TECHNICAL MEMORANDUM

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Simulations of volcanic plumes with the ECMWF/MACC aerosol system

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Abstract

Volcanic aerosols have a large impact on the society at different levels. In recent years, the eruptions of the volcanoes Eyjafjallajökull in Southern Iceland (April 2010), and the Puyehue-Cordón Caulle in Chile (June 2011) have had a big resonance, due to the disruption to air traffic and the large monetary impact on the aviation industry. Although operational simulations of volcanic plumes is not the task of the Global Monitoring for Environment and Security Atmospheric services, the Monitoring Atmospheric Composition and Climate team responded to these events with a series of SO2 tracer simulations that were published on the MACC website shortly after the eruptions. Since that initial effort, there has been a gradual evolution toward a prototype system to handle volcanic eruption in near real time, in support of the work of the Volcanic Ash Advisory Centers and the interested MACC users. This paper describes the initial modifications to the MACC aerosol system to run simulations of volcanic ash plumes. Initial efforts aimed at *ad hoc* solutions which proved quite effective. Subsequent efforts have established an improved methodology to respond to volcanic events, and to provide timely services. This will be briefly outlined here and described fully in a dedicated paper.

1 Motivation

The eruption of the Eyjafjallajökull volcano in southern Iceland in April and May 2010 was an event of unprecedented impact at the European scale. Following the eruption on April 14, 2010 the air space over many countries was closed. Air traffic to and from Europe was suspended for over one week, creating a significant economic and social disruption. At the same time this also represented an opportunity for the whole aerosol modelling and observational communities to be challenged into providing more accurate plume forecasts and quantitative observations of volcanic plumes.

Although the Monitoring Atmospheric Composition and Climate (MACC) project is not tasked officially to provide volcanic plume forecasts, at the time of the eruption MACC was called by its funding agency, the European Commission, to issue a statement regarding the volcanic eruption.

The following statement was posted to the MACC website shortly after the eruption of the Eyjafjallajökull:

“MACC is developing services to support institutions that are providing advice and warnings related to atmospheric composition. In the case of the current Icelandic volcanic eruption, the direct responsibility for advice for aviation for the region lies with the London Volcanic Ash Advisory Centre at the Met Office.

MACC already has the capability to make pre-operational plume forecasts using its advanced data assimilation system for atmospheric composition. Assumptions have to be made about the amount of gas and ash, particle size and weight, and the height of the injection of these constituents into the atmosphere. The latter depends to a large extent on the explosiveness of the eruption. [...] Work is in progress to extend the current capability of gas plume forecasts to include forecasts of volcanic ash particles. [..]

When MACC reaches its operational phase, by 2014 at the latest, it will be able to use actual information about volcanic eruptions in combination with operational observations of atmospheric constituents, for instance from Europe Sentinel satellite missions, to produce plume forecasts in a timely manner. These will be provided on request to the relevant institutions to help them assess the situation and provide detailed information. This would include the Volcanic Ash Advisory Centres but also agencies dealing with the impact on public health. In the meantime, the MACC system will be used to diagnose the current event to learn how accurately the spread of the plume can be forecasted, the impact of the available satellite data, and what new observations are needed for future monitoring and forecasting. More detailed forecasts as well as information about available observations can be found on our dedicated Iceland Volcanic Eruption page (http://www.gmes-atmosphere.eu/news/volcanic_ash/background/”).

Most of the early days volcanic plume simulations were carried out by Johannes Flemming and supported by Antje Inness of the MACC team at ECMWF with the *a posteriori* assimilation of SO_2 data. These plume forecasts were made available on the MACC website shortly after the eruption. Some documentation of these activities can be found in McNally *et al.* [3] and Rix *et al.* [10]. A manuscript by Johannes Flemming and Antje Inness on their effort is also in preparation.

From the point of view of the aerosol modelling and analysis, it was necessary to modify and review most of the "standard" assumptions (for a review of those please refer to Morcrette *et al.* [6] and Benedetti *et al.* [2]). That involved a steep learning curve. At the time of the eruption, in the pre-operational MACC near real time (NRT) experiment running at the time of the eruption, MODIS Aerosol Optical Depth (AOD) data above the latitudes of 60N/60S were blacklisted to avoid issues with snow-contaminated pixels, and this effectively cut off Iceland from the data coverage. Moreover, the thinning of MODIS data is done to a resolution of 0.5 degrees which implied that data around the area of the eruption were quite sparse. Even when these assumptions were relaxed, the analysis did not know of a change in the background conditions, and had no increased aerosols around Iceland in the first guess. Being Iceland a very pristine area with mostly sea-salt as background aerosol, this resulted in most data being rejected at the level of the first guess check. Finally, the aerosol analysis is designed in terms of the total mixing ratio, which is the sum of all the modelled aerosol species: analysis increments in the total mixing ratio are redistributed to the individual species according to their fractional contribution. This implies that the signal from the MODIS data that made it into the analysis was aliased into the most available aerosol for that area: sea salt. A nice plume of sea-salt coming off Iceland can be in fact seen in the pre-operational analysis for the days around the Eyjafjallajökull eruption (Figure 1).

