IMPLEMENTATION OF A ROBUST SATELLITE TECHNIQUE (RST_{ASH}) ON MSG-SEVIRI DATA FOR TIMELY DETECTION AND NEAR REAL-TIME MONITORING OF VOLCANIC ASH CLOUDS FROM SPACE

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Abstract

The RST_{ASH} algorithm is a specific configuration of the Robust Satellite Techniques (RST) multitemporal approach developed for detecting and tracking ash clouds from space. This algorithm was originally proposed and tested with success on AVHRR (Advanced Very High Resolution Radiometer) and MODIS (Moderate Resolution Imaging Spectroradiometer) data, and has been recently implemented on data provided by Japanese geostationary satellites (MTSAT). In this work, the preliminary results achieved exporting RST_{ASH} on MSG-SEVIRI (Meteosat Second Generation - Spinning Enhanced Visible and Infrared Imager) data to study the Eyjafjallajökull eruptions of April-May 2010, which caused an unprecedented air traffic disruption in Northern and central Europe, are reported. This study was carried testing RST_{ASH} in critical observational conditions (e.g. high view angles, cold background, frequent and diffuse cloud coverage), using for the first time an optimized configuration of this algorithm for daytime conditions, and assessing its potential in monitoring ash clouds in real time, exploiting the high temporal resolution of SEVIRI (15 minutes). Outcomes of this work show that RST_{ASH} may be profitably used for an automated and accurate identification of ash-affected areas also at high latitude regions. Accurate detection, in fact, is a mandatory step before to characterize ash clouds from a quantitative point of view by means of retrieval analyses. These results encourage a full implementation of this algorithm on SEVIRI data, in view of a its possible usage in operational contexts.

INTRODUCTION

Ash clouds represent a serious threat for aviation safety because of ash particles capability of causing failure of jet engines, abrasion of windscreen and damages to avionics equipment (Casadevall 1994; Casadevall et al., 1996). Reduction in visibility, damages to flight control systems, flame out and engine shutdown may be the main consequence for airplanes when ash is encountered (Miller et al., 2000). Nine Volcanic Ash Advisory Centers (VAACs) have been established and distributed worldwide for advising international aviation about location and movement of volcanic ash clouds in atmosphere in their assigned airspace. These centers use information coming from different sources (e.g. ground and pilot reports, satellite data, meteorological knowledge) to monitor volcanic plumes and run sophisticated atmospheric numerical models to forecast their dispersion in the atmosphere. Among these sources, information provided by satellite sensors might play an important role in promptly identifying ash clouds and in continuously tracking their space-time evolution. In particular, geostationary satellite sensors may provide timely information also on quantitative parameters of ash clouds at source (e.g. column height, particle size, mass loadings and volumes), generally required as inputs by numerical models devoted to forecast ash dispersion in the atmosphere, although some issues still remain open (ESA-EUMETSAT, 2010).
During April-May 2010 copious amounts of ash affected North and Central Europe as a consequence of the strong explosive eruption of Eyjafjallajökull (Iceland) volcano. Several flights were cancelled for safety issue, on the basis of information provided, to the civil aviation authorities, by the London VAAC

operating at the UK Met Office. The impact on both social and economic activities was particularly strong, with millions of passengers stranded across the world, million dollars lost by air companies for each day of landing and imports and exports activities badly affected by the flight disruptions (ESA-EUMETSAT, 2010). These events revealed some important issues in the operational monitoring of ash clouds, encouraging scientists in improving their methods and procedures devoted to detect, track, and characterize ash plumes and to simulate their dispersion in the atmosphere.

As a result, several research papers have recently been published reporting results of different ground based, airborne and satellite observations (e.g. Dacre et al., 2011; Mona et al., 2011; Newman et al., 2011; Denlinger et al., 2012; Devenish et al., 2012; Christopher et al., 2012; Francis et al., 2012; Prata and Prata, 2012). They have shown that a more efficient identification, quantification and forecast of volcanic plumes is definitively possible and strongly suggested for better supporting decision makers in managing risk associated to the ash events.

