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Aerosol loading maps and hot pixels over Brazil and South America

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Abstract. A system to derive aerosol loading maps from MODIS/Terra and MODIS/Aqua sensors was put together at DSA-CPTEC/INPE, based on NASA computer algorithms. This allows for the prompt retrieval of Aerosol Optical Depth (AOD) maps, mostly originated from biomass burning emissions that occur yearly during the dry season, covering large areas over Brazil and parts of South America. The results obtained by the AOD retrieval system were integrated onto maps of hot pixels detected by several sensors aboard different satellites like NOAA series, GOES-12, Terra and Aqua. This work presents the results obtained by the integrated system, allowing deriving an assessment of internal consistency for a qualitative validation of these satellite products. The results presented here have many possible applications, like monitoring biomass burning emissions, quantitative AOD assimilation into chemical weather forecast or climatic models, or improving atmospheric correction algorithms.

Palavras-chave: biomass burning aerosols, remote sensing of the atmosphere, hot pixel detection, aerossóis de queimadas, sensoriamento remoto da atmosfera. detecção de focos de calor.

1. Introduction

Atmospheric aerosols are solid or liquid particles suspended in the atmosphere, which can originate from natural or man-made processes. Over Brazil the most significant source of aerosols are biomass burning fires that occur every year during the dry season. Long range transport of aerosol particles by air streams can add complexity to this scenario, favoring chemical and physical interferences on atmospheric states not only locally but also potentially over regional to global scales (Freitas *et al.*, 2005). MODIS (Moderate Resolution Imaging Spectroradiometer) is a multi-channel sensor installed on Terra (King *et al.*, 2003) and Aqua (Parkinson, 2003) satellites. Its design allows for global daily retrievals of aerosol loadings in the atmosphere and other aerosol parameters (Remer *et al.*, 2005) by using a NASA/GSFC

(National Aeronautics and Space Administration/Goddard Space Flight Center) computing algorithm that employs the calibrated and geolocated radiances measured by MODIS, together with cloud mask information and ancillary NCEP (National Centers for Environmental Prediction) atmospheric data.

The National Institute for Space Research in Brazil (INPE) has been employing for several years a variety of satellite sensors in an automated system to detect hot pixels from NOAA series, GOES-12, Terra and Aqua satellite imagery (França and Setzer, 2001), as well as estimates of burnt areas (Setzer *et al.*, 2006). Recently an aerosol retrieval system based on NASA/GSFC algorithms was deployed at the DSA-CPTEC/INPE (Satellite and Environmental Systems Division – Center for Weather Forecast and Climatic Studies/ National Institute for Space Research, Brazil), resulting on timely aerosol loading information after each MODIS/Terra and MODIS/Aqua satellite overpasses (Correia *et al.*, 2006). This work shows the results obtained by an integrated system composed of aerosol loading maps superposed onto hot pixel mapping, allowing estimating the internal consistency and a qualitative validation assessment between the two systems.

2. A system to derive validated aerosol loading maps

INPE receives MODIS/Terra and MODIS/Aqua imagery in a ground station located in the city of Cuiabá (15.6°S, 66.1°W), allowing data coverage over most of Brazil and parts of South America. A system to derive aerosol products using MODIS was deployed at the DSA-CPTEC/INPE in 2005 (Correia, 2006; Correia and Pires, 2006). The system employs the raw data acquired at Cuiabá and processes it up to aerosol products. This involves a complex computing chain, starting from the raw data, converting it to MODIS Level 0 data, performing a radiometric calibration and geolocation (Level 1B data), then starting the product chain (Level 2 data) obtaining cloud mask, atmospheric profiles, and finally aerosol and water vapor products. For these retrievals ancillary data are also used such as estimated spacecraft attitude and ephemeris, and weather forecast fields from NCEP.

The Aerosol Optical Depth (AOD) maps retrieved by MODIS are quantitatively validated by comparison with AERONET (Aerosol Robotic Network) "ground truth" measurements (Holben *et al.*, 1998). AERONET AOD results are available in different processing levels: level 1.0 (raw data), level 1.5 (automated cloud-screened data), and level 2.0 (quality-assured data, only available several months after the measurements). As the AERONET processing algorithms do not check for cloud presence while performing measurements, an automated cloud screening procedure is used when passing from level 1.0 to 1.5 data (Smirnov *et al.*, 2000). This automated approach poses some constraints on the accuracy of the cloud screening process, since the particularities of each site cannot be fully taken into account. A more restrictive cloud-screening logic developed by Pires *et al.* (2006) was used to assess quantitatively the validation for the DSA-CPTEC/INPE aerosol retrieval system, resulting in a linear correlation coefficient of 0.92 between the satellite AOD retrievals and AERONET measurements (Correia and Pires, 2006).

