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Original paper

Spatial and temporal variations of atmospheric aerosol optical thickness in northwestern Mexico

Ricardo M. Llamas*, Roberto Bonifaz, Mauro Valdés, David Riveros-Rosas and Amando Leyva-Contreras

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Resumen

El propósito de este trabajo fue el estudio de los aerosoles atmosféricos en el Noroeste de México mediante el parámetro conocido como Espesor Óptico del Aerosol (AOT). Este parámetro representa uno de los coeficientes de extinción de la radiación solar y un indicador de partículas suspendidas en la atmósfera. Para la determinación del AOT recurrimos al uso de sensores remotos localizados fuera de la atmósfera. En particular, el Espectroradiómetro de Imágenes de Media Resolución (MODIS), el cual es capaz de obtener mediciones del AOT atmosférico. La información proporcionada por MODIS debe ser validada antes de considerarse fiable; para esta tarea, se obtuvieron mediciones desde la superficie para establecer una correlación con los datos derivados del sensor remoto. El artículo describe el proceso de validación que fue aplicado a los datos del sensor MODIS en contraste con mediciones obtenidas por uno de los fotómetros de la Red Robótica para medición de Aerosoles (AERONET) ubicado en la ciudad de Hermosillo, Sonora. Adicionalmente, se presenta un análisis temporal basado en el comportamiento de las gráficas del AOT, así como un análisis espacial derivado de la información contenida en los mapas de distribución del AOT.

Palabras clave: AOT, aerosoles, MODIS, AERONET, noroeste de México, análisis temporal, análisis espacial

Abstract

The purpose of this paper was to study aerosol particles in the Northwestern region of Mexico (NWM) through Aerosol Optical Thickness (AOT) parameter in the atmosphere. This parameter represents one of the extinction coefficients of solar radiation and the rate of suspended particles in the atmosphere. For determination of AOT, we considered the use of remote sensors outside of the atmosphere. In particular, Moderate Resolution Imaging Spectroradiometer (MODIS) which can measure the atmospheric AOT thickness. Data from the MODIS sensor must be validated before they are considered reliable. For this task, we required surface measurements to obtain a correlation with the data acquired with the remote radiometer. The paper describes the validation process performed for data obtained with MODIS through measurements provided by an AErosol RObotic NETwork (AERONET) photometer located in the city of Hermosillo, Sonora, NWM. Additionally, we carried out a temporal analysis based on the behavior of the AOT graphics and spatial analysis supported in maps with sufficient information.

Key words: AOT, Aerosols, MODIS, AERONET, Northwestern Mexico, Temporal analysis, Spatial analysis.

R.M. Llamas*
Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO)
Av. Liga Periférico-Insurgentes Sur 4903
Col. Parques del Pedregal
Del. Tlapan, 14010
México D.F., México
**Corresponding author: rllamas@conabio.gob.mx*

R. Bonifaz
M. Valdés
D. Riveros-Rosas
A. Leyva-Contreras
Instituto de Geofísica
Universidad Nacional Autónoma de México
Ciudad Universitaria s/n, 04510
México D.F., México

Introduction

One of the main factors that interact actively with the energy from the Sun is identified as aerosol particles, which influence the processes of absorption, refraction, and scattering of solar radiation that is present in the atmosphere and that create a dynamic climate on Earth as a result of these interactions (Iqbal, 1983). This information from aerosol monitoring is useful not only for others as part of the study of the atmosphere, but it can also find many applications in research on climate change and air pollution caused by human activities and natural phenomena. Many of these applications lie on identifying optimal areas in the use of alternative and renewable energy, such as that from the Sun (Deepak, 1982) (Gueymard and Wilcox, 2011; Broesamle *et al*., 2001).

Recent models for estimating solar resource use require parameters such as topography, vegetation, albedo, and optical thickness of aerosols in the atmosphere among other elements (Bosch *et al*., 2010). The use of ground stations is economically unfeasible for estimating AOT over large territories; thus, the use of satellite images represents a viable option for estimation of several atmospheric and geographic parameters that affect the solar radiation that reaches the Earth's surface (Perez *et al*., 1997).

AOT is used generally to determine the concentration of atmospheric solid particles; their knowledge is useful in conducting studies and in the analysis of smoke from forest fires (Chia *et al*., 2007), air quality in urban areas (Grosso *et al*., 2007), the relationship between AOT and wind speed over the ocean surface (Glantz *et al*., 2006), the influence of anthropogenic aerosols on climate change (Charlson *et al*., 1992), as well in numerous validation studies using instruments located on surface (Bai *et al*., 2008), (Correia and Pires, 2006; Ichoku *et al*., 2002a; Liang *et al*., 2006), among others. One of the most interesting applications of the estimation of AOT in the atmosphere comprises estimation of solar radiation on the surface because of the importance that this implies in the planning and design of solar applications for power generation (Gueymard and Wilcox, 2011; Broesamle *et al*., 2001; Bosch *et al*., 2010; Perez *et al*., 1997).

There are several sensors that orbit the Earth for the acquisition of data from numerous natural variables that are utilized for studies of the Earth's surface and for analyzing the dynamics of the atmosphere. In particular, the MODIS radiometer, is set on-board the platforms Terra (launched on 1999) and Aqua (launched on 2002) and offers the possibility of obtaining values related with a large amount of data among 36 spectral bands spanning from visible to infrared spectrum, 0.425–14.235 µm, respectively, providing images with spatial resolution at nadir of 1 km, and at 500 and 250 m (Wolfe *et al*., 1998). The advantages of MODIS sensor in the study of atmospheric phenomena are very broad and it has specific advantages in the analysis of AOT.

Aerosol data provided by MODIS sensor must be validated by surface-based measurements (Liang *et al*., 2006). For this task, the photometers from AErosol RObotic NETwork (AERONET) can be used. Using this data is possible to obtain optical thickness values at a particular point while the platform in which MODIS is attached performs its coverage over the same area. In the present study, the validation process is developed for Northwestern Mexico (NWM), where to our knowledge no study of this type has been conducted before. The method used for data acquisition and refinement covers the period from 2001–2003, which was selected according to available information for first years of MODIS sensor on Terra satellite and AERONET data availability in the city of Hermosillo, Sonora. In addition, we present the criteria to determine the extent of the area in which AOT values were processed from satellite images, the parameters for granting the same mapping characteristics, and the extraction of spectral bands for the optical thickness spray on the land surface.

Data acquisition and pre-processing

Information source – MODIS

MODIS aerosol products were downloaded from Atmosphere Archive and Distribution System (LAADS Web) of the National Aeronautical and Space Agency (NASA) Goddard Space Flight Center. The products selected were derived from Terra platform level 2 (MOD04 L2) with spatial resolution of 10 × 10 km at nadir in hierarchical data format (HDF) files, which contain values at three different wavelengths for corrected optical depth land (0.47, 0.55, and 0.66 µm) among 62 science data-set options. Data acquisition was performed in terms of NWM as main covered area in all images through h07v06 and h08v06 tiles. Period between 2001 and 2003 was selected as temporal span. Terra products were selected over Aqua due to data availability, regarding the launching date of each platform. All files were reprojected into Lambert conical conformal projection employing the same cartographic parameters that are commonly established by Mexico's National Institute for Statistics and Geography (INEGI, 2011).

The wavelength selected for validation process with AERONET data was 0.66 µm, broadly to 0.675 µm available from sun photometer measurements and regarded in previous studies

(Bai *et al*., 2008; Ichoku *et al*., 2002b; Remer *et al*., 2002). Then, region of interest (ROI) was delimited to obtain the mean value for all pixels with data inside selected area of 50 × 50 km (5 × 5 pixels). The criteria for choosing polygon size depended on lack of congruence between 1 point over the surface where the photometer is located and the dimensions of one single pixel in the image. Furthermore, it is difficult to imagine suspended particles without vertical and horizontal movements along atmospheric strata; hence, determination of the correct area proportions is an important step prior to post-processing. Thus, different area sizes were tested according to previous attempts (Ichoku *et al*., 2002b) (Figure 1). As (Ichoku *et al*., 2002b) mentioned, the average speed of aerosol particles in lower atmospheric layers is 50 km/h, and this represents a 1-h window for AOT data gathered by AERONET instruments in a 5 x 5 pixels polygon of MOD04L2 product.

The reference pixel for ROI was centered over AERONET site coordinates in the Geological Institute Building supported by the National Autonomous University of Mexico (UNAM) at N 29°05′, W 110°58′. Once all of the files were acquired and ROI was set up, all images were stacked to produce time series from which basic statistics (mean and Standard deviation [SD]) were derived.

Information source – AERONET

AOT data from AERONET was downloaded from the level 2 dataset, with an eye toward further analysis; besides this level was used to build the C005 algorithm (Remer *et al*., 2006), which build up the last version of MODIS products. Time period for chosen data was matched with MODIS AOT available images between 2001 and 2003. The UNAM-Hermosillo AERONET station archives a good and continuous data series and was selected for the comparison, taking into account its information availability.

AERONET offers AOT values at eight different wavelengths and records between 7 a.m. and 7 p.m. (local time) every 15 min. In this case, the 0.675-μm wavelength was processed because this wavelength depicts closest matching to the 0.66-μm MODIS band. In order to select the dataset from AERONET based on the MODIS pass, a 3-h range was set up to correlate AOT from the previously mentioned sources in an attempt to overcome the scarce availability of 60-min values at level 2 data. Furthermore, previous analysis of all HDF files depicted that all images were retrieved by MODIS from 4:30 to 7:30 p.m. Greenwich Mean Time (GMT). By means of structured query language (SQL) instructions, mean values were acquired in the same period of time for 2001 and 2002; initially, 2003 was considered in the complete validation process, but non-continuous records yielded the recommendation to omit the third year.