In this work, the RST_{ASH} algorithm (Pergola et al., 2004; Filizzola et al., 2007), based on the largely accepted Robust Satellite Techniques (RST) multitemporal approach (Tramutoli, 1998; 2007), is for the first time tested at high latitude regions, by using data provided by SEVIRI (Spinning Enhanced Visible and Infrared Imager), flying onboard MSG (Meteosat Second Generation) geostationary satellites. The above mentioned Eyjafjallajökull eruption is then analyzed in this work, preliminarily assessing the RST_{ASH} potential in effectively detecting and tracking volcanic ash exploiting the high temporal resolution of SEVIRI.

RST_{ASH}

The RST_{ASH} algorithm is an unsupervised change detection scheme that identifies volcanic ash on the basis of relative, rather than absolute, signal variations (Pergola et al., 2004). Historical series of homogeneous satellite records (i.e. same month, same overpass times) are processed in multi-temporal sequence to generate the spectral reference fields of temporal mean and standard deviation, describing the "normal" behaviour of the signal (i.e. the one expected in absence of ash). Two local variation indexes, are then used jointly to identify volcanic ash and discriminate it from meteorological clouds. These indexes, based on the general formulation of the Absolutely Local Index of Change of the Environment (ALICE; Tramutoli, 1998; 2007), are defined as:

$$\otimes_{\Delta TIR}(x,y,t) = \frac{\left[\left(T_{11}(x,y,t)-T_{12}(x,y,t)\right)-\mu_{T11-T12}(x,y)\right]}{\sigma_{T11-T12}(x,y)} \quad (1)$$

$$\otimes_{MIR-TIR}(x,y,t) = \frac{\left[\left(T_{3}(x,y,t)-T_{11}(x,y,t)\right)-\mu_{T3-T11}(x,y)\right]}{\sigma_{T3-T11}(x,y)} \quad (2)$$

where $T_3(x,y,t)$, $T_{11}(x,y,t)$ and $T_{12}(x,y,t)$ respectively represent the satellite signal (i.e. brightness temperatures) measured in the Medium Infrared band (MIR) at around 3-4 μm, and in the Thermal Infrared bands (TIR), at around 11 μm and 12 μm wavelengths. The terms $\mu_{T11-T12}(x,y)$ and $\mu_{T3-T11}(x,y)$ are instead the temporal means, and $\sigma_{T11-T12}(x,y)$ and $\sigma_{T3-T11}(x,y)$ the temporal standard deviations, of the correspondent brightness temperature differences, computed according to RST multi-temporal processing scheme (Tramutoli, 1998; 2007).

The $\otimes_{\Delta TIR}(x,y,t)$ index takes into account the known reverse absorption effect of volcanic ash compared to water droplets and ice at 11 μm and 12 μm wavelengths (Prata, 1989).

The $\otimes_{MIR-TIR}(x,y,t)$ takes into account, instead, the different reflectance of ash and meteorological clouds in the MIR band during daytime as well as its different emissivity and transmittance in the MIR and TIR spectral bands. Negative values of $\otimes_{\Delta TIR}(x,y,t)$ and positive values of $\otimes_{MIR-TIR}(x,y,t)$ are then computed to detect volcanic ash, with different cutting levels of these indexes suitable also to discriminate regions characterized by a different probability of ash presence. The RST_{ASH} algorithm was previously tested with success on AVHRR (Advanced Very High Resolution Radiometer) and MODIS (Moderate Resolution Imaging Spectroradiometer) records, showing better performances than traditional split windows techniques (see Pergola et al., 2004; Filizzola et al., 2007; Marchese et al., 2007; 2010; Piscini et al., 2011). An extensive validation analysis was also carried out on AVHRR data products over Mt Etna area, to assess RST_{ASH} performances in terms of reliability and sensitivity (Marchese et al., 2008; 2011). Recently, this algorithm has been exported on data provided by Japanese geostationary satellites (MTSAT) to study and monitor the 26-27 January 2011 Shinmoedake eruption (Marchese et al., 2013). In this work, RST_{ASH} is instead implemented on infrared SEVIRI data to identify and track ash clouds at high latitude regions (i.e. at high SEVIRI view angles) and in an area strongly affected by meteorological clouds.