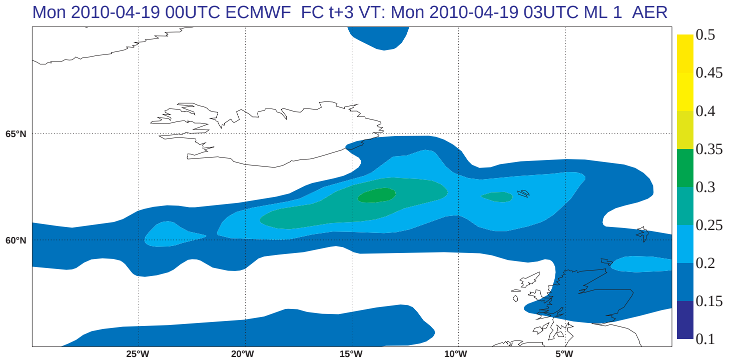

Figure 1: Sea salt plume off the coast of Iceland on April 19, 2010 at 030UTC.

Since the Eyjafjallajökull eruption, several active volcanoes have erupted: Merapi, Indonesia (25-10-2010); Grimsvotn, Iceland, 21-06-2011; Puyehue-Cordón Caulle, Chile, 5-6-2011; Dubbi, Eritrea, 12-06-2011. Experience gained from the eruption of the Eyjafjallajökull volcano has helped in responding quickly to the new situations, and preparing ash plume forecast in quasi NRT. More work needed to automate this process is currently ongoing along with general improvements in the modelling of volcanic plumes.

2 Approach

2.1 Emission parametrisation

The initial response involved specifying emission strength and injection height in an *ad hoc* way directly modifying the physics interface in the Integrated Forecasting System (IFS). The latitude and longitude of the volcano were also specified, along with a search radius that would span at least one grid-box at the chosen model resolution (T159).

Emissions factors of 180,000 tons per day of sulphate, 180,000 tons per day of black carbon and 300,000 tons per day of dust were originally prescribed. In the final configuration, it was decided to implement only dust aerosol as a proxy for volcanic ash. The same configuration was kept to model all volcanic plumes shown here.

As stated in Morcrette *et al.* [6], the IFS dust is represented by a log-normal distribution with mode at 0.29 μm and sigma equals to 2. This distribution is divided into 3 bins with limits at 0.03, 0.55, 0.9 and 20 μm, over which intervals the extinction coefficients, asymmetry factors and single scattering albedos, efficiencies for dry and wet deposition, and sedimentation are computed. Coefficients for all aerosol processes were adapted from the LMD-Z model [5]. For the optical properties, the refractive index of dust is taken from Boucher *et al.* [5] (see also Kinne *et al.* [7]). As the properties of these dust and volcanic ash can be quite different, the model configuration is currently being changed to include a specific aerosol tracer with the physical and optical properties of flying ash.

The injection levels were chosen between 50hPa and 500hPa. A large sensitivity to the choice of these levels for SO_2 tracer simulations was found (J. Flemming, private communication). Similar sensitivities are to be expected also for the aerosol plume. However, it was decided not to pursue investigating the impact of this choice through sensitivity studies, as there are detailed time and height-dependent emission datasets now available for the Eyjafjallajökull eruption. One of them, documented in Stohl et al. [11] is being currently implemented in IFS for more accurate simulations of that case.

2.2 Analysis aspects

In the introduction several changes to the analysis configuration were mentioned. The first and most obvious one was to allow the MODIS data to be used above 60N of latitude. In the standard configuration all MODIS AOD data are black-listed above that latitude and the corresponding latitude in the Southern Hemisphere to avoid including data which are contaminated by snow/ice. Although this can be considered a very conservative assumption, generally it does not result in too much data being rejected as at high latitudes there is little information on background aerosol from the MODIS sensor. The radiometer is in fact sensitive to reflected radiation. Over bright surfaces, such as deserts or snow and ice-covered locations, it cannot distinguish the contribution to the top of the atmosphere reflectance that comes from the surface itself and from the overlying aerosol layer(s).

The other change in the analysis was the removal of thinning of MODIS AOD data to increase data volume, especially over the Northern Hemisphere. The native resolution of the MODIS Level 2 AOD product is 10x10km. In the pre-operational configuration, data are thinned to a resolution of 0.5x0.5 degrees (approximately 60 km) which is more comparable to the resolution of the 4D-VAR outer loop (T159, 1.25x1.25 degrees). This is also done because horizontal correlations in the observation error covariance matrix are neglected: if the data are thinned, the assumption that the observations errors are uncorrelated in the horizontal is more valid. For the volcanic plume, however, the goal was for the analysis to use as much data as possible, and the thinning assumption was completely relaxed. Without thinning, the MODIS data volume is ten times larger: to allow for fast processing of the analysis, data in the Southern Hemisphere were blacklisted because of no influence on the Icelandic volcanic plume. This blacklisting is dependent on the location of the volcano.

The final change was to relax the first-guess check. The first-guess departures (observations minus first-guess) are checked against the standard deviation of the background and observations multiplied by a fixed factor. In the standard configuration this factor is equal two, which means that a departure which is within two sigma of the distribution is allowed to be included in the analysis, and the observation is not rejected. If the departure is larger than two sigma, then the corresponding observation is rejected and is not used in the analysis. This does not mean that the observation is not valid rather that the first-guess departure is large and the adjustment that would be required to match that given observation is too conspicuous to be considered within the assumptions of the incremental 4D-Var (quasi-linearity, Gaussian error distributions, etc.). Occasionally large first-guess departures occur because the given observation is indeed wrong or the forward model, which may include a radiative transfer model, is unable to represent the structure or resolution of the observation. In the case of the volcanic plume, there were a large number of MODIS observations that were rejected, indicating that even with the inclusion of the source term, the plume optical depth was still far from the observed optical depth. Since the aim was to see the impact of the data on the plume, then it was decided to change the factor to six. In that way, even observations that were quite far from the first-guess would be allowed to influence the analysis. Errors in the MODIS observations close to the volcano were decreased to maximise their impact.

