Memorandum

Title: Summary of activities re GRG WP 56 (Targeted analysis of extreme events)	
From: J. Flemming (ECMWF), P. Valks (DLR), M.G. Schultz (JÜLICH), Antje Inness (ECMWF), Angela Benedetti (ECMWF), Jean-Jacques Morcrette (ECMWF) and Richard Engelen (ECMWF)	
To: MACC reviewers and project officer	
Copy: MACC Management board	
Date: 12/12/2013	

1. Why this memo?

In 2010, the eruption of Eyjafjallajökull on Iceland was responsible for severe disruptions in air travel with associated financial losses of European companies and enterprises. The MACC project was asked to provide additional information on the atmospheric impacts of this eruption, and this was achieved through collecting web reports on measurements and model simulations, and by running dedicated data assimilation and forecast simulations which included estimates of the volcanic source of aerosols from Iceland (see http://www.copernicus-atmosphere.eu/news/volcanic_ash/background/for a summary of activities and results).

At the time of this extreme event, there was no formal provision in the MACC work programme to dedicate resources to the analysis and documentation of volcanic eruptions. As a consequence, it was recognized that the MACC system at the time could not provide an immediate reaction to these situations, although the first forecasts were in any case made available just few days after the eruption. In addition, no communication channels with other agencies which are responsible for emergency advisories and public information (in this case the volcanic ash advisory centres, VAACs) had been established prior to the event, and some clarification of the role of MACC (or the future Copernicus service) in such situations was needed.

The recognition of these limiting factors led to the introduction of a specific work package in the work plan of the reactive gases sub-project in the MACC-II project. This is WP 56 titled "Targeted analysis of extreme events". While the primary objective of this work package is the provision of resources in case of a new atmospheric composition event with similarly severe consequences, this WP was also intended to review the activities that took place during the Eyjafjallajökull analysis and to coordinate with the rest of the MACC-II team in order to increase the readiness to respond to other events in the future.
Besides volcanic eruptions, major forest fires were also seen as a potential area of public interest. There have been a couple of incidents which were analysed jointly by team

members from the GRG and FIRE sub projects (e.g. Huijnen et al., 2012), and two FIRE deliverable reports (D31.2 and D32.1) contain information on the activities for these events. Dust storms, which were also identified as a target, have been taken up by the aerosol sub-project (Deliverable D66.3).

The present report summarizes the activities that have taken place at ECMWF and other MACC-II partner institutions in order to improve the readiness to react to future volcanic eruptions. As there is no formal deliverable associated with this report, we chose the format of a memorandum to communicate the relevant activities.

This report summarises the capabilities of the MACC-II system in regards to forecasting volcanic plumes at the time of the 2010 eruption of Eyjafjallajökull and it describes the current status. Suggestions for further steps are also provided.

2. NRT forecast of volcanic plumes with the MACC system

As volcanic ash is a hazard for aviation, its forecast is of great value. Volcanic sulphur dioxide (SO_2) is quite often co-located with ash and can be considered as a proxy for ash (Sears et al, 2013). The MACC system has been used to forecast both volcanic ash (Benedetti et al. 2011) and SO_2 (Flemming and Inness, 2013).

The simulation of volcanic plumes from explosive volcanic eruptions requires an estimate of the emission rate and the injection profile. The emission estimates can be obtained by empirical formulas from plume heights or from satellite observations. The emission parameters vary in time and the estimates have large uncertainties. Moreover, the changing values of the emission parameters after the start of a NRT forecast are unknown. The NRT plume forecasts carried out by several institutions during the 2010 Eyjafjallajökull eruption were based on model simulations which were using approximate emission estimates.

The MACC data assimilation system adds a new aspect to NRT plume forecasting, which is the assimilation of the satellite observations of the plume to correct the initial conditions of the forecasts. Ideally, the assimilation could correct the errors in the assumption about the emissions and the transport prior to the forecast start. In practise, the assimilated observations of the plumes have limitations because of gaps in coverage, low temporal resolution and sensor sensitivity as well as a lack of vertical information.

Since volcanic eruptions are special events, a certain amount of manual intervention by the MACC scientists is necessary to start the plume forecasts. The time needed for this depends on the timeliness of the information regarding the actual eruption as well as the readiness of the model tools to carry out the forecasts. The time needed to start action can be shortened by establishing strong communication links to the VAACs. The time needed to prepare the forecasts can be shortened by further development of the applied tools.

