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Aerosol columnar characterization in Morocco: ELT prospect

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Abstract
The work presented in this paper focuses on site testing in terms of aerosol loadings where ground based measurements are essential. In our case they are materialized by the aerosol optical thickness (AOT) and are provided by the AERONET (Aerosol Robotic Network) network from four stations, Dakhla and Marrakech in Morocco and Santa-Cruz and Izana in the Canary Islands. To fully scan all the area of the Moroccan territories, satellite measurements are certainly the most efficient way. We used the most popular and reliable products. TOMS (Total Ozone Mapping Spectrometer) aerosol index (AI) provided by both TOMS Earth Probe and TOMS OMI (Ozone Monitoring Instrument) along with aerosol optical thicknesses provided by MODIS (Moderate Resolution Imaging Spectroradiometer) and MISR (Multiangle Imaging Spectroradiometer) instruments, onboard Terra platform. The idea is to compare sensing capabilities of each instrument in the region under study, in order to know which is suitable for a given place and when. For that purpose linear regression analysis were performed between satellite data and AERONET observations. Good correlations were observed with the Pearson correlation coefficient, R, varying from 0.68 to 0.92 for MODIS, MISR and TOMS OMI. However for TOMS EP the correlations are fairly poor (from 0.54 to 0.74). A ten years analysis of the TOMS EP index has been performed with a calibration of the aerosol index into TOMS retrieved aerosol optical thickness in the area of interest (Morocco and Canary Islands) and an inter-comparison with the other products was achieved. In the frame of the ELT (Extremely Large Telescope) project prospect, once the appropriate satellite instrument have been chosen and the area scanned, the next step would be to scan aerosol loadings at higher altitude locations. Since vertical distribution of aerosol optical thickness and microphysical properties are not well understood and modelized, we used the relationships related to Izana (Izana's altitude is 2367 m), as a first attempt, to extrapolate the aerosol optical thickness at higher locations in the Moroccan mountains. Izana and Santa-Cruz very close to each other (30 Km) are located in the same satellite pixel and then have the same satellite (AOT) or (AI) whereas AERONET gives very distinct aerosol optical depths. A good linear correlation (R=0.92) has been observed between the AERONET aerosol optical depths at Izana and Santa-Cruz. The seasonal correlation coefficients are 0.85 for winter, 0.87 for spring, 0.91 for summer and 0.87 for autumn The ratio $AOD_{Santa\text{-}Cruz}/AOD_{Izana}$ has a seasonal behavior, reaches the average of 4.5 in winter and 2 in summer time and the subtraction of the aerosol optical thicknesses has an average of 1.3. Finally we retrieved the aerosol optical thickness at Oukaimeden: a Moroccan observatory located at 2700 m above sea level, and about 70 km from Marrakech city. We then converted the aerosol optical depth into astronomical light extinction and compare with previous records measured at the observatory.

Key words: site testing, atmospheric effects, data analysis, photometer.

1- Introduction
Extremely Large Telescopes are considered worldwide as one of the highest priorities in ground based Astronomy. They will advance astrophysical knowledge and could completely change our understanding of the universe and may answer fundamental questions about exo-planets, dark matter and energy…At the present time, many countries are involved in the ELT project prospect, from site testing and selection to instrumentation. Morocco is part in the ELT (Extremely Large Telescope) project prospect. A team of Moroccan astronomers is busy working on site qualification and testing. Since the performance of large telescope at visible and infrared wavelengths is critically dependant on sky transparency and then on atmospheric aerosol cover [Munoz Tunon et al, 2004; Sarazin et al

2006], a quantitative survey of the aerosol loadings and their microphysical and optical properties is an essential part of the site selection process.

The study of sky transparency has been initiated by astronomers, who were carrying about photometric characterization of their observatories. Stellar photometric measurements are carried out in most observatories as routine astronomic observations, since 1950 (1970) for La Silla and (1980) for La Palma. Before daytime photometry being popular, atmospheric scientists took expertise from astronomers [Laulainen et al 1977-a, 1977-b]. [P. Formenti et al; 2002] have used a record of atmospheric nighttime turbidity data from astronomical stellar radiation measurements, in South Africa, to study changes in aerosol concentrations over the past three decades prior to the popularization of sun photometry. Astronomical light extinction coefficient can be converted to aerosol optical depth and vice versa. Since the dilemma concerning the heating of the Earth, the new field of aerosols; their optical and microphysical properties with sun photometry, LIDAR techniques and satellite remote sensing, is emerging and growing very fast. Now astronomers can take advantage of these well developed tools to characterize sky transparency with even more deeper insight.

