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Satellite and ground detection of very dense smoke clouds produced on the islands of the Paraná river delta that affected a large region in Central Argentina

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Abstract

Intense fires were produced on the Paraná river delta islands, Argentina, during most part of 2008, by a combination of an exceptionally dry period and the farmers' use of a fire land-cleaning technique. In April 2008, those fires significantly affected the nearby regions and their inhabitants, from Rosario city to Buenos Aires mega-city. In this work we present satellite as well as ground Aerosol Optical Depth (AOD) at 550 nm data obtained during the propagation of pollution clouds to the central zone of Argentina. The highest value (1.18) was registered at Buenos Aires by atmospheric remote sensing, using the satellite instrument MODIS/Terra on April 18th 2008 at 10:35 local time (= UT − 3 h). On the same day, ground air quality detectors also measured in this city the highest Total Suspended Particle (TSP) value of the month, 2.02 mg/m^3. The AOD(550) daily variation at Rosario Astronomical Observatory, which is located near the Paraná riverside, was derived by combining solar ultraviolet erythemal irradiance data (measured with a YES biometre) with model calculations. On April 25th 2008, from 12:00 to 15:30 local time, a rather high and constant AOD(550) value was registered, with a mean value of (0.90 ± 0.21). Cities located on the side of the Rosario–Buenos Aires highway (San Nicolás, Baradero and San Pedro) were also affected, showing a mean AOD(550) between the Rosario and Buenos Aires values. The particulate matter was collected with gridded samplers placed on the Paraná river islands as well as at the Rosario Observatory. They were analysed with a Scanning Electron Microscope (SEM) and mainly showed a biological origin. Even if normally large particles travel small distances from the source, organic aerosol in the range of 40–100 μm and complex asymmetric structures were registered several kilometres away from the aerosol sources on the islands. Another event of intense UV index attenuation (98.6%) occurred on September 18th 2008, due to very dense smoke clouds that extended over the Rosario area for several hours. The clouds were driven away from the fires by East–northeast and East–southeast winds. The minimum value of this index measured around noon allows to derive a maximum $\mathrm{AOD}(550)_{\max} = (3.65 \pm 0.90)$ at 12:45 local time. Soot clouds extended over the Paraná river, transporting Burned Biomass Debris (BBD) that deposited on Rosario. In particular, burned leaves and small branches with dimensions of 1–20 cm were collected. The mean (BBD) particles deposited on the ground from 7:00 to 19:00 local time were (0.92 ± 0.20) BBD/(m^2 h).

The main purpose of the present work is to contribute to the understanding and quantification of the impact of very dense smoke clouds and BBD that directly and indirectly affected a densely populated area. All the events originated in a very particular and fragile region such as a river delta (with its specific native plants) were registered by using a multi-instrument approach (satellite as well as ground based devices).

The analysis of these events, as detailed in this manuscript, was used as a scientific reference for the judicial claim made at the Supreme Court of Justice of Argentina by the National University of Rosario, against the authorities of the Entre Rios Province where the islands of the Paraná river are placed, in order to take the necessary measures for the suspension of the biomass burning in these islands.

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1. Introduction

Atmospheric particulate matter (or aerosol) is a variable that has significant effects on climate and human health. One of the sources of aerosol is biomass burning, which is produced by nature in different parts of the world (mainly due to lightning during a storm) and by human activities. Biomass burning produced by man is chiefly generated by: (i) Forest clearing, (ii) Grass clearing to introduce agriculture or cattle production or where agricultural exploitation usually takes place, when products other than native pastures are needed, or (iii) The extensive use of resources to achieve higher levels of production.

Biomass burning fires are used as land clearing techniques in several regions of South-America. Dense smoke clouds commonly produced during large biomass burnings, like those generated in Matto Grosso and Amazonia (Brazil), was analysed in detail in the classical SCAR-B (Smoke, Clouds and Radiation-Brazil) experiment (Kaufmann et al., 1998 and subsequent articles).

Intense fires originated in Central Argentina – mainly in the Rosario–Buenos Aires axis– due to an exceptional drought registered at the end of 2007 and for several months of 2008 (SMN, 2007, 2008), and to extensive forest burning on the island as a land clearing technique for cattle production. This is also a common practice used by farmers to speed up the production time of soya beans, wheat, corn and other grains. Unfortunately, biomass burning is not well regulated by the environmental authorities of the region.

The Moderate Resolution Imaging Spectroradiometre (MODIS) aboard the Terra and Aqua NASA satellites frequently detected a large number of fires in South America. In this work we used images of smoke (aerosol) clouds generated during April 2008 events. The MODIS satellite instrument uses 36 spectral bands ranging from 0.4 to 14.4 μm. It holds a scanning pattern of ±55° that achieves a 2330 km swath and provides global coverage every 1–2 days. We would like to point out that our data correspond to a given day. The orbits of the Aqua and Terra satellites are circular, sun synchronous, near-polar, and 705 km above the Earth surface (http://www.modis.gsfc.nasa.gov/index.php).

The Aerosol Optical Depth (AOD) used for this analysis was retrieved from MODIS level 2 database (http://www.ladsweb.nascom.nasa.gov/browse_images/granule_browser. html) and the images have a spatial ground resolution of $10 \times 10\,km^2$ in the nadir direction. The following interpolation procedure to estimate the AOD from satellite data was used: (a) If the coordinates (latitude and longitude) correspond to a point that belongs to 4 neighbouring pixels, the values associated to each pixel are interpolated in order to obtain the final AOD value; (b) If this does not happen, the 16 nearest pixels are used for interpolation.

In Fig. 1 we present MODIS/Terra fire pixel images registered in South America during the period of April 10–29 2008. The highest fire pixels density was detected on the Paraná river delta islands, Argentina (one of the largest deltas in the world) pointing out the great impact of those biomass burning events on a very fragile ecosystem.

Ground data were obtained by using biometres (solar UV erythemal irradiance metres) and a Scanning Electron Microscope (SEM) imaging technique was used for aerosol analysis.

The aerosol cloud generated by intense biomass burning affected air quality after harvest time, producing large-scale smoke pollution events. For several days, continuous nearby smoke emissions reduced visibility and gave rise to several fatal traffic accidents and multiple collisions (http://www.301.es/0rp), damaging the claddings of buildings and houses, monument and artistic sculptures in public places. Additionally, an increase of hospital admissions of patients was registered, due to respiratory problems, eyes irritation, allergy and asthma complications (http://www.301.es/0fu). Moreover, fires were causing the death of delta river animals such as birds, snakes, capybaras, etc.

Biomass burning is an anthropogenic ancient technique currently applied in different countries of South-America and Africa (Eck et al., 2001). It has been compared by Eck et al. (1999) to aerosols from urban/industrial and desert sources. During the Southern Hemisphere autumn/winter of 2008, significant smoke (aerosol) clouds produced by the burning of grass, shrubbery and trees on the islands of the Paraná river delta extended to the Río de la Plata (de la Plata river) mouth and even to Uruguay, the South of Brazil and the Atlantic Ocean. For this reason, the cities surrounding the delta were largely affected, including those located on the banks of both rivers, where about 18 million people live in urban conglomerates, like Buenos Aires (34.58°S, 58.48°W), Rosario (32.57°S, 60.44°W), and their metropolitan areas, which have a population of about 12 and 1.5 millions, respectively.

