NEARLY 20 YEARS OF SATELLITE REMOTE SENSING AT CGE

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The first steps in satellite remote sensing at CGE were made in 1993, in the first years in close cooperation with the Remote Sensing Division of the Institute of Meteorology. The interest in the study of the atmospheric and surface properties using satellite images was first introduced in CGE by Ana Maria Silva and as a first year Master student, the first author here willingly accepted the challenge of developing her Master thesis on this unknown but rather appealing subject. Since then satellite remote sensing has greatly evolved with the launch of satellites with improved capabilities. CGE has taken advantage of these advancements to explore new methodologies applied not only to the atmospheric characterization, but also to land and water surfaces. Since the beginning of the 2000s the research group contributing to the development of satellite remote sensing at CGE has increased, including several eager students.

1 Introduction

The first steps in satellite remote sensing at CGE were made in 1993. The interest in the study of the atmospheric and surface properties using satellite data was first brought to CGE by Ana Maria Silva, head of a recently established Research Centre in Climate Change, which counted with the participation of four Portuguese institutions, under the leadership of the CGE. As a freshly graduated and first year Master student, the first author here willingly accepted the challenge of developing her Master thesis on this unknown but rather appealing subject. At first several difficulties arose, the main being the difficulty by that time of obtaining satellite imagery, which was mainly restricted to the Institute of Meteorology. In this sense, the close cooperation between CGE and the Remote Sensing Division of the Institute of Meteorology was fundamental in those first years, to carry on research in satellite remote sensing. Later on, research stays abroad, the parallel development of internet and also new policies for data distribution by the main satellite agencies worldwide greatly facilitated and granted the access to satellite data of different sources. On the other hand, environmental and also meteorological satellites have also greatly evolved with improved capabilities with respect to the spectral, spatial and temporal resolutions. Nowadays not only environmental and meteorological satellite data are freely provided by most satellite agencies for any interested user, but also satellite derived physical quantities characterizing the Earth's surface and atmosphere are available. CGE team took advantage of the evolution in satellite remote sensing in terms of data quality and accessibility and have come a long way since the early days. The next sections aim at illustrating the evolution of CGE research on satellite remote sensing.

2 Satellite Remote Sensing of Land Surfaces

METEOSAT and NOAA satellite series were used in the first years to evaluate the surface temperature, as well as the land surface albedo, on clear sky days [1, 2]. In spite of the deficient calibration of METEOSAT, its imagery frequency was at the time the only mean of remote sensing available to evaluate both the minimum and the maximum temperatures at the surface of the Earth. On the other hand, although their low temporal resolution, NOAA-AVHRR satellite series presented a good calibration that made it an accurate mean for the evaluation of surface temperatures and albedos.

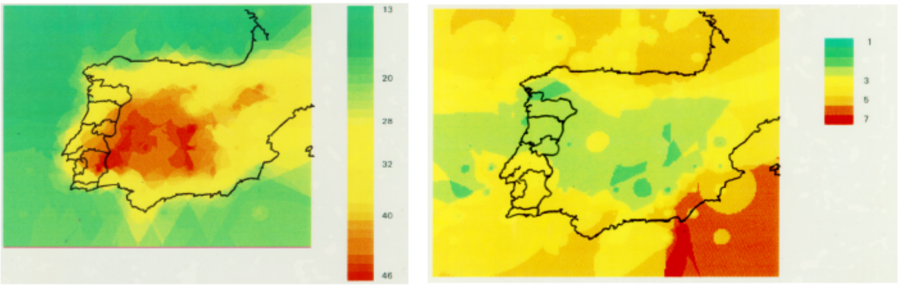


Figure 1. Maximum (left) and minimum (right) surface temperature obtained from Meteosat-5 for 12 July 1996 and 8 February 1996, respectively.

The determination of surface characteristics requires the correction of the atmospheric effects. For this purpose, the physical (radiative transfer) model LOWTRAN 7 was used, together with the vertical profiles of the atmospheric temperature and relative humidity, obtained from the forecasts of the ECMWF at eight atmospheric levels. The effects of absorption / emission and single scattering were taken into account, however multiple scattering in the atmosphere, as well as multiple reflections at the surface of the

Earth and scattering in the thermal infrared spectral region were assumed to be negligible. Figures 1 and 2 shows examples of the maximum and minimum surface temperatures (Fig. 1) and surface albedo (Fig. 2) obtained with the methodologies developed [1, 2].