Results

MODIS-AERONET Validation Process

Once all information was processed, it was developed in a table of data availability for the period 2001–2002. Analysis of MODIS and AERONET files showed that the existence of comparable data was very low. This is because both sources have long periods without AERONET data whereas MODIS data is available, and vice versa. At the end, we compared 57 cases (days)

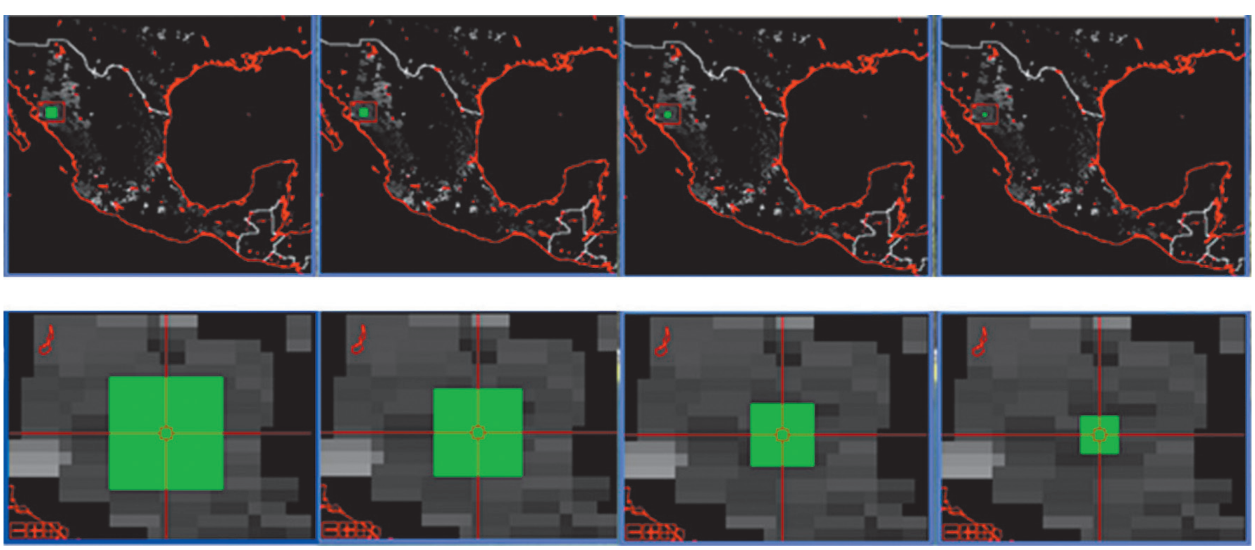


Figure 1. Areas tested to determine region of interest.

over the period 2001–2002 in which values from both MODIS and the AERONET photometer exist in Hermosillo, Sonora.

Time series for both sets of values is very similar (Figure 2). When performing linear regression between them (Figure 3), we identified those >2 SD away from values obtained from the regression. These data were removed for analysis. In total, we performed 2 linear regressions and eliminated 7 data representing 12.3% of outliers. Figures 3 and 4 show graphs obtained from linear regression fit and the analysis of waste before and after filtering the data.

The final determination of co-efficient R^2 = 0.891 was obtained for a set of 50 data between 2001 and 2002. This result, compared with previous studies, presents a higher correlation on confrontation with a co-efficient of R^2 = 0.729 (Ichoku *et al*., 2002b) and was close to results in which the correlation obtained is R^2 = 0.9245 (Bai *et al*., 2008). However, we should note that these measurements were obtained from different regions and different datasets from amounts of records with different values; thus, results are employed as parameter of comparison and not for validation of those obtained in this work.

In order to evaluate the correlation between both data series, MODIS and AERONET, we performed the Spearman rank correlation test and the Pearson rank correlation test. For Spearman test we obtain a correlation coefficient of C=0.887 ($p < 2e-7$, N= 57) and for Pearson test we obtain a correlation coefficient of C=0.834 ($p < 8e-16$, N= 57). The correlation in both tests is high and the probability of error is low enough to be considered negligible.

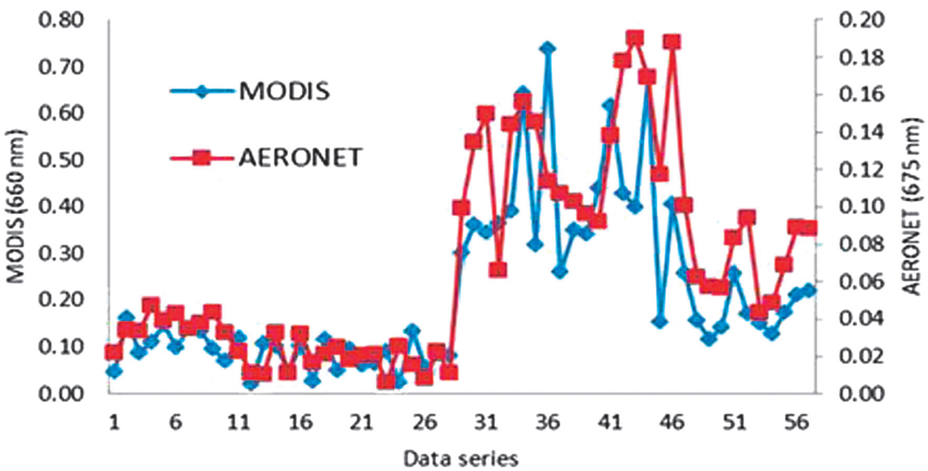


Figure 2. Aerosol Optical Thickness (AOT) data series from Moderate Resolution Imaging Spectroradiometer (MODIS) and AErosol RObotic NETwork (AERONET).

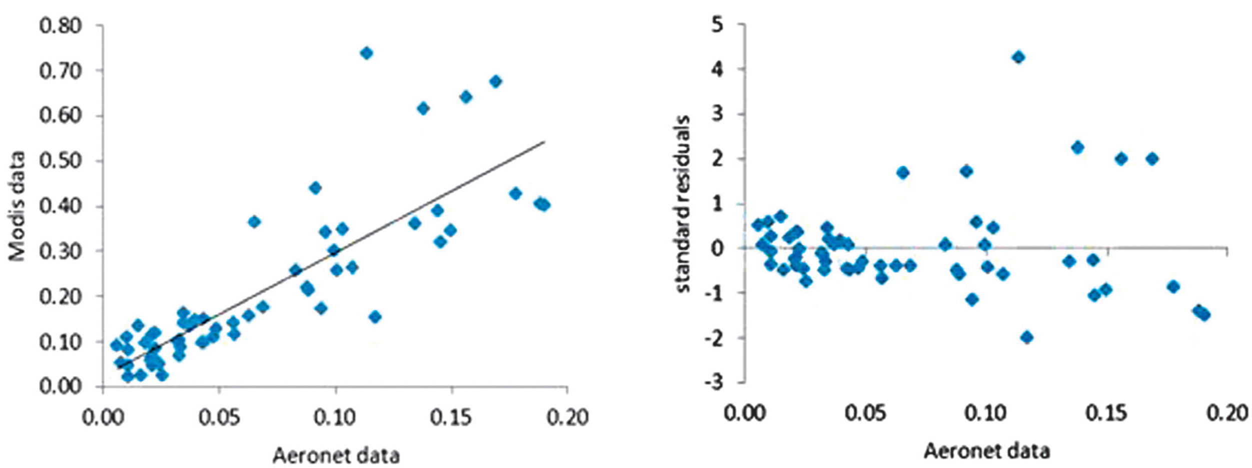


Figure 3. Linear regression and residuals analysis for AErosol RObotic NETwork (AERONET) and Moderate Resolution Imaging Spectroradiometer (MODIS) data. Initial data set.

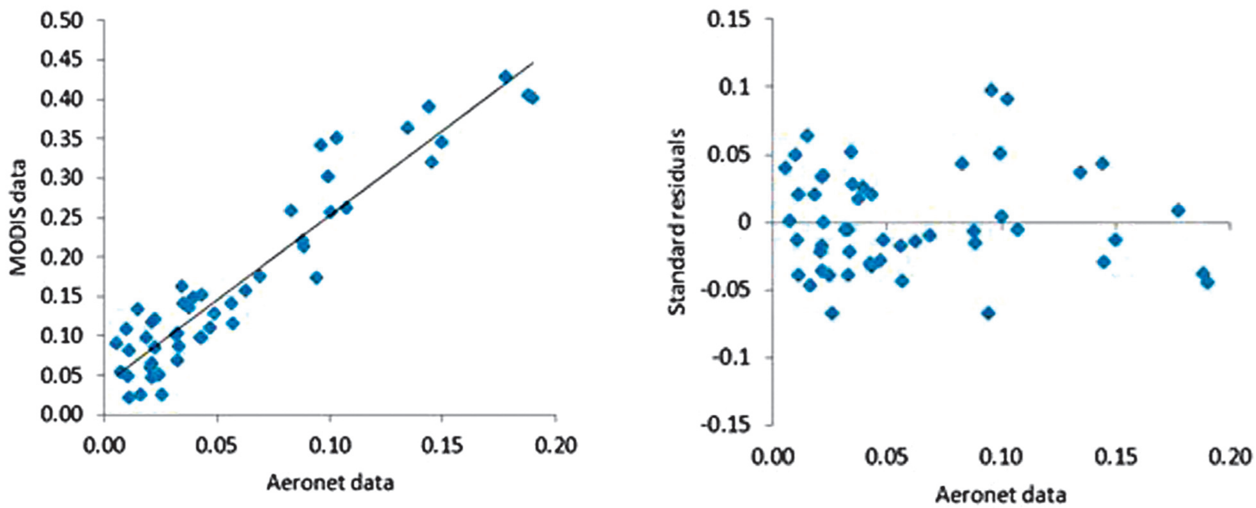


Figure 4. Linear regression and residuals analysis for Moderate Resolution Imaging Spectroradiometer (MODIS) and AErosol RObotic NETwork (AERONET) after filtering of data.

Based on data from the MODIS sensor and once we had completed validation with AERONET measurements in the previous section, we were able to consider that MODIS data are suitable for studying not only temporarily optical thickness behavior spray in the city of Hermosillo, Sonora, but, according to the correlation coefficients, MODIS values can be utilized for spatial analysis of the AOT in the entire coverage area of MODIS images corresponding to NWM, even though baseline data were obtained from the state of Sonora.

Discussion

Time Analysis

The graphs presented in this section (Figures 5 and 6) refer to the average behavior of AOT in a ROI of 2,500 km² (5 × 5 pixels) over city of Hermosillo, which were obtained as measurements for validation of MODIS data and do not refer to variations in optical thickness across the NWM. This is due to that for this second case, it would be necessary to perform digital processing of satellite images to obtain the value at different points, although in this study we report a subsequent spatial analysis based on information reflected on final maps.

Comparative analysis of values in the 3-year period attempts to identify patterns in the presence of suspended particles as well to demonstrate if there is seasonality in the measurements explaining AOT behavior. Thus, other factors determine the concentration of aerosols in the atmosphere.

When we observe the behavior of the AOT data of Hermosillo over the polygon set for study period, there are different peaks with values >0.6 in the months of March, May, and June, while the months with the lowest values are December and January; this shows a decrease of optical thickness in the coldest months (Figure 5).