The astronomical light extinction (A) is determined by comparing the apparent brightness, B, of the standard stars with there intrinsic luminosity at different air masses, through the Beer's law. The Langley technique relying on the plot of ln(B) versus air masses is used to extract the astronomical light extinction which is the slope of the linear regression. Daylight photometry is based on the same physical principles: $I_\lambda = I_{\lambda 0}*\exp(\tau_{tot}*m)$; I_λ is the direct solar irradiance, $I_{\lambda 0}$ is the extraterrestrial irradiance, λ is the wavelength, τ_{tot} is the total atmospheric optical depth; the sum of the optical depths of molecules (Rayleigh scattering), gazes (absorption) and aerosols (Mie scattering and absorption), m is the inverse of the cosine of the zenith angle θ. As for nighttime photometry, the linear regression Langley procedure is applied to extract the atmospheric total optical depth. The aerosol optical depth is then calculated by subtracting to τ_{tot} the aerosol optical depth of Rayleigh scattering τ_R and the Ozone absorption optical depth τ_{O3} in the Chappuis bands, and the absorptions of water vapor, carbon dioxide, methane and nitroxyde, depending on the wavelength used. The astronomical light extinction coefficient A is related to the total optical depth: $A=1.086*\tau_{tot}$. The scattering by molecules has a predictable profile depending on the wavelength, altitude and the refractive index of molecules. The optical thickness of ozone is calculated using daily averages from TOMS satellite.

The rest of the paper is organized as follows. In section 2, we describe the data used in the current study, the area of interest, and the methodology adopted. In section 3, we show the details and the results of the regression analysis performed between ground measurements and the different satellite data. Section 4 deals with comparison of ground measurements of Izana and Santa-Cruz. In section 5, first the TOMS EP index is converted to aerosol optical thickness mapping the area of study, and then we made a comparison of long term satellite AOT retrievals. Finally, we retrieve the AOT at Oukaimeden observatory, by different approaches. In order to compare to previous measurements of astronomical light extinction coefficient performed at the observatory during the year 1997, we converted the AOT to astronomical light extinction coefficient over 1997 using TOMS EP records.

2- Study area, data and method

2-1 Study area

Two AERONET stations located in Morocco; Marrakech (lat=31.6°; lon=-8.15°; alt=420m) and Dakhla (lat=23.7°; lon=-15.95°, alt=12m), have delivered data during at least two years. Close to Morocco, two other AERONET stations located in the Canary Islands; Izana (lat=28.3°, lon=-16.5°; alt=2367m) and Santa-Cruz(lat=28.5°, lon=-16.25°, alt=52m) have delivered data during relatively a long period of time. The mape showing the locations of the AERONET sun-Sky radiometers used in this study is shown in figure1. These sites span desert dust aerosol predominant environment.

2-2 Data source

a- AERONET aerosol optical thickness

We used data acquired by The AERONET (AErosol RObotic NETwork) program established by NASA and LOA-PHOTONS (CNRS). The instruments deployed are automatic sun and sky scanning radiometers (CIMEL). The photometer makes measurements of, direct sun and diffuse sky radiances, within the spectral range 340-1020 nm. The direct sun measurements are acquired in eight spectral channels. The 940 nm band is used to estimate total precipitable water content. The bandwidths of the interference filters vary from 2 to 10 nm. The total spectral optical depth is computed through the Beer-Lambert-Bouguer law after correction taking into account gaseous absorption. Sky measurements are performed at 440, 670, 870 and 1020 nm with two basic sky observations "almucantar" and "principal plane". The philosophy is to acquire aureole and sky radiances observations through a large range of scattering angles from the sun through a constant aerosol profile to retrieve size distribution, phase function and single scattering albedo.

