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Identification of dust outbreaks on infrared MSG-SEVIRI data by using a Robust Satellite Technique (RST)

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ABSTRACT

Dust storms are meteorological phenomena of great interest for scientific community because of their potential impact on climate changes, for the risk that may pose to human health and due to other issues as desertification processes and reduction of the agricultural production. Satellite remote sensing, thanks to global coverage, high frequency of observation and low cost data, may highly contribute in monitoring these phenomena, provided that proper detection methods are used.

In this work, the known Robust Satellite Techniques (RST) multitemporal approach, used for studying and monitoring several natural/environmental hazards, is tested on some important dust events affecting Mediterranean region in May 2004 and Arabian Peninsula in February 2008. To perform this study, data provided by the Spinning Enhanced Visible and Infrared Imager (SEVIRI) have been processed, comparing the generated dust maps to some independent satellite-based aerosol products. Outcomes of this work show that the RST technique can be profitably used for detecting dust outbreaks from space, providing information also about areas characterized by a different probability of dust presence. They encourage further improvements of this technique in view of its possible implementation in the framework of operational warning systems.

1. Introduction

Dust outbreaks are important meteorological phenomena that may strongly impact on climate, environment, social and economic human activities. Desert dust aerosol is mainly composed by particles having a diameter ranging from 0.1 to 10 μm, with a long lifetime (from hours to weeks) and generally transported for several thousand miles in the atmosphere [1]. The Sahara Desert is the most important source area of soil-derived aerosols, which are mainly composed by silicate minerals such as quartz and feldspars, sometimes associated also to other minerals as the calcite [2].

Satellite remote sensing represents one of the most important tools for detecting and monitoring dust events [3]. Polar satellite sensors such as AVHRR (Advanced Very High Resolution Radiometer) and MODIS (Moderate Resolution Imaging Spectroradiometer), and especially the geostationary ones as SEVIRI (Spinning Enhanced Visible and Infrared Imager), which fly aboard MSG (Meteosat Second Generation) satellites providing data with the best temporal

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sampling currently available (15 min), are particularly suitable for timely detecting dust clouds close to their source (as deserts and semi-desert regions), as well as for tracking their space-time evolution over wide areas.

Several techniques have been up to now proposed for detecting and tracking dust clouds from space (e.g. [4–16]). These methods generally exploit the different spectral behavior of silicate particles, compared to ice crystals and water droplets, at 11 and 12 μm wavelengths to identify dust particles in the atmosphere. In particular, these BTD (Brightness Temperature Difference) methods usually apply fixed thresholds tests to $\Delta T = T_{11} - T_{12}$ brightness temperature difference in order to discriminate silicate-rich clouds from meteorological ones (e.g. [4,5–8,14]), with the ΔT signal mainly sensitive to the fine fraction of the dust aerosol particles [17,18]. These spit-window techniques although performing fairly well under specific observational conditions (e.g. semi-transparent dust clouds; low water vapor content in the atmosphere) are generally affected by several factors as the nature of background (e.g. land/sea; desert/no desert areas), and the specific aerosol properties [19–23].

Recently, more complex detection methods have shown that improvements in dust outbreaks identification and tracking from space are definitively possible (also integrating data from different satellite sensors) (e.g. [12–16]), even if some environmental and/or atmospheric factors may still impact on the effective identification of the meteorological phenomena from space, especially in operational contexts.

In this paper, the largely accepted Robust Satellite Techniques (RST) multi-temporal approach [24,25] is implemented, for the first time, on infrared night-time SEVIRI data for identifying dust outbreaks. This method was in fact previously tested, with good results, on a recent dust storm affecting Australia during 2009, by using infrared Multi-functional Transport Satellite (MTSAT-1R) data [26].

Two important dust events, which occurred in Mediterranean region [27] and Arabian Peninsula [28] in recent years are analyzed here, by means of a qualitative comparison of the RST dust detections with some independent satellite aerosol products based on TOMS (Total Ozone Mapping Spectrometer) and MODIS data. Results of this study are presented and discussed in detail in Section 3.