From the end of 2007 until late 2008, the unusual weather conditions registered in the Litoral region of Argentina produced an accumulated precipitation that reached about half the normal values of the last decades for the same period, as given in the Argentine National Weather Service web page: http://www.smn.gov.ar. Another important factor that significantly contributed to the production of high density fires was the expansion of the cattle border in this fragile region. The main reason of this expansion was the intensive production of soya beans and other grains in the delta region men-

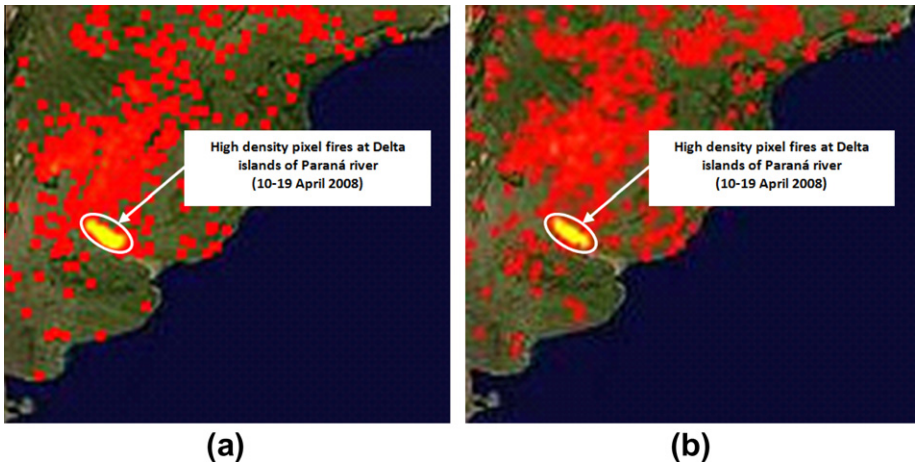

Fig. 1. Adapted MODIS images of fire pixel distribution in South America (mainly Central and East of Argentina, Uruguay and South of Brazil). *Red* corresponds to normal fire pixels and *yellow* to the region with intense fires in the Paraná river delta, Argentina. (a) Period of April 10–19 2008; (b) Period of April 20–29 2008. Adapted from http://www.rapidfire.sci.gsfc.nasa.gov/firemaps/. (For black and white figures, the circled white colour corresponds to normal fire pixels in the region with intense fires in the Paraná river delta, Argentina). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

tioned above, which caused the movement of cattle from these zones toward less suitable regions.

Normally, a smoke cloud has a significant attenuation effect on UV radiation, which is characterised by an AOD wavelength dependent variable. The optical depth typical of clouds produced in biomass burning, like those studied in the present work, can be described by the Ångström formula

$$AOD(\lambda) = \beta\lambda^{-\alpha}, \quad (1)$$

where β is the coefficient of extinction and α the Ångström exponent. If the AOD value is known at a given wavelength, this relation permits to obtain the AOD at another (rather near) wavelength, through the following relation

$$AOD(\lambda_2) = (\lambda_1/\lambda_2)^{\alpha} AOD(\lambda_1), \quad (2)$$

An exponent value near 1 corresponds to large particle (Mie scattering) dispersion with respect to the wavelength of the incident radiation and a value of 4 corresponds to the smaller ones (Rayleigh scattering). Typical α values for biomass burning are in the 1–2 range (see for instance Eck et al., 1998, 2001; Wolfram et al., 2004; Russell et al., 2010).

In the present work we analyse an extreme event of biomass burning pollution recorded for the first time in decades in Rosario, Argentina and its environs, whose origin is the deliberate burning of grass on the Paraná river islands opposite this city.

Two particular effects were registered: (a) The strong influence of dense smoke clouds on UV Index attenuation, and (b) The unusual transport of large (centimetric) Burned Biomass Debris (BBD) to a densely populated city like Rosario, some kilometres away from the source on the Paraná river delta islands. In fact, very few studies present results about the effects of very dense smoke clouds. Jones and Christopher (2009) indirectly investigated BBD in the range of one millimetre with a Weather Surveillance Radar in a biomass burning event in Georgia, USA, in May 2007. This was done in order to derive the plume evolution of the smoke cloud, since it was assumed to be an overlap between the smoke and debris clouds. Otherwise, Janhäll et al. (2010) visually observed the fallout of centimetric BBD and even larger debris particles.

Our results show direct evidence of centimetric range BBD (see item 2.3) and its land surface density, after deposition on Rosario. It must be pointed out that the present work was used as the only scientific evidence presented for the legal claim made by the National University of Rosario at the Supreme Court of Justice of Argentina against the authorities of the Entre Ríos province, to which the islands belong, urging them to put an end to biomass burning on the Paraná river islands.

Fig. 2. Adapted MODIS image for April 4th 2008, showing the Paraná river delta region in Argentina and the position of the cities affected by the aerosol clouds generated by intense fires on the islands.

2. Results

2.1. Aerosol over Buenos Aires city and adjacent regions

In April 2008 North winds transported contaminant clouds from the islands, where fires originated, towards the Rosario-Buenos Aires axis. In Fig. 2, we present a MODIS image of April 4th 2008 showing clear sky conditions. The positions of the cities of Buenos Aires, San Pedro, Baradero, San Nicolás and Rosario, which are near the source of fires or were strongly affected by fires, are indicated, as well as the island location where measurements were made.

The daily behaviour of the AOD(550) detected by MODIS Terra and Aqua satellites for the cities of Rosario, San Nicolás, San Pedro, Baradero and Buenos Aires during April 2008 is shown in Fig. 3. The first peak registered on April 9th was so significant that it produced a considerable visibility reduction, which caused several deaths in the Rosario–Buenos Aires highway, as it was described above. In particular, the MODIS/Terra satellite measured value (1.18) for April 18th at 10:35 local time (= UT − 3 h) in Buenos Aires, corresponds to the highest AOD(550) value registered for the April time series. This value is about three times higher than the monthly mean, indicating a strong pollution event and similar to that obtained in the Amazonian (high density) forest (see for instance, Kaufmann et al., 1998 and subsequent articles of the SCAR-B experiment). Otherwise, the AOD value determined at 500 nm by the AERONET (Aerosol Robotic Network)/NASA sunphotometre operating at CEILAP (http://www.aeronet.gsfc.nasa.gov) in Buenos Aires metropolitan area was 1.19. In order to transform this AOD(500) into a 550 nm value, Eq. (2) was used, assuming an Ångström exponent equal to unity. Thus, an AERONET AOD(550) value of 1.08 was obtained, which is in good agreement with the satellite derived value of 1.18, since the corresponding percentage relative difference amounts to only 8.5%.