In the case of 2002, the behavior of AOT was depicted despite the limited availability of data. In June 2001 and 2002, there is a maximum AOT value as a result of gradual increase in the first half of the year. After June, a decrease of AOT concentration is observed during the second half of the year. Unlike 2003, AOT values remained relatively low throughout the year; this trend is also suggested with the available data. This suggests a seasonal pattern that advice to verify information for prior years and after ones as well. In addition, there are small peaks in August and September and lonely spots between November and December as well as between January and March.

By interpreting the annual behavior of the AOT during the 3 years (Figures 6 and 7), it is clear that 2001 and 2002 exhibit similar behavior. Figure 7 shows that higher average values correspond to the months of June, with measurements >0.4 units for 2001 and 2002. The lowest values occur in the months of November, December, and January, the same in both cases, indicating an agreement with months with lowest temperatures.

We must take in account that data availability in 2002 (Figure 6) is scarce or non-existent during a few months; thus, in this case, the behavior is deduced by observing the monthly data and

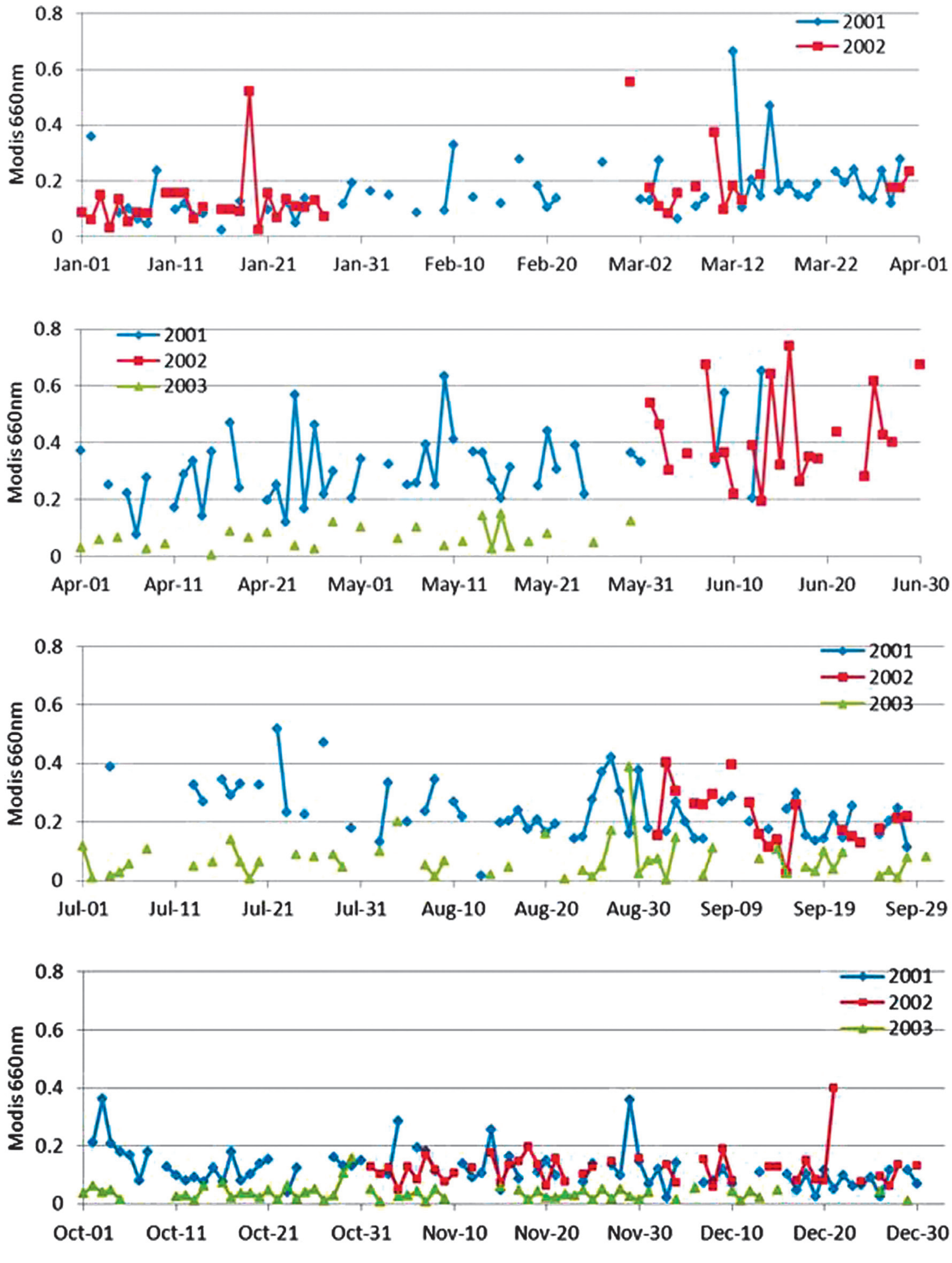


Figure 5. Variations in Aerosol optical thickness (AOT) behavior, over 5 x 5 pixels polygon set on Hermosillo, Sonora, for the period comprising January 2001 to December 2003.

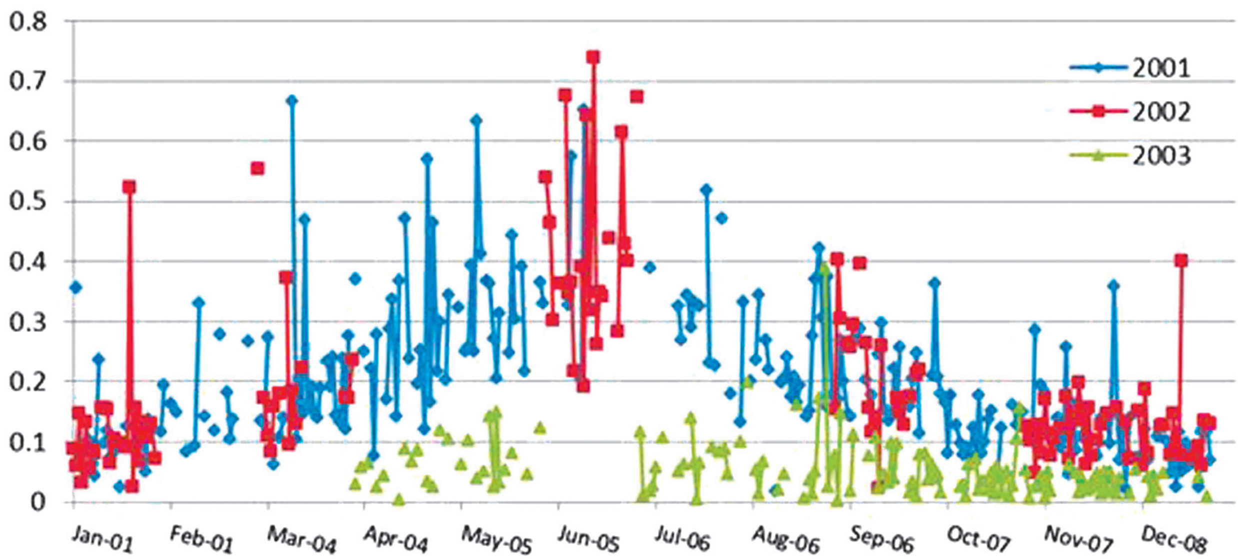


Figure 6. Comparative graph of Aerosol optical thickness (AOT) behavior for 2001, 2002, and 2003.

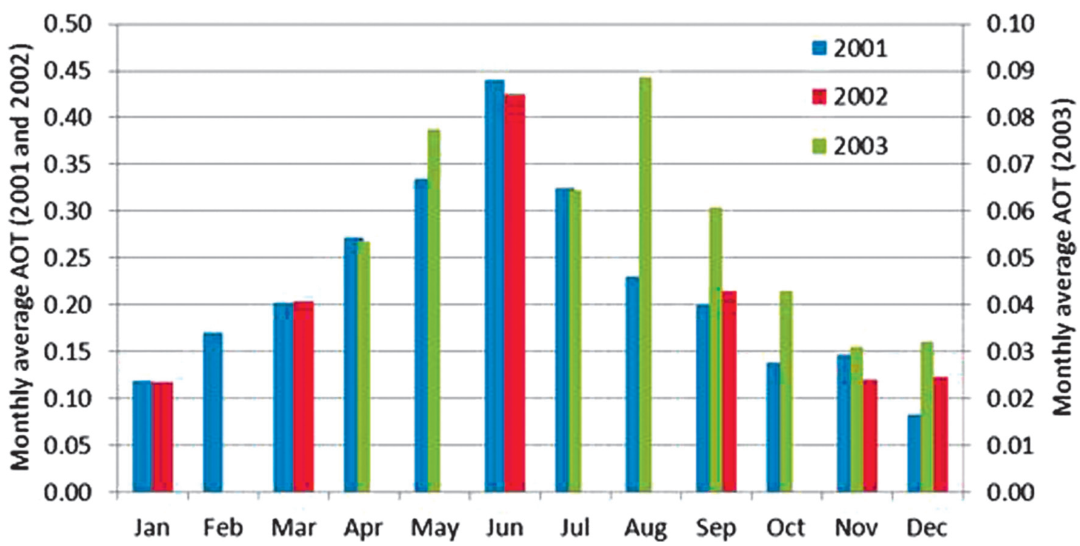


Figure 7. Monthly comparison graph of AOT behavior for the years 2001, 2002, and 2003.

analysis in relation to other years in order to infer AOT trends over the year, although analysis of the complete study period must be considered in determining patterns in the particle concentration. In 2003, there are 8 months with available data, excluding the first 3 months of the year and the month of June, which does not allow for clearly analysis of the annual performance of optical thickness. However, available data show that in the months of May through October, there is a gradual increase, and a decrease in AOT values around June. This appears to confirm the seasonal pattern observed in the previous 2 years, although absolute AOT values for the entire year of 2003 are lower than those of previous years.

Finally, to compare AOT behavior during the 3-year period, it is noteworthy that while in the annual charts the cyclical behavior of the concentration of atmospheric particles is not clearly observed, when we considered all data together, there is a clear seasonal pattern of an increase and a decrease in optical thickness values, in which measurements are higher from the second third of the year.

For 2001 and 2002, this was fulfilled by presenting the highest values in March and June with two peaks in their respective charts. However, the year 2003 differs from this behavior and exhibits highest values in August and September, which would be strange if we take prior years as reference. However, when considering the behavior of the atmosphere along the last year (2003), it is possible to correlate these measurements with the presence of two major cyclonic events that exerted an influence on the region during that year.