RST_{ASH} IMPLEMENTATION ON SEVIRI data

SEVIRI is a scanning radiometer providing data in twelve spectral bands, from the visible to the thermal infrared region. This sensor has a spatial resolution of 3 km at nadir (i.e. IFOV covers approximately 10 km^2) in the standard channels and of 1 km in the High Resolution Visible (HRV) channel.

Since the end of 2004, SEVIRI data are acquired and archived at School of Engineering of University of Basilicata, by means of a EUMETCAST receiving system. For the aim of this paper, a SEVIRI sub-scene of 502 $\times$ 246 pixels in size, including Northern Europe, was extracted from the original full disk images acquired in April and May from 2005 to 2009 (5 years). Satellite data were stratified on the basis of the same month and the same acquisition time to generate the spectral reference fields of temporal mean and standard deviation, computed after applying a cloud mask procedure for selecting cloud-free pixels, according to the general RST scheme (Pergola et al., 2004). The cloud detection procedure implemented within the SEVIRI data processing scheme usually combines the standard EUMETSAT CLM product (EUMETSAT, 2007; 2010) to an automatic RST-based cloud detection method (OCA-One Channel Cloudy radiance detection Approach; Pietrapertosa et al., 2000; Cuomo et al., 2011). However, in this study this procedure, capable of assuring an effective identification of cloudy pixels was not applicable. The CLM product is, in fact, not generated for the whole Earth-disc coverage of SEVIRI, being the MPEF (Meteorological Products Extraction Facility) processing area defined as 65 degrees geocentric angle around the sub-satellite point (EUMETSAT, 2011). Practically, processing area approximately extends from 65 S to 65 N, along the Greenwich meridian, and from 65 W to 65 E along the equator. Therefore, being Iceland at margin of the MPEF processing area, only the OCA cloud detection scheme was applicable in this work, with the generated spectral reference fields which resulted, in general, residually contaminated by cloudy radiances.

RESULTS

On 14 April 2010, a phreatomagmatic eruption took place at Eyjafjallajökull volcano (63°38′ N 19°36′ W), emitting large quantities of fine ash of trachyandesite composition and producing an eruptive column that reached an altitude of 5-9 km in the atmosphere. Because of the wind direction, the plume moved towards SE and thereafter over central Europe. During the first phase of explosive eruptions (14-17 April) more than 50% of the emitted solid material had a radius less than 50 μm in diameter and about 24% of ash particles was smaller than 10 μm (ESA-EUMETSAT, 2010; Petersen, 2010).

In the evening of 18 April the second phase of the eruption began (lasting until 4 May), with the eruption style which changed from phreatomagmatic to magmatic and with the eruption intensity that decreased with a consequent reduction of the emitted volcanic ash. On the basis of field observations and individual grain size analysis, the tephra produced was coarser than previous phase and the percentage of very fine ash was reduced (Gudmundsson et al., 2012). During the third eruptive phase (5-17 May), when magmatic fragmentation was dominant, the explosive activity renewed and volcanic ash affected once again Europe, while since 18 May (fourth eruptive phase) the eruptive activity progressively decreased to end on 22 May. The study presented here reports some results achieved analyzing the first and the third phases of Eyjafjallajökull eruption.

In Fig. 1a, the RST_{ASH} map of 15 April 2010, generated processing the relative SEVIRI data of 12:00 GMT (i.e. during the first phase of eruption), is reported. This ash map was generated implementing, for the first time, an optimized configuration of the RST_{ASH} algorithm specifically tailored for daytime conditions. Such a configuration implements the local variation index $\otimes_{VIS}(x,y,t)$, based on radiance measured in the visible channel of SEVIRI at around 0.6 µm, still computed according to the general formulation of the ALICE index, for a preliminary filtering of meteorological clouds (taking into account their reflectance in the visible band), before the application of the indexes defined in equations (1),(2) used to identify ash plumes and to discriminate them from different features.