2.1. State of the data assimilation and forecasting system at the time of the Eyjafjallajökull eruption (April 2010)

The NRT MACC system running at the start of the 2010 Eyjafjallajökull eruption did not capture or forecast a volcanic plume. The signal of the eruption in the MODIS AOD retrievals was not assimilated because quality control (QC) prevented the assimilation of MODIS data north of 60 °N. The signal from the plume which was present in the data south of 60 °N produced a plume in AOD which was attributed to sea salt because of the lack of a representation of volcanic aerosol in the MACC aerosol model. The assimilation of SO_2 retrievals was not in place yet. Within 48 h after the eruption, model forecasts were started which contained a tracer plume based on an arbitrary emission estimate. The tracer was released 6 km above the volcano. This plume forecast agreed well on a qualitative level, with the forecast of other institutions and was published on the MACC web site.

2.2. Developments of the MACC system and current status

Since 2010, the MACC system has been substantially improved to better forecast the plumes of volcanic eruptions. It has been applied to the eruptions of Eyjafjallajökull (2010), Merapi (2010), Grimsvoetn (2011) , Nyamuragira (2011), Puyehue-Cordón (2011), and Nabro (2011). The current status of the capabilities to forecast volcanic plumes is summarised in Table 1. Newly developed modelling capabilities of the MACC system are:

- tracer variable for volcanic aerosols in the aerosol scheme
- namelist-based setup of emissions for volcanic SO_2 and aerosol tracers for eruptions
- chemical loss (lifetime) and wet deposition for SO_2 tracer
- compilation of emissions for permanently outgassing volcanoes
- Procedure to estimate SO_2 emissions from SO_2 UV-VIS observations

The default MACC aerosol configuration includes 12 prognostic variables (11 aerosols and tropospheric SO_2). A recent version now includes three additional variables, all specifically linked to gas and aerosols of volcanic origin, namely ash, SO_2 and SO_4. The new model functionality enhances the assimilation performance of plume observations. In particular, the volcanic aerosol model variable ensures that assimilated AOD observations of the plume do not change the non-volcanic aerosol species if volcanic aerosol is the dominant aerosol component in the plume area. It is therefore necessary to have information about the emissions of volcanic aerosol. The forecast system for volcanic ash has been tested with improved estimates of the Eyjafjallajökull ash emissions by Stohl et al. (2012) as documented in Benedetti et al. (2011).

The assimilation of SO_2 uses a single volcanic SO_2 tracer, which is independent of the SO_2 of the chemistry scheme. New optimised back ground error statistics for volcanic SO_2 have been compiled in such a way that the assimilation algorithm places the SO_2 plume at a prescribed single plume height. It is therefore possible to successfully assimilate SO_2 plumes without an assumption about the emission rate. Further, several options of variable transformation have been tested.

Because of the importance of the emission parameters, a method has been developed to estimate injection height and emission rate of volcanic SO_2 using UV-VIS satellite observations of SO_2 (Flemming and Inness, 2013). The method is based on the comparison of test tracers injected at different heights and observed SO_2 total columns. It can estimate the emission parameters for a period of 24 hours before the time of the observations. The estimated injection heights are needed by the SO_2 assimilation system to place the plume at the assumed model level.

The choice of the observation data sets used for assimilation and emission parameter estimates is an important factor. Total column retrievals from OMI, GOME-2 and SCIAMACHY have been inter-compared with respect to the maximum values and SO_2 budgets as well as coverage. The GOME-2 retrievals appear most suited because of their good spatial coverage. The GOME-2 SO_2 retrieval is described in more detail in Section 3.

Finally, a method to compare different plume forecasts in a quantitative way has been developed for the SO_2 plume forecast. This is needed to identify the best approach for analysis and forecasts. The SO_2 analyses represent the plume location and the maximum values very well but have a tendency to exaggerate the extension of the plume. The IFS forecasts without assimilation do not maintain the high maximum values recoded by the observation over long periods, possibly because of too large diffusion. Overall, the combination (INIEMI) of using emission data (EMI) and assimilation (INI) leads to the best forecasts. This is demonstrated in Figure 1, which shows 24 h forecast for two days during the 2010 eruption. The EMI forecast provide a good forecast close to the volcano. The INI forecasts provide a better forecast for the older plume. The INIEMI forecasts combine both properties.