Figure 2 shows observed, first guess, and analysis aerosol optical depth for the 1200UTC analysis on 19 April 2010. Differences in analysis and first guess (increments) are also shown. The area over the North Sea, shows a big reduction of the plume intensity operated by the analysis with respect to the first guess. These observations were originally rejected by the system because the departures did not satisfy the first-guess check. Having relaxed the bounds of the acceptable departures, the observations are used in the analysis and have large impact on the increments.

In addition to the above-mentioned analysis changes, it would be necessary also to change the background error covariance matrix to reflect the "unusual" background conditions in a volcanic eruption. The background error covariance matrix for total aerosol mixing ratio is computed for average conditions from 6-months of forecast differences (Benedetti and Fisher [1]). The background errors for average conditions do not reflect the errors in the background field for a volcanic eruption. It might happen that the volcano is situated in a pristine area, such is the case for the Eyjafjallajökull, where the background aerosol is low. Moreover, at upper tropospheric levels the aerosol amounts are generally low, even in highly polluted areas. Consistently the background errors that are computed for normal conditions, will be small at upper levels. To account for the errors in the simulation of volcanic aerosols, one should at least increase the errors at the levels where the plume was inserted for a region around the volcano. This was attempted for the SO_2 assimilation by A. Inness (private communication). However, it is not an approach that can be easily made operational. Only with a fully flow-dependent formulation of the background error covariance matrix, as that achieved in the operational Ensemble Data Assimilation system it will be possible to account for anomalous situations, and to compute the "errors-of-the-day" (Bonavita et al [9]). For the simulations performed so far, however, the background error statistics were not modified with respect to the standard configuration.

3 Results

3.1 Plume forecasts for the Eyjafjallajökull eruption

The plume forecast for April 19, 2010 shows a consistent picture up to day 5 of a plume moving from Iceland towards Northern Europe with high optical depths (see Figure 3). High winds aloft shown in Figure 4 funnelled

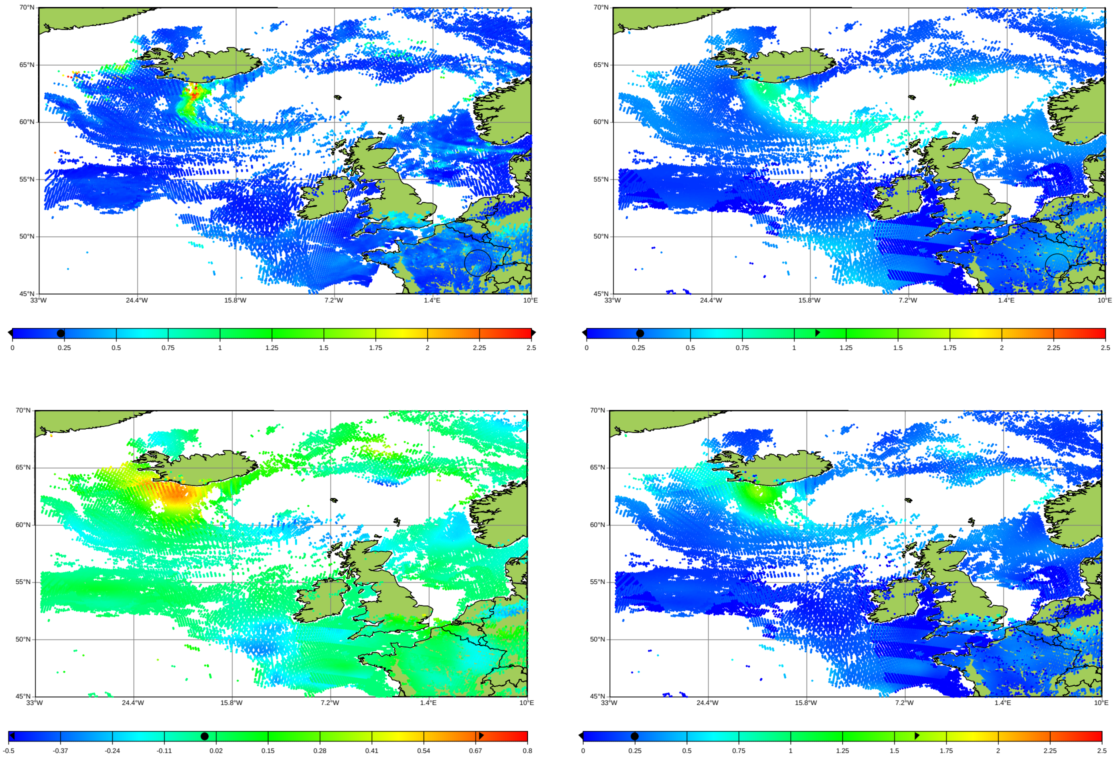

Figure 2: Analysis of MODIS data on April 2010 at 1200UTC: assimilated AOD MODIS observations at the native resolution from the Terra and Aqua satellites (top left), model first guess AOD (top right), increments (bottom left) and analysis AOD (bottom right) at the observation locations