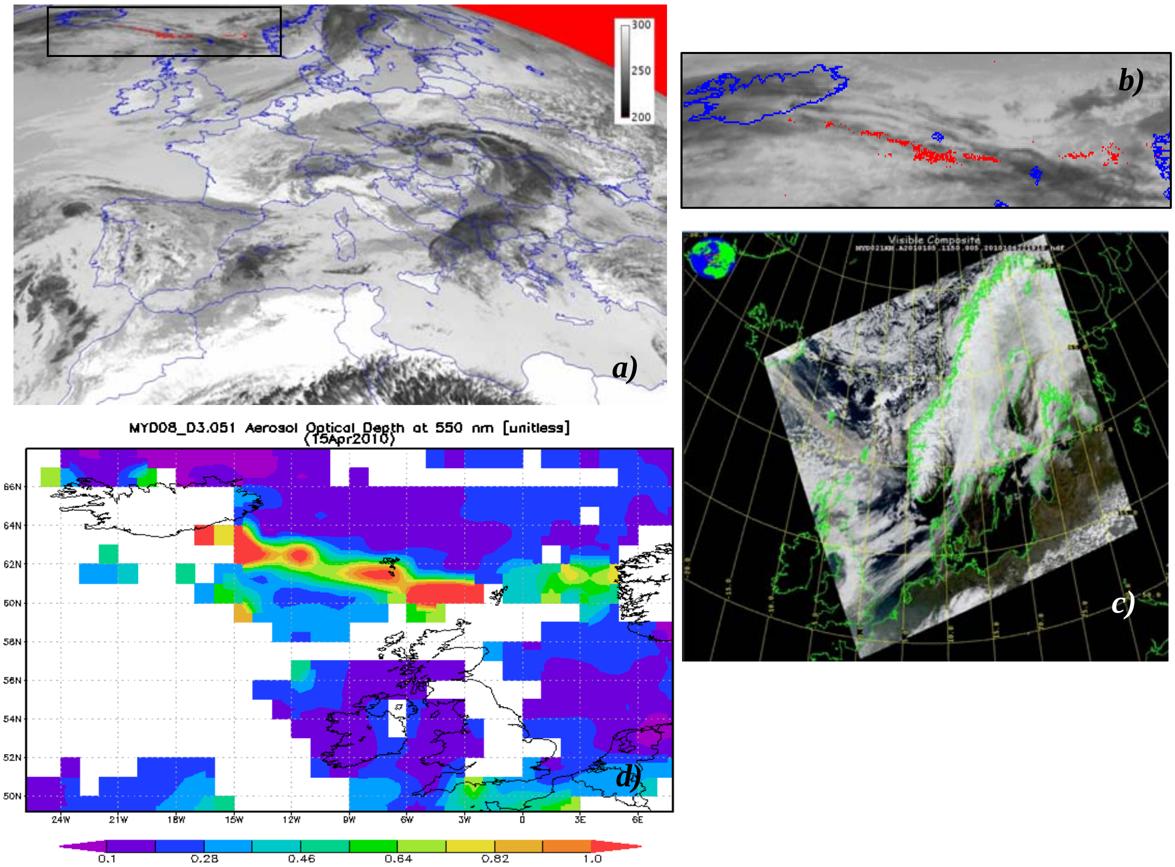

Figure 1: ***a)*** **RST_{ASH} map of 15 April 2010 at 12:00 GMT reporting, in red, ash pixels detected by RST_{ASH} (with $\otimes_{\Delta TIR}(x,y,t) < -3$ AND $\otimes_{MIR-TIR}(x,y,t) > 1$) after the implementation of a local variation index used to filter surfaces highly reflective in the visible band (i.e. filtering those having values of $\otimes_{VIS}(x,y,t) > 3$). The SEVIRI channel 9 (10.5 µm) image has been used as a background;** ***b)*** **zoom of ash plume detected by RST_{ASH};** ***c)*** **Aqua-MODIS true colour image (Red = ch1 ; Green = ch4 ; Blue = ch3) of 15 April 2010 at 11:50 GMT;** ***d)*** **Aqua-MODIS AOD daily product at 550 nm of 15 April 2010 (Goddard Earth Science Data and Information Services Center, 2013).**