According to the U.S. National Hurricane Service (NOAA, 2003a), in 2003, atypical landfall in NWM occurred, the second strongest tropical cyclone of the season: the first, *Ignacio*, became hurricane on August 26 and entered into the Gulf of Baja California with a slow movement that brought heavy rainfall, while the second, *Marty* began to develop on September 10 and peaked on day 22 of the month as a hurricane (NOAA, 2003b).

This may partially explain the high AOT values in these months due to the presence of large numbers of hygroscopic nuclei in large cloud formations due to cyclonic events and to the attenuation of the passage of solar radiation at the Earth's surface as a result of the high concentration of suspended particles (Iqbal, 1983).

It is also notable that during the 3 years, months with the lowest optical-thickness values correspond to December and January 2001 and 2002, while in the case of 2003, the month of December has the lowest values. Despite that there is no data for the January period, the graphical behavior of the 3 years indicates that in each year, the months mentioned show the same characteristics in terms of particle concentration in the atmosphere.

Spatial Analysis

Once MODIS data were validated with AERONET sensor data from the city of Hermosillo, MODIS images can be used for data acquisition of optical thickness throughout area covered by sensor snapshots. For the image selection representing the best description of optical depth in NWM, monthly data median was selected from AERONET in order to determine the day that shows most representative AOT distribution in the study area most clearly. Considering that the availability of images is not complete in each month of the 3-year period and that in many cases all values are concentrated at short period of time in the month we found most useful median usage. If we had used mean to get monthly values, those had been representative just of a part of month instead of entire monthly period. However, when we use median, we take into account AOT behavior at the most possible middle of the month. Also, it is known that the mean could be affected by extreme values, while the median is not (Triola, 2008).

In the preparation of maps based on information from the images, variations of the particle concentration of aerosols are shown not only over the area of 2,500-km² plot in the city of Hermosillo, but also in space for the entirety of NWM, in addition to information contained in images taken with the MODIS aerosol-type product to know the origin of the particles in each map. In the images presented in this subsection (Figure 8), we observe the behavior of the optical thickness across the NWM, and by means of image analysis, it is possible to interpret not only the patterns of aerosol-particle concentration, but also the distribution of particle type, mainly in the state of Sonora, which is represented in all of the final maps.

These maps, in conjunction with the correlation work previously performed with photometer measurements of the Hermosillo City AERONET networks, represent valid data for all areas of Mexico and the parts of the U.S. that are represented in the final maps. Furthermore, these maps cover NWM on many days different from those ones which data for validation processing were obtained. Hence, the behavior observed in the previous graphs maintains strict concordance solely with adjacent pixels over Hermosillo instead of each one of covered area in the final maps, although closest pixels show similar trends.

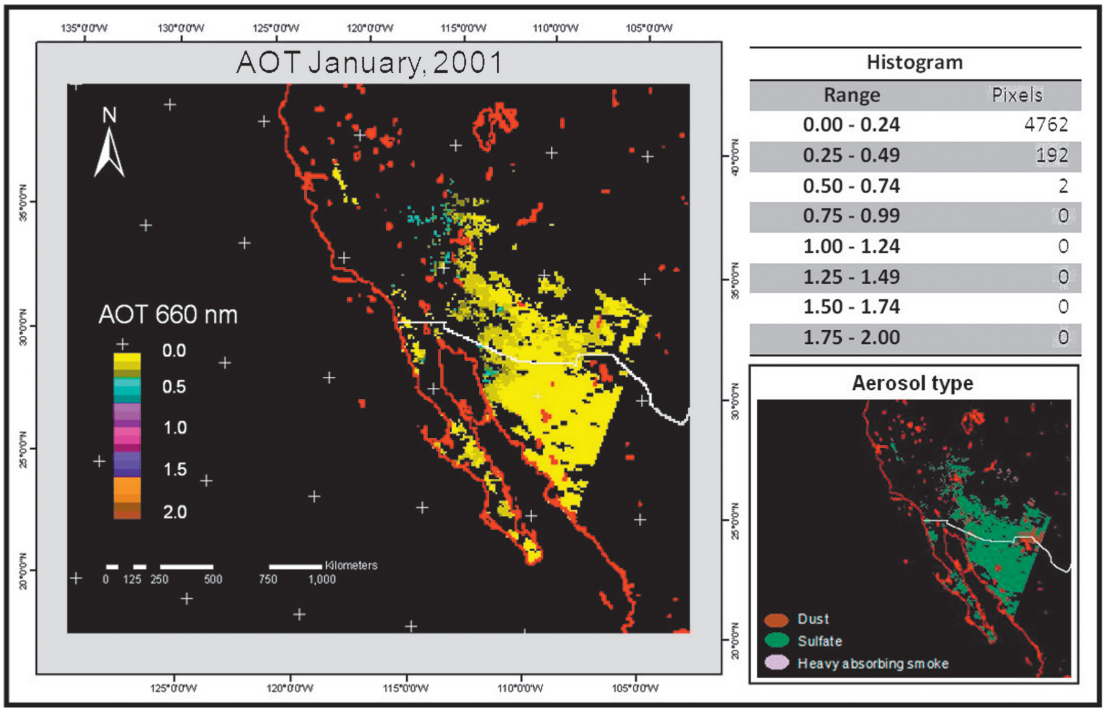
In 2001, through analysis of maps of every month of the year, there is a notorious gradual increase that reaches its peak on July and then gradually decreases until December; additionally, the month of January presents the lowest optical-thickness values for the entire region.

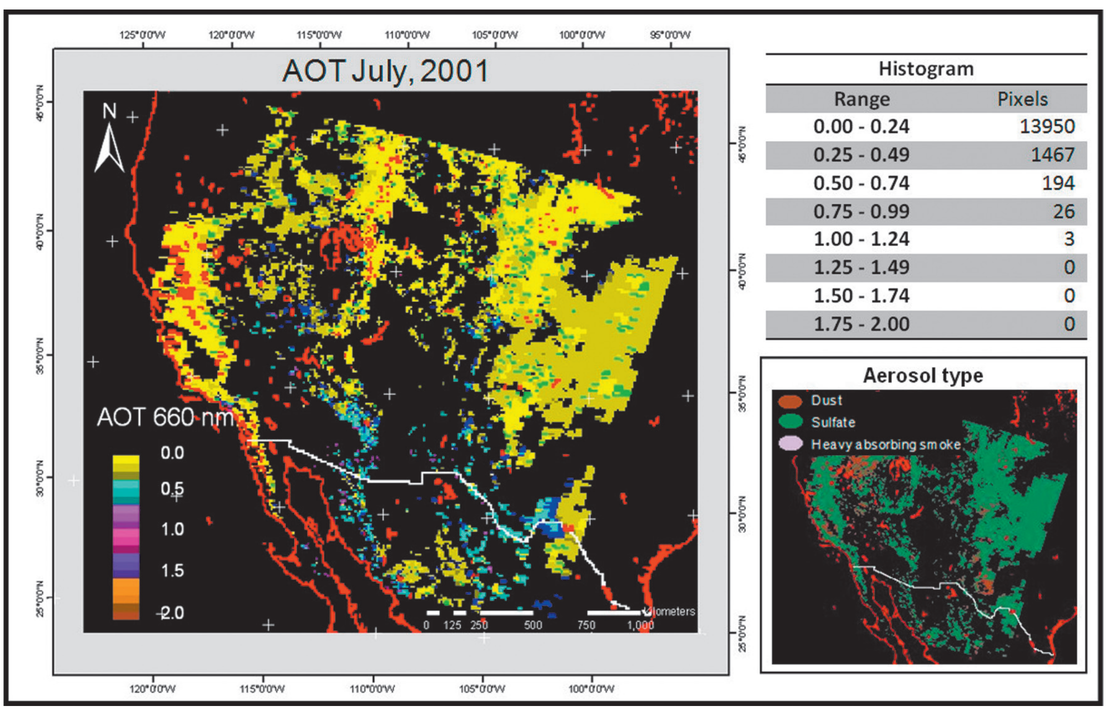
During 2002, although we do not have maps of every month, it is possible to identify a similar pattern of rise and fall as in the previous year, with highest values in June. According to the monthly image, there is an abrupt increase of AOT in relation to the information available for the first half of the year.

In this same year, after the maximum value observed in June is clearly observed a decrease in optical thickness, even with the lack of maps for every month of the second quarter of 2002, the images of September, November, and December clearly illustrate a gradual decrease among each of these, which means that this pattern is consistent with AOT behavior in the months for which no data are available.

In 2003, by interpreting the images, it can be concluded that although there are no maps of the first 3 months of the year, there is an increase in optical-thickness values from April, reaching its highest peak, as in the previous 2 years, between June and July, but in this case by presenting a second increase in August and September.

Figure 8. Aerosol optical thickness values along 2001–2003 over NWM, small images show representative months derived from MODIS aerosol-type product.





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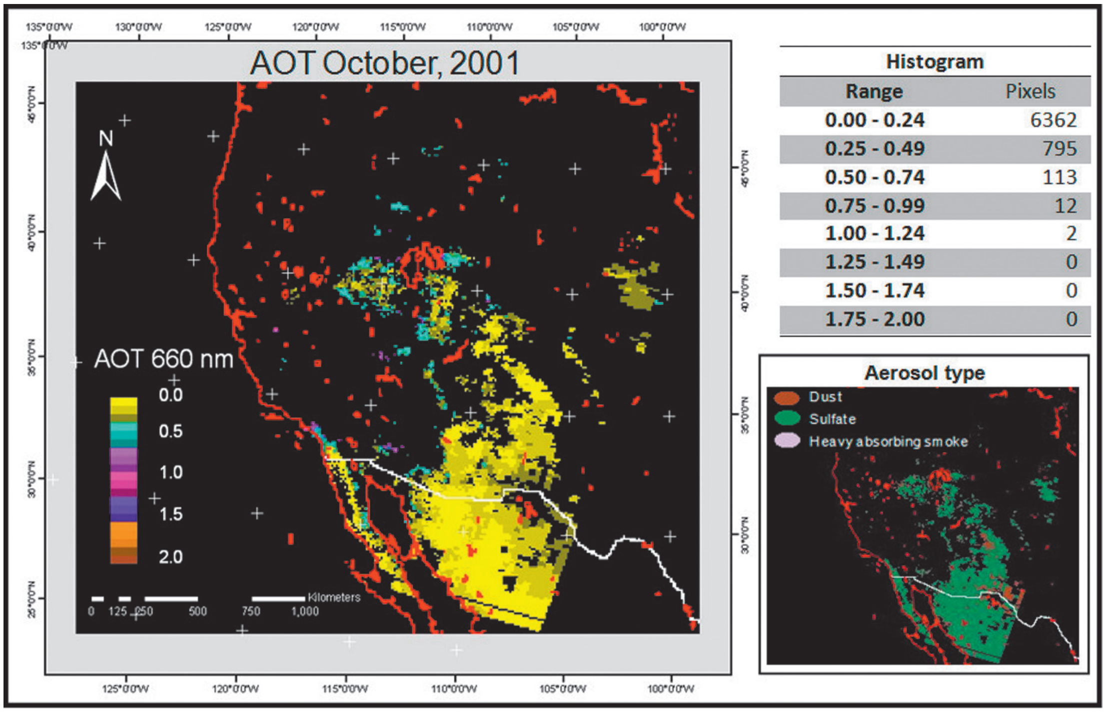