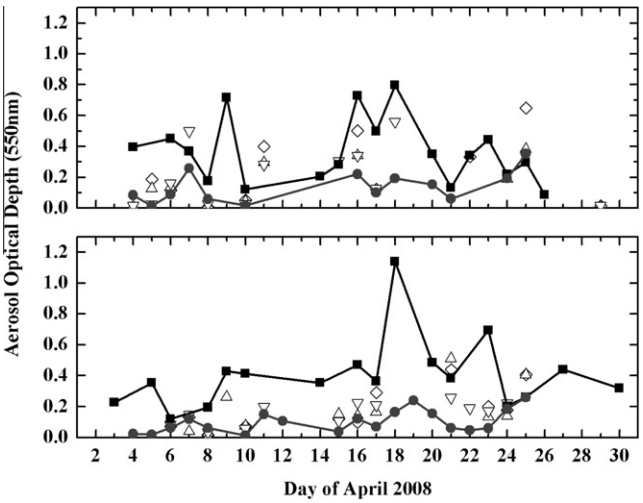

Fig. 3. AOD(550) values registered in April 2008, during the intense biomass burning fires generated at the delta of Paraná river in Argentina, affecting the cities of Buenos Aires (square and bold line), Baradero (up triangle), San Pedro (rhombus), San Nicolás (down triangle) and Rosario (circle and bold line). Top: MODIS/Aqua data. Bottom: MODIS/Terra data.

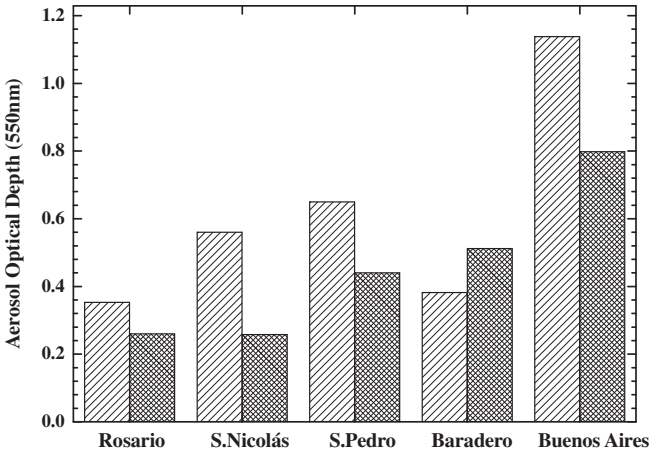

Fig. 4. Maximum AOD(550) values registered during April 2008 by MODIS (as given in Fig. 3) aboard the Aqua satellite (left column) and Terra satellite (right column), at different locations near the Paraná river delta.

In Fig. 4, mean AOD(550) maximum values are shown, which were registered during April 2008 by MODIS aboard the Aqua and Terra satellites, in the cities located on the west bank of the Paraná river, near its delta: Rosario, San Nicolás, San Pedro, Baradero and Buenos Aires. Considering the Aqua and Terra mean maximum data, it can be seen that Buenos Aires was the most affected city. The local Environment Secretariat has a particulate matter detection program with weather stations operating at different locations. The Total Suspended Particle (TSP) values for April 2008 that we are analysing are represented in Fig. 5. The

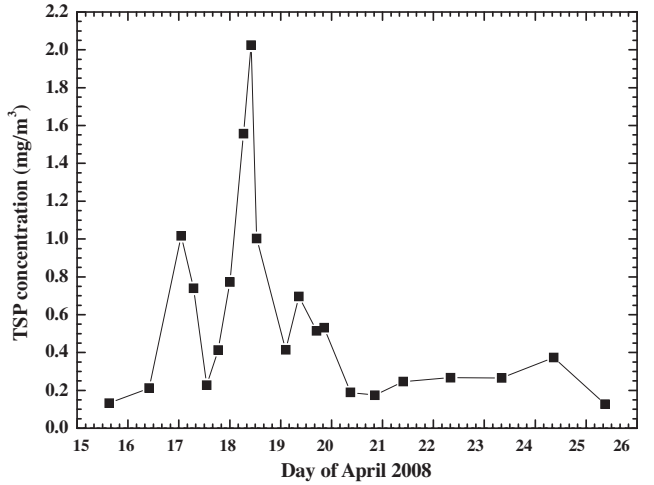

Fig. 5. Total suspended (aerosol) particles (TSP) concentration (per hour) measured in Buenos Aires city during the second half of April 2008.

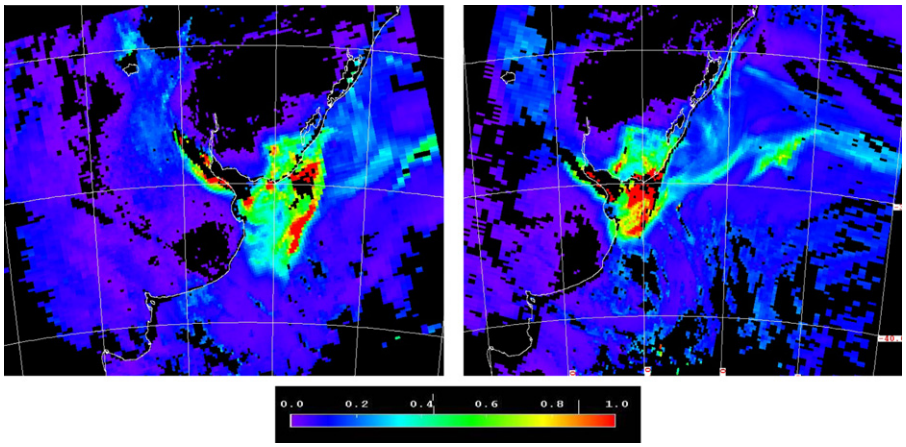

Fig. 6. MODIS images for April 18th 2008, corresponding to AOD(550) obtained by MODIS aboard the Aqua satellite (left) and the Terra satellite (right). Note: The smoke cloud is shown in *different colours*, *as indicated in the scale below*. (In black and white figures, the smoke cloud is shown in different grey colours and white indicates the greater AOD).

maximum aerosol concentration was registered on April 18th 2008, with a value of 2.02 mg/m^3, which is four times higher than the city acceptable limit of 0.5 mg/m^3.

In Fig. 6, the adapted MODIS images show that the environmental air (smoke) pollution event of April 18th affected different places in Argentina and Uruguay, Río de la Plata and Atlantic Ocean. More than 18 million people living or working in many cities of Argentina were affected. It was the most intense event registered in the region at least in the last four decades. It produced an increase in human diseases such as asthma and allergy, among other health problems and in the environment, contamination of outer as well as inner surfaces (see the item Discussion and perspectives).

The space–time evolution of the smoke (aerosol) cloud in the large region of the Paraná river delta up to Buenos Aires city and its surroundings, can be followed through an air mass back-trajectory analysis (Schoeberl and Newman, 1995; Pickering et al., 2001). In Fig. 7, we show the behaviour of the air mass that evolved at low level altitude (below 1500 m) from April 16th to 18th 2008. We can see that the trajectory curve over-passed the biomass burning sources in the delta indicated above (last part of the black trajectory curve before arriving in Buenos Aires) and finished at low altitude in the Buenos Aires region.