2. Methodology

The RST approach, of which a detailed description can be found in previous papers [24,25], is an original scheme of satellite data analysis proposed and used for studying and monitoring several natural/environmental hazards e.g. [29–33]. This method uses the Absolutely Local Index of Change of Environment (ALICE) for recognizing anomalous variations of the signal associated to possible perturbing events. Such an index, in its general formulation, is defined as:

$$\otimes_V(x,y,t) \equiv \frac{[V(x,y,t) - V_{ref}(x,y)]}{\sigma_V(x,y)} \tag{1}$$

where $V(x,y,t)$ is the signal measured at a pixel level (x,y) and at time t, while $V_{ref}(x,y)$ and $\sigma_V(x,y)$ respectively represent the temporal mean (or other parameters such as the minimum or the maximum, depending on application), and the temporal standard deviation of the same signal.

These spectral reference fields are generated analyzing a multi-year time series of cloud-free satellite records, collected at the same location (x,y), in the same hour of the day and in the same period of the year (i.e. same month).

For detecting dust outbreaks a specialized local variation index [24] is computed as:

$$\otimes_{\Delta TIR}(x,y,t') \equiv \frac{[\Delta T(x,y,t) - \mu_{\Delta T}(x,y)]}{\sigma_{\Delta T}(x,y)} \tag{2}$$

In Eq. (2), $\Delta T(x,y,t)$ is the brightness temperature difference $T_{11}(x,y,t) - T_{12}(x,y,t)$ of the signal measured at 11 μm and 12 μm wavelengths, while $\mu_{\Delta T}(x,y,t)$ and $\sigma_{\Delta T}(x,y,t)$ respectively represent the temporal mean and standard deviation of the same brightness temperature difference.

The $\otimes_{\Delta TIR}(x,y,t)$ index is sensitive to the presence of fine dust particles in the atmosphere, with negative values of this index mostly reflecting dust particles having a diameter less than 10 μm which cause an inversion of the BTD signal because of the different extinction of the signal in the split window bands ([7,34,35]). As shown and discussed in several previous papers, RST is a tuneable technique, therefore different cutting levels of the $\otimes_{\Delta TIR}(x,y,t)$ index can also be used for discriminating regions characterized by a different probability of dust presence in the atmosphere. Specifically, the higher the ALICE modulus, the greater such a probability.

3. Results

On 13 May 2004 an intense Saharan dust storm crossed into North Africa, Libya and most of Europe lasting for several hours [27]. During February 2008, a rare winter case of northerly “shamal” winds (producing gusts of 35 mph) generated a massive cloud of blowing dust and blowing sand. The dust cloud was blown far out into the Arabian Sea, crossing the Gulf of Aden and passing the island of Socotra (Yemen) affecting the whole region for some days [28].

Both these events are analyzed here to assess RST performances in detecting dust outbreaks by using infrared night-time SEVIRI data. To implement the RST method, the SEVIRI records of 00:00 UTC, acquired in February and May between 2004–2011 were processed, by using a cloud screening procedure, which integrates the EUMESAT [36] and a RST-based cloud detection scheme [37], for filtering weather clouds before the spectral reference field computation.

These RST dust products are evaluated here firstly by means of a spatial comparison with an independent Aerosol Index (AI) map generated by using TOMS data. The AI measures how much the wavelength dependence of backscattered UV radiation from an atmosphere containing aerosols (Mie scattering, Rayleigh scattering, and absorption) differs from a pure molecular atmosphere (pure Rayleigh scattering). Under most observational conditions, the AI is positive for absorbing aerosols (such as desert dust, smoke, volcanic ash) and negative for non-absorbing aerosols (e.g. sulfate aerosols, weakly absorbing aerosols too close to the surface). Therefore, the higher the AI, the greater the absorbing aerosol amount in the atmosphere. The daily TOMS Earth Probe Aerosol maps, available from July 1996 to 2005, are provided at a global scale and are made freely available online by the National Aeronautics and Space Administration (NASA) [38].