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the plume into a relatively narrow band across the North Sea. Stable high pressure conditions and lack of precipitation in the first couple of days of the forecast contributed to sustaining the feature. Note that even with the constant emissions, the main modulating factor of the plume intensity is precipitation through wet deposition and rain-out. This is visible in the 72h forecast of Figure 4 when a precipitation system sweeps over South-East Iceland and contributes to the reduction of the plume optical depth. Conditions of cloud cover dominated by low to medium clouds at 24h and 48h, transitioning to middle to high clouds at 72h also reflect the fact that the plume could propagate undisturbed. It is evident that the propagation of the plume is in this case dominated by the meteorological situation. However, the details of the interaction between the volcanic ash particles and clouds/precipitation are in general very important, and a correct specification of the sedimentation parameters is the key to a good plume forecast beyond day 1 or 2. Subsequent sensitivity tests using a dedicated volcanic ash prognostic variable, that will be discussed in an upcoming paper by Jean-Jacques Morcrette show that was the case for this eruption, and even more so for other eruptions from volcanoes in tropical areas where convective precipitation systems can actively contain the spreading of the plume (for example the Merapi and Dubbi eruptions).

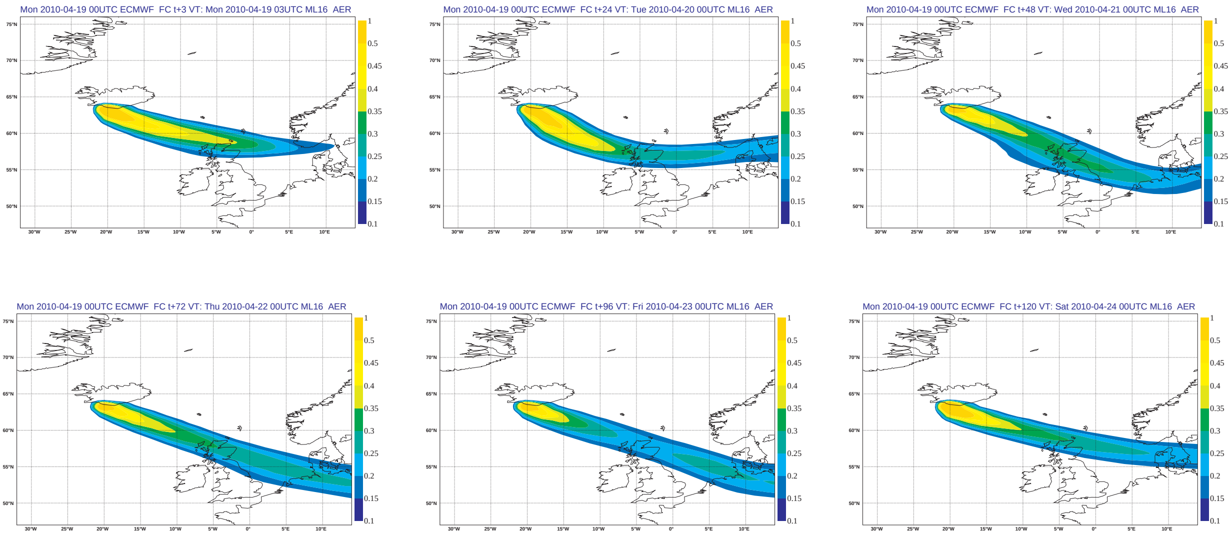

Figure 3: Dust optical depth from the forecast with constant volcanic source showing a plume off the coast of Iceland. Forecast start time is April 19, 2010 00UTC, shown are steps 3, 24, 48, 72, 96 and 120.

3.2 Qualitative verification using IASI and AIRS data

Brightness temperature data from the Advanced Infrared Sounder (AIRS) and Infrared Atmospheric Sounding Interferometer (IASI) are routinely assimilated in the operational NWP system at ECMWF. In this context, the radiative effects of (coarse) aerosols complicate the forward modelling of the observations in a similar manner to the radiative effect of water and ice clouds. From the operational NWP system's point of view it makes no difference whether observed data are contaminated by cloud or aerosols. Nevertheless, the operational data assimilation system is capable of distinguishing between cloud and aerosol contamination as part of the cloud detection scheme. Different types of aerosols are not discriminated.

The scheme for detecting aerosol-contaminated elements of AIRS and IASI data is built upon the output of the cloud detection scheme introduced by McNally and Watts [4]. Detection of aerosol is only carried out if