2.2. Aerosol over Rosario city and its nearest region

Aerosol Optical Depth can be also derived from solar UV erythemal irradiance measurements combined with model calculations. We used the UV sensor of a Davis automatic weather station, which was calibrated against the YES biometre (Model UVB-1, serial number 970809) installed at the Rosario Astronomical Observatory. This biometre is part of Argentina's National Weather Service (NWS) UV Monitoring Network (Cede et al., 2002a,b)

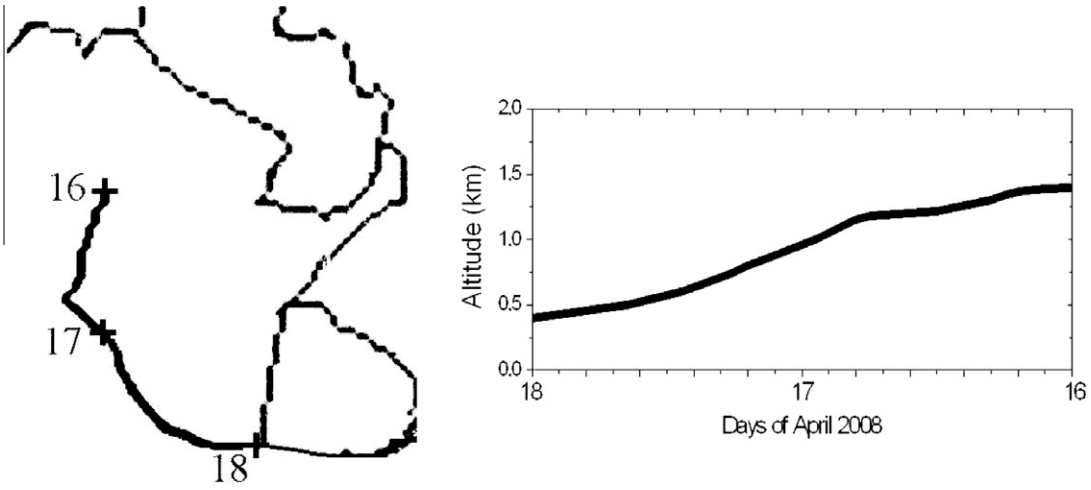

Fig. 7. Back-trajectory analysis of the air mass that arrived in Buenos Aires on April 18th 2008. Left: Evolution of the air mass in the last two days (line between the points indicated by the plus symbol). Note: Numbers 16 and 17 indicate the previous days, and 18, the actual day. Right: Altitudinal behaviour of the air mass that over-passed the biomass burning region and arrived in Buenos Aires city near ground level (http://www.croc.gsfc.nasa.gov/aeronet).

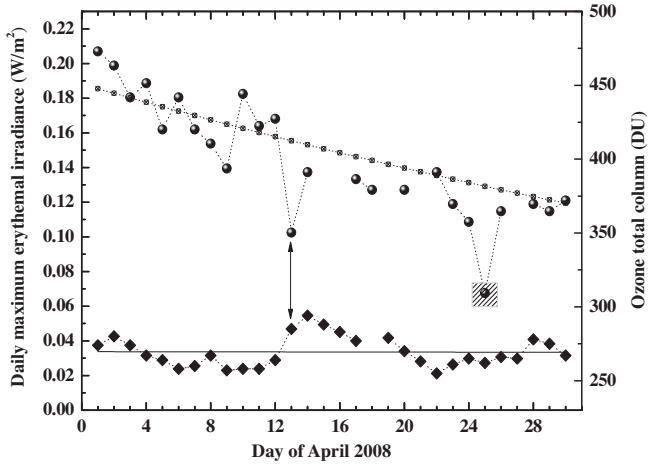

Fig. 8. Daily maximum value of erythemal irradiance measured at the Rosario Astronomical Observatory (closed circle) and modelled with the TUV algorithm (upper dashed line and open circle), considering the ozone values measured by OMI/KNMI equipment aboard the AURA/EOS satellite that are also shown (solid diamond, and lower solid line for the mean value). The single scattering albedo is 0.93 and the soil reflectivity (albedo), 0.06. Note: The strong reduction of erythemal irradiance on April 25th 2008 (indicated by a grated square) can be directly assigned to the contaminant (smoke) cloud attenuation generated on the nearby Paraná river islands.

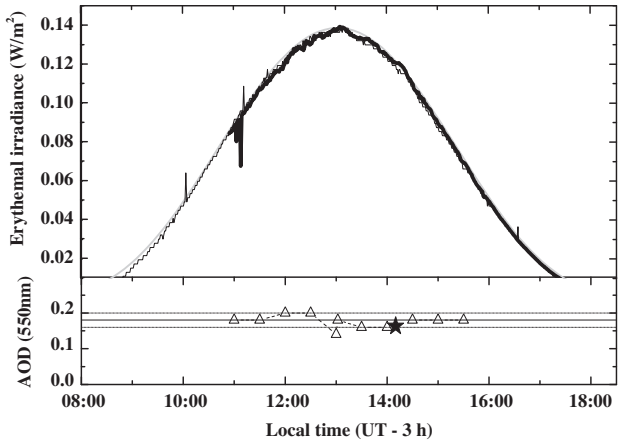

Fig. 9. Top: Erythemal irradiance as function of the hours of the clear sky day April 17th 2008, measured with a YES biometre (thick solid line) and a UV sensor of the Davis weather station (thin solid black line), both operating at the Rosario Astronomical Observatory. Radiative transfer TUV model calculations (grey line) are also shown, considering a total column ozone value of 277 DU, a single scattering albedo of 0.93 and an albedo of 0.06. Bottom: AOD(550) derived from TUV results (open triangle) and given by MODIS (closed star). Note: the horizontal line is the mean ground value (0.18 ± 0.02) in the calculated period.

and was provided by the World Meteorological Organisation (WMO).

In Fig. 8, the daily maximum solar erythemal irradiance during April 2008 in Rosario, and the total column ozone for each day given by the OMI/KNMI equipment aboard the Aura/NASA satellite are shown. It can be seen that solar irradiance reduction on April 25th is not related to a high value in the total column ozone. On this day, a large contaminant (smoke) cloud extended over the place where the instrument was recording erythemal irradiance data. It should be pointed out that very probably the second large reduction comes from cloud attenuation. The ozone and aerosol content of the atmosphere on April 25th was not very different from the mean of the month.

We calculated the AOD(550) for April 17th (with clear sky conditions) using the Atmospheric Radiative Transfer TUV model (Madronich, 1993a,b; see also http://www.cprm.acd.ucar.edu/Models/TUV/) in order to compare it with the AOD(550) corresponding to the dense smoke cloud event of April 25th 2008. This algorithm solves the solar radiative transfer equation, with the following main input data given for Rosario on April 25th 2008: single scattering albedo = 0.93 and ground albedo = 0.06 (Salum et al., 2004). The total column ozone for this day obtained from the OMI/NASA data base was 277 DU. As a result of this modelling, we derived a mean AOD(550) = (0.18 ± 0.02) for clear sky conditions. This value is similar to the one determined by MODIS/Aqua: 0.163 at 14:10 local time (= UT − 3 h).

