &\rightarrow H_2SO_4 + M \qquad (3) \end{aligned}$$

where M denotes either N_2 or O_2. The net result is the production of sulfuric acid, which collects on tiny particles of ash or dust, creating larger acid drops by nucleation, and hence acid rain [7].

While ash is the primary concern for air travel, SO_2 is, in general, easier to identify and quantify since there is good sensitivity to absorption by SO_2 in both the ultraviolet and infrared regions, meaning there are many different satellite instruments which can be used to detect it. Also background levels are generally low. Ash detection, however, can be hampered by the presence of overlying clouds [8]. Another difficulty with the detection of ash is that sometimes ash clouds do not display sufficient thermal contrast to distinguish them from the underlying terrain. Also, the presence of ice in the ash can affect their identification [9]. Hence it would seem sensible to use detection of SO_2 as an indication of the presence of ash. However this would make the assumption that ash and SO_2 are always collocated. The objective of the project is to quantify the validity of this assumption.

1.2 Evolution of a volcanic cloud

During a volcanic eruption gases and ash are projected out of the volcano in a turbulent, convectively driven plume, which then stops rising when the constituent particles reach their level of neutral buoyancy (LNB), where the plume spreads out laterally into an ‘umbrella plume’. A laboratory simulation of an eruption plume carried out by Holasek et al. suggested that after a period of 10^3–10^4 seconds a secondary intrusion will form, when particles in the plume (i.e. the volcanic ash) drop below that of the volcanic gases (e.g. SO_2) and reach a different LNB due to their higher density, forming a secondary umbrella plume below the original one [10]. This means that after a number of hours the ash and SO_2 should be vertically separated. In the presence of vertical wind shear, this implies that the ash and the gases could follow very different trajectories and as a result may well not be collocated a short period of time after eruption. The ash will slowly fall to the ground with its lateral motion controlled by ambient winds, while the less dense gas will continue to spread horizontally more and more slowly until removed by chemical processes [10].

This theory is confirmed by a study of the 1982 eruption of El Chichón, Mexico, where it was found that due to the strong vertical wind shear, the SO_2 moved to the west of the volcano at a height of 22–26 km, while the ash was at a height of only 19–21 km and moved to the east [11]. Significant separation of ash and SO_2 was also apparent in studies of the eruptions of Hudson (1991), Lásca (1993) and Soufrière Hills (1997) [12, Table 6]. In 2006 the first study was carried out which actually used simultaneous measurements of ash and SO_2 from the same satellite [13]. The eruption in question was that of Karthala on Grande Comoro in 2005, and the study confirmed the separation of ash and volcanic gases due to wind shear. A study of an eruption in the Kuril Islands in 2009 recorded the ash and SO_2 clouds remaining collocated for much of the time, but also observed some separation at certain points [14].

1.3 Retrieval techniques

1.3.1 Sulfur dioxide

The instrument used for the detection of SO_2 was the Infrared Atmospheric Sounding Interferometer (IASI) on board the EUMETSAT MetOp satellite, which completes a global scan once every 12 hours. The instrument itself works in the thermal infrared region and uses a Fourier transform spectrometer covering the spectral range 645–2760 cm^{-1} (3.62–15.5 μm). Its field-of-view consists of four circles, each of radius 10 km, within a square of 50 km × 50 km, step-scanned across track in 30 steps, giving a swath of approximately 2000 km.

The two absorption bands used for the retrieval were the ν_1 (8.7 μm) and ν_3 (7.3 μm) bands. The latter has the strongest absorption; however, it lies within a strong absorption band for water vapour and as a result is not very sensitive to emission from the lower atmosphere. The 8.7 μm band is weaker, but lies in an atmospheric window (i.e. not much absorption of radiation by any other substances found in the atmosphere) and so contains a total column SO_2 signal. However, on its own it does not necessarily contain enough information about the plume height and profile, and thus both bands were used. The radiances obtained from IASI were then converted into SO_2 heights (in mb or km) and amounts (in Dobson Units (DU)) using a retrieval code, which includes algorithms for removing signals from other compounds, particularly meterological cloud, to leave just the SO_2 trace (note that one Dobson Unit is defined as the thickness (in units of 0.01 mm) of a layer of all of a particular trace gas in the air, were it to be just above the ground and at standard temperature and pressure [15]). The retrieval output also contains further information for each pixel, such as the time of measurement, the error in the particular height value etc. (information in section 1.3.1 from [16]).

1.3.2 Ash

The device used for the detection of ash was the Advanced Along Track Scanning Radiometer (AATSR) instrument aboard the Envisat satellite. This instrument measures the radiance over seven different channels ranging from the visible to the thermal infrared. One of the defining features of AATSR is the fact that it takes two images, one of which is a nadir view (i.e. vertically downwards) and the other a forward view at an angle of 55° to the normal to the land surface. This allows the radiance from the surface and the radiance from particles in the atmosphere to be distinguished from each other, since in each view the signal must travel a different distance through the atmosphere. Following any particular forward view image, it takes only ~ 150 seconds for the satellite to be in a position such that the nadir view samples the same region, and as such the two views are near-simultaneous. The instrument has a swath width of around 500 km (with 555 pixels across the nadir swath and 371 pixels across the forward swath) and global coverage is achieved every 3–6 days. The resolution of this instrument is better than that of IASI (~ 1 km as opposed to ~ 12 km), but the small swath width and relatively infrequent coverage of any particular area does limit the usefulness of the data from AATSR (AATSR information from [17]).

The measured radiances were converted into ash heights by using the parallax between the two images. The brightness temperature difference between the 11 μm and the 12 μm channels could also be used as a first order indication of the amount of ash present in each pixel. The underlying theory behind this, described in [14, section 2.2], means that this brightness temperature difference gives a negative value where ash is present, but a positive value where water vapour or ice (i.e. cloud) is present (note that for AATSR an additional condition on the brightness temperature difference between the 3.7 μm and 11 μm channels must also be imposed as a means of removing false detections). Hence this can be helpful in distinguishing between ash and meteorological clouds. As for the IASI retrieval, further information such as the time of measurement is also included in the data files.