In Fig. 1a, the RST dust map generated processing the night-time SEVIRI data of 13 May 2008 at 00:00 UTC is reported. The map shows that a dust outbreak affected Mediterranean region at time of analyzed satellite observation, providing information also about regions characterized by a different probability of dust occurrence, where different negative values of $\otimes_{\Delta TIR}(x,y,t)$ index were recorded.

In particular, among pixels detected by RST, those located SW of Greece over Mediterranean sea, characterized by lower values of the $\otimes_{\Delta TIR}(x,y,t)$ index (i.e. $\otimes_{\Delta TIR}(x,y,t) < -2$; see brownie pixels within cluster Y), indicate a higher probability of dust presence over the scene. Fig. 1b reports the spatial trend of the $\otimes_{\Delta TIR}(x,y,t)$ index along the A–B transect crossing the clusters X and Y of Fig. 1a, better emphasizing region where this index further decreased in value. Positives values of RST index occurred instead in correspondence of the B edge of the transect as a consequence of meteorological clouds, as indicated by the analysis of SEVIRI data.

The RST dust map reported in Fig. 1a seems to be consistent with the AI TOMS product reported in Fig. 2, which shows the presence of an extended aerosol layer over Mediterranean region on 13 May 2004. In particular, in spite of a difference in the sensing time of several hours, the dust affected areas in Fig. 1a fitted fairly well with the regions where higher was the amount of aerosol according to the map of Fig. 2 (see clusters X and Y). This comparison confirms the long persistence time (24–36 h) of analyzed dust event over these areas, as indicated by independent sources [27].

The main differences between the two satellite products characterize in fact the cluster Z, where no evidence of dust was provided by RST, in spite of the high AI index value over the map of Fig. 2 (see Fig. 1a). This difference can be addressed to the thick cloud coverage affecting NE of Libya (see the SEVIRI TIR image used as background in Fig. 1a) that probably obscured dust signature in the split window bands.

However, to better evaluate performances of $\otimes_{\Delta TIR}(x,y,t)$ index in detecting dust, the simple BTD signal (i.e. $\Delta T = T_{11} - T_{12}$) has been analyzed, as shown in Fig. 3. In particular, Fig. 3a shows as computing different detection

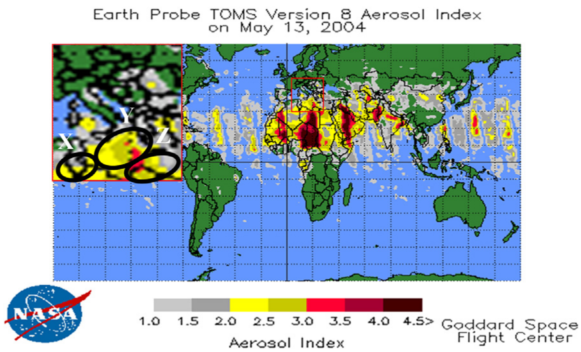

Fig. 2. TOMS AI daily map of 13 May 2008 [36].

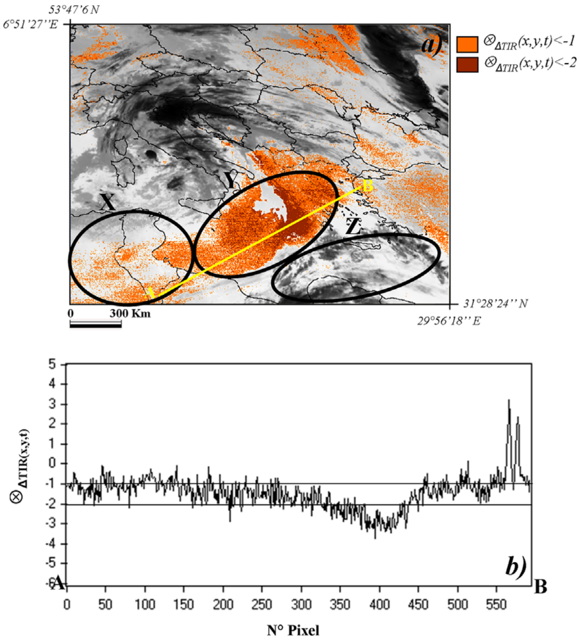

Fig. 1. In (a) the RST dust map derived processing night-time infrared SEVIRI data of 13 May 2008 at 00:00, reporting regions (in different colours) characterizing by different probability of dust presence (see text) is showed; in (b) the spatial trend of $\otimes_{\Delta TIR}$(x, y ,t) along the A-B transect over the map is reported.