At the top of Fig. 9, solar erythemal irradiance measurements done with two instruments, a YES biometre and a Davis automatic weather station, at the Astronomical Observatory in Rosario are shown. Solar irradiance calculated with the TUV model is also shown. At the bottom, we plot the AOD(550) values calculated for different moments of the day and the MODIS/Aqua AOD(550).

In Fig. 10, adapted images of the MODIS Terra and Aqua satellites for April 25th 2008 showing the evolution of the aerosol cloud in a complementary way at two different moments of the day, 16:40 and 20:55 local time respectively can be seen. On this day, the smoke cloud travelled in the opposite direction (to the West) with respect to its behaviour on April 18th, affecting Rosario and the East of Argentina, Uruguay, South of Brazil and the regions adjacent to the Atlantic Ocean.

The evolution of those aerosol clouds was also emphasized by the variability of the visibility values measured at the Rosario Astronomical Observatory. Meteorological data for this day are shown in Table 1 and were obtained with the Davis automatic weather station operating at the Observatory and from the Argentine National Weather Service station located at Rosario International Airport. Wind speed and direction values for different moments on April 25th 2008 are also shown in this Table.

In Fig. 11, we show solar erythemal irradiance attenuated by the aerosol cloud as function of the hours of the day April 25th measured at the Rosario Astronomical Observatory with a YES biometre and the UV sensor of a Davis weather station and also on the Paraná river islands with a portable IL1400A biometre (calibrated against the YES instrument).

In the same way, we calculated AOD(550) for April 25th, which showed a large-scale contamination event. In this case, the total column ozone was 262 DU. The AOD(550) has a mean value of (0.90 ± 0.21), between 12:00 and

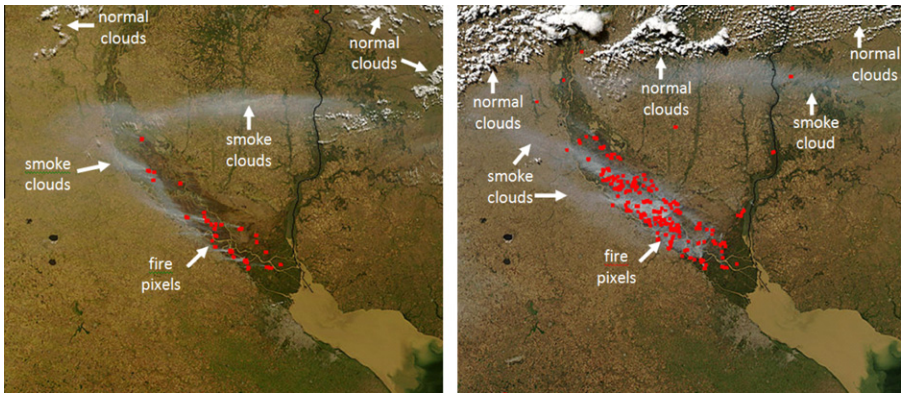

Fig. 10. Adapted MODIS images for April 25th 2008, showing the aerosol cloud evolution (diffuse light grey) obtained by MODIS aboard the Terra satellite (left) and the Aqua satellite (right). Note: Red pixels indicate fire points. (In black and white figures, white pixels indicate fire points). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Meteorological conditions for September 18th 2008 in Rosario, Argentina. Data were provided by a Davis automatic weather station operating at the Astronomical Observatory near downtown Rosario, and by the National Weather Service station located at Rosario International Airport, in an open area (data in parenthesis).

Local time (UT − 3)	Temperature (C)		Humidity (%)		Pressure (hPa)		Wind velocity (kmhr^{-1})		Wind direction	
00:00	14.1	(12.6)	60	6.4	6.4	(1018.4)	6.4	(11)	ENE	(E)
3:00	10.3	(10)	74	1.6	1.6	(1018.4)	1.6	(7)	ESE	(E)
6:00	8.4	(9.2)	82	–	–	(1018.0)	–	(17)	–	(E)
9:00	12.0	(12.3)	73	11.3	11.3	(1018.4)	11.3	(20)	ENE	(E)
12:00	18.6	(19.7)	52	6.4	6.4	(1017.4)	6.4	(15)	NE	(E)
15:00	22.0	(24)	36	1.6	1.6	(1013.6)	1.6	(20)	ESE	(E)
18:00	21.6	(23)	38	3.2	3.2	(1012.6)	3.2	(20)	E	(E)
21:00	18.5	(19.2)	45	4.8	4.8	(1014.9)	4.8	(18)	ESE	(E)
23:00	15.6	(17.4)	58	8	8	(1015.2)	8	(18)	ENE	(E)

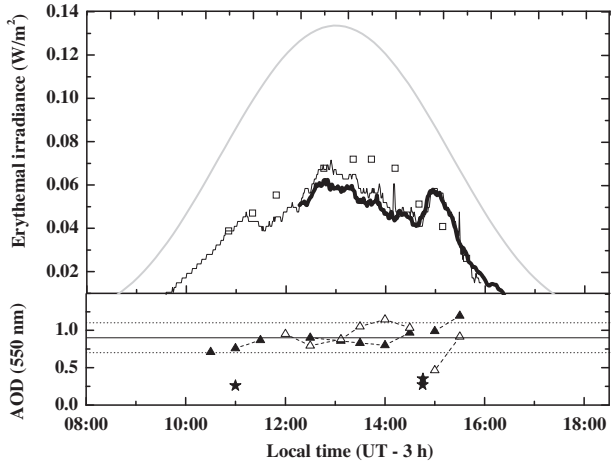

Fig. 11. Top: Similar to Fig. 9, for April 25th 2008, with the inclusion of the data taken on one of the Paraná river islands (15 km away from Rosario) with a portable IL 1400A biometre (open square). The TUV radiative transfer calculation considered the following parametres: total column ozone of 262 DU, a single scattering albedo of 0.85 (typical value for biomass burning, see Gleason et al., 1998) and an albedo of 0.06. Bottom: Aerosol Optical Depth at 550 nm derived from TUV results obtained at the Rosario Astronomical Observatory (open triangle) and on the islands (closed triangle). Note: The solid horizontal line is the mean value and the dashed lines correspond to plus/minus one standard deviation in the calculated period. The mean values for both sets of data are (0.90 ± 0.21). The MODIS satellite AOD(550) value is also indicated (closed star) for Aqua (at 10:40 local time) and for Terra (at 14:55).

15:30 local time for the Rosario Astronomical Observatory, a value quite similar to that of the biomass burning source on the islands (0.89 ± 0.14) at the same time interval. The satellite AOD(550) values are: (a) 0.26 at 10:40 local time at the island location measured by the MODIS Terra satellite instrument, (b) 0.27 at 14:55 local time at the Rosario Astronomical Observatory made by MODIS Aqua, and (c) 0.35 at 14:55 local time on the islands. In Fig. 11, it is also shown that the highest attenuation with respect to normal conditions was 61% at 14:00 local time.