Automated, no intervention	NRT intervention (working hours)	1-2 day delay intervention
• Assimilation of OMI SO_2 retrievals above 5DU at prescribed heights • Assimilation of MODIS AOD in existing aerosols	• Emit SO_2 and ash in model at volcano location using ad-hoc emission estimate • Relax QC and reduce thinning for assimilated MODIS observations • Active assimilation of TRM SO_2 retrieval (GOME-2, OMI)	• Estimate SO_2 emission rate and injection height based on UV-VIS satellite retrievals • Rerun MACC system for eruption period with improved settings and emission estimates

Table 1 Status of MACC system to forecast volcanic SO_2 and ash plumes with different levels of required intervention

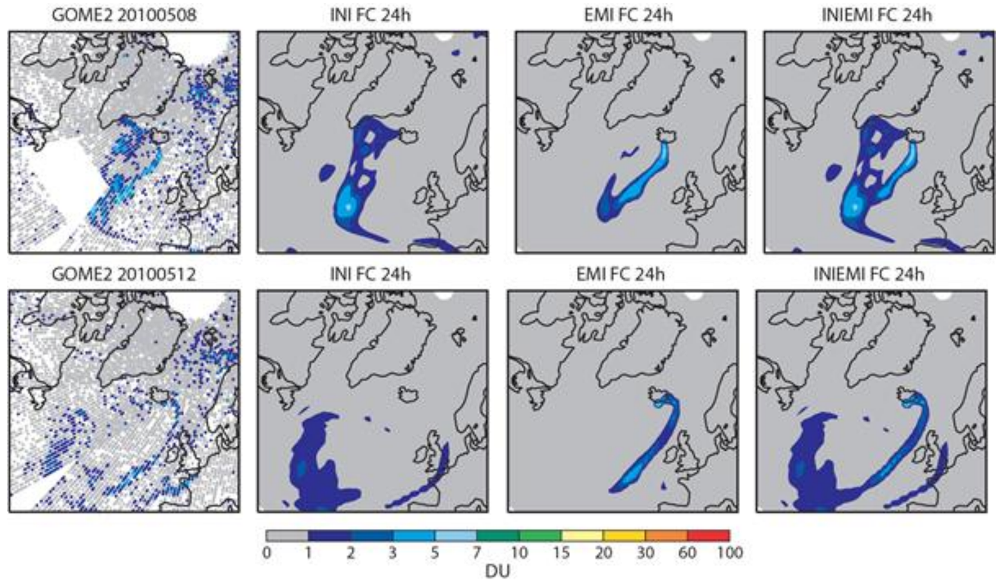

Figure 1 GOME-2 observations (left) and the 24h TCSO2 forecasts using only initialisation with SO_2 analysis (INI), only the estimates emission parameters (EMI) and a combination of both (INIEMI) for 8 May (top) and 12 May (bottom) 2010 in DU.

3. Satellite observations of volcanic SO_2 by GOME-2

Satellite-based instruments operating in the ultraviolet (UV) spectral region have played an important role in monitoring and quantifying volcanic SO_2 emissions. The Total Ozone Mapping Spectrometer (TOMS) was the first satellite instrument to detect volcanic SO_2 released during the El Chichon eruption in 1982. The newest UV satellite sensors OMI on EOAS-Aura (since 2004) and GOME-2 on MetOp-A and -B (since 2007 and 2012) make it possible to monitor volcanic activity and eruptions on a global scale and daily basis.

The operational GOME-2 SO_2 products are provided by the German Aerospace Center (DLR) in the framework of EUMETSAT's Satellite Application Facility on Ozone and Atmospheric Chemistry Monitoring (O3M-SAF). ECMWF/MACC and other end users receive the GOME-2 SO_2 near-real time products in less than two hours after sensing (dissemination via EUMETCast, WMO/GTS and the internet), with a committed service 24 hours a day and 365 days of the year.

3.1 GOME-2 SO_2 retrieval algorithm

GOME-2 is a nadir-scanning UV-VIS spectrometer that measures the back-scattered radiation from the earth-atmosphere system in the spectral range 240–790 nm, and crosses the equator at 9:30 LT. The default ground pixel size is 80 km × 40 km (across-track x along-track) covering a swath width of 1920 km, which allows global coverage at the equator in about 1.5 days. The GOME-2 instruments on MetOp-A and -B are operated in a tandem configuration. Currently, GOME-2 on MetOp-A measures with a higher spatial resolution of

40 km × 40 km (and a reduced swath width of 960 km), while GOME-2 on MetOp-B measures in default mode (ground pixel size of 80 km × 40 km).