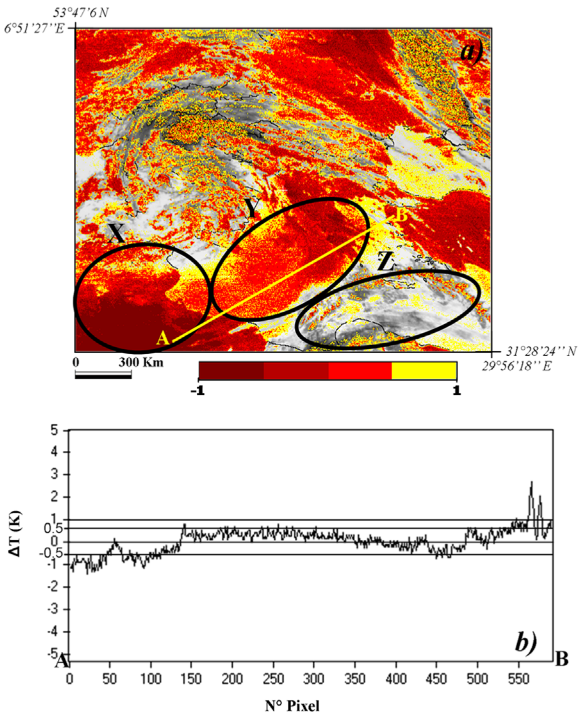

Fig. 3. In (a) the dust map generated applying different thresholds on BTD signal for the same data and hour of the figure 1 is showed; in (b) the spatial trend of $\otimes_{\Delta TIR}$(x, y ,t) along the A-B transect over the map is reported.

thresholds to BTD signal, on the same infrared SEVIRI data of Fig. 1a, the Saharan dust was more difficult to be discriminated from different features. Thresholds performing better in terms of reliability (e.g. $\Delta T < -0.5$) underestimated in fact the presence of dust over sea areas, while those performing better in terms of sensitivity erroneously identified as dust wide regions of Central and Eastern Europe clearly affected by a meteorological clouds (see Fig. 1a for comparison).

In addition, the plot of Fig. 3b, which reports the spatial trend of BTD signal along the same transect of Fig. 1a, shows that although the signature of dust over desert regions was more evident than Fig. 1b, the simple ΔT spectral difference is strongly affected by the nature of background.

The good performances offered by the method used in this work for detecting dust outbreaks on infrared night-time SEVIRI data are confirmed by the analysis of another dust event, which affected Arabian Peninsula and Yemen on 3 February 2008. In this case, to assess quality of RST detections a comparison with some independent MODIS aerosol products (1×1 degree of spatial resolution) [39] has been reported. The Aerosol Optical Depth (AOD) is a measure of radiation extinction because of scattering and absorption by aerosol particles in the atmosphere. Therefore, the higher the AOD value, the larger the aerosol quantity in the atmosphere. The comparison of the RST map of 3 February 2008 at 00:00 UTC in Fig. 4 with the Terra-MODIS AOD daily product at 550 nm of Fig. 5a for the same data shows that the areas affected by dust, according to the proposed method, were in a good spatial agreement with regions were higher AOD values were independently retrieved (i.e. Gulf of Aden and part of Red Sea). Considering once again the different times of analyzed satellite products, this comparison confirms the persistence of dust over above mentioned regions, in good agreement with independent observations [28].