3. Methodology

A set of Terra and Aqua overpasses was used to assess the matching between high aerosol loadings and location of hot pixels on satellite imagery, amounting to 291 files of 5-minute slabs of data called "granules", corresponding to the month of August 2006. For the sake of statistical computation, a maximum threshold AOD value of 0.20 was used to classify pixels as "clean" or "polluted", according to experimental results by Artaxo *et al.* (2006). Scenes were then sorted according to their proportion of polluted pixels and selected cases are shown in the next section.

Hot pixel locations as determined by the vegetation fires detection system operating at INPE (http://www.dpi.inpe.br/proarco/bdqueimadas), based on NOAA series, GOES-12, Terra and Aqua satellites, were added to RGB compositions of MODIS imagery. These compositions were obtained using MODIS channels 1, 4, and 3, from the radiance product derived during the MODIS AOD processing chain system deployed at DSA-CPTEC/INPE.

4. Results and discussions

Figure 1 shows an example of results obtained using the integrated system. **Figure 1a** shows an RGB composition for a relatively clean scene obtained with calibrated radiances from MODIS/Terra on 02 August 2006 14:19 UTC, just before the onset of the burning season in the year of 2006. **Figure 1a** shows also a small number of identified hot pixels highlighted in red. **Figure 1b** shows the corresponding AOD map retrieved, indicating a homogeneous cover with an average AOD of about 0.20, in accordance with the low number of identified hot pixels in the scene. **Figures 1c** and **1d**, in contrast, show a very different scenario only two weeks later, on 16 August 2006, from a Terra overpass on 14:32 UTC. One notices on the RGB composition in **Figure 1c** a large number of hot pixels from forest fires which originate the thick smoke plumes that can be distinguished over the dark background of forest canopy and also above brighter deforested areas. The corresponding retrieved AOD map shown in **Figure 1d** indicates regions with high AOD values in excess of 1.0, with clouds masked out and indicated as deep blue regions.

The highlighted region in **Figure 1c** corresponds to a very thick smoke plume, that can be manually identified from its spectral, spatial variability and visual texture characteristics. On the other hand, the automated AOD retrieval algorithm is currently unable to distinguish plumes like this from clouds, as can be seen by the masking highlighted on **Figure 1d**. Actually distinguishing aerosols from clouds from satellite imagery remains today still an elusive task and a challenge to computer algorithms designed for aerosol detection from space, and this issue needs to be addressed on future algorithm developments.

Figure 2 shows the results obtained for a Terra overpass on 23 August 2006 14:38 UTC. On this day alone a total number of 8,260 fire spots were identified in Brazil and 17,193 on South America, according to the forest fire detection system at INPE. In **Figure 2a** one notices the large number of fire spots identified in Brazil and Bolivia, and the corresponding