The SO_2 columns are retrieved with the GOME Data Processor (GDP) version 4.7 from GOME-2 UV backscatter measurements of sunlight in a two-step procedure (Valks et al., 2013; Rix et al., 2012). In a first step, slant column densities (SCD) of SO_2 are determined using the Differential Optical Absorption Spectroscopy (DOAS) method in the wavelength region between 315 – 326 nm. Input parameters for the DOAS fit include the absorption cross-section of SO_2, for which the temperature is adjusted depending on the assumed height of the volcanic SO_2 plume, and the absorption cross-sections of interfering gases, ozone and NO_2. A further correction is made in the DOAS fit to account for the ring effect (rotational Raman scattering).

In a second step, the slant column densities of SO_2 are converted to geometry-independent vertical column densities (VCD) through division by an appropriate air mass factor (AMF): VCD = SCD/AMF. For SO_2, the AMF is strongly dependent on measurement geometry, surface albedo, clouds, aerosols, and most importantly, the shape of the vertical SO_2 profile in the atmosphere. For the AMF calculations, an a priori volcanic SO_2 profile is assumed with a predefined central plume height and a Gaussian SO_2 distribution. As the correct plume height is rarely available at the time of measurement, the SO_2 column is computed for three different assumed volcanic plume heights: 2.5 km, 6 km and 15 km above ground level. The lowest height represents passive degassing of low volcanoes, the second height effusive volcanic eruptions or passive degassing of high volcanoes and the third height explosive eruptions. The AMFs are calculated with the radiative transfer model LIDORT.

A first prototype version of the SO_2 Plume Height Rapid Inversion (SOPHRI) retrieval algorithm for GOME-2 has been developed during MACC-II. SOPHRI provides a NRT estimation of the SO_2 plume through a combination of the DOAS method to retrieve the total SO_2 column and a minimization method for matching simulated GOME-2 spectra to retrieve the plume height (Rix et al., 2012). An important parameter that affects the accuracy of the retrieved plume height is the total SO_2 column. The retrieval works best for high total columns, as a clear SO_2 signature in the GOME-2 spectrum is needed.

3.2 GOME-2 observations of volcanic SO_2

Eyjafjallajökull (2010)

During the early eruptive episode until 4 May, GOME-2 and other satellite instruments detected only small amounts of sulphur dioxide that were mostly located close to the volcano.
During the eruptive activity following 4 May, large amounts of SO_2 were emitted into the atmosphere and the volcanic gas plume could be traced by GOME-2 for several days. Fig. 2 shows the GOME-2 observations for 6 and 7 May, when part of the volcanic SO_2 cloud was transported towards Spain. SO_2 and ash were well collocated during this period of the eruption, therefore the SO_2 plume could be used as tracer for the eruption cloud. SO_2 emissions from the Eyjafjallajökull eruption could be detected until the eruption ceased on 23 May. Including all daily emissions, the total emissions can be estimated to ~1.2 $\pm$ 0.5 Tg,

which is comparable to the total SO_2 emissions estimated from GOME-2 observations during the Kasatochi eruption in August 2008 (Rix et al., 2009).