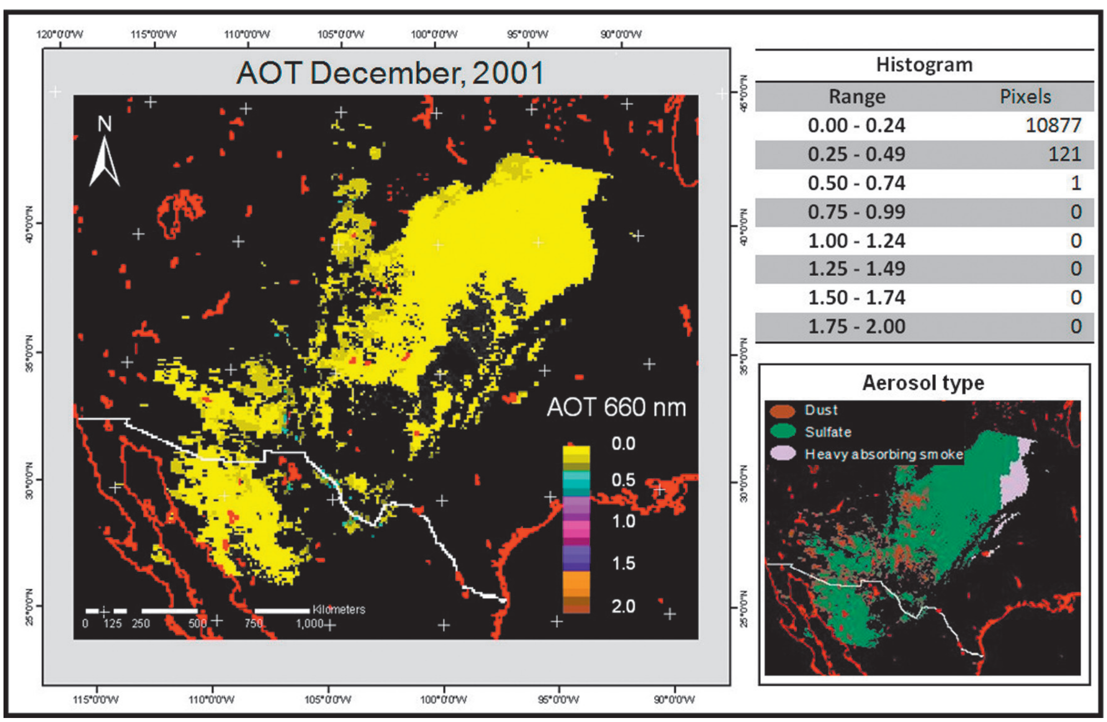

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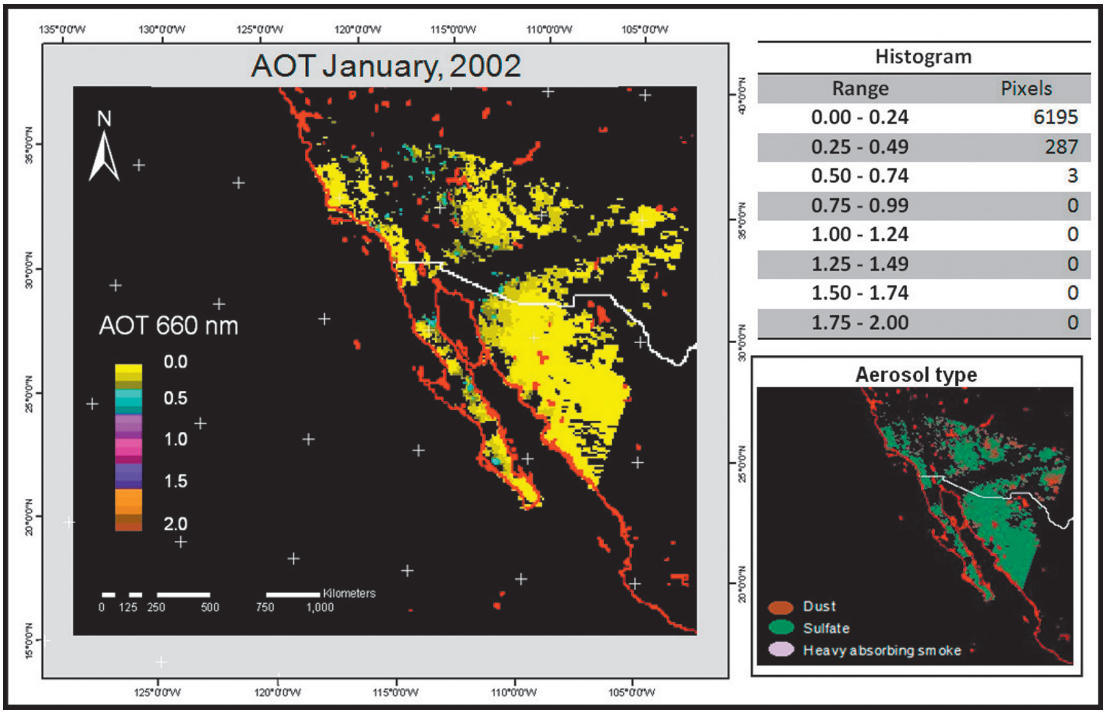

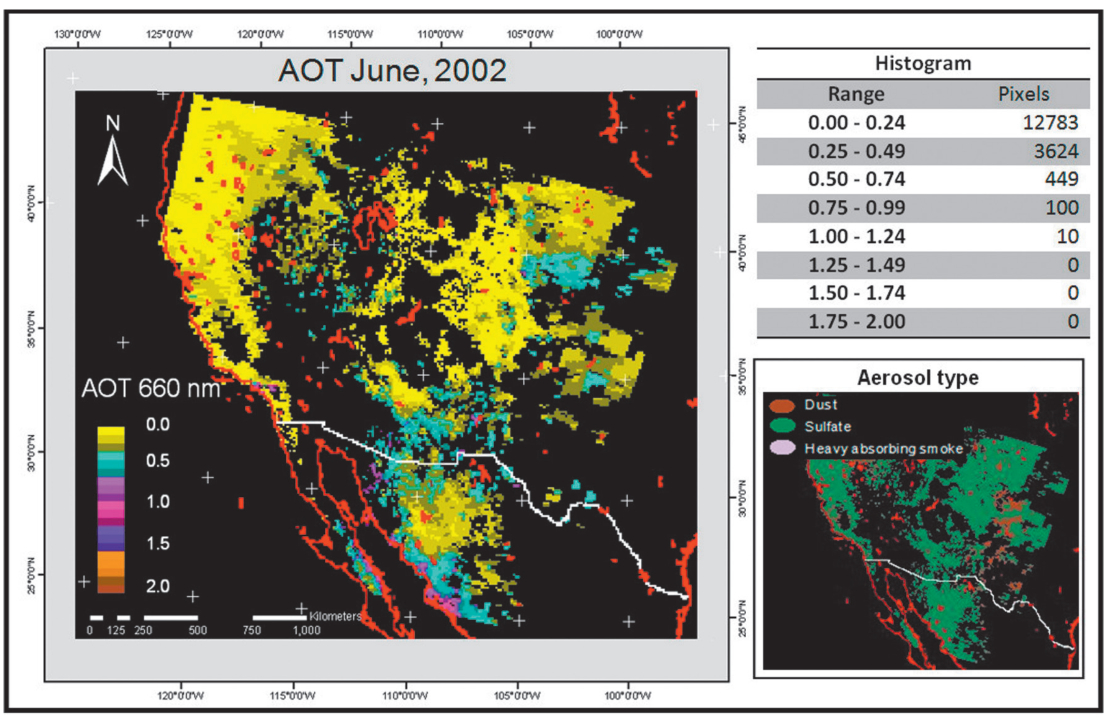

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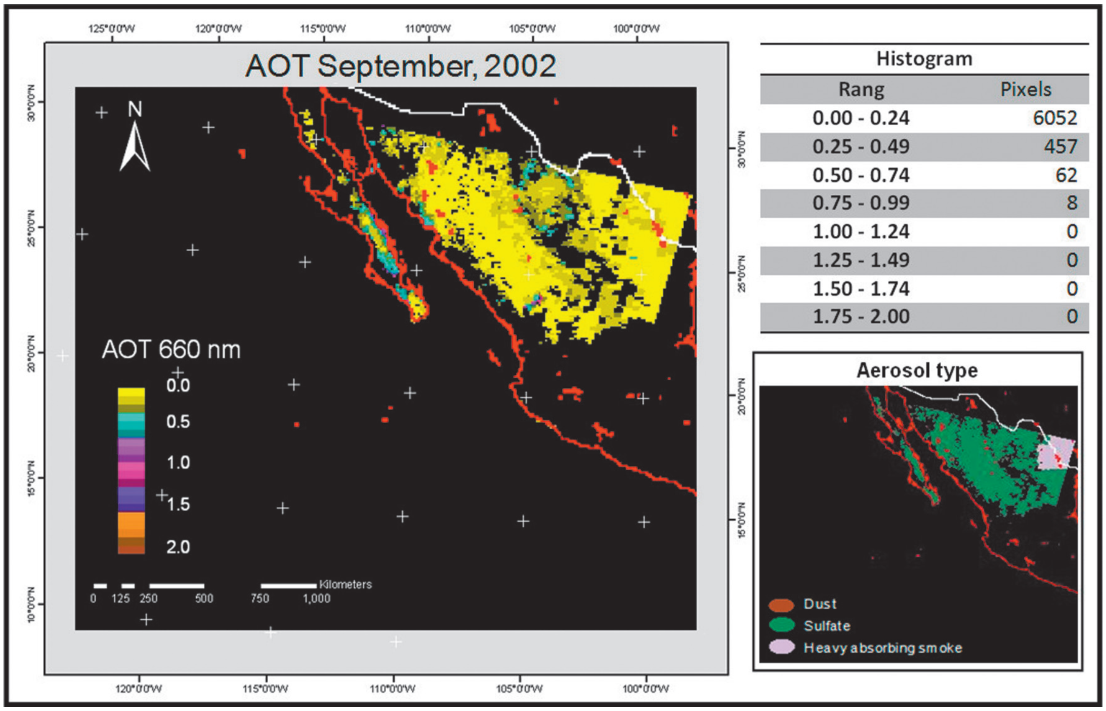