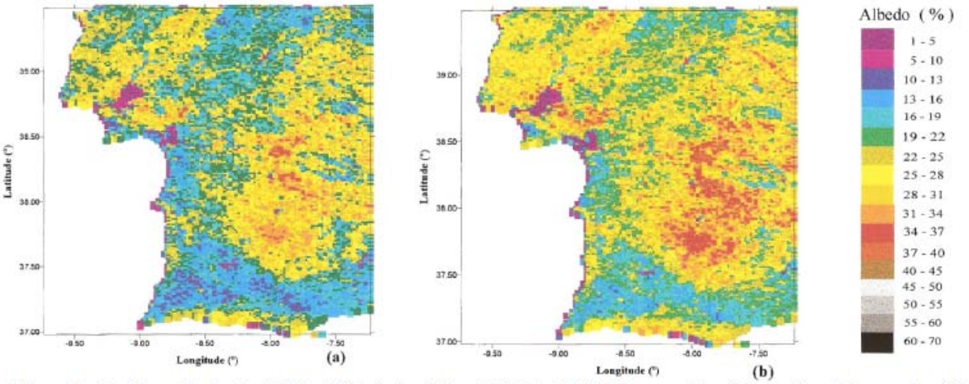


Figure 2. Surface albedo for 9 July 1996 derived from NOAA-AVHRR, assuming: (a) continental aerosols; (b) maritime aerosols.

The validation of the methods proposed for the evaluation of the surface temperature was done by comparison with observations of the land surface temperature available from surface meteorological stations, taken within the area of analysis. As for the surface albedo, the values obtained were compared with literature. Although the first satellite based methodologies derived were devoted to the characterization of land surfaces in terms of their temperature and reflectivity, atmospheric variables were already a concern. Therefore in the next years the attention diverged to atmospheric characterization, at first particularly to the complex problem of aerosol characterization, later on also to gaseous constituents and cloud characterization.

3 Satellite Remote Sensing of the Atmosphere

The synergistic use of low earth orbit (LEO) and geostationary earth orbit (GEO) satellite data for aerosol-type characterization, as well as aerosol optical thickness retrieval and monitoring over the ocean, was explored. These properties are central for the estimation of the direct shortwave aerosol radiative forcing, which in turn is a key variable for climate studies. The synergy serves the purpose of monitoring aerosol events at the GEO time and space scales (15 to 30 minutes; ~3 km) while maintaining the accuracy level achieved with LEO instruments. Aerosol optical properties representative of the atmospheric conditions were obtained from the inversion of high-spectral-resolution measurements from the Global Ozone Monitoring Experiment (GOME). The aerosol optical properties were then input for radiative transfer calculations for the retrieval of the AOT from GEO visible broadband measurements, avoiding the use of fixed aerosol models available in the literature [3, 4]. The retrieved effective aerosol optical properties represent an essential component for the aerosol radiative forcing assessment.

The method was applied to several aerosol events including strong desert dust outbreaks and biomass burning event over the ocean. The retrievals of the aerosol optical properties were checked against retrievals from sun and sky radiance measurements from the ground-based Aerosol Robotic Network (AERONET) as well as from independent aerosol products from different satellites and a considerably good accuracy was found for the AOT [5].

The combination of measurements from satellites in different orbits (LEO and GEO) having different spectral, spatial, and temporal resolutions, with the intention of developing an effective aerosol monitoring tool during strong aerosol events over the ocean was a novelty introduced [3, 4, 5] with respect to other satellite-based algorithms in use at the time. Satellite-based methods were directed either to aerosol monitoring or to a more accurate aerosol characterization, falling short of providing both aspects, which are equally important for climate studies. The method developed is not subject to this shortcoming, presenting as key features the improved accuracy of the aerosol characterization with respect to the methods based on GEO measurements and the stretching of the spatial and temporal coverage of the LEO retrievals to the GEO spatial-temporal scale.