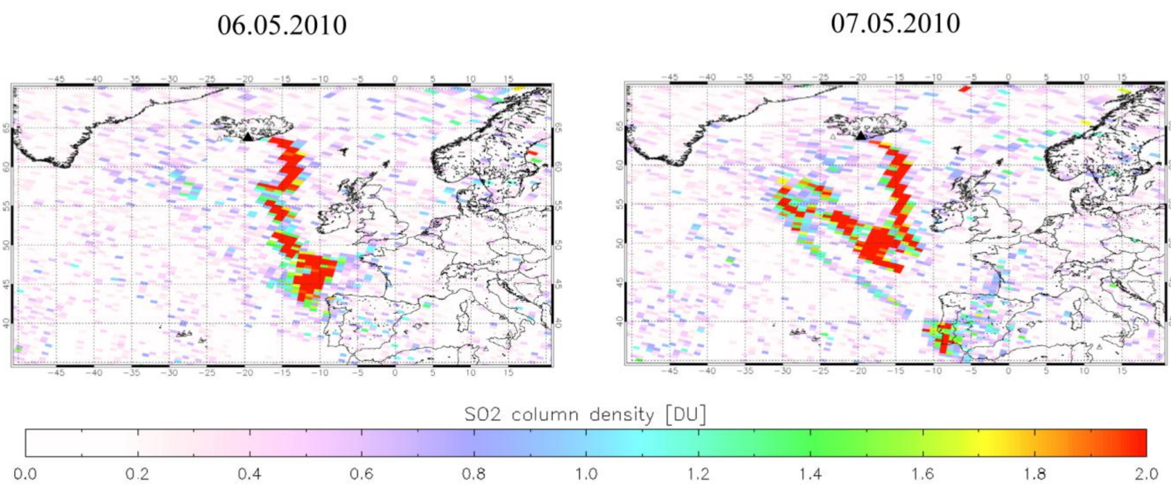

Figure 2: Volcanic SO_2 cloud from the Eyjafjallajökull eruption on 6 and 7 May 2010 as seen by GOME-2.

Major eruptions in 2011-2012

The three major eruptions of 2011 were the eruptions of the Icelandic Grìmsvötn volcano (21-28 May), the eruption of the Chilean Puyehue-Cordón Caulle volcano (4-7 June), and the eruption of the Eritrean Nabro volcano (12 June - 7 July). A characteristic feature of the Grìmsvötn eruption is that a large amount of SO_2 was ejected northwards while the ash cloud went to the southeast (see Fig. 3). The SO_2 cloud, which travelled over Canada and came back over Europe, was monitored by GOME-2 during 3 weeks. The explosive eruption of the Eritrean Nabro volcano on 12 June 2011 ejected a huge amount of SO_2 in the atmosphere, threating international flight routes from the far east to Europe. GOME-2 SO_2 measurements show that on the 14th of June, the Nabro volcano spewed a volcanic plume across the route of many flights over East Africa and the Middle East.

The eruption of the Chilean Copahue volcano (23-25 December) was the largest eruption in 2012. The GOME-2 instruments on MetOp-A and B detected an SO_2-rich plume associated with ash emissions. The volcanic plume was transported over Chile and aviation authorities in South America warned airlines to avoid the area.

3.3 Current and future developments on GOME-2 SO_2 retrieval

In 2013, several improvements in the SO_2 column retrieval for GOME-2 on MetOp-A and -B have been implemented in the latest operational retrieval algorithm GDP 4.7. The main improvement is the usage of two additional O_3 pseudo-cross-sections in the DOAS retrieval to mitigate the non-linearity of the O_3 absorption and reduces the effect of the interference between O_3 and SO_2 in the retrieval. Using this approach, the interference correction that has been applied in previous versions of the GDP is no longer needed. In addition, the offset correction that is applied to the SO_2 slant column values to account for any systematic bias in the SO_2 column, has been improved.

Current research on the GOME-2 SO_2 retrieval is focused on the implementation of a so-called empirical DOAS method, which can improve the accuracy of the retrieved SO_2 columns, especially for high SO_2 values (> 30 DU). Further improvements of the SOPHRI NRT plume height retrieval algorithm for GOME-2 are planned as well, which are based on an empirical approach.

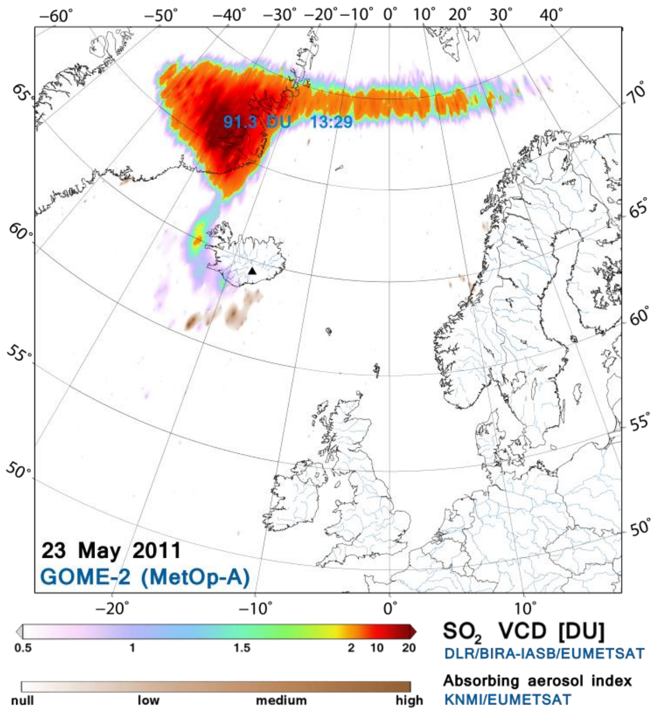

Figure 3: SO_2 and aerosols (ash) detected by GOME-2 (Grìmsvötn eruption, 23 May 2011). The GOME-2 data has been used for the Support to Aviation Control Service (SACS), see Brenot et al. (2013).

