A NEW APPROACH ON THE DETECTION OF VOLCANIC ASH CLOUDS

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Abstract

In this work we present a new approach on the space-borne detection of volcanic ash. Our algorithm detects ash-contaminated regions as well as ash-free regions utilizing the infrared brightness temperatures measured by SEVIRI with its high spatial (3 km x 3 km) and high temporal resolution (5 to 15 min). The algorithm, based on a backpropagation neural network, is trained by simulated brightness temperatures for the SEVIRI channels, which have been obtained from radiative transfer calculations (libradtran) [Mayer and Kylling 2005], representing a comprehensive range of different atmospheric conditions usually occuring as a function of latitude and season. In addition, and to account for volcanic eruptions and their manifold distributions of ash load, a broad range of particle concentrations for different ash types has been included in various layers of the modeled atmospheres. Beside the detection of ash-contaminated and ash-free airspace, the algorithm gives additional information on e.g. the column mass concentration and the top altitude of detected volcanic ash clouds, and a mask of high clouds derived by the COCS algorithm [Kox 2012], which may cover the eruptive ash cloud, so that the ash cloud cannot be detected. First examples and comparisons of detected volcanic ash and classified airspace are shown for the eruptions of the Eyjafjallajökull 2010, and the Puyehue 2011.

INTRODUCTION

The volcanic eruptions of the Eyjafjallajökull in 2010 and the Grimsvöttn in 2011 had large impact on aviation, resulting in the most extensive restriction of the airspace over Europe since the end of World War II. More than 100 000 flights all over Europe were cancelled affecting more than 10 million passengers. In order to minimize the impact of such events with closed airspace and cancelled flights and to prevent hazards of volcanic ash to aircrafts, a reliable detection of such eruptive volcanic ash clouds is necessary.

In order to cope the challenges in space-borne and in-situ detection of volcanic ash and to fill gaps within air traffic management procedures the DLR-wide project Volcanic ash impact on the Air Transportation System (VolcATS) was launched end of 2012. One of the main outcomes of this project is a novel approach on the detection of volcanic ash and its nowcasting with geostationary satellites, currently focusing on the Spinning Enhanced Visible and InfraRed Imager (SEVIRI) aboard Meteosat Second Generation (MSG, [Schmetz et al, 2002]). This instrument combines the ability to observe earth's atmosphere during day and night time due to its infrared channels (e.g. 6.2 – 13.4 µm) with its high temporal resolution of 5 – 15 minutes for a whole „disc“ covering a latitude from around 80° N to 80°S and a longitude of 80° W to 80° E. Different works have already shown, that infrared brightness temperature measurements either with polar or geostationary imager data can be used to detect volcanic ash clouds based on threshold tests [Prata 2009, 1989], which makes this kind of retrieval rather inflexible and may be limited in certain atmospheric situations. The algorithm introduced here is based on a backpropagation neural network, called VADUGS (Volcanic Ash Detection Utilizing Geostationary Satellites) and is able to retrieve the column mass concentrations [kg/m^2] of volcanic ash as well as its top altitude [km]. In general an artificial neural network combines an extremely flexible way to describe a parametric functional dependency of an output vector to an input vector with a method to determine its parameters.

The VADUGS algorithm is supported by the highly sensitive Cirrus Optical properties derived from CALIOP and SEVIRI during day and night (COCS) algorithm [Kox 2012]. As an example the cirrus optical thickness retrieved by COCS is shown in Figure 1 for the 17th May 2010 at 12:00 UTC. COCS utilizes, similar to the here presented VADUGS algorithm, the measurements of SEVIRI's infrared channels and retrieves the optical thickness of cirrus clouds as well as their top altitude. COCS is sensitive to cirrus clouds with an optical thickness $\tau \geq 0.1$ with detection efficiencies greater than 98% and a very low false alarm rate lower than 4.8% (both at τ=0.1). The detection efficiency increases for thicker cirrus clouds, while the false alarm rate decreases.