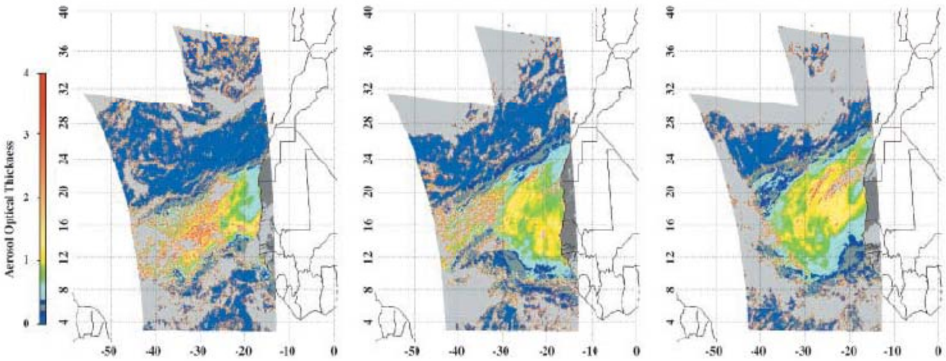


Figure 3. Aerosol optical thickness maps derived from Meteosat-6 full-disk VIS imagery for 6, 7 and 8 June 1997, (1200–1230 UTC), when the dust was blowing off the Sahara Desert and crossing the Atlantic Ocean. Cloudy pixels are assigned light grey and land pixels darker grey (taken from [3]).

In sequence of the methodologies developed to characterize atmospheric aerosols over the ocean, a new challenge appears around 2004 in the form of a contract with the Portuguese Electrical Company (EDP). The study aimed at the identification and characterization of aerosols plumes emitted from some of the EDP Power Plants using satellite measurements, with the purpose of monitoring the emissions of pollutants and of studying their atmospheric dispersion. The novelty with respect to the previous work was the underlying surface, instead of only the relatively dark ocean surface (low reflectance), it was required to deal also with the varying reflectance of land surfaces. A methodology was successfully developed, taking into account the wind speed (intensity and direction) at the power plant tower height and the background aerosol contamination [6, 7], as shown in Fig. 4.

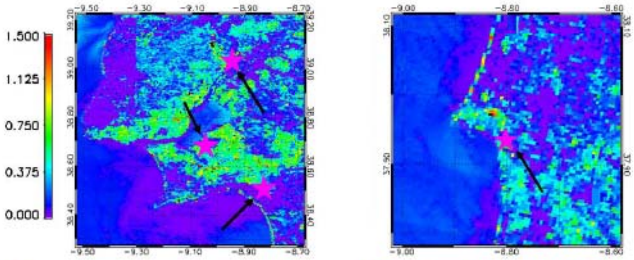


Figure 4. Aerosol optical depth for Carregado, Barreiro, Setúbal (a) and Sines (b) EDP power plants.

Meanwhile the work naturally evolved to extend also to cloud characterization (microphysical and optical) from satellite remote sensing methods, becoming also the effects of aerosols on clouds and radiation a concern [8, 9]. The awareness of the importance of the role that aerosols and clouds play on the climate system, constituted a main motivation to pursue the research in this sense. As an example, the aforementioned developed methodologies [3, 4, 5] were applied to a dust event that occurred between China and Korea. A significant finding was the extremely low single scattering albedo obtained (0.76), much smaller than previous values in literature for Asian dust or Saharan dust, suggesting that Asian dust can become a much more absorbing aerosol during movement when mixed with pollution materials produced over the industrial/urban area of China [8]. This may result in substantial atmospheric heating and surface cooling, as illustrated in Fig. 5.

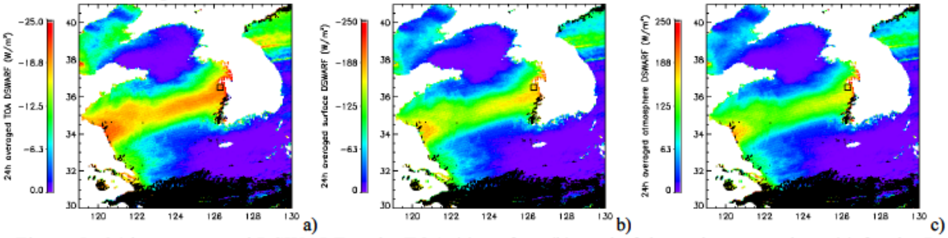


Figure 5. 24 hour averaged DSWARF at the TOA (a) surface (b), and of the entire atmosphere (c) for the 7 April 2000. Pixels contaminated by clouds at any time of the day are represented in black.