Data are transmitted through the DCS Data Collection System operating the geosynchronous GOES, METEOSAT, and GMS satellites and are available at the sun photometer home page http://aeronet.gsfc.nasa.gov. The instruments are described in detail in [Holben et al, 1998] and the inversion procedure is well documented in [Dubovic et al; 1998, 2000-a, 2000-b, 2002]. Aerosol optical depth data are computed for three data quality levels: Level 1.0 (unscreened), Level 1.5 (cloud screened), and Level 2.0 (cloud-screened and quality assured). Cloud screening procedures are detailed in [Smirnov et al; 2000].

b- TOMS aerosol index

The TOMS (Total Ozone Mapping Spectrometer) instruments allow an efficient method of space based aerosol detection: TOMS Aerosol Index [Torres et al, 1998]. TOMS AI is a measure of the change of spectral contrast in the near ultraviolet (341 and 380 nm) due to radiative transfer effects of aerosols in a Rayleigh scattering atmosphere. The AI is defined as:

$$AI = -100\left[\mathrm{Log}_{10}\left(\frac{I_{331}}{I_{380}}\right)_{mes} - \mathrm{Log}_{10}\left(\frac{I_{331}}{I_{380}}\right)_{calc}\right]$$

where I_{mes} is the backscattered radiance measured by TOMS and I_{calc} the radiance calculated using a radiance transfer model for a pure Rayleigh atmosphere. TOMS data used in this work are daily gridded level-3 product at a resolution of 1° latitude and 1.25° longitude, The AI data were acquired from the NASA/GSFC TOMS ozone processing team at http://toms.gsfc.nasa.gov/ftpdata.html and are related to TOMS EP and TOMS OMI aboard Earth Probe and AURA platforms respectively.

c- MISR aerosol optical thickness.

MISR is one of five instruments launched into polar orbit aboard NASA's Terra spacecraft in August 1999. The MISR instrument provides high sensitivity for a wide range of scene reflectance (0.02% to 100%) without change in gain. MISR has 9 cameras so the instrument can view successively a same point of the Earth at this number of angles simultaneously. Most of the information about aerosol and cloud particle properties, and some of the information about surface structure, come from studying observations taken at different scattering angles. In each of the nine MISR cameras, images will be obtained in four spectral bands, i.e. in four different colours, one each for blue, green, red, and near-infrared. The canter wavelength of each of these bands is 446, 558, 672, and 867 nanometers respectively. MISR has a periodic coverage between two and nine days depending on the latitude [Martonchick et al, 2002]. Its unique combination of multiple bands and angles enables it to retrieve aerosol optical thickness and additional particle properties at a resolution of 17.6 Km over both land and ocean, with no assumption about the absolute land surface reflectance or its spectral characteristics in the aerosol retrieval algorithm [Martonchick et al, 1998, 2002]. The bands in the red and near-infrared (670 and 865 nm) provide vegetated surface identification, and are also useful for marine aerosol studies since water is nearly black at these wavelengths. The green band at 555 nm is near the peak of the solar spectrum, and thus will be given high weight in studies to estimate broadband reflecting properties (albedos). The MISR wavelengths have been selected to avoid known ranges of strong atmospheric gas absorption and solar Fraunhofer lines.

d- MODIS aerosol optical thickness:

MODIS (or Moderate Resolution Imaging Spectroradiometer) is a key instrument aboard the Terra (EOS AM) and Aqua (EOS PM) satellites. Terra MODIS and Aqua MODIS are viewing the entire Earth's surface every 1 to 2 days, acquiring data in 36 spectral bands between 0.405 and 14.385 µm. The MODIS instrument has a viewing swath width of 2,330 km and it acquires data at three spatial resolutions 250m, 500m, and 1,000m. MODIS retrieval algorithm is based on the "dark object" method for aerosol estimation [Kaufman et al, 1997-a, 1997-b, 2002]. The basic assumption is that if the surface is densely vegetated, the middle infrared reflectance around 2.1 µm (MODIS band 7) ρ_7 is linearly related to surface reflectance at the blue band (band 3 around 0.49 µm) ρ_3 and the red band (band 1 around 0.66 µm) ρ_1. Since most aerosol sizes are smaller than the middle-infrared wavelength, aerosol effects in band 7 are negligible and its surface reflectance can be easily estimated. Based on surface measurements, Kaufman et al. (1997-b) established the following empirical formulae: $\rho_7/\rho_1=0.25$, and $\rho_3/\rho_7=0.5$. After calculating surface reflectance of band 3 and 1 from their linear relationships with band 7 reflectance, aerosol optical depths at band 1 and 3 can be estimated by using look-up tables. These look-up tables are pre-calculated for each aerosol model and pre-defined for a given location and time.

Along with all the data from other instruments on board the Terra spacecraft and Aqua Spacecraft, MODIS data are transferred to ground stations in White Sands, New Mexico, via the Tracking and Data Relay Satellite System (TDRSS). The data are then sent to the EOS Data and Operations System (EDOS) at the Goddard Space Flight Center. After Level 0 processing at EDOS, the Goddard Space Flight Center Earth Sciences Distributed Active Archive Center (GES DAAC) produces the Level 1A, Level 1B, geolocation and cloud mask products. Higher-level MODIS land and atmosphere products are produced by the MODIS Adaptive Processing System (MODAPS), and then are parcelled out among three DAACs for distribution.