2 Method

For each eruption studied, IASI picked up data for almost the whole region of interest (with just a small area of land at low latitude not fully covered due to a small gap between adjacent orbits), capturing the scene twice in every 24 hour period. The available AATSR data was a lot more restricted and only a small number of images were available, each covering a very limited area. In each case the IASI orbit which was closest in time to the AATSR image was chosen for comparison. In most cases studied, the two images turned out to be not more than half an hour apart and so for the purposes of this investigation they could be considered to be simultaneous (any horizontal motion in this time period under normal wind conditions would be insignificant). For each pair of corresponding images, the ash and SO_2 retrievals were run, producing maps of both the amount and height of the emitted SO_2, as well as the ash height (where available), and a false colour image of the AATSR swath region.

2.1 Height comparison

As discussed in section 1.2, one way to predict a difference in spatial location between two substances is to look at whether they are being observed at the same height. If they are at the same height then they will experience the same horizontal wind and so will most likely end up in the same location. Initially the whole region of interest was split into a regular grid, and then each available pair of corresponding images (IASI and AATSR) taken in turn and both the SO_2 and ash retrieved heights (where available) averaged within each grid box in each case. Scatter plots could then be created of these heights to observe whether any correlation was evident.

2.2 Spatial location comparison

To directly determine the spatial locations of the two substances, the image was once again split into a regular grid, but this time it was simply flagged whether or not there was any ash or SO_2 detected within each grid box. Care needed to be taken due to the fact that the AATSR swath only covered a fraction of the whole image in each case, but some fairly informative plots could be produced by using this method and colouring each outcome. These plots used a grid box of side length equivalent to 0.5° longitude and latitude. It would perhaps have been better to use a smaller grid size since this would increase the resolution, but unfortunately when this was tried the large spacing between adjacent IASI pixels meant that some grid boxes fell completely between pixels and so erroneously flagged areas as containing no SO_2. Interpolation between pixels could get around this, but without very careful manipulation there is a danger of interpolating between two completely different sections of a plume. Therefore this was not explored. It should be noted that any apparent non-collocation at the edge of the plume is not necessarily indicative of a significant difference in the location of the two species in reality, due to the arbitrary nature of the grid used, so this was taken into account when analysing the images. The original retrieval maps were used to help determine whether or not there was actually collocation in these cases.

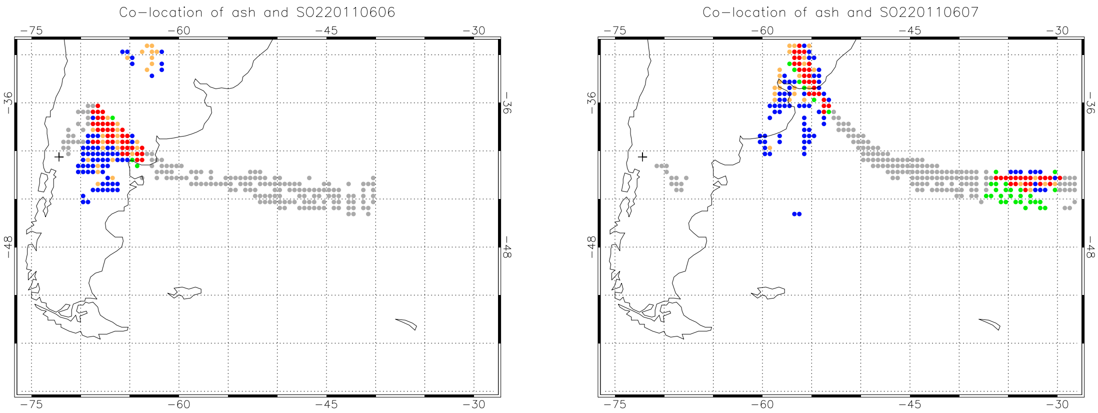
3 Studies of particular eruptions

3.1 Puyehue 2011

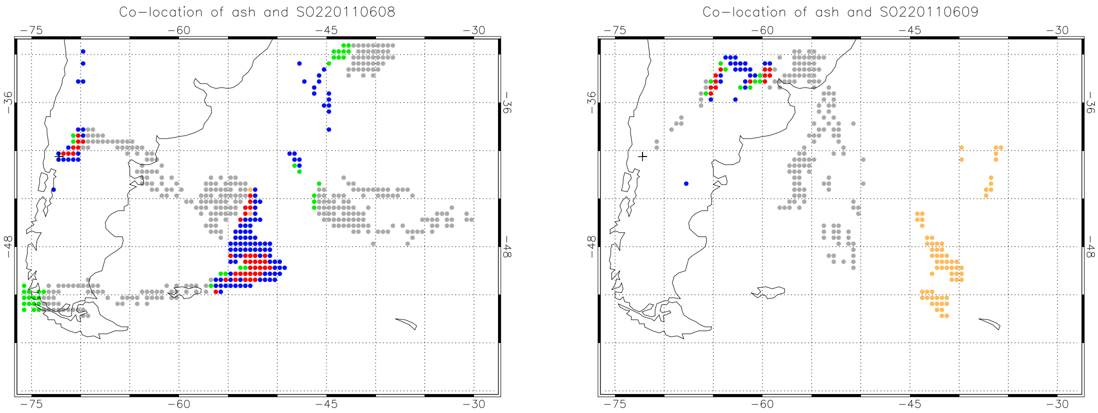
Beginning in June 2011, there was a volcanic eruption from the Puyehue-Cordón Caulle volcanic complex, Chile (40.5° S, 72.2° W; 1793 m a.s.l.). IASI covered the whole region twice a day, and one AATSR snapshot was available for each day from 6–9 June.