For the smoke cloud contamination condition, the AOD(550) value is approximately four times higher than the AOD(550) value in a clear sky condition. At the top of Fig. 11, solar erythemal irradiance measured at the Astronomical Observatory with a YES instrument and a Davis weather station is shown. Also, measurements made on the island with a portable IL1400A biometre are represented in the same figure. In addition, TUV model calculation results can be seen at the bottom of Fig. 11, where we plotted AOD(550) values for different moments of the day.

2.2.1. Scanning Electron Microscope (SEM) analysis of atmospheric particulate matter

In order to check if the particles producing solar erythemal irradiance attenuation were mainly of biological origin, we collected them with a passive captor installed on top of the Rosario Astronomical Observatory building

during 24 h, starting at 18:00 local time on April 24th 2008. At the top of Fig. 12, selected Scanning Electron Microscope (SEM) images of these microscopic particles are shown. Three of them can be clearly defined as biological matter, with estimated mean diametres in the range of 40–100 μm. The analysis of the particles collected on the islands opposite Rosario (at about 15 km away from the first collection place) also shows similar components (bottom of Fig. 12). It should be noted that one of the particles can be identified as pollen.

2.2.2. UV index attenuation

In this work we also present the results of the study of very dense smoke clouds generated on September 18th 2008 by biomass burning on the same islands of the Paraná river delta, which significantly affected Rosario city and neighbouring zones. Atmospheric particles in a cloud can absorb or scatter incident solar radiation. Their influence increases as wavelength decreases, affecting energy transfer through the atmosphere and consequently the Earth's energy budget and climate. The UV Index can be used as a good indicator of the solar radiation attenuation produced by a smoke cloud.

In Fig. 13, we show a photographic image of dense smoke (aerosol and BBD) clouds generated by the biomass burning event that took place on the Paraná river islands on September 18th 2008. It was taken at the roof of the Rosario Astronomical Observatory near sunset. The pollution cloud can be clearly distinguished from the normal clouds (that can be seen at a higher altitude) as well as from the fires. This atmospheric event produced a great impact on the city in a short period of time, since clouds were transported by a wind blowing essentially from the ENE direction up to about 9:00 local time, and by a wind blowing from the ESE during the rest of the day. Wind intensity was constant almost all day long (with a mean speed of 4.8 km/h near downtown Rosario and of 16.2 km/h at the Rosario International Airport, in a time interval from 00:00 to 23:00), as indicated in Table 1. It produced a considerable amount of pollutants such as Burned Biomass Debris, which precipitated on the urban region. It should be pointed out that the native flora of the islands, mainly composed by trees -sauce, ceibo and espinillo-, grassland, reeds, and also aquatic plants like camalote, was burned.

Due to the great influence of aerosols on UV radiation, we carried out a systematic study of the AOD aerosol cloud generated by biomass burning in the region described above. The UV Index – as defined, for example, in the review article of McKenzie et al. (2003) – and meteorological data (temperature, humidity, wind speed and direction, pressure, precipitation, and solar total radiation) were measured with a YES biometre and a Davis weather station respectively. In Fig. 13, it is shown that fires occur on the islands opposite Rosario. It should be noted that the Paraná river has an extension of about a kilometre between the city and the nearest islands.

Time evolution of the UV index values for September 18th 2008 is represented in Fig. 14. It can be observed that the UV index does not follow the typical Gaussian behaviour for clear sky days. It strongly oscillates mainly due to the presence of biomass burning pollution clouds. Moreover, a very small value was registered near solar noon at 12:45 local time. Actually, the measured UV Index was as low as 0.11, which is approximated by zero when

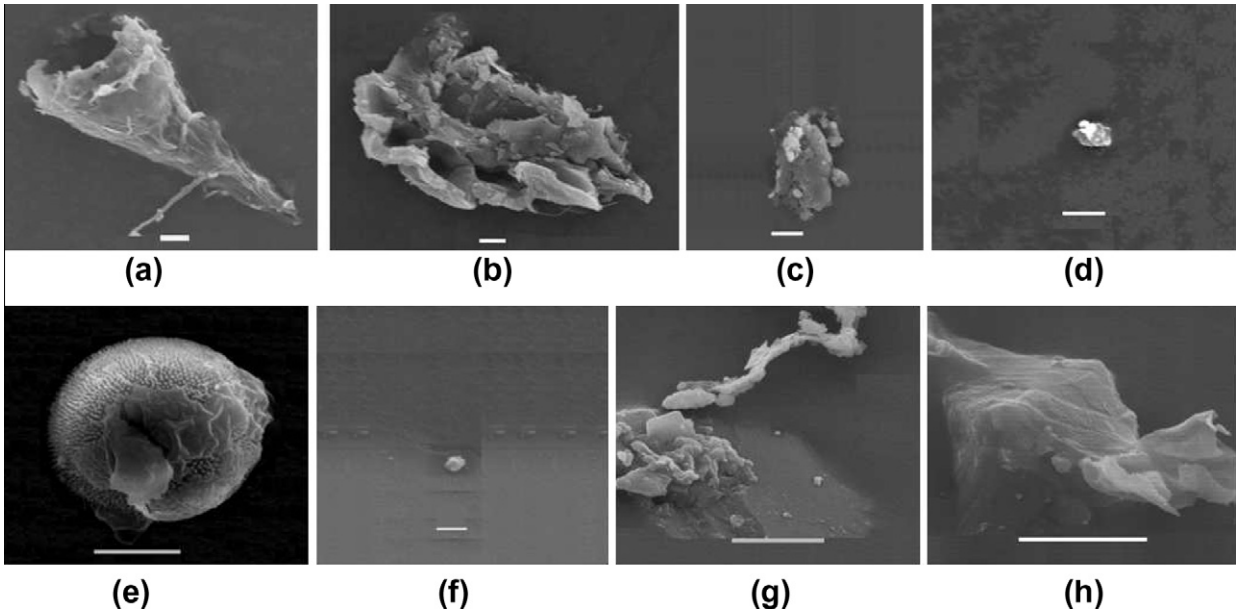

Fig. 12. Scanning Electron Microscope images of aerosol particles obtained by adherence on a passive captor. Top: Images from a captor placed on top of the Rosario Astronomical Observatory building during 24 h, starting at 18:00 local time (=UT − 3 h) on April 24th 2008. Bottom: Images from the captor placed on the Paraná river delta islands opposite the Rosario Astronomical Observatory during 24 h, starting at 20:00 local time, on April 25th 2008. The small bars indicate 10 μm in all images except image (f), which is 1 μm. Note: Images (a), (b), (c) and (e), can be identified as biological aerosols, image (e) being a pollen particulate.