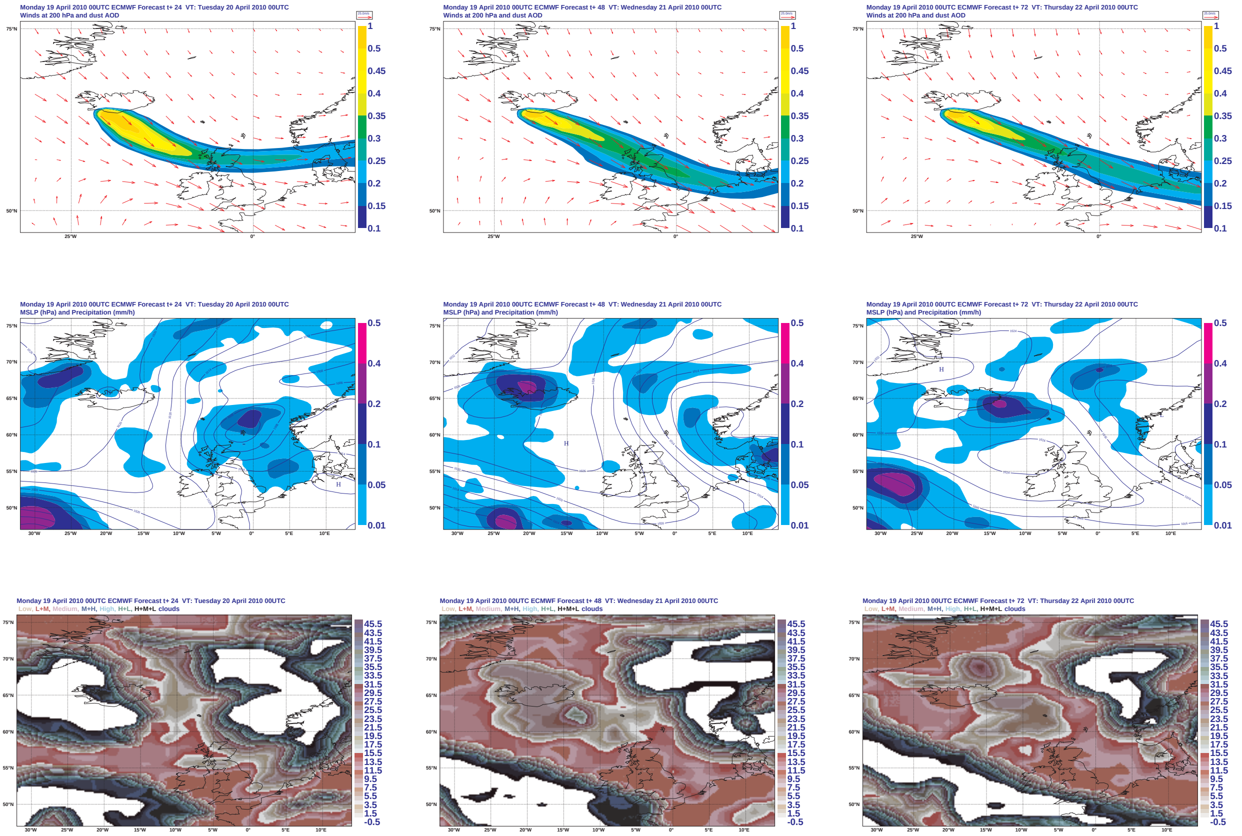

Figure 4: Dust optical depth and 200 hPa winds (m/s), total precipitation (mm/h) and Mean Sea Level Pressure (hPa), and cloud cover for the 24h, 48h and 72h forecasts initialised at 00UTC on April 19 2010.

presence of a cloud in the sounder field-of-view is diagnosed by the cloud detection scheme. In such a case, first guess departure data on eight pre-defined channels are used for determining whether the diagnosed cloud consists of aerosol particles rather than water droplets or ice crystals.

The eight channels used by the aerosol detection scheme are chosen such that radiative effects of dry aerosol particles can be differentiated from that of ice or water clouds or first guess humidity errors. These channels span wavelengths of 8–9 μm in a window region of the infrared spectrum, and they do not hit any major absorption lines. Using least-squares algebra, a line is fitted to the first guess departure data on these channels, and presence of aerosols is diagnosed if the slope of the fitted line exceeds an empirically-determined threshold value.

On April 20, 2010 the aerosol detection scheme showed strong presence of aerosols around Southern Iceland, close to the Eyjafjallajökull volcano. The plume forecast initialised from the 00UTC analysis of April 19 was qualitatively verified against the IASI and AIRS data. Good agreement was found between the data and the direction of the plume from the forecast, although the maximum of the latter is slightly displaced with respect to the data. Referring back to the increment in the left bottom panel of Figure 2, we can see that the analysis of MODIS data on April 19 at 1200 UTC tried in fact to correct the plume in the immediate south-west direction of the volcano by increasing the AOD (positive increments) and to decrease it further down to the south-east (negative increments). The comparison with the independent IASI/AIRS data, albeit qualitative, confirms this general assessment.

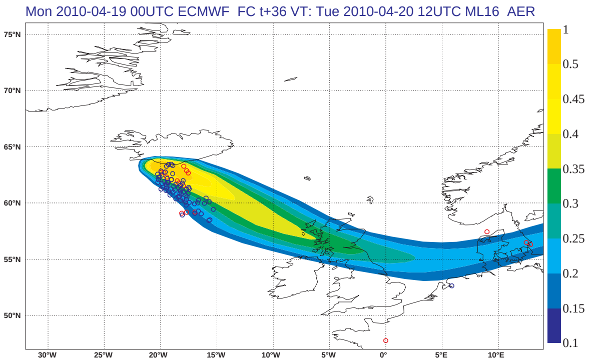

Figure 5: Dust optical depth forecast valid at 12UTC on April 20, 2010. Symbols indicated presence of aerosol as detected from the IASI (blue) and AIRS (red) sensors.