Trajectory predictions for this particular eruption run using the HYSPLIT web-based model [18] demonstrated that in this particular case, substances at different heights should indeed follow subtly different paths. However, the model is limited in the time period it can be run for, and does not take into account any perturbations to the atmospheric system caused by the presence of the volcano. Furthermore, it became obvious that using the height retrievals for these particular data introduced significant uncertainty; plots comparing the ash and SO_2 heights (produced as described in section 2.1) appeared to show no correlation at all between the two heights. Various methods were used to try to remove uncertainty to obtain a more definite correlation, including using a larger box dimension, and filtering outliers, but even with these filters in place the results gave no useful information.

The spatial location plots described in section 2.2 for this eruption provided much more useful information than the height plots and are shown in figure 1. Figure 1a shows that on 6 June, two days after the start of the eruption, there is a clear area of the plume where the ash and the SO_2 are collocated (red points), and this plume is clearly visible in the original height retrieval plots from both IASI and AATSR (Fig. 2), albeit with the two retrievals showing very different heights. It should be noted that the ash plume height for this particular image has been confirmed by Grainger et al. using an alternative method [19] so it must be concluded that



(a) 6 June 2011 (b) 7 June 2011



(c) 8 June 2011 (d) 9 June 2011

Figure 1: Maps showing the location of ash and SO_2 from the Puyehue eruption for (a) 6 June, (b) 7 June, (c) 8 June and (d) 9 June 2011. In each map the black cross marks the location of the volcano. **Red**: Both ash and SO_2 present; **Green**: Only SO_2 present; **Blue**: Only ash present; **Grey**: No AATSR data, but SO_2 present; **Orange**: No IASI data, but ash present.

either the SO_2 height retrieval is flawed, or the two species lie at significantly different altitudes. As mentioned in section 1.2, however, if the two species were at different heights, then it would be expected that they would not be spatially collocated and so the former seems more likely. Unlike the AATSR one, the IASI height retrieval is unverified and so should be treated with caution as it can be affected by many variables, including the presence of large quantities of ash. Thus in a case like this it could well be giving a false result, which could explain why the height comparison plots showed no correlation. Although no AATSR data is available, an educated guess would suggest that the grey points in figure 1a would most likely be mainly red in colour if the AATSR data was available. It can thus be proposed at this stage that the two species are well collocated throughout this plume. As can be seen in figure 2, there is also a secondary ash cloud to the south of the main plume and at a much lower altitude, which shows up in figure 1a as blue points. However, this is a much lower density cloud [20] and so does not need to be considered as part of the main volcanic plume. In figure 1a there does also appear to be a further ash cloud to the north at a latitude of $\sim 32^\circ$ S, although this is barely visible in figure 2. This

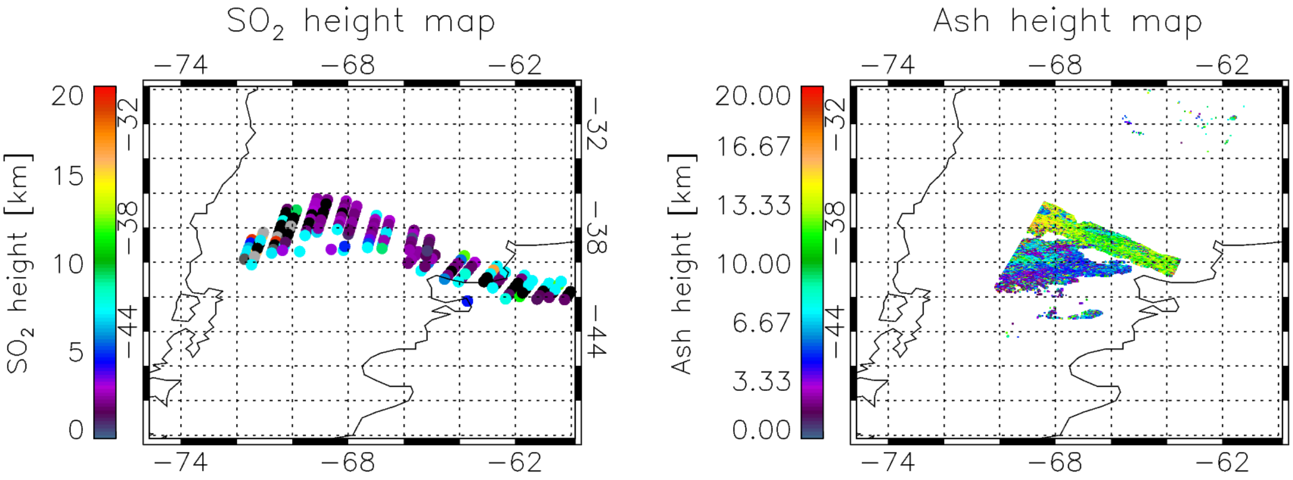


Figure 2: Height retrieval plots from IASI (left) and AATSR (right) for 6 June 2011

suggests that only very small amounts of ash are being picked up here and there is a chance that it could just be cloud contamination or, if ash, a lower density cloud which does not need to be considered as part of the plume.

Figure 1b shows the same area on 7 June and it can be seen that by this time the whole plume has been blown in a North East direction. Again, the main plume with the species collocated is clearly visible, as is the secondary ash-only cloud. It should be noted that the grey points at ∼ 70° W are from a different IASI orbit to those at higher longitude and so can be ignored. This time, data from a second AATSR image was available at greater longitude, showing a snapshot further along the plume. Again the species appear to be essentially collocated, but with some spatial separation becoming apparent and the SO_2 seeming to end up on the south side of the plume. This image does, though, further reinforce the speculation that the grey points in figure 1a should be red, although it should be added that at the edges of the plume separation may have occurred.