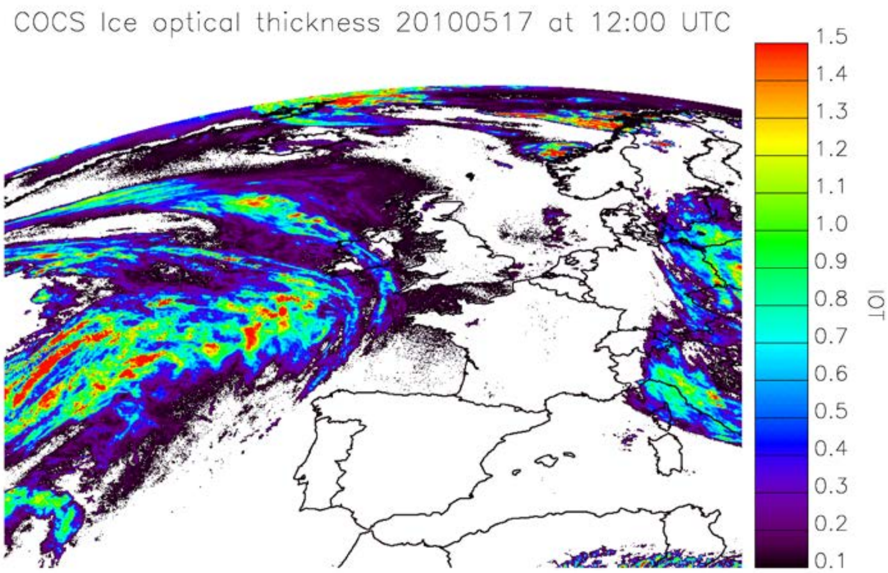

Fig. 1: Measurements of the ice optical thickness of cirrus clouds retrieved the COCS algorithm on the 17th May 2010 at 12:00 UTC.

VADUGS – VOLCANIC ASH DETECTION UTILIZING GEOSTATIONARY SATELLITES

VADUGS, based on a comparable setup as the COCS algorithm, consists of one input layer with 17 inputs (infrared brightness temperatures of SEVIRI, several differences of the infrared brightness temperatures, and auxiliary data such as surface temperature, a land-sea-mask, and the satellite's viewing zenith angle), one hidden layer with 600 neurons, and one output layer with two outputs (column concentration of the volcanic ash layer and its top altitude). Due to the training with a highly variable dataset representing almost any possible state of the atmosphere with different types of ashes and ash layers a big advantage compared to "fixed threshold" tests and algorithms is realized.

TRAINING DATASET

The training dataset of the neural network consists of simulated infrared brightness temperatures retrieved via radiative transfer calculations based on atmospheric profiles of the European Centre for Medium-range Weather Forecasts (ECMWF) modified with different cloud situations and varying volcanic ash clouds. The radiative transfer calculations are performed with the library for radiative transfer [Mayer and Kylling 2005]. The volcanic ash clouds were not only modified by their vertical extent, concentration, vertical and geographical position, but also by their composition. Therefore, different spectral and mineralogical definitions of volcanic ash were used, i.e. ash of the Eyjafjallajökull eruption in 2010 [Helbert 2010], different basic volcanic minerals such as andesite or rhyolite, and a mixture of several basic minerals [Klüser 2011]. A definition of mineral dust was added as well to facilitate the airborne validation of VADUGS with measurement flights over the Saharan desert and the Caribbean. Overall, for each ash composition the training dataset consists of almost ten million profiles in order to represent as many atmospheric situations as possible.

To summarize, the training dataset of the neural network consists of:

- Brightness temperatures of the seven infrared channels of SEVIRI (6.2, 7.3, 8.7, 9.7, 10.8, 12.0, 13.4 µm)
- and its differences (8.7-9.7, 8.7-10.8, 8.7-12.0, 8.7-13.4, 9.7-12.0, 9.7-13.4, and 6.2-7.3 µm)
- Auxiliary datasets (viewing zenith angle, land-sea-mask, surface temperature)
- Column mass concentration (kg/m^2) and top altitude (km) of the volcanic ash layer