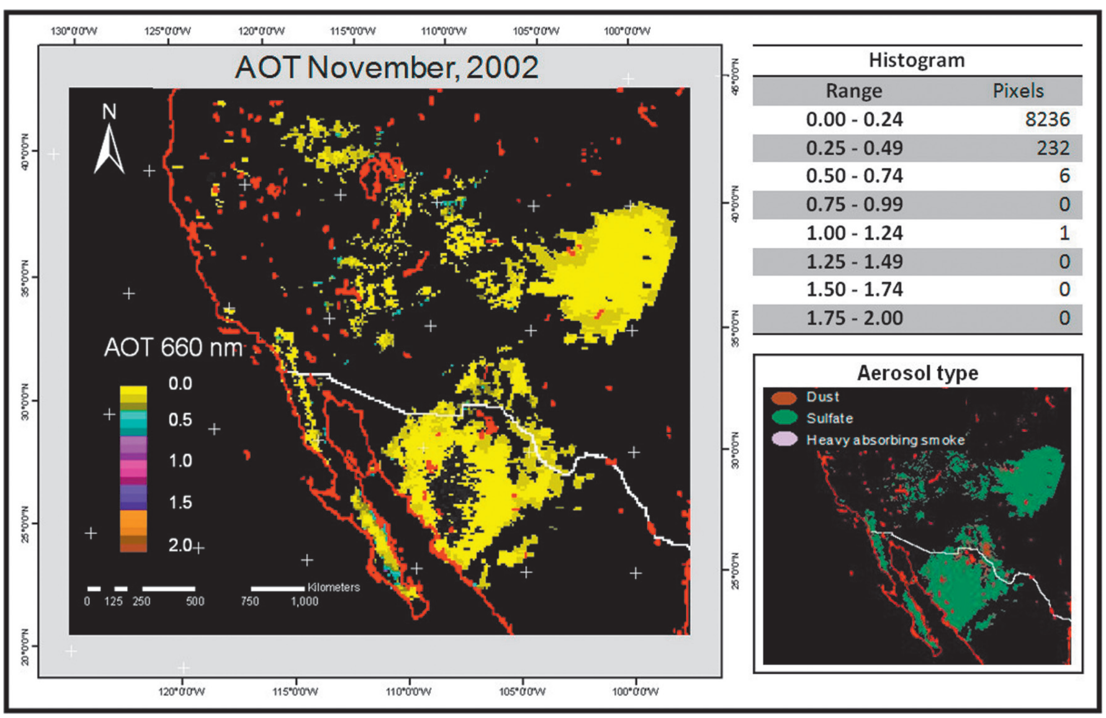

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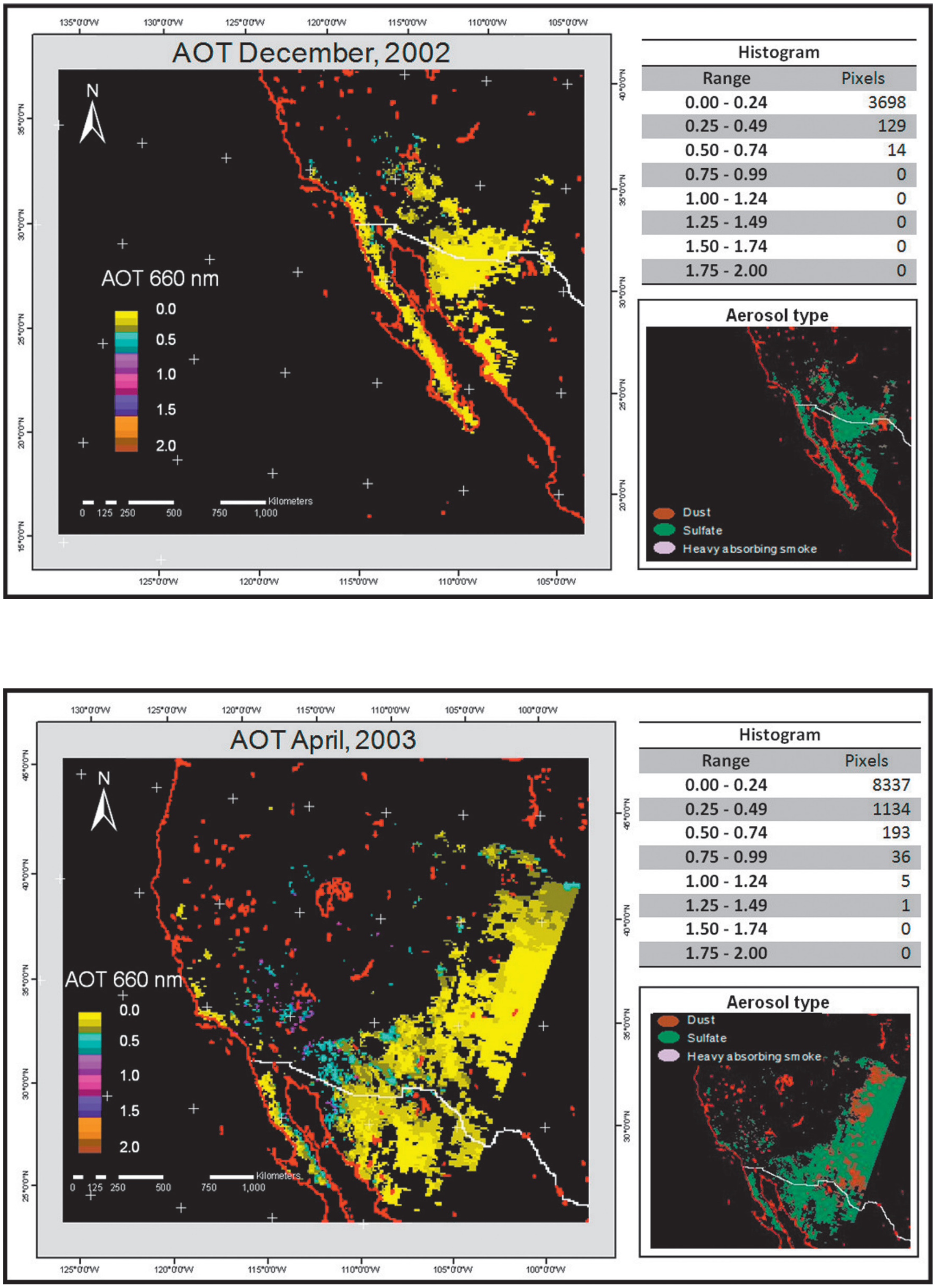

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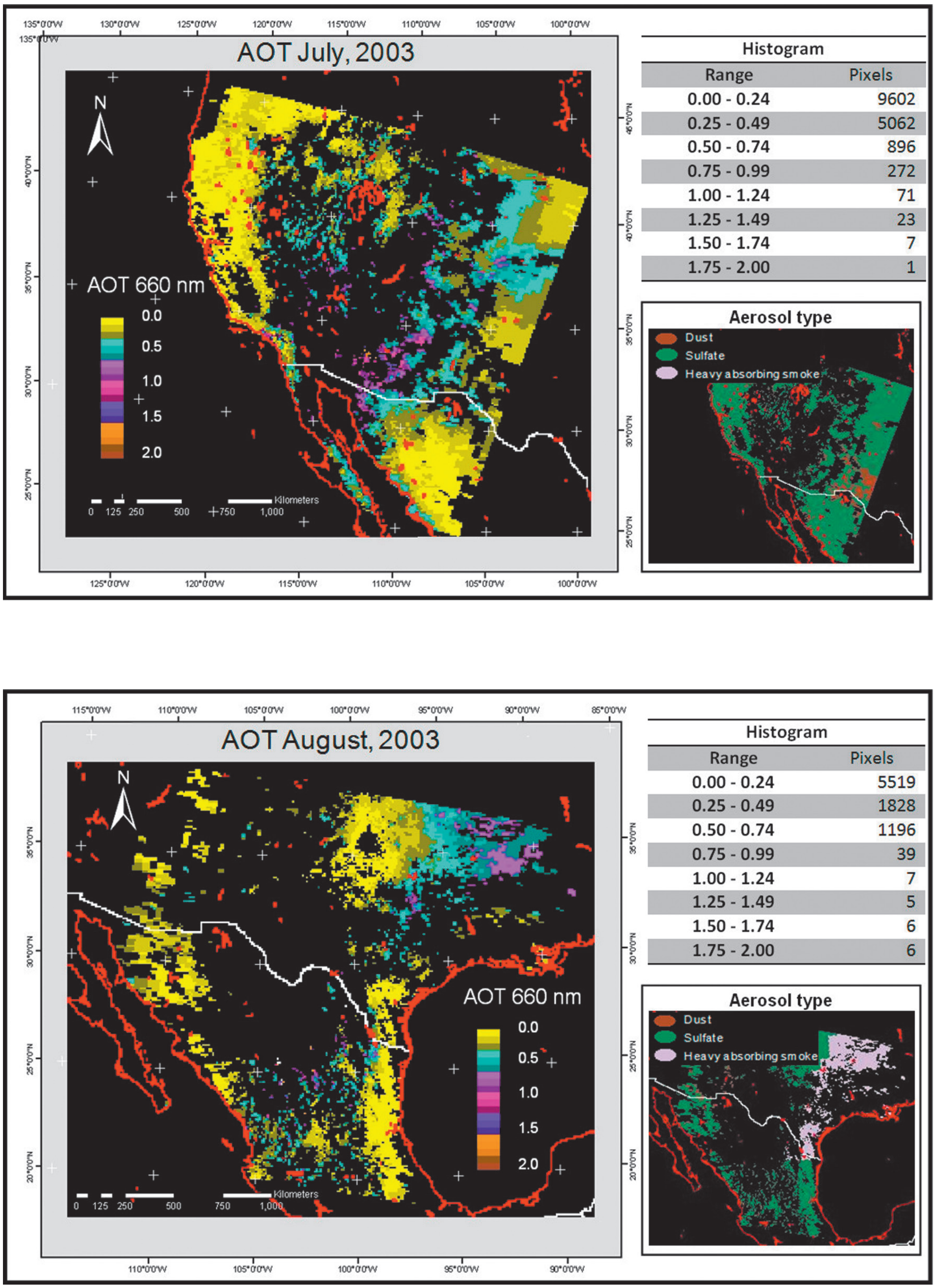