Figure 1c shows the situation on 8 June, and it can be seen that the wind has blown the main plume around to the south and then west, creating a C-shaped plume. The lack of AATSR data makes it very difficult to make a detailed analysis of this image. However, the small amount of data at the ‘start’ of the plume (i.e. at ∼ 40° S, ∼ 70° W) suggests that again the ash and the SO_2 are relatively well collocated near the volcano (allowing for possible errors at the edge of the plume as described above), but in the part of the plume at the centre of the image, the collocation is poorer, with a lot of ash showing without any corresponding SO_2.

Finally, figure 1d shows what has happened by 9 June and the lack of available IASI data on the right hand side of the image, coupled with the usual lack of AATSR coverage, make this not a particularly insightful image. The small amount of data that is present does suggest a reasonable amount of separation between the two species since there are a lot of blue and green points. Having said this, the spread-out nature of the data here means that a higher resolution of points would be desirable and the results obtained should be treated with caution. In addition, observation of the AATSR height retrieval image shows that the ash which is being flagged up is very spread out, and is not present in anywhere near the quantity that is observed in the main plume in figure 2 and so may potentially only be present in low, though not negligible, concentrations. It is disappointing that no IASI data was available for the right hand side of this image as this ash is in a reasonably substantial cloud and hence would be more likely to give an accurate result – it would therefore be useful to know whether or not SO_2 was present at this point.

3.2 Eyjafjallajökull 2010

In April and May 2010 there was a major eruption of the Eyjafjallajökull volcano, Iceland (63.63° N, 19.62° W; 1666 m a.s.l.), with the main explosive phase of the eruption beginning on 14 April. Again, IASI data was available for the whole eruption with two images per day, and a limited selection of AATSR images were also available for comparison with the IASI ones. The brightness temperature difference information described in section 1.3.2 was also available and this was plotted for each image in addition to the standard retrieval maps. For this eruption images were available for a much longer period of time (15 April–17 May) and so the behaviour of the two species could be observed over the period of a whole month. However, the same problems with the height retrievals were found as for Puyehue, even for the much larger number of images used for this eruption. It is unlikely that in reality the heights of the two substances are uncorrelated; however the errors inherent in the retrieval process mask any trend which might be present. Apart from the potentially flawed SO_2 height retrieval, one of the most likely reasons for these huge discrepancies is the presence of meteorological cloud which affects the AATSR height retrievals, and it can be seen in the AATSR false colour images for many of the regions and times studied that significant cloud was often present.

Figures 3, 4, 5 and 6 show a small selection of the spatial location plots available for this particular eruption spread over the entire month. In figure 3 the main eruption has been ongoing for just a day and a clear plume can be identified. As seen for Puyehue, the two species appear to be relatively well collocated, with any apparent separation at the edge of the plume potentially being a result of the arbitrary grid used, and again it can be suggested that the points without AATSR data would also show collocation.

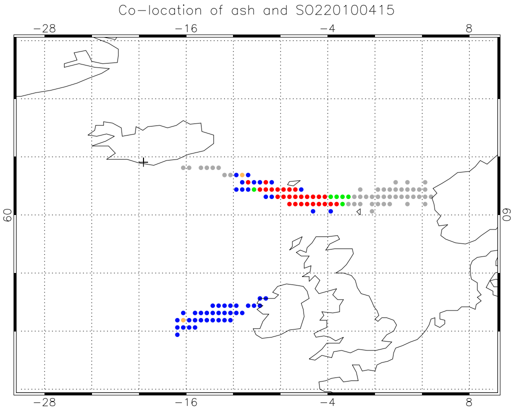
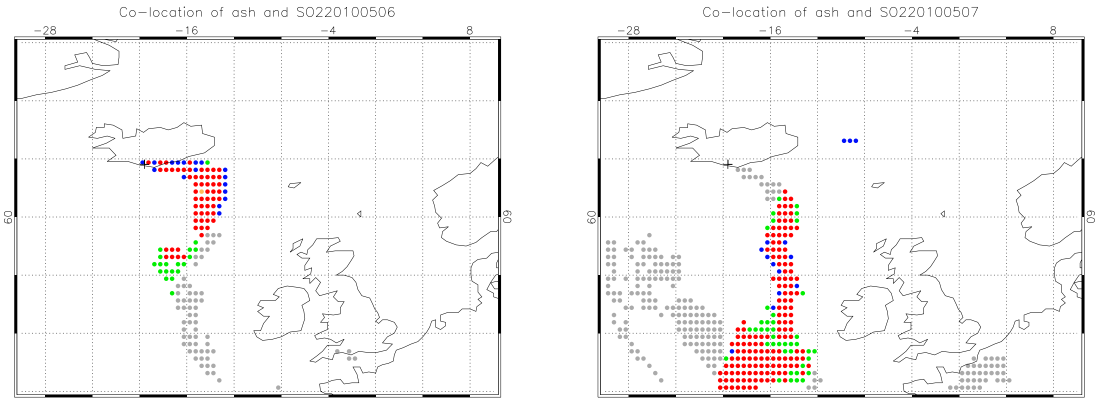


Figure 3: Map showing the location of ash and SO_2 from the Eyjafjallajökull eruption for 15 April 2010. The black cross marks the location of the volcano. Colour key as Fig. 1.

However, detailed study by Prata and Thomas suggests otherwise, since satellite data they have used from the Spinning Enhanced Visible and Infrared Imager (SEVIRI) and Ozone Monitoring Instrument (OMI) show the SO_2 to be in general located to the east of the ash and indeed they state that there is “little gas associated with the area of densest ash” and vice versa [21]. This suggests that the missing data to the east of the AATSR swath should potentially be green (i.e. SO_2 is present, but no ash) and that to the west should be blue (i.e. ash present, but no SO_2). Another feature of note is the presence of a cloud consisting only of ash off the coast of Ireland. The brightness temperature difference map for this date hardly shows this additional cloud at all, suggesting that it is either very fine ash, or is very low in concentration. One explanation is that the initial stages of the eruption were low in SO_2 since the eruption occurred from beneath a glacier, the SO_2 reacting to form sulfuric acid (as in equations 1–3) before it even made it into the plume. Thus the cloud visible here could be left over from a small ash emission a number of hours or days previously. This theory is backed up in a paper by Wadsworth, in which he states that during the initial stage of the eruption “little SO_2 was released . . . possibly because SO_2 was initially sequestered (dissolved) into the glacial melt water” [22].