The figure shows that an ash plume NE directed, partially masked by meteorological clouds, was correctly identified by RST_{ASH} over the analyzed satellite scene (see also Fig. 1b). The Aqua-MODIS true colour image of the same day at 11:50 GMT reported in Fig. 1c, as well as the Aqua-MODIS (Aerosol Optical Depth) AOD at 550 nm daily product reported in Fig. 1d, generated by NASA and made freely available online (Goddard Earth Science Data and Information Services Center, 2013), well corroborate indeed RST_{ASH} detection. In particular, the comparison with the independent aerosol product reported in Fig. 1d show a good spatial agreement between areas characterized by higher AOD values, indicating a larger aerosol loading in the atmosphere, and regions where volcanic ash was identified by the algorithm used in this work. Moreover, also in the presence of a diffuse cloud coverage affecting the analyzed geographic area (evident looking at Fig. 2b), no false detections were generated over the entire analyzed satellite scene.

Fig 2a reports, the ash map generated processing the SEVIRI data of 6 May at 00:00 GMT (i.e. during the third phase of eruption) showing the presence of an ash plume over Northern Europe, SE directed, that was once again successfully identified by RST_{ASH}, without generating significant false positives over the scene.

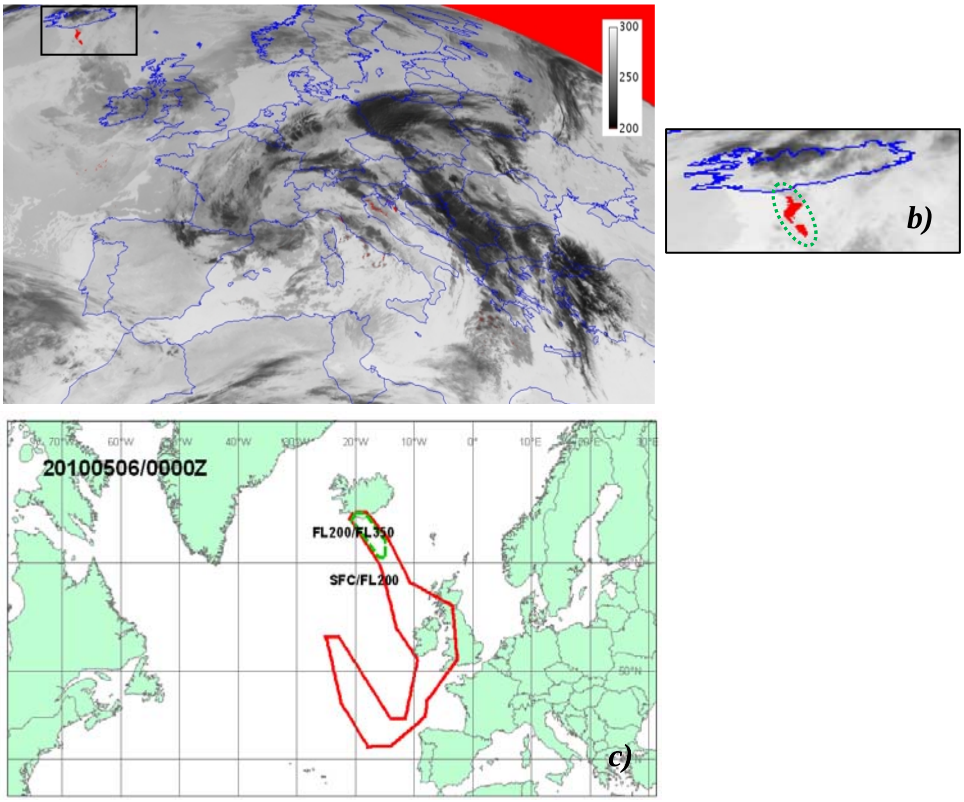

Figure 2: ***a)*** **RST_{ASH} map of 6 May 2010 at 00:00 GMT reporting, in red, ash pixels detected by RST_{ASH} (with $\otimes_{\Delta TIR}(x,y,t) < -3$ AND $\otimes_{MIR-TIR}(x,y,t) > 1$), with indication of detected plume (red pixel within black ellipse), and with the SEVIRI channel 9 (10.5 µm) image used as a background;** ***b)*** **zoom of ash plume detected by RST_{ASH};** ***c)*** **Ash plume forecast product generated using NAME model for 6 May 2010 at 00:00 GMT performed at London VAAC (Met Office, 2013).**

Fig. 2c reports the ash forecast product for the same day and same hour generated at London VAAC by using NAME (Numerical Atmospheric-dispersion Modelling Environment), a numerical model capable of predicting dispersion over distances ranging from a few kilometres to the whole globe (Met Office, 2013). The comparison with RST_{ASH} product reported in Fig. 2a and in Fig. 2b, shows that the plume identified by RST_{ASH} was just inside the area which was forecasted by the NAME model at an altitude of about 20,000-35,000 feet (i.e. at FL200/350).