4. Suggested developments

In this section we suggest further steps for the development of the MACC system with respect to the NRT forecast of volcanic eruptions. It has to be decided to what extent these developments can be carried out in the remainder of the project.

It is necessary to harmonise the code development for the volcanic ash and the SO_2 tracer. Both should use the same mechanism to communicate the emission information to the IFS. The setup should be documented so that any ECMWF MACC scientist can quickly activate the erupting volcano in the model. First guess choices for injection height and emission rate should be prepared in advance to avoid delays in starting the plume forecast. It has to be decided if the plume forecasts are provided as part of the MACC system run by the forecast department, or if a separate system will be activated during eruptions.

The method to estimate SO_2 emissions could be adapted to the estimation of ash emissions. However this requires further investigation. The estimation of the ash emissions is more complicated because of the higher aerosol background values and the need to simulate the aerosol optical depth of the test ash tracers.

It could be tested if the assimilation of other retrievals of SO_2 or ash (assuming they are available in NRT) is more suited for the assimilation of the plumes. Assimilation tests of GOME-2 SO_2 retrievals from Metop-A and Metop-B in the NRT system will be started soon. Furthermore, IR based SO_2 retrievals from AIRS or IASI are not limited to day-time conditions and would therefore provide information at a higher temporal resolution. However, large biases have been reported between the IR and UV retrievals (Thomas and Prata, 2011) A NRT SO_2 product from IASI will be delivered operationally by EUMETSAT by the end of 2014.

A general problem is the projection of the emission estimate for the duration of the NRT forecast. It might be interesting to explore the practicality of emissions scenarios such as continuation or increase or cessation of the emissions. Likewise an ensemble of forecasts injected at different heights could be of interest to better account for the uncertainties of the injection height estimate in NRT. Using meteorological ensembles to assess how much the uncertainty of the meteorological forecasts affects the plume forecasts could also be envisaged.

More test cases could be considered, in particular ones that are well documented in the literature such as the eruptions of Kasatochi (August 2008), Sarychev (June 2009) or the Pinatubo (June 1991). For eruptions that reach the stratosphere the conversion of SO_2 to sulfate aerosol needs to be better modelled. Simulating the June 1991 Pinatubo eruption and the subsequent plume of ash, SO_2 and SO_4 is on-going work. It mainly aims at adjusting some aerosol model parameterisations in order to get reasonable values for the SO_2 plume that circle the globe for some months after the eruption. The radiative impact of the SO_2 / SO_4 plume is investigated.

5. Coordination of activities and communication strategy

The forecast of volcanic plumes is a cross-cutting issue and will benefit from improved coordination within ECMWF, within MACC-II and with external institutions.
Since volcanic aerosol could contaminate the retrievals of meteorological variables as well as affect the radiation budget of the Earth, the MACC-II work at ECWMF should be linked to the work other ECMWF Research activities, such as meteorological satellite data assimilation, ensemble forecasting, and probabilistic forecasting.
Within the MACC-II project, the activities of AER and GRG could be better harmonised to enhance the readiness of the system. MACC-II needs to work on the unified presentation of the plume forecast to users but also to a wider audience (press releases etc.)

MACC-II should gauge the interest of the VAACs for the additional MACC-II products. The distinction between now-casting (clear responsibility for the VAACs) and short to medium-range forecasting could help to define the added value of the MACC-II services. MACC-II should establish links with institutions (Icelandic met office, Ministri Dipartimento della Protezione Civile, etc.) which monitor volcanic eruptions (e.g. plume height observations from radars) to get quicker access to these observations during an eruption.
The cooperation with institutions producing satellite retrievals of volcanic plumes should be strengthened. MACC-II can provide important feedback to the data producers. This may lead to improved retrievals in terms of data quality and NRT provision.