(a) 6 May 2010

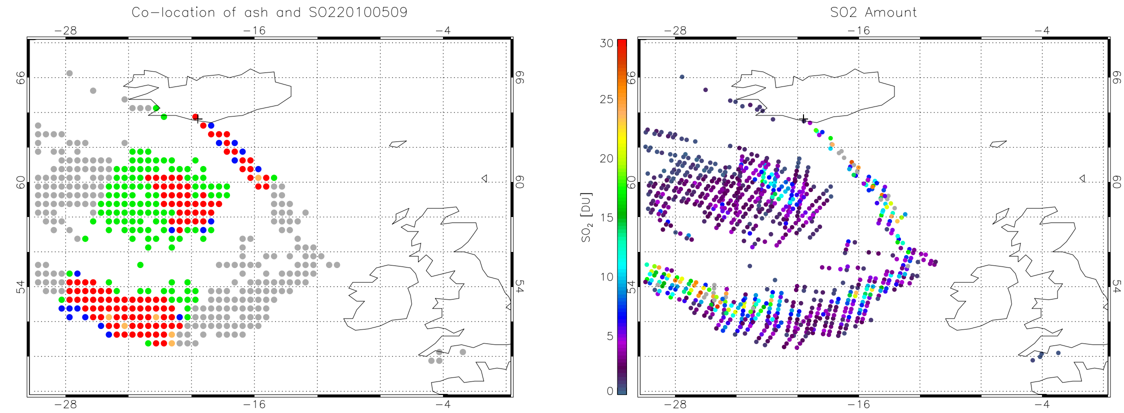
(b) 7 May 2010

Figure 4: Maps showing the location of ash and SO_2 from the Eyjafjallajökul eruption for (a) 6 May, (b) 7 May 2010. In each map the black cross marks the location of the volcano. Colour key as Fig. 1.

By 6 May, as shown in figure 4a, the wind has obviously changed direction to blow the plume southwards, but it is clear that the volcano is still erupting. Very close collocation of species is observed in the main part of the image, with a hint of separation at the bottom of the plume, signified by the green points.

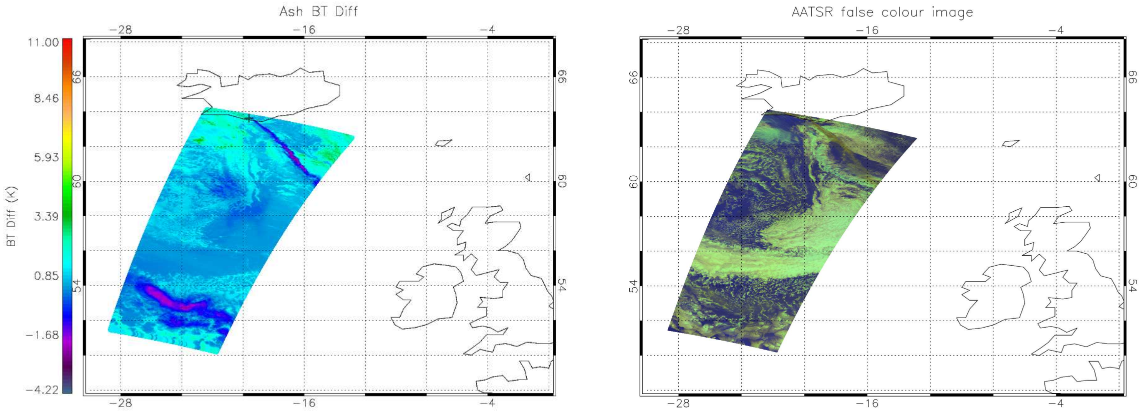
Figure 4b shows the plume on 7 May. Again the majority of the plume shows good collocation, with the exception of a small stripe with no ash at $\sim 54°$ N. This may be because there was a brief lull in the eruption, with only small amounts of gas and ash emitted. It could be that the small quantity of ash given off during this lull was just below the detection threshold of AATSR and does not show up here. The results obtained agree with those presented by Prata and Thomas in [21, Fig. 4], whose ash data from SEVIRI and SO_2 data from IASI and the Global Ozone Monitoring Instrument 2 (GOME-2) confirm that the SO_2 column amount in the 'lull' region is extremely low. This suggests that the ash amount could also be very low, explaining why it may be below the detection threshold.

Figure 5 shows a full set of images for 9 May, to allow for greater analysis to be made. From the collocation map (Fig. 5a) it can be seen that, as usual, the main plume is mostly red (i.e. species are collocated), but with a small amount of separation at the plume edges. Here this still seems to be the case even though the plume has been blown round so it turns through 180°. However, there also appears to be a large cloud of SO_2 in the middle of this main plume with only a fraction of it also containing ash. In this case it is useful to look at the maps showing both the SO_2 and ash amounts (Fig. 5b and 5c respectively), from which it can be seen that the region where the red points lie is where the SO_2 concentration is highest in this extra cloud (blue and green points), and in the rest of the cloud the SO_2 amount is extremely low (purple points). Thus, as for the small region on 7 May, the ash amount here must be below the detection limit of AATSR but may still be present. From the ash map (Fig. 5c) it is clear that even where ash is detected in this secondary cloud, the amount present is significantly less than in the main plume as evidenced by the noticably less negative value of brightness temperature difference. Finally, figure 5d gives the AATSR false colour image, revealing the presence of water cloud, which must be taken into account as this can affect the AATSR retrieval results. It also demonstrates that in a false colour image the plume itself is very difficult to identify, and impossible to see at all when the ash is in low concentrations. This shows why additional height retrievals, brightness temperature difference plots etc. are needed to carry out detailed analysis.