2-3 Methodology

This work lies within the scope of the ELT project, with the goal of prospecting the best sites for astronomical observations by means of aerosol cover. A means to determine the properties of atmospheric aerosols in all the area would be to place solar or stellar photometers in at least at several tens of places and to achieve measurements there during several months to be able to extract from substantial information. This looks hard and time and energy consuming, then a pre-selection study should be achieved before photometric measurements. The tools we have with this intention are AERONET and satellite data. As previously mentioned we have four AERONET stations; Marrakech, and Dakhla in Morocco and Santa-Cruz and Izana in the Canary Islands. We must note that in our analysis the stations of primary importance are Marakech, Izana and Santa-Cruz. That of Dakhla will be only used to validate the results of correlations between AERONET and satellite data. Izana is an important site because it is located at 2400 m of altitude and thus through its study, we will have the occasion to see the order of magnitude and the variations of the AOT in altitude. Santa-Cruz being located at 12 m above sea level and at meadows of 30 km Izana, its study will allow the quantification of the AOT disparities between the low and high altitudes. Marrakech, being located at the bottom of the High Atlas mountains, its AOT will be used for to extrapolate the optical thickness in neighbouring high altitude places, taking advantage of previous results concerning Izana and Santa-Cruz.

The satellite data used are the aerosol index (AI) provided by both Earth Probe and OMI, and the aerosol optical thicknesses provided by MODIS and MISR. Linear regression analyses were performed between these satellite data and all the available AERONET AOT. At each station, we will make an inter comparison of the satellite products.

The feasability of using the aerosol index (AI) derived from TOMS measured radiances to characterize the temporal and spatial distribution of tropospheric aerosols over both land and water have been demonstrated since 1996 [Hermann et al, 1997 Hsu et al, 1999]

We summarise this paper as follows; we will establish the correlation between AERONET aerosol optical thickness and TOMS Earth Probe and TOMS OMI aerosol index individually in every station of the four sites mentioned before A linear relationship involving all AERONET data of the region of Morocco and the Canary Islands and their corresponding Earth Probe aerosol index is used to calibrate the TOMS EP AI into 'SAOT' Satellite aerosol optical thickness over the area containing Morocco and the Canary Islands. A long term record of ten years analysis of the SAOT is then provided. As MISR and MODIS instruments provide satellite aerosol optical thicknesses, we will establish the correlation between ground AOT and satellite AOT and make an inter-comparison between satellite products. As Izana is at 2370 m of altitude, all the established relationships related to it are going to be used to extrapolate the aerosol optical thickness at elevated places located in the Moroccan mountains. The derived relationships are then used to map aerosol loadings over areas where AERONET data are not provided. We will deduce optical properties over Oukaimeden: a Moroccan astronomical observatory, located in the Atlas mountain at 70 Km from Marrakech city and at 2700 m above sea level. This retrieved AOT will be then converted to light astronomical extinction and compared to previous in-situ measurements done at the observatory.

This is helpful to retrieve the AOT of ELT pre selected sites in Morocco from either satellite or ground measurements.

3- Satellite measurements and ground measurements comparison.

3-1 TOMS aerosol index and AERONET aerosol optical thickness correlation.

The only available long term record of atmospheric aerosols over both oceanic and continental areas is provided by TOMS. Indeed TOMS data are delivered since 1978 until now; Nimbus 7 from November 1978 until May 1993, Meteor 3, from August 1991 until December 1994, Earth Probe from September 1996 until December 2005 and OMI from 2004 until now. The primary importance of this instrument resides in the fact that it is possible to study the variability of the aerosols over the last three decades in the area of interest as long as a satisfying relationship between sun photometer and TOMS data is derived. [Hsu et al, 1999] has shown that the TOMS AI measurements are linear proportional to the AOT derived independently from ground based sun photometers instruments over regions of biomass burning and regions covered by African dust. Their theoretical model simulation has demonstrated that the AI depends on the aerosol optical thickness (AOT), single scattering albedo (SSA), the aerosol layer height and viewing geometry; which makes the quantitative interpretation of the AI very difficult. However the strong dependence of the AI on the height distribution of the aerosol decreases its sensitivity to the aerosol presence at altitude below 1.5 Km. An inversion procedure that retrieves aerosol properties from TOMS radiance has been developed by [Torres et al, 1998, 2001, 2002]. [Torres et al, 2002] confirms the good agreement between TOMS AOT and AERONET data for mineral, carbonaceous and sulphate aerosols. [Ginoux et al 2003] developed an empirical relation to express the TOMS AI for the case of dust plumes, as an explicit function of four physical quantities: the single scattering albedo, optical thickness, altitude of the plume and surface pressure.