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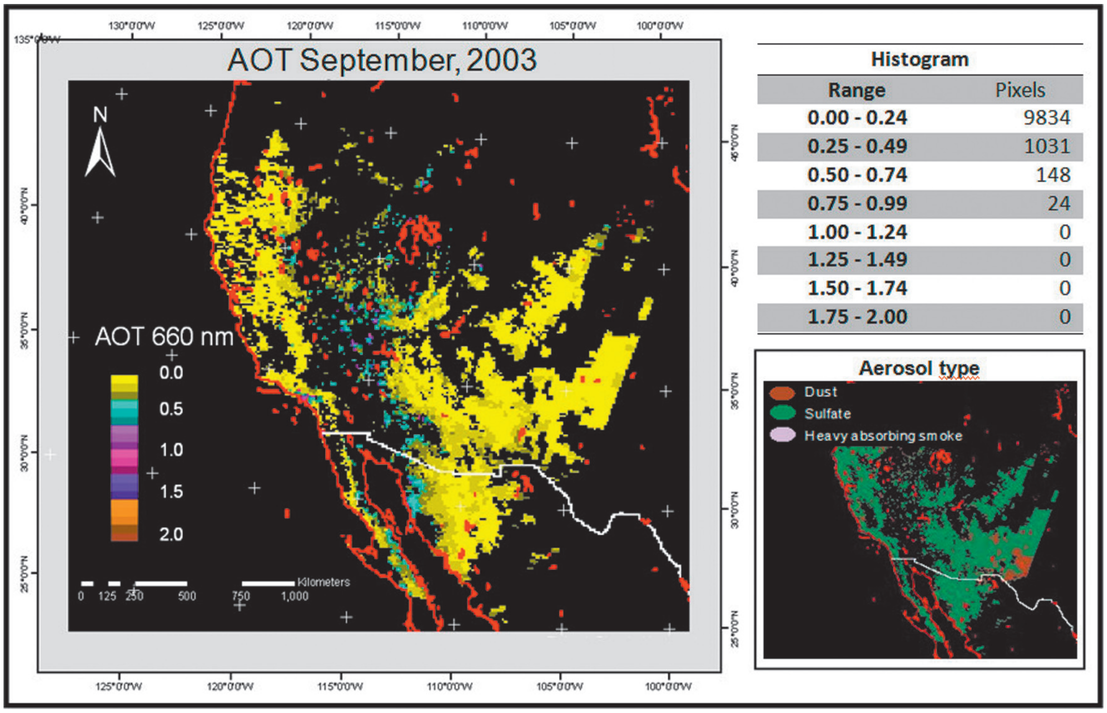

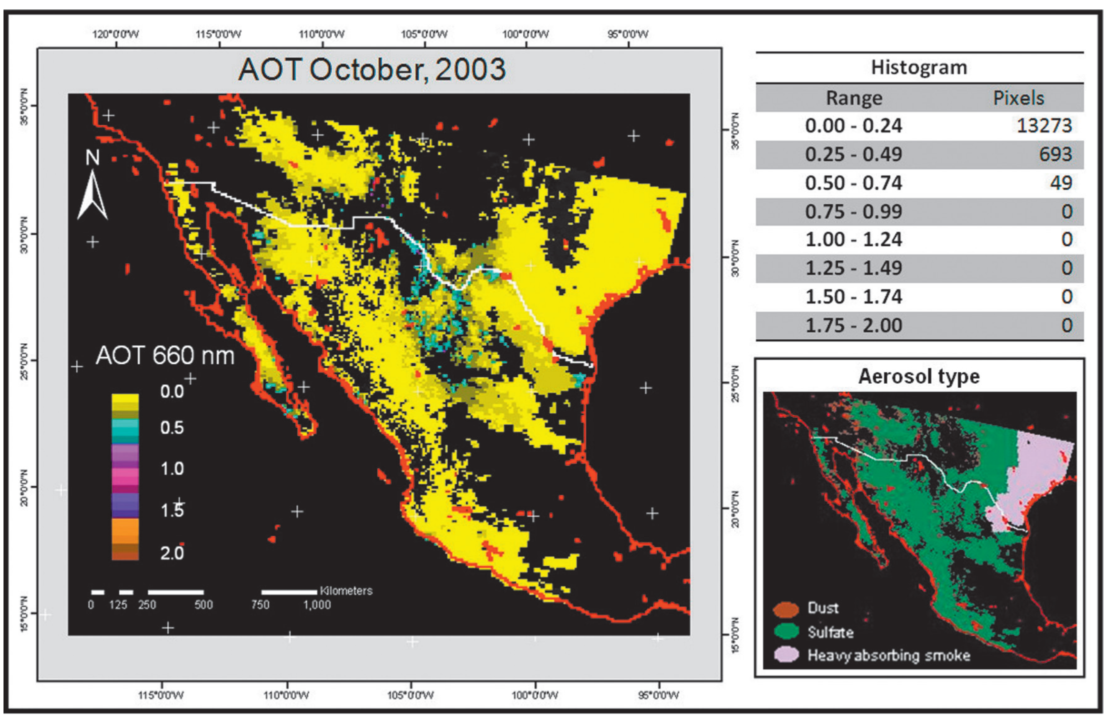

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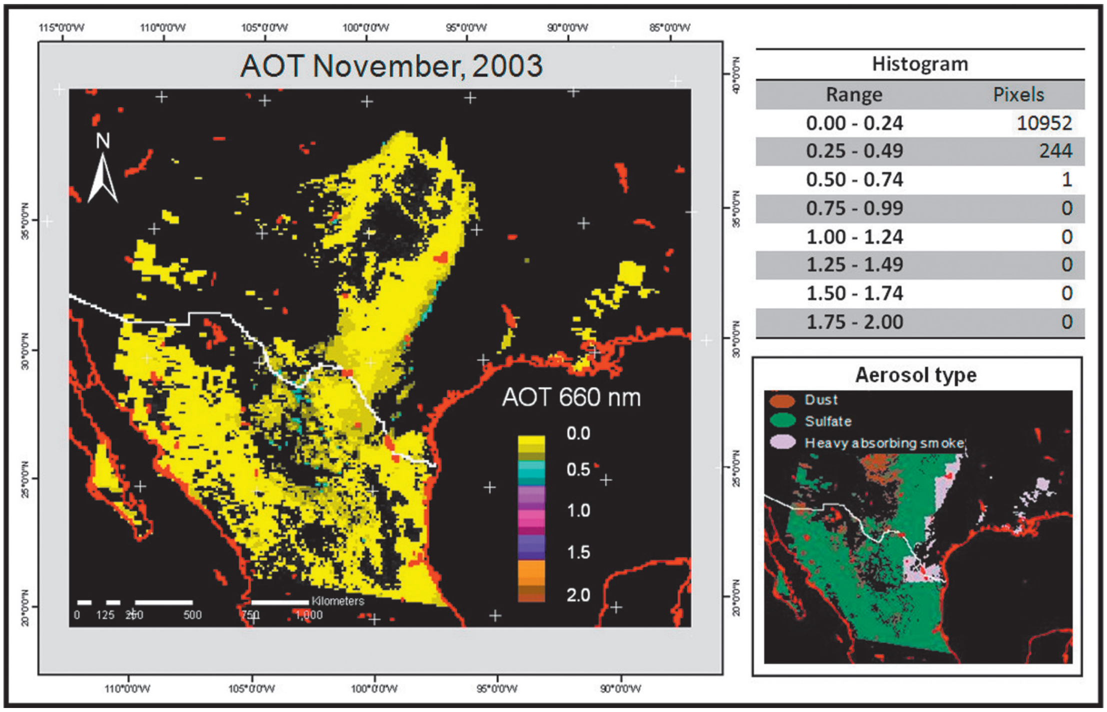

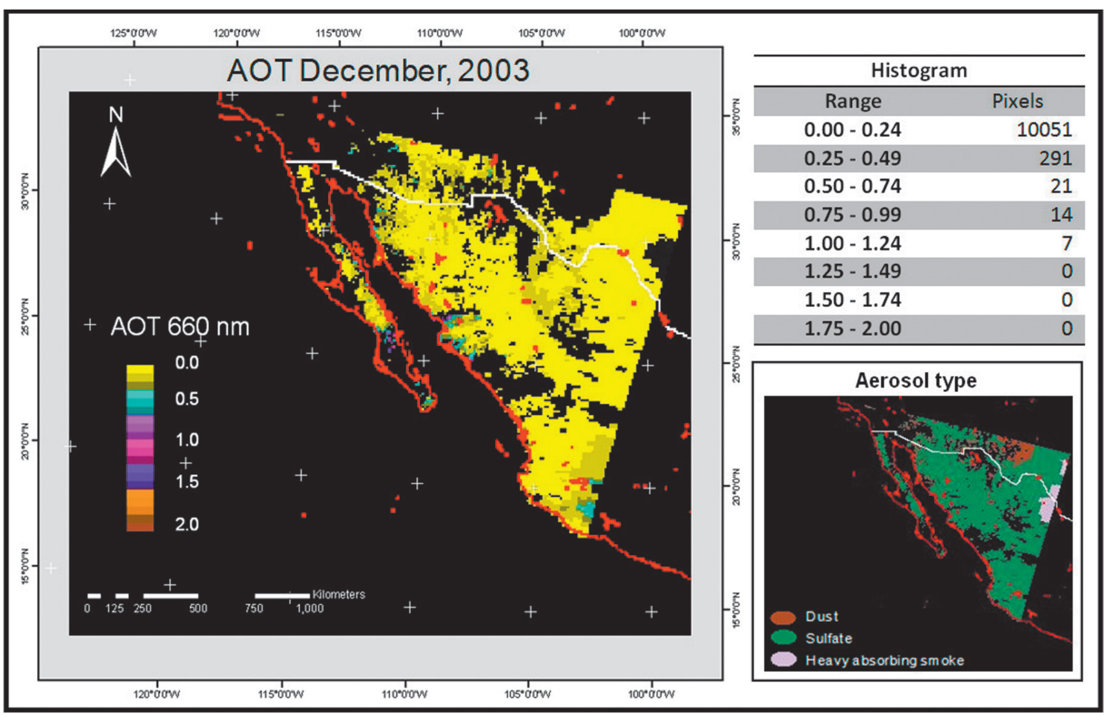

In general, highest values (>0.5) are located in the northwestern portion of Sonora, near Desert of Altar and northern coast of the state, although in this case it is possible to assume a similar distribution even when the images do not provide data for the whole area. These values are possibly related with the arid conditions of the region, because sparse vegetation and presence of the desert facilitate the incorporation of particles into the atmosphere that ultimately are recorded by the MODIS sensor.