(a) Map showing the location of ash and SO$_2$. Colour key as Fig. 1.

(b) Map showing amount of SO$_2$



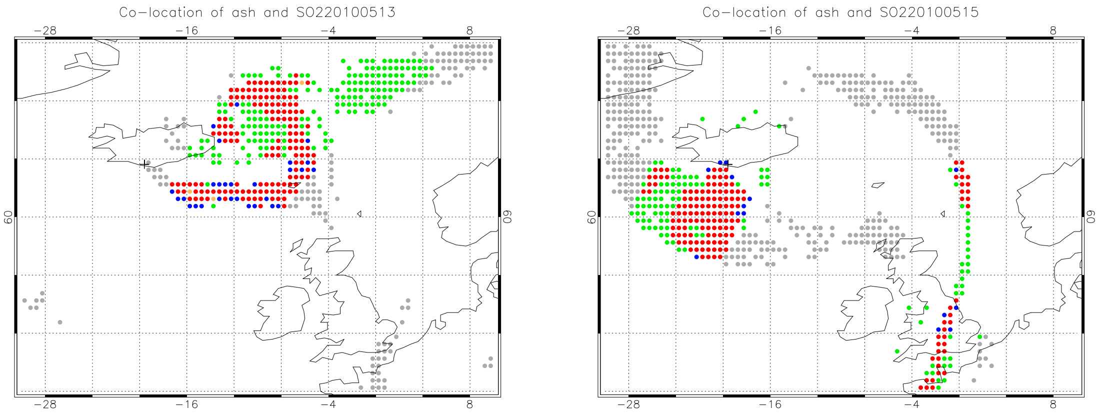
(c) Map showing ash brightness temperature difference

(d) Map showing AATSR false colour image

Figure 5: Maps showing data from the Eyjafjallajökull eruption for 9 May 2010. In each map the black cross marks the location of the volcano.

The plot for 13 May (Fig. 6a) shows that by this time the plume has changed direction and most of the cloud lies to the North East of the volcano. However, the same pattern is observed as for the previous images, with the majority of the main plume displaying collocation and then, some distance from the volcano, a region showing only SO$_2$ bordering the main plume. Prata and Thomas back up these findings, with their plots almost completely mirroring those in figure 6a [21, Fig. 7a, 7c]. The original SO$_2$ retrieval shows that the region in the North East of the map which shows only SO$_2$ has it in extremely low amounts (each pixel in this plume has a retrieved amount of $\sim 2\,\mathrm{DU}$, while the main plume gives values of $\sim 10\,\mathrm{DU}$) and so as before there may also be very fine ash in low concentrations which is not being picked up.

Figure 6b shows the situation on 15 May and once again an area of collocation can be seen close to the crater itself and then some separation occurs as we move further away. An interesting feature of this image is the plume which stretches down the eastern side of the United Kingdom and appears to consist of a gas cloud with intermittent occurrences of ash. The height retrieval and brightness temperature difference plots show that this ash is very sparsely spread and most likely not in very large concentrations. It may be that there is ash all the way down this plume, but just under the detection threshold as it seems somewhat unlikely that ash should



(a) 13 May 2010

(b) 15 May 2010

Figure 6: Maps showing the location of ash and SO_2 from the Eyjafjallajökull eruption for (a) 13 May, (b) 15 May 2010. In each map the black cross marks the location of the volcano. Colour key as Fig. 1.

only appear at two points in the plume. Alternatively, the sporadic nature of the ash detection may be due to the presence of overlying clouds. Unfortunately the conclusions that can be drawn are somewhat limited due to the lack of more AATSR data. It does however seem that overall for this eruption the two species do not, in general, separate out significantly as predicted, but instead remain collocated for a long period of time.

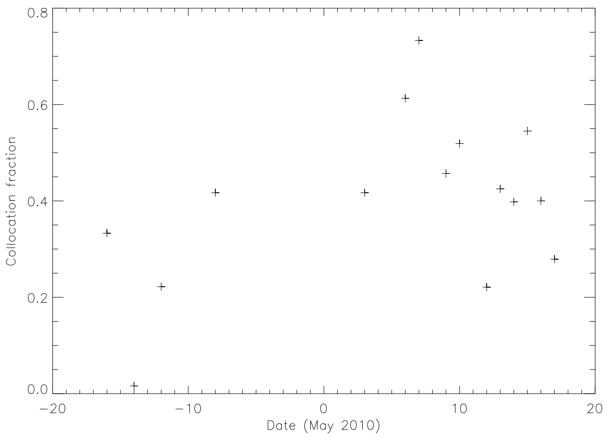


Figure 7: Graph plotting spatial correlation fraction as a function of time for the Eyjafjallajökull eruption

3.3 Analysis

Ideally it would be beneficial to know whether separation varies as a function of time. However, this would rely on being able to see the whole region in each image, or being able to track a specific small cloud of ash and SO_2 from day to day, rather than seeing a random snapshot each day. Using the available data, the collocation fraction (proportion of those points containing ash or SO_2 which contain both) was plotted as a function of date for the Eyjafjallajökull eruption (Fig. 7) and, as expected, there is no obvious trend. It can be seen from this plot that the spatial collocation fraction is 0.4 ± 0.2 (using the mean and standard deviation of the raw data), compared to the value of 0.3 ± 0.1 obtained from the limited data for Puyehue. These values seem very low, since they claim that collocation only occurs in around 40% of cases. However, looking at only the later part of the Iceland eruption, taking into account the fact that sometimes ash does not show up even when it is most likely still present, it can still be concluded that in general the two species are collocated for the majority of the plume, but more importantly that ash with no corresponding SO_2 is only very rarely seen, and certainly not in any significant quantities.