The development of a methodology to derive cloud properties was encouraged by the existence of a new generation of GEO satellite measurements such as those of the Spinning Enhanced Visible and Infrared Imager (SEVIRI) flying on Meteosat Second Generation (MSG). This innovative sensor opened new perspectives with respect to past GEO systems since it provided the necessary additional spectral measurements, supplied before exclusively by LEO satellite sensors. Fog was also a very interesting and challenging occurrence to study using satellite remote sensing. Being an important phenomenon not only from the point of view of air quality but also for ground and air traffic purposes, the early fog detection and the identification of its extension are therefore essential. Cloud characterization, as well as fog detection and identification were addressed and methodologies developed based on the use of multi-spectral satellite data [9, 10, 11, 12]. The most suitable methods for the detection of fog arose from the difference of brightness temperature between infrared spectral channels at 3.9 and 10.8 μm, and at 8.7 and 10.8 μm. The best solution found for the detection of fog employed the 3.9-10.8 channels during night and daytime, and the 8.7-10.8 during sunrise. An example of the results obtained from the fog detection method developed is shown in the images of Fig. 6.

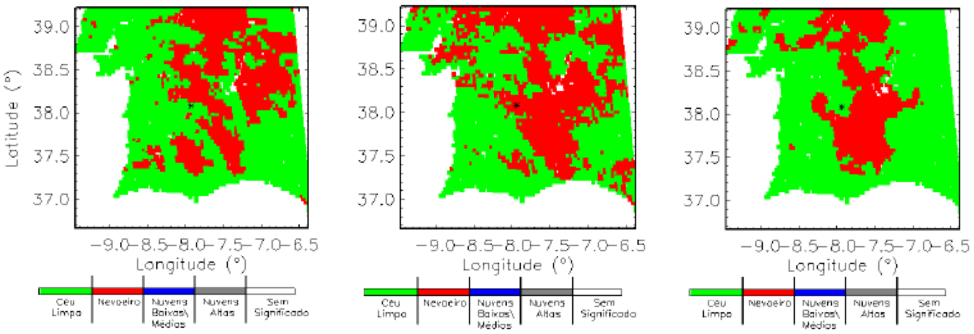
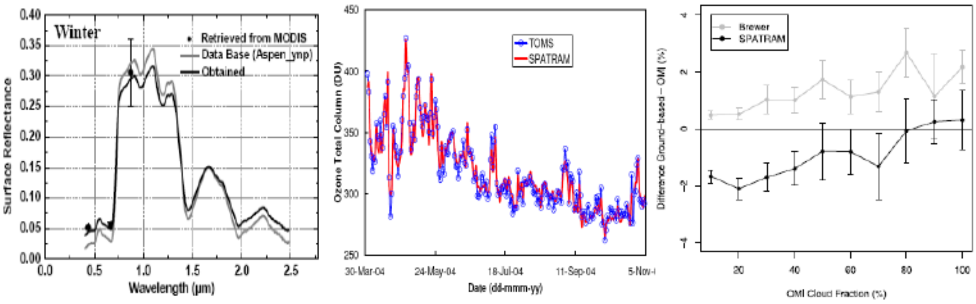


Figure 6. Satellite remote sensing of fog detection (red) around Beja (black *) on 28 July 2006 (at 04:12, 07:12 and 08:57 UTC). Fog was observed in Beja from 04:40 UTC to 08:35 UTC.

After the mid 2000s the Atmospheric Physics Observatory of CGE started to gain importance with reference instrumentation installed, therefore satellite remote sensing was also focused in the region in order to allow for the validation of methodologies by comparison with ground measurements taken at CGE.