Similarly, in relation to temporal variations, values close to 1.0 or higher on NWM set up during July 2001, June 2002, May 2003, and June 2003. Implying the existence of seasonal pattern between the rainy and the dry season, because based on the analysis of annual precipitation, we know that these months represent the driest period and then the beginning of rainy season, which is influenced by the Mexican monsoon when all of the dust particles work as hygroscope nuclei in cloud formation. Thus, it is possible to deduce that there is a pattern in the annual behavior, presenting highest values in June and July for 3 years and lowest values on December and January for the 2001–2003 period.

The pattern of increasing and decreasing of AOT over the first and second halves of the years, respectively, are clearly presented in 2001 and 2002, while in 2003, a second peak in AOT concentration is observed in plots and images. It happens on August and September, mainly in the portion near to interior coast of Gulf of Baja California, the Altar Desert, and the center of the peninsula, which might be related with the presence of two stronger cyclonic events during hurricane season in 2003. These were cyclones Ignacio and Marty respectively (NOAA, 2003a; NOAA, 2003b) while in the month of October of the same year, after the passage of two hurricanes, the pattern of behavior was re-established and exhibited a decrease in AOT values in December as in two previous years. In addition, it took into account the periods with higher rainfall, consistent with the summer and fall months (year 2003), during which it is known that rainfall is greatest in NWM, also due to moisture penetration on the continent connected with Mexican Monsoon and Southwest Monsoon of America (Reyes *et al*., 1994).

In the case of Baja California peninsula, throughout the study period, we identify the highest values (0.5–1.0 and over), on May, June, July, and August 2001, June 2002, and in April, May, and July 2003. Generally, we observed that the peninsula has the highest values throughout the period, unlike the NWM mainland. Possibly related with the narrow north-south profile of this physiographic province, which is influenced by aerosols of marine origin throughout East-West extension and that is reflected in measurements made by the sensor and in processed images.

Additionally, by analyzing the histograms of each image and once identified those areas with highest concentration of particles in the region and seasonal patterns, we are able to notice that images with the highest concentration of valued pixels show lower ranges (0.00–0.24 and 0.25–0.99); especially in January, February, March, and April 2001, increasing from May until July. In this increase, the pixels are related with classes or ranges between 0.5 and 0.99, subsequently decreasing from August to December of that year.

This behavior is repeated in the same way in 2002 and 2003, years covered in the study, which also has the highest concentration of pixels of <0.49 in the first and last months of each year, while there was an increased presence of values >0.5 in total existing pixels in the images presented in June, 2002, May 2003, and July 2003.

In relation to these histograms, it is noteworthy that their analysis is relative, because the amount and location of the pixel value is not uniform in all images and covered area is different for each image. Nonetheless the observed behavior corresponds to the criteria given previously and reaffirms spatial and temporal patterns of AOT.

In each map presented, there is also attached information related with the predominant aerosol type in the atmosphere, which was obtained from a sub-product of MD04L2 related to this parameter. This exhibits a notoriously large predominance of sulfate aerosols in contrast with the other types shown in NWM images, in which a direct relationship was not identified between aerosol type and particle-concentration values expressed by AOT. It is interesting to notice that dust-related aerosols are generally located in northern areas of states of Chihuahua, Coahuila and Nuevo León and in the southern U.S. along border areas (Figure 8).

The third type of aerosol, heavy absorption smoke, was not identified on NWM. Thanks to coverage of some images and to availability of information of this parameter is possible to determine its concentration in the entire Northern coastal area Gulf of Mexico, where oil is probably the activity that affects particle emission to the atmosphere. The same type of aerosol particles is also identified is also identified in the lower Mississippi River Basin, mainly in the agricultural region of the U.S. which extends from Illinois to the border with Mexico in the State of Texas. While our work is focused on NWM, there is no presence of this type of particle in any analyzed image.

Furthermore, we observe in the images that highest values are located mainly near to the coast of the Gulf of Baja California and these values decrease in the interior region of the state of Sonora, increasing again, but less so than on the coast, on western slope of Sierra Madre Occidental. In this area the presence of natural vegetation encourages the emission of biomass into the atmosphere in larger quantities than in the areas located in the center of the entity, where there are drier zones.

Additionally, it is notorious that in most of the maps, highest AOT values are found near latitude 30°, which is possibly related to the transport of particles from the arid Southwestern U.S., under influence of trade winds and westerlies. Although it should be remarked that the influence of Santa Ana winds (JPL, 2002) in NWM may explain the higher concentration of suspended particles in Baja California peninsula and the coastline of the states of Sonora and Sinaloa. Despite we do not observe their overall influence on AOT spatial-temporal variation for the entire region from October to March, when Santa Ana winds occur, this does not correspond to months with the greatest increase in optical thickness.

As part of the analysis of AOT images, we also undertook identification of hotspots in satellite images provided by the National Commission for the Knowledge and Use of Biodiversity (CONABIO, 2010) to determine whether during study period, the occurrence of wildfires was active in terms of particle emission to the atmosphere. However, no direct relationship was found because, in all images analyzed. We identified that the greatest concentration of hotspots is related to wild fires in the central and southern part of Mexico. Thus, while it is appropriate to take the occurrence of these events into account, we not considered that they have a higher weight in AOT values.

Finally, by comparing the behavior of AOT along 3-year study period, we were unable to observe a gradual increase in the concentration of particles in the atmosphere because, according to the graphs of temporal AOT variation, the year 2003 in general exhibited values below those of the average. Despite what we might expect if we relate these variations to chronic expansion of urban areas throughout the country and consequently increasing emissions of anthropogenic aerosols. Based on the criteria presented in this subsection related to analysis of final maps, to histograms of each graph, and to AOT behavior, these appear to confirm the identification of a seasonal pattern in the behavior of optical thickness in NWM during 2001–2003. Besides this pattern can also be influenced by the occurrence of extraordinary events throughout each year, but in general there were no significant changes in the space-time trend.

Conclusions

By means of performing a study of the correlation between data measured by the AERONET sensor in the city of Hermosillo, Sonora, Mexico, and those of the MODIS satellite, we obtained a correlation coefficient of $R^2 = 0.891$. The study allows us to observe the behavior of the aerosol particles at this site during the 2001–2003 period. Thus, we consider that the data employed in this research are reliable for their purposes and useful in identifying temporal and spatial patterns in AOT behavior.

The main pattern observed depicts highest AOT values during the rainy season in NWM and in the 2 prior months. The relationship between these values can be associated with low atmospheric pressures due to high temperatures, which cause convergence of air masses related to North American monsoon. The convective air currents encourage and facilitate the incorporation of particles into the atmosphere before rainy season and the formation of high vertical developed clouds from August to October.

Furthermore, other factors were identified in AOT behavior, as well hurricanes during the rainy season in 2003, generating highest values for that year despite its low values in comparison with the whole 3-years period.

In addition to the influence of the physiographic shape of Baja California peninsula and inland NWM in AOT values, the presence of large areas with scarce vegetation aids to stimulate the emission of particles from the ground. In the same way, high-density vegetation areas increase biomass emission in mountain ranges located on eastern portion of Sonora.

Finally, it was not possible to compare the results of this research with others, considering that to our knowledge, there are no previous attempts to study aerosol behavior in NWM. Thus, further work is required to build up a stronger database in order to helps monitor and understand how AOT values are influenced by different factors and how these are related to information from researches in several scientific fields.

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APPENDIX 1

Table 1. Data availability from Moderate Resolution Imaging Spectroradiometer (MODIS) and AErosol RObotic NETwork (AERONET).

Date	MODIS (660 nm)	AERONET (675 nm)	Date	MODIS (660 nm)	AERONET (675 nm)
15/11/2001	0.047000	0.02151636	05/06/2002	0.362714	0.13462458
16/11/2001	0.163150	0.03446177	08/06/2002	0.345778	0.14995492
17/11/2001	0.087000	0.03355362	09/06/2002	0.365000	0.06558950
19/11/2001	0.110375	0.04732900	12/06/2002	0.390875	0.14424058
20/11/2001	0.147600	0.03939413	14/06/2002	0.642000	0.15638400
21/11/2001	0.098000	0.04258614	15/06/2002	0.319500	0.14523883
25/11/2001	0.139846	0.03491987	16/06/2002	0.739000	0.11349450
27/11/2001	0.134500	0.03744760	17/06/2002	0.262231	0.10734983
28/11/2001	0.097308	0.04334970	18/06/2002	0.350000	0.10298600
01/12/2001	0.068889	0.03290827	19/06/2002	0.341333	0.09602550
02/12/2001	0.120050	0.02228500	21/06/2002	0.439333	0.09180567
03/12/2001	0.022143	0.01115900	25/06/2002	0.615000	0.13830422
13/12/2001	0.108263	0.01001254	26/06/2002	0.428000	0.17784543
16/12/2001	0.101826	0.03282064	27/06/2002	0.401000	0.19024858
17/12/2001	0.047667	0.01083812	30/06/2002	0.674333	0.16896028
18/12/2001	0.100737	0.03201989	01/09/2002	0.154000	0.11731225
19/12/2001	0.025385	0.01651793	02/09/2002	0.404000	0.18827701
20/12/2001	0.116947	0.02131789	05/09/2002	0.257280	0.10057900
21/12/2001	0.050429	0.02466560	12/09/2002	0.157333	0.06258500
22/12/2001	0.097143	0.01854000	13/09/2002	0.116000	0.05697200
23/12/2001	0.060143	0.02065667	14/09/2002	0.140957	0.05644433
24/12/2001	0.065250	0.02142057	16/09/2002	0.258667	0.08315050
25/12/2001	0.089650	0.00585738	21/09/2002	0.172524	0.09421967
26/12/2001	0.025200	0.02577600	22/09/2002	0.151000	0.04333180
05/01/2002	0.133684	0.01517575	23/09/2002	0.128400	0.04876790
06/01/2002	0.054333	0.00776320	25/09/2002	0.175000	0.06890750
07/01/2002	0.085143	0.02254000	27/09/2002	0.212333	0.08882033
08/01/2002	0.081563	0.01104217	28/09/2002	0.220000	0.08812280
03/06/2002	0.302125	0.09941730			