3.3 Plume forecasts for the Puyehue-Cordón Caulle

On June 4 2011, Puyehue and Cordón Caulle volcano complex in the Puyehue National Park Chile erupted. The eruption was associated with an explosive ash cloud. On June 5 and 6, the eruption weakened but continued. The area nearby the volcano was evacuated and areas downwind of the volcano woke up covered in a thick ash layer. In the following days the ash was advected to the north-east towards Argentina, Brazil and Uruguay, prompting the closure of airports. As the volcano continued to erupt, injecting ash at upper levels (above 10km) the plume travelled across the Pacific Ocean and forced flight cancellations to and from Australia and New Zealand.

Figure 6 shows the plume of dust simulated by the MACC system, assuming emission characteristics similar to the Eyjafjallajökull volcano, constant over the integration period. In this case, it is possible to see that in the first days of the forecast, the plume was correctly advected to the north-east. Later in the forecast (starting at day 3 into days 4 and 5), strong upper-level westerly winds pushed the ash over the Pacific Ocean. Relative low precipitation and low-to-medium cloud conditions downwind of the volcano facilitated the spreading of the volcanic ash.

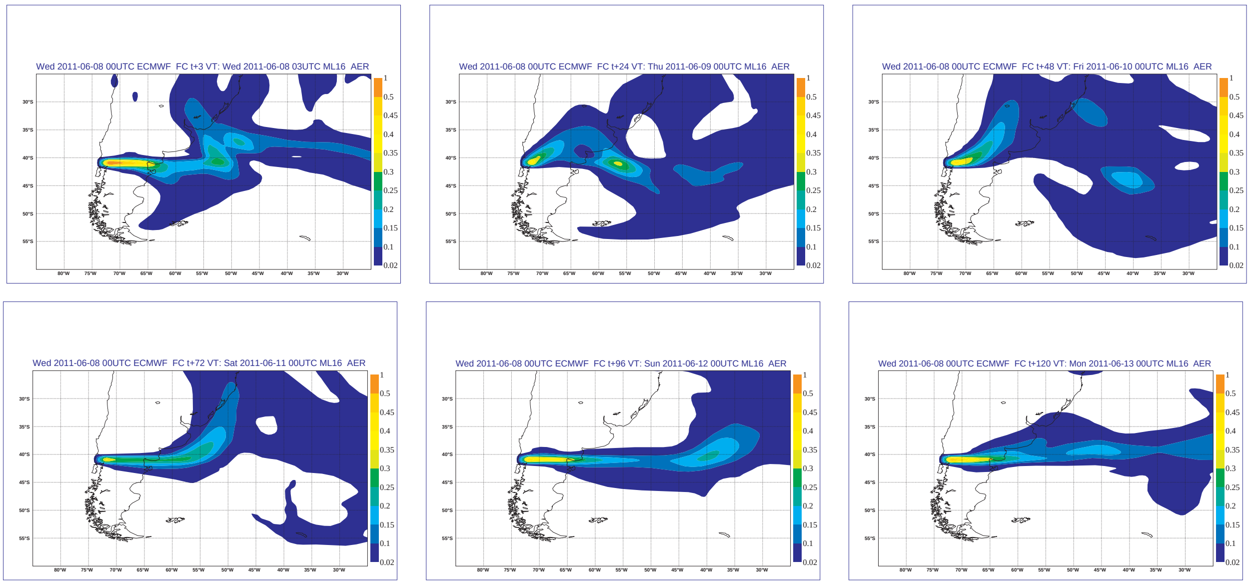

Figure 6: Dust optical depth from the forecast with constant volcanic source showing a plume over Chile and Argentina extending eastward. Forecast start time is June 8, 2011 00UTC, shown are steps 3, 24, 48, 72, 96 and 120.

The forecast valid at 12UTC on June 9 a 6UTC was qualitatively compared with the official EUMETSAT ash index produced by the Free University of Bruxelles (ULB) and the Belgian Institute for Space Aeronomy (BIRA), based on IASI observations (see Figure 8). The plume is correctly located around 50S extending between 30-90E, indicating a good degree of skill of the model.

4 Current and future work

The results presented in this technical memo show what initially was implemented in the MACC aerosol assimilation and forecasting system in response to the eruption of the Eyjafjallajökull and other volcanoes.

While the results obtained are encouraging and show the ability of the system to simulate volcanic plumes with realistic structure, via ad-hoc assimilation of MODIS AOD data, several areas of improvements were identified.

(i) Emission source: the data assimilation system is not able to produce an ash plume if no volcano-like emissions are prescribed. This situation is different from assimilation of SO_2 where the analysis can increase the background values of SO_2 if enough observations are available (A. Inness, private communication). For aerosols, if there is a signal in the assimilated observations, then the analysis will try to alias this signal into any available aerosol in the location of the volcano (sea salt for the case of the Icelandc volcano). When a volcanic source is specified, the analysis tries to make adjustments to the general distribution of the total AOD, but often might not be able to address deficiencies in the parameterization of the emission source itself. This specific point may be addressed by extending the control variables used in the assimilation to include emission parameters along with the initial conditions on the aerosol mixing ratio. This full-blown assimilation strategy