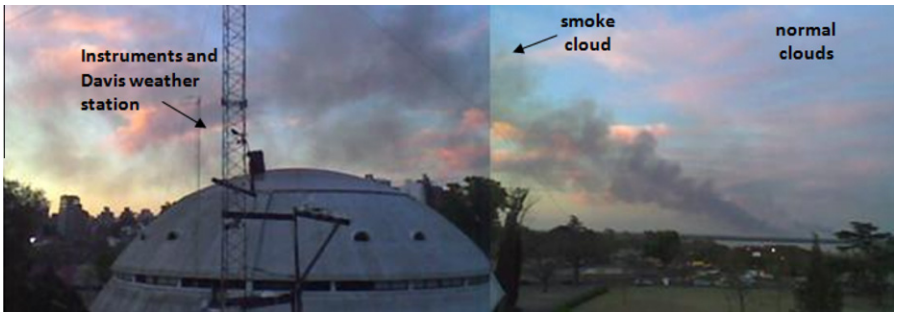

Fig. 13. Photographic image of the intense aerosol cloud (in dark grey) generated during the biomass burning event that took place on September 18th 2008 on the Paraná river islands. The fire was a few kilometres away from Rosario, Argentina.

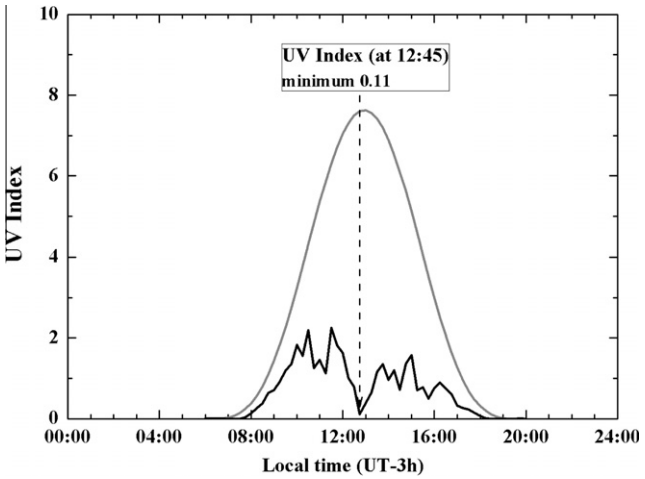

Fig. 14. UV Index as function of local time on September 18th 2008, at the geographical position of the Astronomical Observatory in Rosario, Argentina. The black curve corresponds to the measurements done with a YES biometre. The grey (Gaussian type) curve represents the UV Index values obtained with the TUV model assuming clear sky condition.

informed as integer numbers. At that moment of the day only some normal clouds were present, giving rise to a few percent UV Index attenuation (and consequently within uncertainty of the AOD determination), as shown by Cede (2001) and Cede et al. (2004) for the type of clouds and cloud cover considered in the present work. In particular, cloud cover was not significant but rather tenuous, as observed visually and through satellite images (http://www.ladsweb.nascom.nasa.gov/browse_images/).

In order to better understand and describe the attenuation produced on UV radiation by a pollution cloud, we used the TUV algorithm for the determination of the UV index. The total column ozone (287 DU) for September 18th 2008, when the biomass burning event happened, was obtained using information derived from the OMI/KNMI spectrometre aboard the Aura/EOS-NASA satellite, at http://www.jwocky.gsfc.nasa.gov. Parametres for a clear sky day, i.e. soil reflectivity (UV range) = 0.06, single scattering albedo (ssa) = 0.93, AOD(550) = 0.1 and $\alpha = 1$, were selected from previous works (Micheletti and Piacentini, 2002; Piacentini et al., 2004; Salum et al., 2004). In particular, at 12:45 local time, the TUV model result (UV Index = 7.6 for clear sky conditions) allows us to determine the percentage reduction caused by dense smoke clouds.

By considering the mean and the indetermination range of ssa and alpha values, which are typical of biomass burning events, i.e. ssa = (0.85 ± 0.02) (Eck et al., 1998, 2001) and $\alpha = (1.8 \pm 0.3)$ (Eck et al., 1999; Russell et al., 2010) and the same surface albedo, mean, minimum and maximum AODs were determined. In order to determine the maximum AOD(550), we used the TUV algorithm and we compared the obtained UV index results against that registered with the YES biometre placed at Rosario Astronomical Observatory (minimum value of 0.11 at 12:45 local time). After several iterations we obtained $\mathrm{AOD}(550)_{\max} = (3.65 \pm 0.90)$.

Comparing the present results to those obtained from the Brazilian regions indicated above, we observed that the soot cloud over Rosario city on September 18th 2008 had a maximum AOD(550) value (3.65) similar to or even higher than the values normally registered in Matto Grosso and Amazonia (Eck et al., 1998), and in several other places (Russell et al., 2010), which emphasizes the importance of the event. In particular, considering the UV index ratio between the model calculation result for clear sky conditions and the value registered during the densest contaminated cloud passing, an extreme solar UV attenuation of 98.6% was obtained near noon. It should be pointed out that measurements and model calculations of solar total UV radiation incident were done in the past (Piacentini et al., 2002) at the same place, but this is the highest solar UV radiation reduction registered by the YES instrument in Rosario. Even during a large part of the day, from about 10:00 to 16:00 local time, the UV index attenuation was so important that the daily measured UV index maximum of 2.4 was only 35.5% of the expected value, if there were clear sky conditions. Otherwise, a similar smoke cloud attenuation in the UV range in another Southern Hemisphere location (Darwin, Australia) was analysed by Kalashnikova et al. (2007), obtaining an attenuation of 50% at the most.

2.3. Burned Biomass Debris transported by smoke clouds

An important pollution event was associated with those smoke clouds: The deposition over Rosario of a layer of

BBD transported by winds within smoke clouds. Debris deposition extended about 2 km away from the Paraná riverside. Particles in the range of millimetres to centimetres in size were found, which indicated the intensity of the fires. Those debris were transported by smoke clouds across the Paraná river, which separates the city of Rosario from the islands of Entre Ríos province. Although biomass burning activity is common at this time of the year, there has been no record of a debris deposition of this size in this region in the last decades.

Due to their size, BBD interact with solar UV radiation minimally attenuating (through scattering) the corresponding biological solar irradiance. Attenuation through absorption of solar photons must also be low due to the presence of a small number of these particles in the smoke clouds, as can be seen from the deposited BBD surface density number.

In order to give a qualitative and quantitative description of BBD (chiefly, burned leaves and small tree branches) deposited on the surface of the Urquiza Park, where the Rosario Astronomical Observatory is located, we delimited two zones of 20 and 25 m^2. In those areas, BBD were carefully collected in order to avoid breaking its overall structure. Representative samples of large particles are shown in Fig. 15. The largest collected debris measured up to about 20 cm long and 1 cm width (middle and bottom of Fig. 15). The mean surface density was (11 ± 2) BBD/m^2, corresponding to a deposition of large (more than 1 cm) black debris that lasted several hours (from 7:00 to 19:00 local time) during September 18th 2008. The mean BBD deposition per square metre per hour on the ground was (0.92 ± 0.21) BBD/(m^2 h). It must be pointed out that on the basis of the authors' personal experience, and the personal experience of many inhabitants of Rosario as well, the negative impact of the laying down was significant, since it affected buildings, artistic statues, clothes and other stuff exposed outdoors.