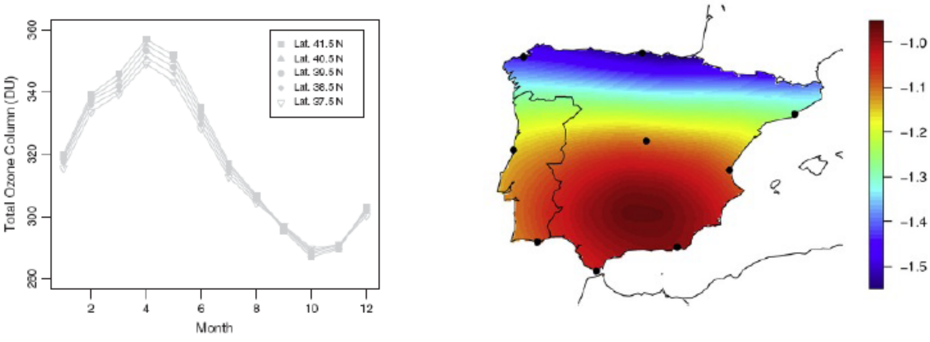
[13, 14, 15] displayed in Fig. 7 are examples of this combination or comparison of data from different atmospheric platforms (satellite and ground-based), aiming at providing increasingly accurate climate-relevant atmospheric quantities, such as the surface spectral reflectances and the ozone total column over Évora.



(a) (b) (c)

Figure 7. (a) Surface spectral reflectance values (taken from [13]); (b) Ozone total column (taken from [14]); (c) Differences between OMI total ozone column and ground-based instruments as a function of OMI cloud fraction (taken from [15].

The spatial–temporal structure of total ozone column over Portugal, as well as its variability and trends over the Iberian Peninsula during the last 30 years were also deeply analyzed [16, 17] and several relevant conclusions could be drawn from the studies, with a moderately strong latitudinal dependence found, as shown in Fig.8.



(a) (b)

Figure 8. (a) Monthly evolution of total ozone column over Portugal for five latitudinal bands (taken from [16]); (b) Spatial distributions of the trends (expressed in percentage) over the Iberian Peninsula for the periods 1979 – 2008 (taken from [17]).

Aerosol effects on clouds and radiation have also been extensively investigated, not only using satellite remote sensing, but also using atmospheric modeling techniques [18, 19], as illustrated by the cloud radiative forcing results shown in Fig. 9.

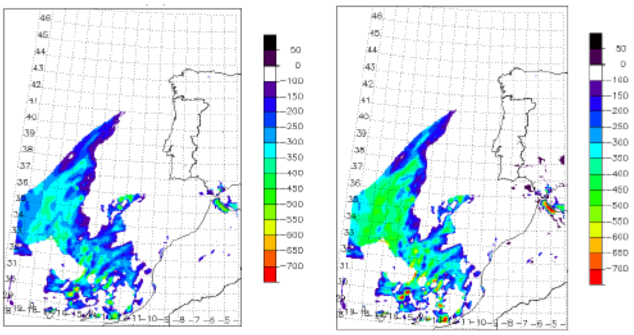


Figure 9. Surface cloud shortwave radiative forcing, in Wm-2, in the absence (left) and in the presence (right) of desert dust aerosols, for 27 May 2006.

Research is also progressing regarding radiative transfer and inversion algorithms, which are fundamental issues in satellite remote sensing [20, 21], aiming at proposing a new improved cloud inversion algorithm. In this regard two new grants were recently funded: a PhD focusing on the problematic of cloud remote sensing and of cloud effects on solar and terrestrial radiation; a Post-Doc exploring the combination of satellite and ground-based measurements to improve the understanding of radiative balance over the Southwestern Iberian Peninsula, especially due to aerosols and water vapour.

Another emerging topic of interest in the last years is the analysis of satellite derived precipitable water to detect the transport of (sub)tropical moisture to higher latitude regions, also known as Atmospheric Rivers. Special attention has been dedicated to atmospheric river structures in the pathway of Madeira Island, which act to increase moisture in the lower atmospheric levels and together with the orographic lifting induce heavy precipitation events [22]. The use of satellite remote sensing for the early detection of these features can be a valuable aid in the prediction and early warning of extreme precipitation events over Madeira.