Application

Once the training is finished, VADUGS can be applied to SEVIRI data retrieving column mass concentration and top altitude of a volcanic ash layer. As the runtime of both algorithms including data acquisition is less 600 s on a common office computer, the combination of COCS and VADUGS is well suited to be part of an operational software package. A first result of VADUGS retrieving the column mass concentration of volcanic ash during the Eyjafjallajökull eruption on the 17th May 2010 at 12:00 UTC is shown in Figure 1 (left). On the one hand different concentrations of ash are visible with the highest values above the eruption site in Iceland. Close to the volcano some high cirrus clouds (black) partly cover the ash plume, while the aged plumes west of Norway and east of the UK show rather low concentrations. The concentrations range from $1.8 * 10^{-3}$ kg/m^2 down to $0.1 * 10^{-3}$ kg/m^2. For the same timeslot the top altitude of the different volcanic ash layers is depicted (Figure 2), but without the cirrus clouds being masked. The altitudes of the volcanic ash plumes range from 10 km close to the Eyjafjallajökull volcano down to 4-6 km over the North Sea, which is well within the measurements of the DLR research aircraft Falcon on the same day. Both figures make the advantage of the combination of cirrus cloud and volcanic ash detection obvious, especially for the volcanic ash plume at the eruption site in Iceland, where high clouds cover part of ash contaminated airspace in Figure 1.

Without the information whether the volcanic ash is covered by cirrus clouds or not is crucial for the correct interpretation of the scene measured by imager data.

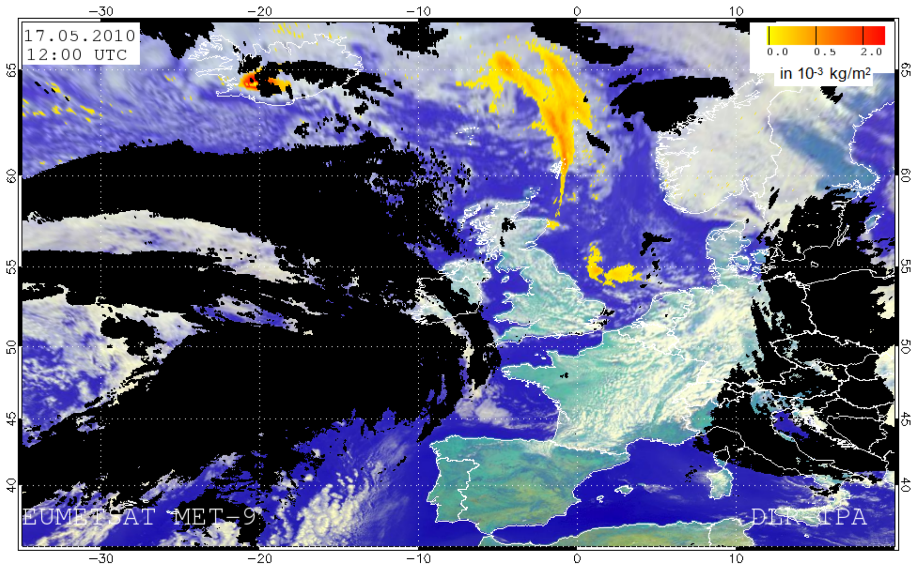

Fig. 2: Column mass concentration of volcanic ash clouds during the Eyjafjallafökull eruption on 17th May 2010 at 12:00 UTC. Cirrus clouds are masked black.

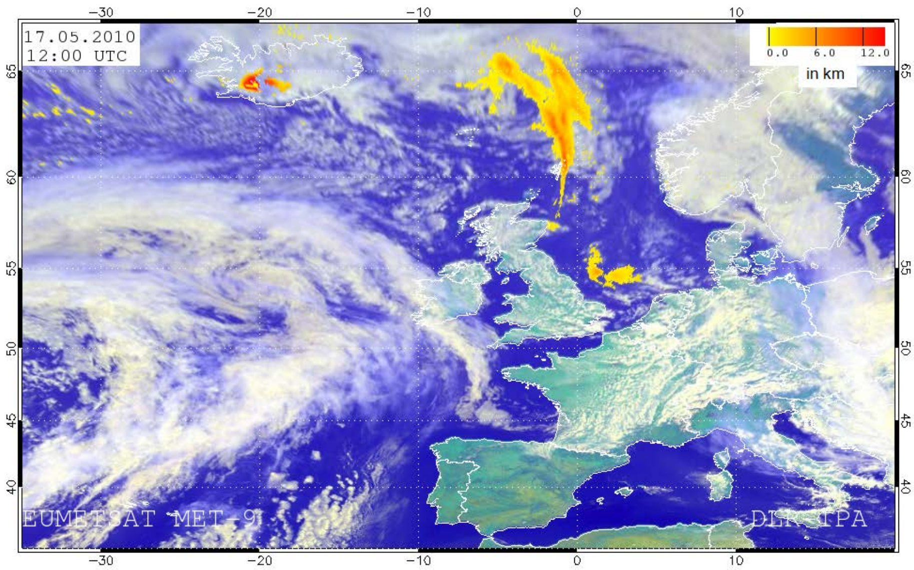

Fig. 3: Top altitude of volcanic ash clouds during the Eyjafjallafökull eruption on 17th May 2010 at 12:00 UTC.