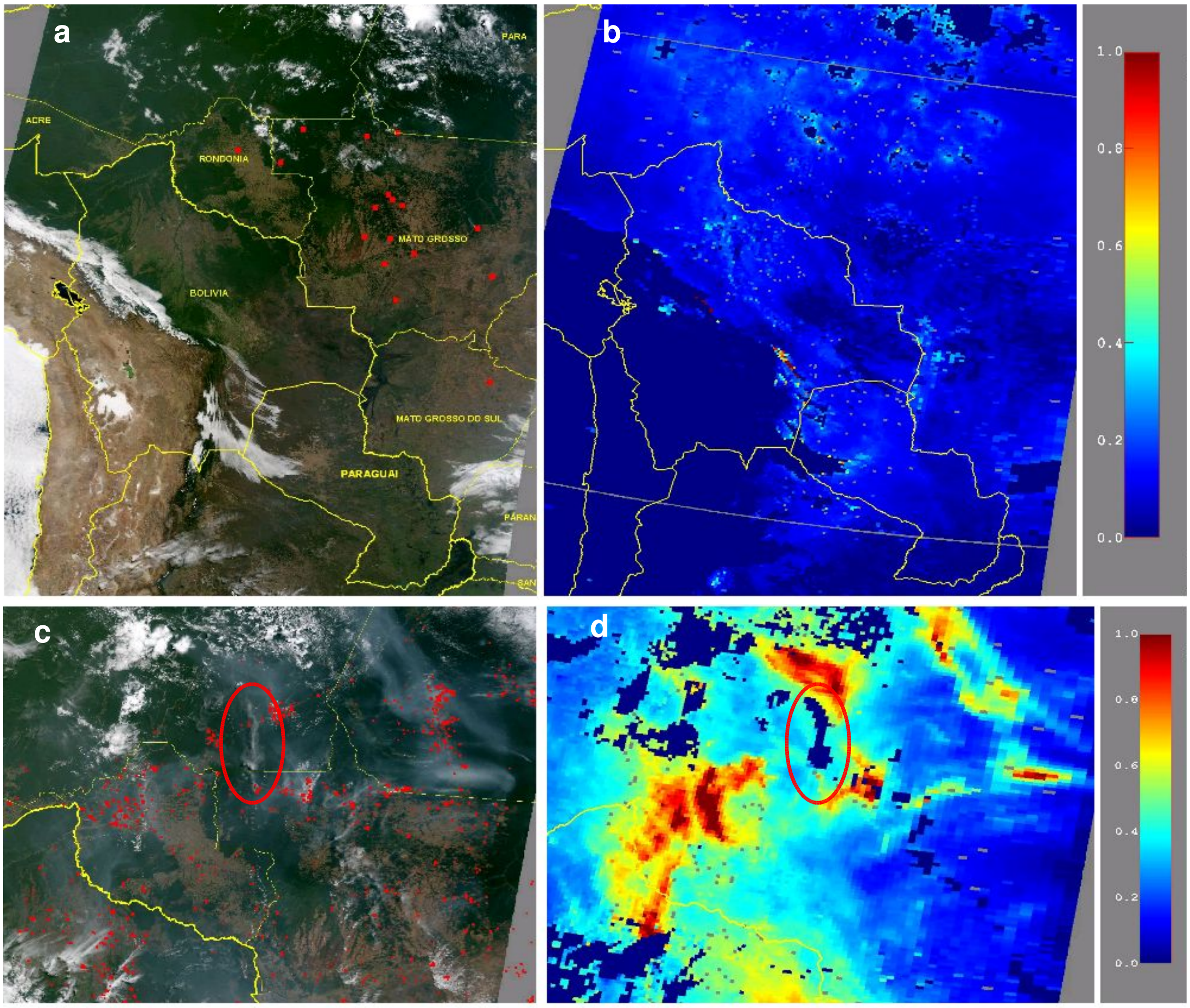

Figure 1*. Aerosol maps and hot pixels obtained for: (a) and (b) relatively clean conditions from Terra 02AUG2006 14:19 UTC; (c) and (d) a polluted scene from Terra 16AUG2006 14:32 UTC. See the text for the explanation on the highlighted regions.*

smoke plumes emitted from fires. These smoke plumes follow the wind circulation pattern in the region, so the pollution originated from biomass burning fires can affect regions several thousands of km downwind from the emission region, like for instance the otherwise pristine environment of Western Amazon Basin, as shown in **Figure 2a**. This particular situation on undisturbed regions of the Amazon Basin was analyzed by Koren *et al.* (2004) who showed that the impact of biomass burning aerosols on shallow clouds tends to inhibit cloud formation and development. The retrieved AOD map corresponding to the scene depicted in **Figure 2a** is shown in **Figure 2b**, where one can notice that a large area extent is affected by heavy pollution with AOD above 1.0, specially downwind from regions under high fire pixel count.

Another result arising from the integration between the aerosol retrieval system and the hot pixel detection system is shown in **Figure 3**. **Figure 3a** shows an RGB composition acquired from an Aqua overpass on 12 August 2006 17:44 UTC. A large number of shallow

