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Comment

Interactive comment on “A comparison of DOAS observations by the CARIBIC aircraft and the GOME-2 satellite of the 2008 Kasatochi volcanic SO₂ plume” by K.-P. Heue et al.

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Authors Comment:

We thank the referees for the extensive review and all the helpful comments.

Interactive comment on "A comparison of DOAS observations by the CARIBIC aircraft and the GOME-2 satellite of the 2008 Kasatochi volcanic SO₂ plume" by K.-P. Heue et al.

Anonymous Referee #1 Received and published: 22 February 2010

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General comments:

The manuscript, 'a comparison of DOAS observations by the CARIBIC aircraft and the GOME-2 satellite of the 2008 Kasatochi volcanic SO₂ plume, by Heue et al. described the comparison of the SO₂ plume observed by the DOAS instrument onboard CARIBIC with the GOME-2 measurements. The trajectory model was used to calculate the location of the SO₂ plume because of the temporal difference between CARIBIC and GOME-2 observations. The interesting part of the paper is that the authors have tried to include the aerosol and clouds information in the calculation of SO₂ air mass factors. I can see that lots of efforts have been made to get accurate SO₂ vertical columns. However, limited by the cloud and aerosol data, wind data, there are still uncertainties in the SO₂ vertical columns. The authors have provided lots of details about the data analysis and finally the agreement between the CARIBIC and GOME-2 SO₂ VCD are very good.

Specific comments:

Page 527, line 17. In this paragraph the authors explained the Box AMFs and the sensitivity of the different telescopes. I suppose the Box AMFs is calculated by the McArtim model. Can you introduce the RTM model first, and then explain the Box AMF and the AMF to convert the SCD to VCD?

The referee is right, that it might be slightly confusing to show model results without introducing the model first. But from my point of view it makes more sense to first describe the AMF and Box AMF in general and describe one model to estimate these quantities later. The model results in Figure 1 are shown to illustrate the BoxAMF in general, to give an example.

Some more details about flight altitude, cloud thickness and cloud optical thickness are included.

Fig.1 What are the cloud bottom heights for the two clouds? The box AMF seems

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decreased to 0 rapidly below the cloud top. Is it related to the assumed cloud optical thickness and geometric thickness?

The rapid decrease is mainly related to the cloud extinction, which is the ratio of COT and geometrical thickness. We also simulated different clouds (extending the cloud to 6 km altitude) but that did not improve the comparison to our observation.

Can you include the cloud properties in the caption of Fig. 1 or in the texts? The flight altitude is indicated in Fig. 1 at 11 km. Can you add the flight altitude in the caption?

Done

Page 528, Line 25. As I understand the Ring spectrum used in the DOAS fit for the CARIBIC is different as the Ring spectrum used in the GOME-2 DOAS fit because you used different references. What is the reason for that? Does it effect the fit?

Although different references are given, the underlying algorithm is the same, both ring spectra are calculated according to Bussemer (1993) based on the reference spectrum, observed with the same instrument.

A reference to the basic algorithm is included and the fact that both ring spectra are calculated on the basis of reference is more emphasized.

Page 529, Line 2, 'As the reference SCD is unknown it might add an offset (+/-6.5E15 molec/cm2) to the time series. . . ' Where does this SO₂ value come from? Is it the background SO₂ value?

*This number is mainly the fit error or the noise in the background data.
This statement was clarified.*

Fig. 3 Could you indicate the region where the SO₂ plume was observed by CARIBIC?

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This is a nice plot to show the SO₂ pattern but not clear for the plume that is analyzed in this paper.

The respective region was marked in the figure, and mentioned in the caption.

Page 532, Line 22. The cloud top altitude is determined from the rapid increase of cloud liquid water. I wonder if the cloud water is really liquid water or ice. If the cloud top is at 11 km there could be more ice particles than water droplets. Is the cloud water only measured at the cloud top? If these are continuous measurements, you could know the cloud water along the flight track when the aircraft pass through the clouds.

According to the ambient temperature (-50⁰C), the flight altitude and the cloud type (Cirrus) the clouds the cloud water we can assume that cloud "droplets" were rather ice than water. The instrument however only measures water vapour, the cloud particles are evaporated for the detection.

There are continuous measurements along the flight track, and we thank the referee for the idea of estimating the cloud base level this way, although this approximation is only valid for the dense cloud, below the main plume, see comment on the cloud type.

Page 532, Line 23, ' . . . the cloud optical thickness (COT) was adjusted to approximate the clouds' optical properties.' What clouds' optical properties do you mean? I assume that the SO₂ AMF is calculated at one or several wavelengths between 312 and 330 nm. The single scattering albedo of 0.99 is relative low for clouds, which can cause large absorptions, 0.999 might be a better value for clouds in the UV wavelength. Do you use ice or water clouds in the RTM model and what kind of scattering phase functions is used?

The wavelength of 320 nm was used for the calculation of the SO₂ AMF.

To estimate the cloud optical thickness the O₄ observation 360 nm (fit interval 336-367nm) was compared to simulated O₄ columns at 360 nm. We used the

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Henvey-Greenstein approximation for the aerosols with an asymmetry factor of 0.85 for the cloud droplets.