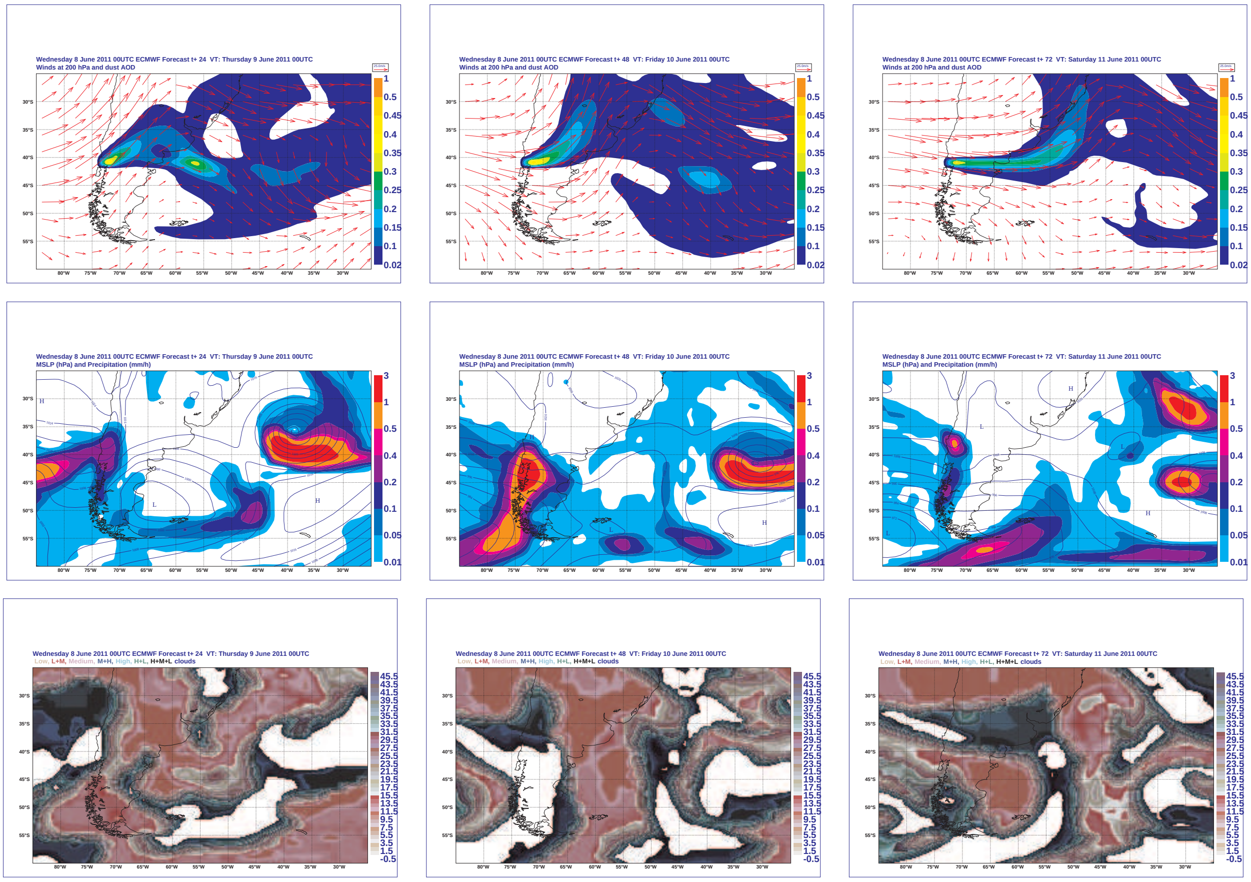

Figure 7: Dust optical depth and 200hPa winds (m/s), total precipitation (mm/h) and Mean Sea Level Pressure (hPa), and cloud cover for the 24h, 48h and 72h forecasts initialized at 00UTC on June 08, 2011.

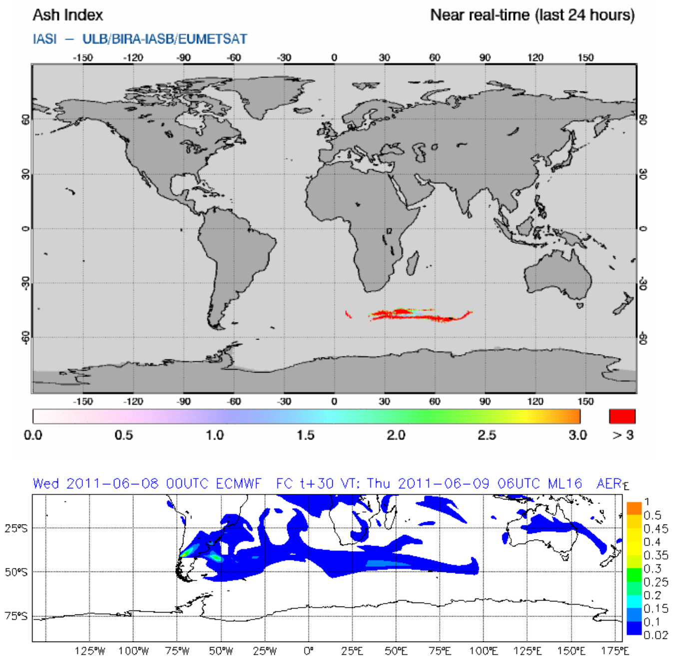

Figure 8: Dust optical depth forecast valid at 6UTC on June 9, 2011 compared to ULB-BIRA/EUMETSAT Ash Index for the same day.

can, however, be costly. A simpler approach for the short term could be investigated, for example including a dedicated volcanic ash control variable in the analysis.

Inversion models can also help in addressing the issue of the source estimation and provide a description of the emissions closer to "truth" (see Stohl et al [11]).