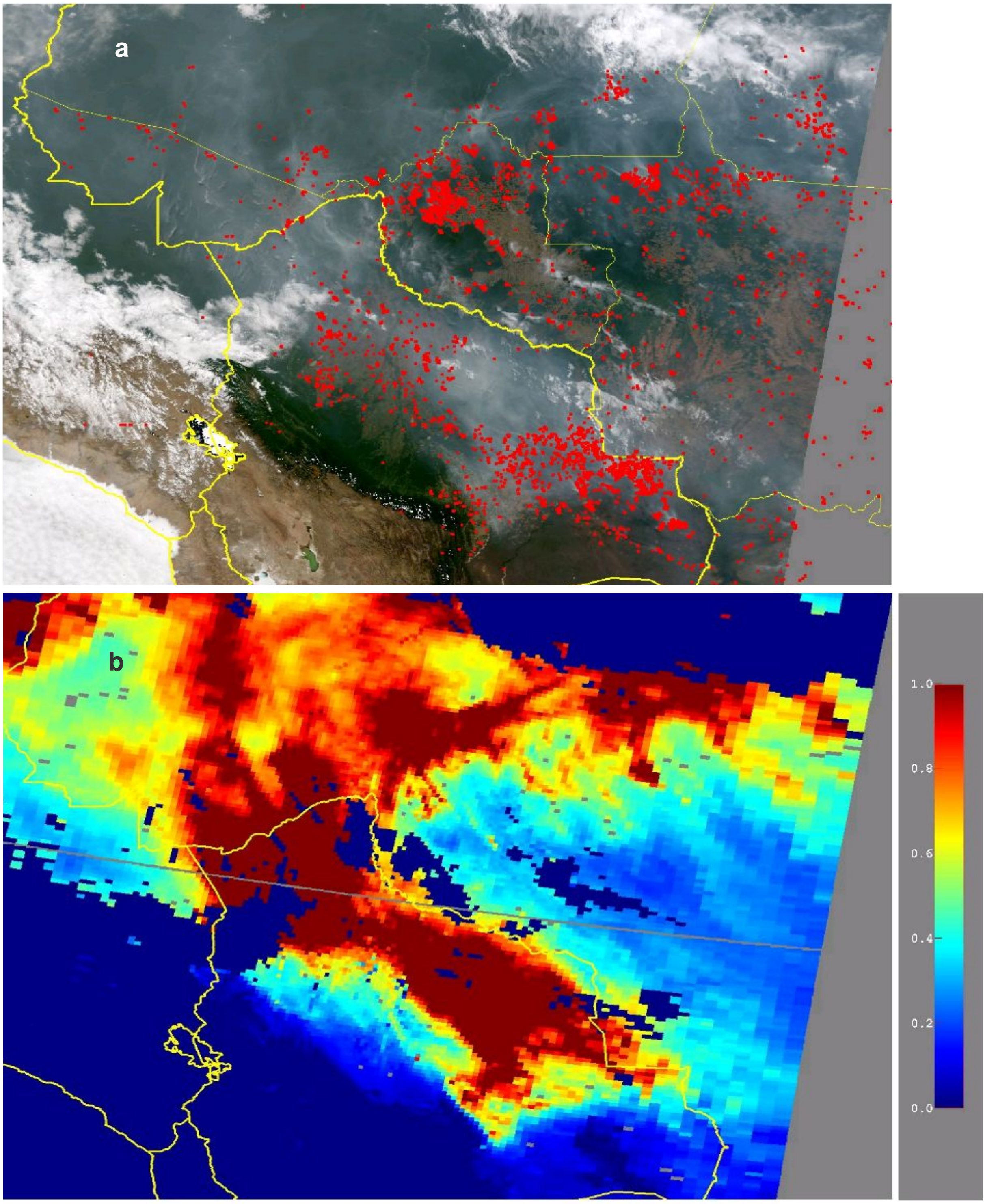

***Figure 2**. Results obtained from a Terra overpass on 23 August 2006 14:38 UTC: a) MODIS RGB composition and hot pixels; b) retrieved aerosol optical depth map.*

clouds can be seen over the Brazilian Amazon Basin, oriented according with the prevailing wind direction in an organized weather system. **Figure 3b** shows the corresponding AOD map under the same color code than the previous maps. **Figure 3c** is a composition from **Figures 3a**, **3b** and the identified fire spots, by which the AOD map is superimposed to the