Concerning the low SSA in the clouds, the referee mentioned the possibility of volcanic particles inside the cloud and the consequence for the SSA of the cloud droplets. See also comment 6 by N. Krotkov.

The simulation-wavelength was added to the manuscript in Sec. 2.2.

Page 533, Line 1. The authors explained that it was not possible to compare the COT with MODIS. Have you tried to use the COT product from SEVIRI/MSG? There are more cloud products available from SEVIRI besides COT.

We thank the referee for the hint to additional cloud information, according to this information it was a cirrus cloud the plane crossed, and there are strong indicators for additional clouds at lower altitudes.

The fact that the aeroplane mainly flew over cirrus clouds justifies the optical density of 10 and the rather low optical extinction.

The cloud type and several layers of clouds are included in Sec. 3.2.

Do you have any information about the SO₂ plume height along the trajectory? What is the error in the ECMWF wind?

The 8 days backward trajectories from the TRAJKS showed that the plume stayed at an altitude around 11 km since the eruption, also for the next hours there is no change in the plume's altitude according to the ECMWF / TRAJKS.

The error in the ECMWF wind data might be up to 5 m/s \approx 16% of the observed wind speed.

The error and altitude are added to the estimate of the optimized wind speed.

Probably the 1 degree resolution is not enough to resolve all the variations in the wind

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field. Actually from the GOME-2 images SO_2 peak close to 20 degree east seems separated from the main plume, it suggests that there are variations in smaller scale.

Also the DOAS SO_2 suggests that the smaller plume is separated from the main plume, in the aerosol number density, however, the local minimum between the two parts of the plume is much less pronounced. Whether or not it really was a separate sub plume or not, can not be answered based on the observations. But there seem to be small scale variations which are not resolved by the ECMWF model.

The respective comment in the paper is more emphasised in Sec. 4.3

Fig. 4 The telescope with -10 degree detected the SO_2 plume earlier than the +10° telescope. Is it an extra piece of information about the plume altitude and distance from the aircraft?

Yes, if the +10° SO_2 SCD observed were observed in the same wavelength range as the downward directed ones, this might have been used for a better profile estimation. However, the wavelength range of the +10° spectrometer is slightly different, therefore these SO_2 data are noisier and the errors are much bigger.

It is explained in the manuscript more explicit in Sec. 3.2.

It is difficult to distinguish thin and thick clouds from Fig. 5. What is the cloud type for the thick clouds? Do you have vertical velocity measurements when the aircraft is inside the clouds?

Unfortunately we don't have the vertical wind speed in our data set, but according to the cloud water and the video camera, this cloud was about 5 km thick. The satellite images e.g. Modis or NOAA 17 showed that the clouds were part of a large frontal cloud system. The NOAA 17 image taken at 9:07 UT is included, next to camera image. According to the Meteosat cloud analysis (<http://www.eumetsat.int/Home/index.htm>, April 2010), the plane flew over cirrus clouds for most of the time, only close to Frankfurt

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Alto cumulus or Cumulonimbus were observed, probably there were several layers of clouds.

The information on the cloud type as well as the respective reference is included in Sec. 3.2.

Fig. 6. What is the unit for the cloud water?

Both cloud and gaseous water are measured in ppm, for the measurements the cloud droplets are evaporated.

Figure 6 is corrected.

Page 533, Line 24. ' . . . the sharp decline in the observed SO₂ column might be a reduced SO₂ concentration due to scavenging by the cloud droplet.' Do you have measurements about the chemical components in the cloud water? Do you see the aerosol composition is different inside and outside of the clouds?

The temporal resolution of the aerosol chemical composition measurements is about 90 minutes, therefore we can not resolve the changes when descending into the cloud. No changes were made in the manuscript

Page 538, Line 17. The aerosol layer was assumed to be extended from 11 to 12 km. So the aerosol layer is above the clouds. Why it is not possible that the aerosols are also partly inside the clouds? In this case aerosol reduces the total SSA more efficiently.

The referee is absolutely right, according to our aerosol number concentration measurements it is very likely, that there are aerosols at least in the highest layer of the cloud. This might be one reason why with the higher SSA it is impossible to simulate a decrease in the intensity as observed during the first SO₂ peak.

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The SSA is still assumed to be 0.99 but the possible influence of the dark aerosol is included as additional information.

Page 539, Line 10. The authors find that the influence of the different clouds on the SO₂ AMFs is almost negligible for CARIBIC. Could you explain the reasons?

The main reason is the same as for the similar effect observed for the GOME-2 AMF (see comment 6 from Nicolay Krotkov). The AMF can only be enhanced if the additional scattering events occur. Compared to the geometrical approximation the light path is enhanced by 14% due to scattering at air molecules (cloud free simulation). Including a cloud in the simulation only adds a few additional scattering events just above the cloud surface.

Additional interpretation of the GOME-2 AMF is included.

References

Bussemer, M. , Der Ring-Effekt: Ursachen und Einfluß auf die Messung stratosphärischer Spurenstoffe, diploma thesis, Univ. of Heidelberg, Heidelberg, Germany 1993.

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