6. Summary

As a result of the activities described in this report we believe that MACC-II is in a good position to quickly analyse and document major events with severe impacts on the atmospheric composition on a global scale (volcanic eruptions, wildfires, etc.). While there recently has been no such event triggering formal requests from policy makers to the MACC-II project, a number of past volcanic eruptions have been studied. It is important to recognize that there is no formal mandate for MACC-II (nor for the future Copernicus Atmosphere Service) to provide and guarantee such information in real-time. Moreover, the resources allocated to the project would not allow a 24/7 operation of any such warning service. Nevertheless, the data assimilation and forecasting system of MACC-II, and the involvement of a large number of atmospheric research institutions in Europe in this project, enable the atmospheric service to provide value-added information on extreme events on a relatively short notice and with generally high quality.

References

Benedetti, A., J. W. Kaiser, J-J. Morcrette, R. Eresmaa and S. Lu (2011), Simulations of volcanic plumes with the ECMWF/MACC aerosol system, December 2011, ECMWF Technical Memorandum, 653,

Brenot, H., N. Theys, L. Clarisse, J. van Geffen, J. van Gent, M. Van Roozendael, R. van der A, D. Hurtmans, P.-F. Coheur, C. Clerbaux, P. Valks, F. Prata, O. Rasson, K. Sievers, and C. Zehner, Support to Aviation Control Service (SACS): an online service for near real time satellite monitoring of volcanic plumes, submitted to Nat. Hazards Earth Syst. Sci., 2013.

Flemming, J., and A. Inness (2013), Volcanic sulfur dioxide plume forecasts based on UV satellite retrievals for the 2011 Grímsvötn and the 2010 Eyjafjallajökull eruption, J. Geophys. Res. Atmos., 118, doi:10.1002/jgrd.50753.

Huijnen, V., J. Flemming, J. W. Kaiser, A. Inness, J. Leitão, A. Heil, H. J. Eskes, M. G. Schultz, A. Benedetti, J. Hadji-Lazaro, G. Dufour, and M. Eremenko (2012), Hindcast experiments of tropospheric composition during the summer 2010 fires over western Russia, Atmos. Chem. Phys., 12, 4341–4364.

Rix, M., P. Valks, N. Hao, J. van Geffen, C. Clerbaux, L. Clarisse, P.-F. Coheur, D. Loyola, T. Erbertseder, W. Zimmer, S. Emmadi (2009), Satellite Monitoring of Volcanic Sulfur Dioxide Emissions for Early Warning of Volcanic Hazards. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 2(3), 196-206.

Rix, M., P. Valks, N. Hao, D. Loyola, H. Schlager, H. Huntrieser, J. Flemming, U. Koehler, U. Schumann, A. Inness (2012), Volcanic SO2, BrO and plume height estimations using GOME-2 satellite measurements during the eruption of Eyjafjallajökull in May 2010, J. Geophys. Res., 117, D00U19, doi:10.1029/2011JD016718.

Thomas, H. E. and Prata, A. J (2011), Sulphur dioxide as a volcanic ash proxy during the April–May 2010 eruption of Eyjafjallajökull Volcano, Iceland, Atmos. Chem. Phys., 11, 6871-6880, doi:10.5194/acp-11-6871-2011.

Sears, T. M., G. E. Thomas, E. Carboni, A. J. A. Smith, and R. G. Grainger (2013), SO_2 as a possible proxy for volcanic ash in aviation hazard avoidance, J. Geophys. Res. Atmos., 118, doi:10.1002/jgrd.50505.

Stohl, A., A.J. Prata, S. Eckhardt, L. Clarisse, A. Durant, S. Henne, N. I. Kristiansen, A. Minikin, U. Schumann, P. Seibert, K. Stebel, H.E. Thomas, T. Thorsteinsson, K. Tørseth, and B. Weinzierl (2011), Determination of time- and height-resolved volcanic ash emissions and their use for quantitative ash dispersion modeling: the 2010 Eyjafjallajökull eruption, Atmos. Chem. Phys., 11, 4333–4351, doi:10.5194/acp-11-4333-2011.

Valks, P., Loyola, D., Hao, N., Rix, M., and Slijkhuis, S., Algorithm Theoretical Basis Document for GOME-2 Total Column Products of Ozone, Minor Trace Gases and Cloud Properties (GDP 4.5 for O3M-SAF OTO and NTO), DLR/GOME-2/ATBD/01, Iss./Rev.: 2/H, available at: http://o3msaf.fmi.fi, May 2013.