From the results obtained, it may be concluded that for Puyehue there was a lot more ash without corresponding SO_2, and so SO_2

Phase	**Eruption**	**SO_2 fraction(%)**	**Missed ash fraction(%)**
Early	Eyjafjallajökull	94 ± 11	80 ± 17
	Puyehue	65 ± 19	65 ± 5
Late	Eyjafjallajökull	51 ± 17	17 ± 13
	Puyehue	-	-

Table 1: Table summarising the obtained results

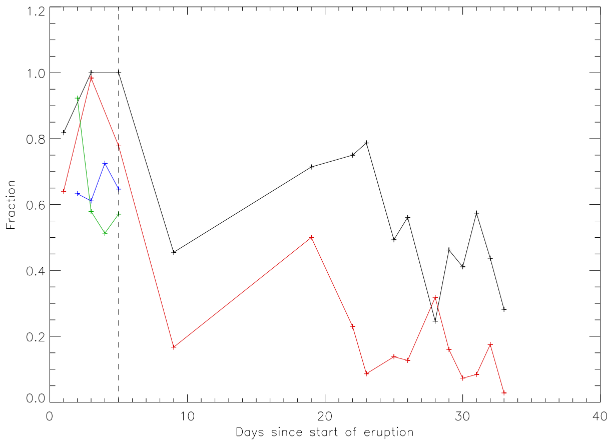


Figure 8: Graph plotting SO_2 fraction and missed ash fraction for Puyehue (green and blue lines respectively) and Eyjafjallajökull (black and red lines respectively). The dashed line denotes the boundary between 'early' and 'late' eruption phases.

could not be used as a proxy for ash, while for Eyjafjallajökull, in general, the species were collocated or have SO_2 without ash, and so it could be used. However, for Puyehue only the first five days of the eruption were analysed, while for Eyjafjallajökull the entire first month was used. In fact, some of the early images from Eyjafjallajökull, while not included in this report, had a large amount of ash showing with no SO_2. Though this may be due to the presence of glacial ice on the volcano, it could also be that this is what one would expect to observe in the early stages of any volcanic eruption. Two useful values were calculated for each eruption: firstly the 'SO_2 fraction' which denotes the fraction of the points where SO_2 is detected which also contain ash (i.e. the smaller this fraction, the more using SO_2 as a proxy will overestimate the amount of ash present), and secondly the 'missed ash fraction' which is the fraction of the ash which is missed by using SO_2 as a proxy. The relevant quantities for the two eruptions (averaged over the whole available period) are as follows:

Eyjafjallajökull
SO_2 fraction:$(60 \pm 20)\%$
Missed ash fraction:$(30 \pm 30)\%$

Puyehue
SO_2 fraction:$(65 \pm 19)\%$
Missed ash fraction:$(65 \pm 5)\%$

Hence it would seem that the Puyehue eruption was much more ash-heavy relative to SO_2 than Eyjafjallajökull. However, these quantities are plotted in figure 8 for both eruptions as a function of time since the start of eruption, and it can clearly be seen that in the case of Eyjafjallajökull the amount of ash missed drops significantly in the later part of the eruption, as does the SO_2 fraction. In the early stages of both eruptions, high values are obtained for both these quantities. Thus if Eyjafjallajökull is split up into an 'early' and a 'late' eruption phase (the split denoted by the dotted line in figure 8) then a better comparison can be made (see table 1). It should be noted that because there may well be small quantities of ash present even where it is not detected, the 'SO_2 fraction' lines should potentially be higher and the 'missed ash fraction' lines lower in the later stages of the eruption. It is unknown how the detection threshold for AATSR compares with the cut-off ash level for allowing aircraft to fly (currently 2 mg m^{-3} [21]), but it may be that this undetected ash would not be in large enough quantities to be harmful to aircraft and so could be ignored.

4 Conclusions

To conclude, this project has studied in detail the paths of volcanic ash and sulfur dioxide from two different recent volcanic eruptions, Puyehue in 2011 and Eyjafjallajökull in 2010.

Overall the evidence suggests that the separation of ash and volcanic gases such as SO_2 depends on many variables, including the wind profile at the relevant locations and the geography and geology of the volcano itself. Although it is sometimes sufficient to use SO_2 as a proxy for ash, this method can potentially miss over 60% of the ash present, and so it cannot be relied upon, and thus in most situations both ash and SO_2 must be tracked to determine any regions which may be unsafe for aircraft to pass through. On their own, the results obtained from the two case studies suggest that the early stages of an eruption (the first ~ 5 days) are more ash-heavy and as such during this period, if SO_2 is used as a proxy for ash, then $(73 \pm 11)\%$ of the ash will be missed, a clearly unacceptable result. After this initial stage only $(17 \pm 13)\%$ of the ash is missed. Although this is a much more satisfactory result than for the first phase of the eruption, it is still high enough that one would not want to risk using only SO_2 detection when deciding which areas should be designated as no-fly zones and it also tends to overestimate the amount of ash present by a significant amount, potentially causing a much larger than necessary no-fly zone to be implemented. In conclusion, for the purposes of detecting ash in order to protect aircraft, SO_2 detection alone is insufficient and, although much of the missed ash will be very low in concentration, a reliable ash detection method should be used in conjunction with the SO_2 measurement to accurately track the presence of volcanic ash.

The results of this project were not as conclusive as was desired due largely to the very different apparent behaviour of the two eruptions, and using only two eruptions by no means gives a definitive answer. Moreover it is known that the initial stages of both the Eyjafjallajökull and Puyehue eruptions did not give out much SO_2 compared with other volcanoes [22, 23] and that the wind shear at these locations was not as dramatic as is sometimes the case. Future work could include the study of further eruptions with available data to see what behaviour they display, or the study of the Puyehue 2011 eruption over a longer time frame to see if the trend follows that of Eyjafjallajökull. Also, an ash flag could be developed for IASI, which would allow full ash coverage and as such could allow a better comparison between the two species to be made.

Acknowledgements
The author would like to thank Dr E. Carboni, Dr R. Grainger and Dr G. Thomas for all the help and support they have given during this project, as well as the provision of the IASI and AATSR data and retrieval codes.