To give a first overview of RST_{ASH} potential in tracking ash clouds, exploiting the high temporal resolution of SEVIRI, the ash product reporting the anomalous pixels detected by this algorithm on five consecutive satellite images, acquired with a temporal interval of 15 minutes, is reported in Fig. 3. In this figure lower critical levels of the $\otimes_{\Delta TIR}(x,y,t)$ index were analyzed to better detail the plume. In particular, the ash map of Fig. 3 shows the space-time evolution of the emitted ash cloud during the night of 6 May 2010 (i.e. between 00:00-01:00 GMT), revealing capabilities of the used algorithm in recognizing the short-term changes in the plume direction and extent, revealing for instance a drift of its proximal region towards NE. This analysis highlights the high potential offered by SEVIRI in monitoring ash clouds in real time, when advanced detection methods are used.

More in detail, these results show that, in spite of some issues (as for instance a difficulty in detecting the plume regions optically thicker) the algorithm used in this work, which is completely automated and not requires any ancillary information, may be particularly suitable for an operational implementation within specific warning systems, for effectively detecting ash pixels before to characterize the volcanic plumes from a quantitative point of view.

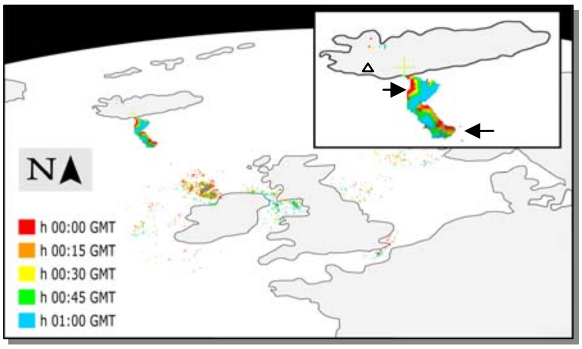

Figure 3: Ash plume detected by standard RST_{ASH} technique on night-time SEVIRI data of 6 May 2010, between 00:00 - 01:00 GMT (with values of $\otimes_{\Delta TIR}(x,y,t) < -2$ AND $\otimes_{MIR-TIR}(x,y,t) > 1$). **Different *colours represent ash maps at different hours of acquisition. The white triangle indicates location of Eyjafjallajökull volcano.***

CONCLUSIONS

In this paper, the preliminarily results of a retrospective study performed to assess performances of RST_{ASH} algorithm in detecting the ash clouds emitted by Eyjafjallajökull volcano during April-May 2010 eruptions have been presented. Two different test cases have been analyzed in this work, verifying the RST_{ASH} capabilities in correctly identifying volcanic ash during different phases of eruptive activity, also experimenting an optimized configuration of this algorithm for daytime conditions, presented and tested here for the first time. Outcomes of this study show that RST_{ASH} may be implemented with success on SEVIRI data to automatically detect and track ash clouds in real time. More in detail, this study confirms that RST_{ASH} may be exported on different satellite data and used in different geographic areas, including the high latitude regions. Further improvements of RST_{ASH} are expected by the use of additional spectral channels of SEVIRI like the one centred at 8.6 µm and located in one of the most important absorption bands of sulphur dioxide. These improvements should further increase performances of this algorithm in correctly discriminating ash from different features, making it more suitable for operational contexts. Finally, achieved results show that, even if applied in critical observational (e.g. high view angles) and environmental (e.g. diffuse cloud coverage) conditions, RST_{ASH} may contribute in supporting activities devoted to mitigate impacts of ash clouds on both social and economic human activities.

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