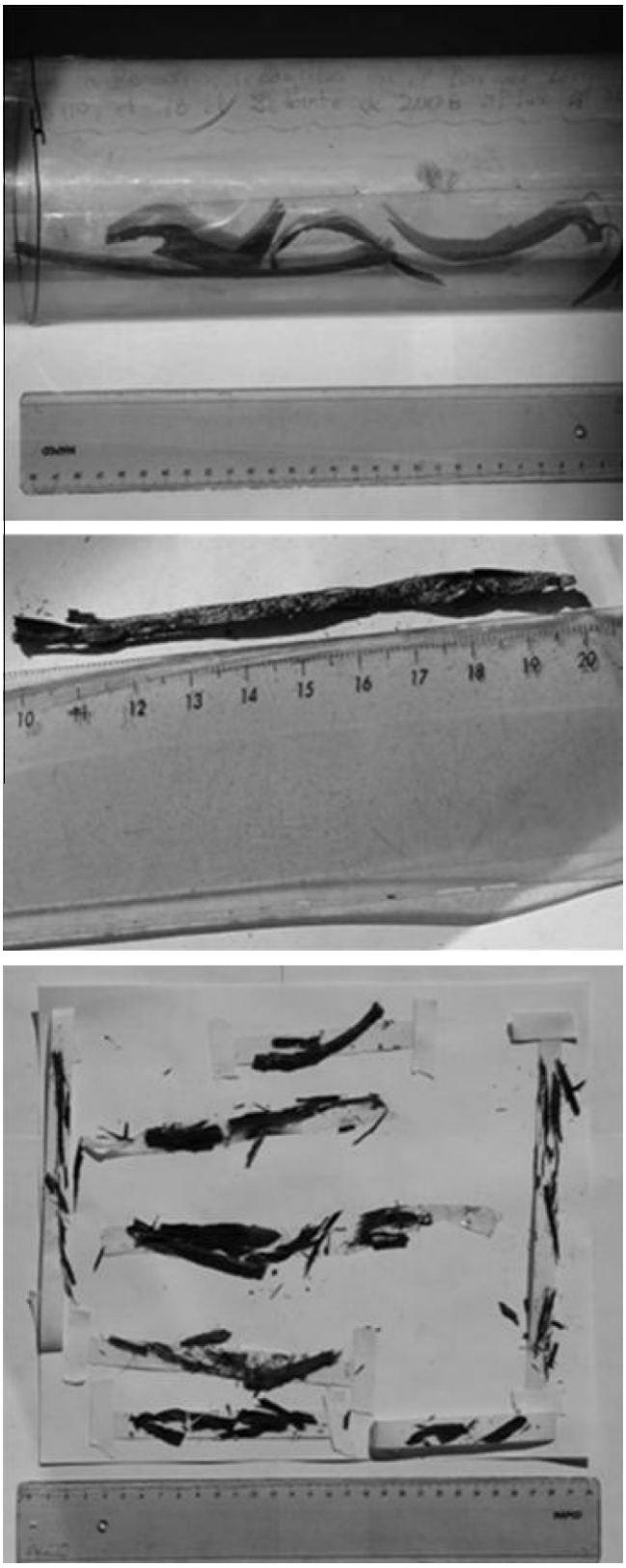

Fig. 15. Photographic record of typical 1 Burned Biomass Debris (BBD) collected at the Urquiza Park, Rosario, Argentina, on September 18th 2008. Note: A rule (centimetres scale) is shown to compare lengths.

3. Conclusions and perspectives

The main conclusions of the present work are:

- Large aerosol clouds generated during intense biomass burning were detected in the Rosario–Buenos Aires region, Argentina, coming from fires caused by human activity to clear the soil for agriculture or cattle production. The space-time evolution of those clouds coming from the Paraná river delta islands, could be followed as a result of the high quality images and data provided by the MODIS instruments aboard the Aqua and Terra NASA satellites.
- Ground measurements of solar erythemal irradiance (UV index) gave us the possibility, with the help of radiative transfer model calculations, to derive the Aerosol Optical Depth of the contamination cloud, assuming all other parametres and variables (mainly ozone) were known.

- Particle types and dimensions were known by using the SEM technique. Large biological 40–100 μm particles were collected. It must be pointed out that the analysis of the aerosol particles collected at the Rosario Astronomical Observatory during a large-scale event, in September 2008, indicated the presence of a great amount of millimetre and centimetre-sized particles, which highlights the intensity of fires.
- The Argentine Ministry of Health informed that numerous patients received medical treatment as a consequence of these pollution events. People suffered several health problems and even died due to visibility reduction, like the accidents that occurred on April 9th 2008 on the Rosario–Buenos Aires highway. Those accidents could have been avoided if the authorities had controlled the source of aerosols mainly produced by anthropogenic factors.
- The biomass burning anthropogenic activity on the Paraná river delta islands on September 18th 2008 produced a large contamination cloud that reduced the UV index up to 98.6% near noon, resulting in an Aerosol Optical Depth at 550 nm as high as (3.65 ± 0.90). This is the highest (pollution) cloud reduction in UV radiation registered by the YES instrument in Rosario in more than a decade.
- The fire was so intense on September 18th 2008 that it introduced a huge amount of aerosols and debris in the atmosphere, particularly those larger than 1 cm, resulting in a deposition on Rosario characterised by a surface density of (11 ± 2) BBD/m^2.
- The results of this study were used as scientific evidence for the judicial claim made by the National University of Rosario at the Supreme Court of Justice of Argentina against the authorities of the Entre Ríos Province, to which the islands belong, in an attempt to stop biomass burning on the Paraná river islands.
- This is the first study of an exceptional (in decades) BBD event registered in Rosario, Argentina, which had a significant environmental impact. It will be further developed by a more extended study (in space and time) to be carried out in the region where Tucumán city is located ($26.81°\text{S}, 65.21°\text{W}, 437$ m a.s.l.), since we found out from the people living there (for instance, J. González, Researcher at the Miguel Lillo Foundation, National University of Tucumán, Argentina, private communication) that events similar to the ones described in this paper happen after sugar cane crop and related biomass burning. Since this type of events extends for months, it will give us the possibility to determine aerosol and BBD distribution, and to extend the normal (sometimes bimodal or even trimodal) distribution of these particles (see, for example, Turco, 1999) to very large masses and equivalent diametres. It must be pointed out that normal aerosols and BBD caused damage to building claddings when those particles covered the city (as it was reported by local press media).

In conclusion, we characterised large particulate atmospheric pollution events registered during April and September 2008 in the Rosario-Buenos Aires region by using ground as well as satellite instruments. Those significant events affected the normal lives of more than 18 million people for several days, showing the negative impact of uncontrolled human activities such as the use of fire to clear the land from grass.

The results can be used to improve the UV Index forecast by considering the attenuation produced by a smoke cloud and the available information about wind propagation and speed. Moreover, the results can be used as an indication that the UV index measurement can be a way to evaluate the severity of a contaminant (smoke) cloud.

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