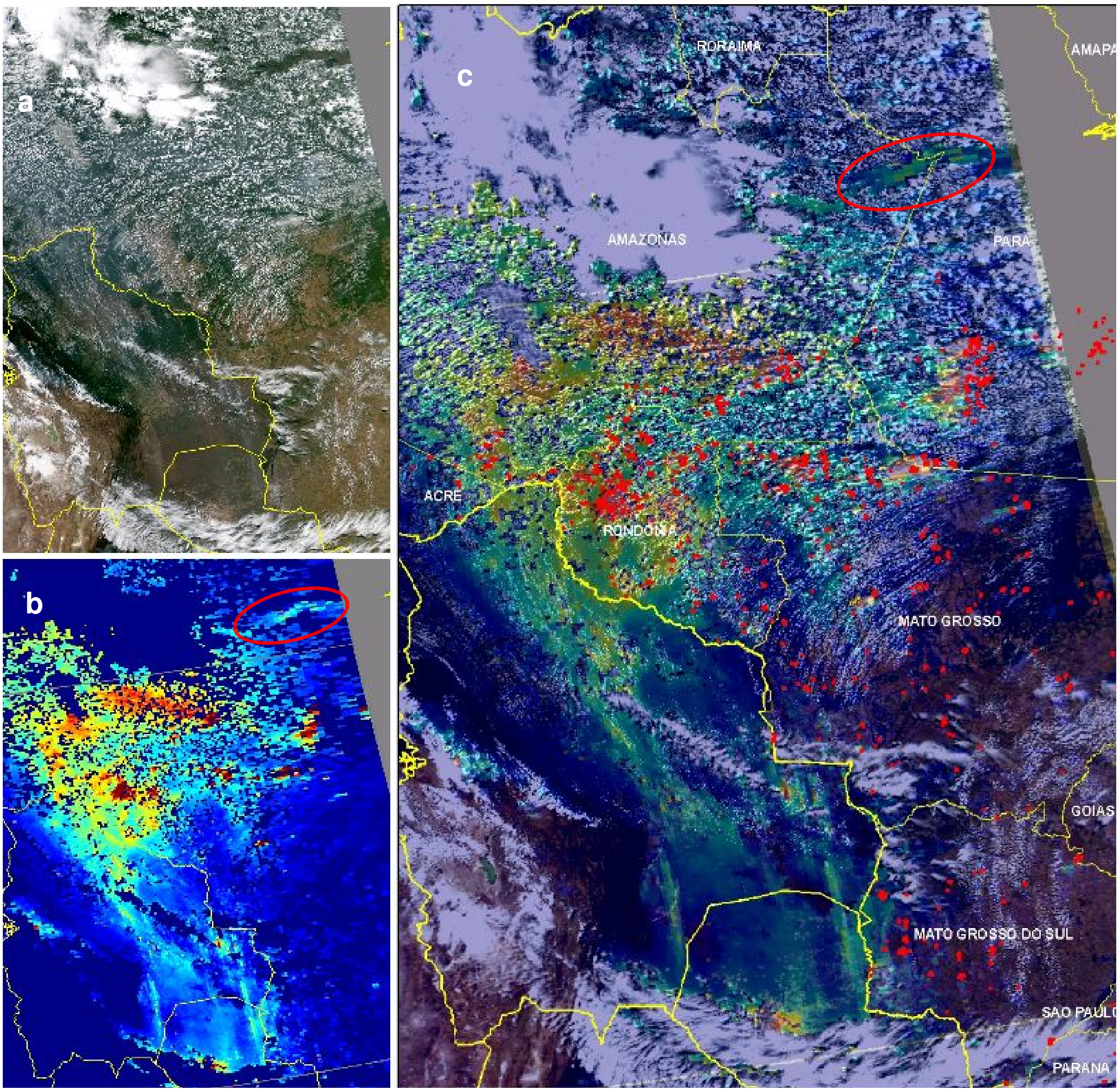

***Figure 3**. Integration between the systems for aerosol retrieval and fire detection shown in a Aqua overpass on 12 August 2006 17:44 UTC: a) MODIS RGB composition from calibrated radiances; b) retrieved aerosol map; c) superposition of a), b) and fire spots. See explanation on the text about the highlighted area.*

RGB composition, allowing identifying regions dominated by clouds, fire spots, and smoke plumes with AOD quantification. Some of the regions affected by high AOD values on **Figure 3b** are in the middle of cloud fields. This could raise some concern about cloud contamination contributing to the high AOD values observed in **Figure 3b**. However, by analyzing **Figure 3c** one notices the regions with high AOD values are close and downwind from fire spots identified in **Figure 3a**, what qualitatively corroborates the quality of aerosol maps retrieved amidst a broken cloud field, besides the quantitative validation discussed by Correia and Pires (2006).

The highlighted areas in **Figure 3** show higher AOD values retrieved over the very dark water surface over the Amazon River. This is most likely an artifact originating from limitations on the aerosol retrieval algorithm to derive correctly the surface reflectance in the area. Surface reflectance determination is the first source of error for the current aerosol detection algorithm, as discussed by Remer *et al.* (2005). In order to address this issue, a new precessing mask will be implemented on the DSA-CPTEC/INPE system based on the NDVI index and the scattering angle between the sun, the target pixel and the satellite sensor.

5. Final remarks

This work showed results obtained from the integration of two systems operating at INPE: the aerosol retrieval system using MODIS sensor and the system to detect hot pixels based on several satellite platforms, such as NOAA series, GOES-12, Terra and Aqua. The integration of results allows obtaining information on the monitoring of vegetation fires that is not available when using either system alone. There is internal consistency between the two systems under clean or polluted conditions. These results help corroborate the validity of AOD estimates obtained by the DSA-CPTEC/INPE system. Possible applications for the derived satellite products are monitoring biomass burning emissions, quantitative AOD assimilation into chemical weather forecast or climatic models, or improving atmospheric correction algorithms.

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