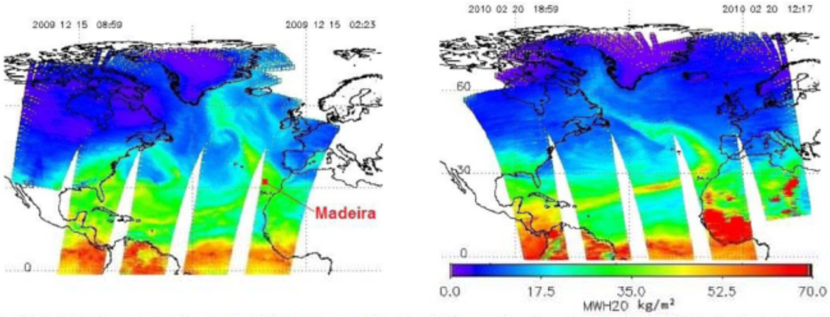


Figure 10. Satellite images of precipitable water obtained from the Atmospheric InfraRed Sounder (Aqua-AIRS) for 15 December 2009 (left) and 20 February 2010 (right).

4 Satellite Remote Sensing of Water Surfaces

At the same time atmospheric remote sensing was developing further at CGE, around 2005 an opportunity of exploring satellite remote sensing applied to the study of water surfaces emerges thanks to the collaboration with José Teixeira da Silva (at the time with the Faculty of Sciences, Univ. of Lisbon) [23]. This work also permitted to establish an enduring collaboration with the water laboratory of the University of Évora.

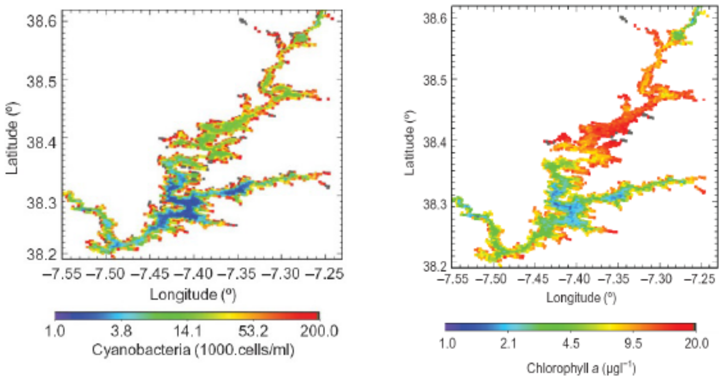


Figure 11. Cyanobacteria density and Chlorophyll a concentration over the whole Alqueva Reservoir surface on 14 November 2007 (taken from [23]).

The potential of the MEdium Resolution Imaging Spectrometer (MERIS) to describe variations of optically active substances over Alqueva artificial lake was investigated. Limnological laboratory analyses of the water samples collected monthly, from 2003 to 2006, by the UE water laboratory were used in combination with MERIS. The water surface spectral reflectance was derived from Level1b MERIS data, using radiative transfer calculations to account for the atmospheric effects. The lake water spectral surface reflectance was then combined with laboratory analyses of cyanobacteria total densities, chlorophyll a concentrations and turbidity, and empirical algorithms for these quantities were derived (Fig. 11). The results obtained were compared with independent laboratory analyses from different years with respect to those used, with good correlation coefficients obtained [24, 25, 26]. The methodology proposed has been developed to inexpensively monitor Alqueva Reservoir water quality in terms of cyanobacteria, chlorophyll a and turbidity, on a regular basis, and to provide useful information to the authorities. On the other hand, turbidity, a measure of the amount of light extinction in the water column, may induce changes in the lake's vertical thermal structure, which in turn plays an important role in autochthonous primary production and in the evolution of the water surface temperature, a key variable in the water-atmosphere transfers. Thus turbidity is deemed an essential parameter towards the improvement of lake parameterization schemes in weather forecast and climate models. The importance of the lake optical characteristics in the evolution of lake surface temperature and heat fluxes was also demonstrated [26].

Work is now ongoing aiming at retrieving the attenuation coefficients of different types of water, not only at the surface but also at different water depths, through the combination of satellite and ground-based remote sensing, as well as laboratory analyses.

5 Summary

CGE team benefited from the developments in satellite technologies and remote sensing as well as radiative transfer techniques in the last two decades and have come a long way since the early days. Nowadays the research is applied to a wide range of domains, mostly dedicating to atmospheric and water quality satellite remote sensing.

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