(ii) Sensitivity to aerosol parameters: away from the source processes like gravitational sedimentation and wet depositon are likely to become more dominant in explaining, together with the prevalent meteorology (wind and precipitation), how the plume spreads and dissipates. For a quantitative assessment of the plume, it will be necessary to understand which are the more important driving parameters, and how those need to be prescribed/adapted in such cases. This is ongoing work which will be presented in a follow-on paper.

(iii) Added value of the analysis: if detailed information on the plume height and intensity were avaialable would it be enough to run a plume forecast without an aerosol analysis? What would be the value added by the assimilation of aerosol observation in that scenario? And how would this value change if the emission source is only roughly known? These questions are currently under investigation, and results will as well be presented in a separate follow-on paper.

Finally, there could be the need to transition to a probabilistic approach to be able to answer quantitative questions related to the ash distribution at longer ranges than 2-3 days. This has been tried in forecast mode by Johannes Flemming (private communication) for SO2 simulations by running ensembles of plume forecasts with different characteristics for plume height assignement, source intensity, etc to make up for the large uncertainties in the prescription of these parameters in near real time. From the point of view of the assimilation, this can be explored using the Ensemble of Data Assimilation system now operational at ECMWF (Isaksen *et al.* [8]) which has been recently run with the prognostic aerosols. The cost and benefits of this probabilistic approach to volcanic plume forecasting will be investigated.

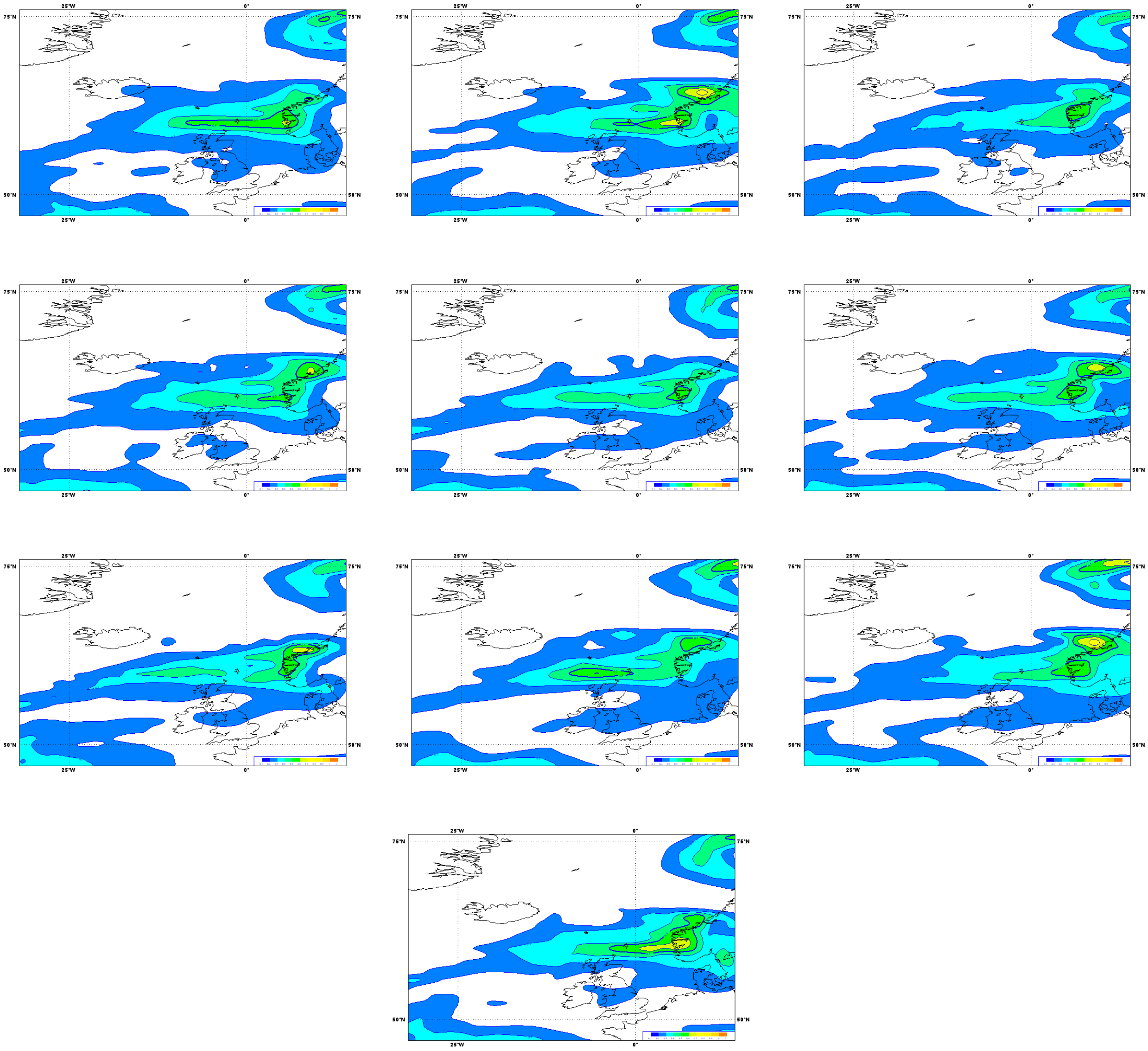

Figure 9: Sea salt plume off the coast of Iceland on April 20, 2010 at 000UTC from ensemble forecasts initialized at 00UTC on April 19, using the analyses from the ECMWF Ensemble of Data Assimilation system.

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