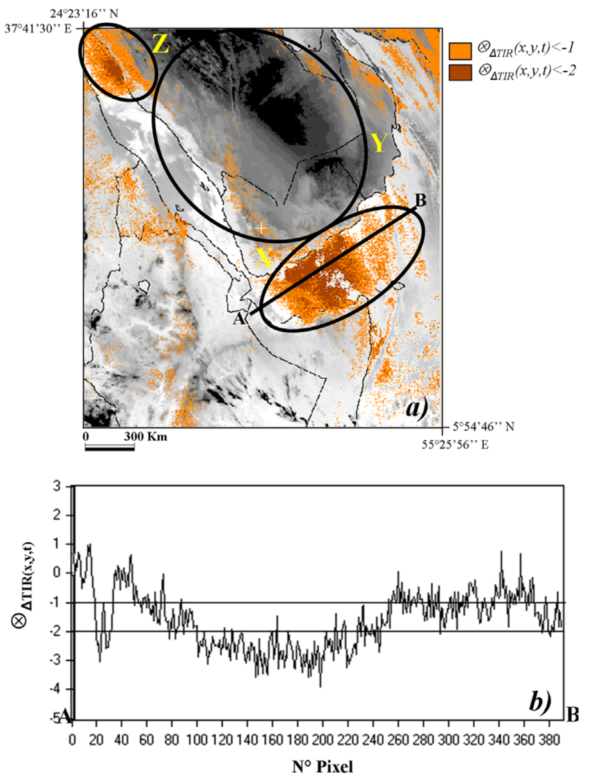

Fig. 4. In (a) the RST dust map derived processing night-time infrared SEVIRI data of 3 February 2008 at 00:00, reporting regions (in different colours) characterizing by different probability of dust presence (see text) is showed; in (b) the spatial trend of $\otimes_{\Delta TIR}(x, y, t)$ along the A-B transect over the map is reported.

The comparison with the Aqua-MODIS Deep Blue Aerosol Optical Depth product at 550 nm of Fig. 5b, giving information about AOD over spectrally reflective regions (e.g. [40]), seems to confirm, instead, a certain difficulty of RST in detecting dust outbreaks over desert areas, especially in the presence of lower dust loadings, although this possible limitation needs to be better verified.

This study gives a first overview of RST potential in detecting Saharan dust events by means of infrared SEVIRI data. To better assess performances of this method (both in night-time and daytime conditions) other investigations are currently under test, assessing RST detections also on the basis of independent ground-based aerosol products, with results that will be aim of a future work.

4. Conclusions

In this paper, the performances of the RST technique in detecting dust outbreaks by means of infrared night-time SEVIRI data have been preliminarily assessed.

Two different dust events, affecting the Mediterranean region in May 2004 and the Arabian Peninsula in February 2008 respectively, have been analyzed here, evaluating quality of RST detections on the basis of a first comparison with some independent satellite-based aerosol products.

Outcomes of this work show that, in spite of some limitations, as a possible reduction of sensitivity over desert regions and a residual dependence on meteorological clouds, the RST technique is generally capable of guaranteeing a better identification of dust affected areas compared to traditional split window techniques, providing also information about the different probability of dust occurrence.

This technique offers, in fact, a good trade-off between reliability and sensitivity of detection, that should positively impact also on accuracy of estimations and time of elaboration processes of retrieval analyses devoted to characterize dust clouds from a quantitative point of view.

This study confirms also the exportability of RST detection scheme to different geographic areas as well as to different satellite sensor data.

Although further analyses are required for better assessing performances of this technique under critical observational conditions (e.g. desert areas, diffuse cloud coverage), results presented in this work highlight potential of proposed method in identifying and tracking Saharan dust events.