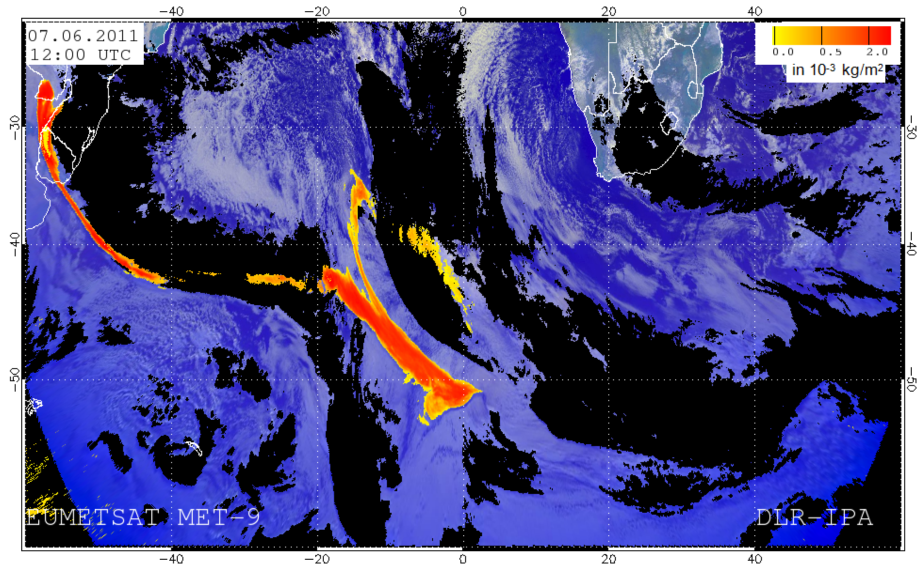

Fig. 4: Column mass concentration of volcanic ash clouds during the Eyjafjallafökull eruption on 17th May 2010 at 12:00 UTC. Cirrus clouds are masked black.

Another example for the performance of VADUGS is demonstrated in Figure 4 showing a scene covering wide parts of the southern hemisphere covering parts of the southern Atlantic Ocean, southern Africa, and the southern Indian Ocean. In June 2011 the Puyehue volcano erupted in Chile. Due to the main wind direction the volcanic ash clouds were transported from South America over the Atlantic Ocean and continuing their way to Australia and New Zealand, where the ash layers caused airspace and airport closures. Different ash concentrations occur not only depending on the age, but also on the intensity of the eruptions. Compared to the eruption of the Eyjafallajökull (Fig. 2) much higher concentrations are detected of up to 2.5 * 10^{-3} kg/m^2. Again parts of the ash cloud are covered by cirrus clouds east of South America. Therefore, no reliable detection of the ash cloud is possible is rather large areas of the scene.

Conclusions and Outlook

In this work we have introduced a novel approach to detect volcanic ash and to retrieve its column mass concentration and top altitude in order to support airline controllers, pilots, and authorities. With its low runtime the combination of cirrus cloud and volcanic ash detection has proven its operational character. First results and examples were shown. Within the timeframe of the VolcATS project a detailed validation focussing on airborne measurements (in-situ and lidar) during the Eyjafjalla eruption 2010 as well as measurement flights during the Saharan Aerosol Long-range Transport Aerosol-Cloud-Interaction Experiment (SALTRACE), where Saharan dust was measured over Africa, the Atlantic Ocean, and in the Caribbean. Additional sources like other space-borne retrieval or ground-based measurements still have to be identified. Another major task is the development of a nowcasting method to allow for short term forecasting of the movement and expansion of the volcanic ash cloud. Furthermore, the movement of overlying cirrus clouds shall be distinguishable from the movement of volcanic ash clouds in different altitudes. Different attempts are taken into account such as vector displacement, or modelled wind field data.

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