References

[1] Thomas J. Casadevall. The 1989–1990 eruption of Redoubt volcano, Alaska: impacts on aircraft operations. *Journal of Volcanology and Geothermal Research*, 62(1–4):301–316, 1994.

[2] L. Vogel, B. Galle, C. Kern, H. Delgado Granados, V. Conde, P. Norman, S. Arellano, O. Landgren, P. Lübcke, J. M. Alvarez Nieves, L. Cárdenas Gonzáles, and U. Platt. Early in-flight detection of SO_2 via differential optical absorption spectroscopy: a feasible aviation safety measure to prevent potential encounters with volcanic plumes. *Atmospheric Measurement Techniques*, 4(9):1785–1804, 2011.

[3] NASA. Volcanic cloud data for aviation, 2011. `http://appliedsciences.nasa.gov/pdf/Volcanic_Ash_Report.pdf`, Accessed 15 March 2012.

[4] Thomas J. Casadevall and Thomas M. Murray. Advances in volcanic ash avoidance and

recovery. *Boeing Aero Magazine*, (9), 2000. `http://www.boeing.com/commercial/aeromagazine/aero_09/volcanic_story.html`, Accessed 2 January 2012.

[5] A. Bernard and W. I. Rose. The injection of sulfuric acid aerosols in the stratosphere by the El Chichón volcano and its related hazards to the international air traffic. *Natural Hazards*, 3(1):59–67, January 1990.

[6] IATA. Volcano crisis cost airlines $1.7 billion in revenue – IATA urges measures to mitigate impact. IATA Press Release, 2010. `http://www.iata.org/pressroom/pr/Pages/2010-04-21-01.aspx`, Accessed 15 March 2012.

[7] Peter L. Ward. Sulfur dioxide initiates global climate change in four ways. *Thin Solid Films*, 517(11):3188–3203, 2009.

[8] C. Zehner, editor. *Monitoring Volcanic Ash from Space.* Proceedings of the ESA-EUMETSAT workshop on the 14 April to 23 May 2010 eruption at the Eyjafjoll volcano, South Iceland. Frascati, Italy, 26–27 May 2010. ESA-Publication STM-280.

[9] Simon A. Carn, Arlin J. Krueger, Nickolay A. Krotkov, Kai Yang, and Keith Evans. Tracking volcanic sulfur dioxide clouds for aviation hazard mitigation. *Natural Hazards*, 51(2):325–343, 2008.

[10] R. E. Holasek, A. Woods, and S. Self. Experiments on gas-ash separation processes in volcanic umbrella plumes. *Journal of Volcanology and Geothermal Research*, 70(3–4):169–181, 1996.

[11] David J. Schneider, William I. Rose, Larry R. Coke, Gregg J. S. Bluth, Ian E. Sprod, and Arlin J. Krueger. Early evolution of a stratospheric volcanic eruption cloud as observed with TOMS and AVHRR. *Journal of Geophysical Research*, 104(D4):4037–4050, 1999.

[12] W. I. Rose, G. J. S. Bluth, and G. G. J. Ernst. Integrating retrievals of volcanic cloud characteristics from satellite remote sensors: a summary. *Philosophical Transactions Mathematical Physical and Engineering Sciences*, 358(1770):1585–1606, 2000.

[13] A. J. Prata and J. Kerkmann. Simultaneous retrieval of volcanic ash and SO_2 using MSG-SEVIRI measurements. *Geophysical Research Letters*, 34(5):1–6, 2007.

[14] Daniel B. Williams and Helen E. Thomas. An assessment of volcanic hazards to aviation – a case study from the 2009 Sarychev Peak eruption. *Geomatics, Natural Hazards and Risk*, 2(3):233–246, 2011.

[15] Support to Aviation Control Service. `http://sacs.aeronomie.be/info/dobson.php`, Accessed 19 April 2012.

[16] E. Carboni, R. G. Grainger, J. Walker, A. Dudhia, and R. Siddans. Sulphur dioxide retrieval from satellite measurements (IASI): a new optimal estimation retrieval scheme and results for recent volcanic eruptions. Poster on `http://www.atm.ox.ac.uk/group/eodg/posters/2011/2011ec1.pdf`, 2011. Accessed 15 March 2012.

[17] A. M. Sayer, G. E. Thomas, and R. G. Grainger. A sea surface reflectance model for (A)ATSR, and application to aerosol retrievals. *Atmospheric Measurement Techniques*, 3(4):813–838, 2010.

[18] `http://ready.arl.noaa.gov/HYSPLIT.php`, Accessed 25 January 2012.

[19] R. G. Grainger, D. M. Peters, G. E. Thomas, A. Smith, R. Siddans, E. Carboni, and A. Dudhia. Measuring volcanic plume and ash properties from space, in remote sensing of volcanoes and volcanic processes: Integrating observation and modelling. *The Geological Society Special Publication*, (270). Submitted.

[20] Oxford University Atmospheric Oceanic and Planetary Physics Sub-department, Earth Observation and Data Group

webpage. http://www.atm.ox.ac.uk/project/volcano/puyehue/index.html, Accessed 15 March 2012.

[21] H. E. Thomas and A. J. Prata. Sulphur dioxide as a volcanic ash proxy during the April–May 2010 eruption of Eyjafjallajökull Volcano, Iceland. *Atmospheric Chemistry and Physics Discussions*, 11(14):6871–6880, 2011.

[22] F. B. Wadsworth. Rock & ice: Eyjafjallajökull and climate change, news and views from AGU fall meeting 2010. *Geoscientist Online Special*, 21(03), April 2011.

[23] A. Robinson, S. Hannon, S. DeSouza-Machado, and L. Strow. Using AIRS to detect volcanic ash from Puyehue eruption. News item from AIRS website, 2011. http://airs.jpl.nasa.gov/news_archive/2011-06-29-Puyehue-Eruption/, Accessed 4 March 2012.