This potential if better assessed will make RST, which is completely automated and not requires any ancillary information, particularly suitable to be used in operational contexts. Finally, the full implementation of RST on

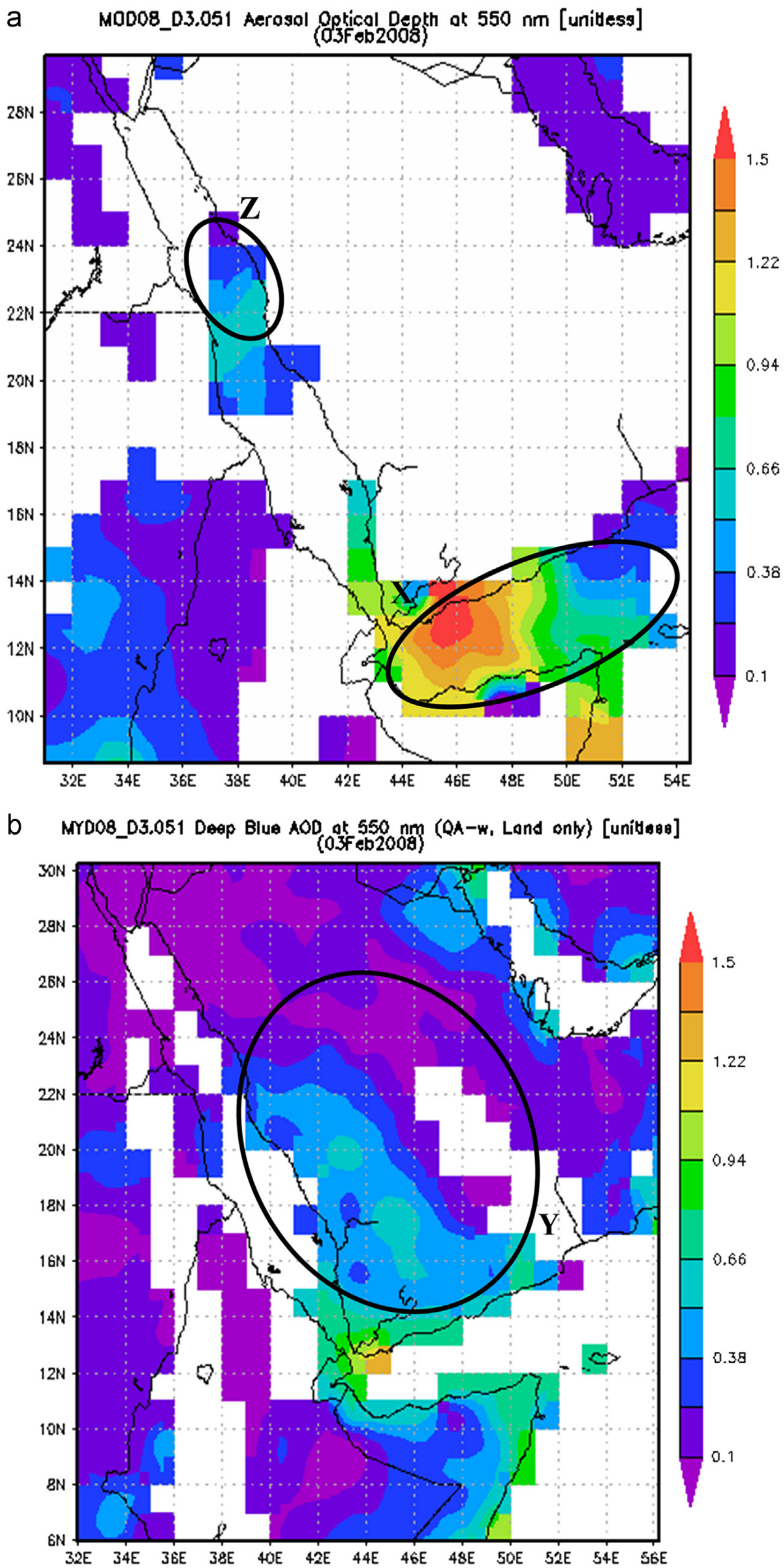

Fig. 5. In (a) the Terra-MODIS AOD daily product at 550 nm of 3 February 2008 is reported; in (b) the Aqua-MODIS Deep Blue Aerosol Optical Depth daily product at 550 nm of 3 February 2008 is showed [37].

geostationary satellites, currently assuring the highest revisiting times today achievable, will allow for an actual real-time monitoring of dust events at large scales.

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