For consistency we choose the 440 nm channel, because the 340 and 380 nm channels are not available in all sites. For large particles such as dust, the wavelength dependence in AOT between 340 and 440 nm channels is very small, so that the 440 nm AOT value is approximately the same as the 340 nm AOT, as previously reported by the TOMS team. First we will give an order of magnitude of the aerosol index at Dakhla, Marrakech, Izana and Santa-

Cruz during a long period of time, from 1997 until 2005. We can see from figure 2 that Dakhla's index is very high, the index at Marrakech is moderate and at Izana and Santa-Cruz, it is relatively low. Santa-Cruz is located exactly at the border of two TOMS pixels. In figure 2, $AI_{Santa\text{-}Cruz}$ is related to the index of the joint pixel of Izana, and for the regression analysis, the index at Santa-Cruz is the average index of the two pixels.

Annual behaviour of the index (figure 2) depicts evident seasonal effects with maximum in summer and minimum in winter. In summer time high AOD events occur in this region of the world due to its proximity to the Saharan desert. However with different magnitudes depending on the geographic position, thus Dakhla receives more Saharan dust than Marrakech and Santa_Cruz and Izana. Linear regression analysis has been performed, between sun photometer and TOMS data, individually in every station; the results are illustrated in table 1. The derived relationships can be applied to this long term record of the EP TOMS to convert the AI to AOT. Then we can have inter-annual and intra-annual variability of the AOT for a decade.

Linear regression analysis are performed in the form :$AOT_{AERONET}=A*AI+B$. The linear annual and seasonal relationships between AOT and AI are illustrated in table 1; A; is the slope, B; the intercept, N; the number of data with coincident AOT and AI, and the average AOT, and AI for the full range of data. TOMS maximum absolute error bounds are within 95% confidence level to the TOMS calculated AOT. The period studied for every site is the duration of availability of AERONET data. The AOT considered are the daily average ones, instead of overpass time values, because daily variability from daily means are less than 10% [Smirnov et al, 2002].

The sun photometer at Dakhla was functioning during the years 2002, 2003 and 2004, with some months of non availability during this period. Data of 2002 and 2003 are level 2 data and data of 2004 are level 1.5. The TOMS index at Dakhla is from the Earth Probe only, because the OMI index was available since the end of 2004. Since most of the AERONET data are level 2, we did not remove the days where the number of measurements is less than ten, like we did at Izana and Santa-Cruz where the data are level 1.5. At Marrakech, Izana and Santa-Cruz, the index used is from Earth Probe and OMI platforms.

The annual average of the EP index is 1.90 for Dakhla (2002-2003-2004), 1.03 for Marrakech (2004-2005), 0.82 for Santa-Cruz (2005) and 0.82 for Izana (2004-2005), the corresponding AOT averages are, 0.33, 0.27, 0.22 and 0.09. Izana being at high altitude, its AOT is very low, 2.5 times lower than the average at Santa-Cruz. AOT at Dakhla is very high because it is often in the pass of dust storms from the desert to the Atlantic. The slope for Dakhla is 0.12, the same as the one for Santa-Cruz. The slope depends on absorption properties and the height of the aerosol layer. If the aerosols at Dakhla are more absorbent than the aerosols at Santa-Cruz, then they should reside at higher altitudes. As the AOT at Dakhla has a maximum value of AOT higher than the one of Santa-Cruz, then the corresponding single scattering albedo should be different. We expect that the slope of Izana is lower than Santa-Cruz one because its AOT is low. The slope at Marrakech is 0.07, which is a low value. One reason for that may be because the data are related to the summer-autumn period and do not cover the whole year, or may be because the AOT versus AI scattergram for 2005 has wide dispersions. The summer mean AOT at Dakhla is very high, 0.56; contrasting with spring value, 0.25. One surprising thing is that spring value at Marrakech, 0.35; is higher than spring one at Dakhla. TOMS Earth Probe gives low correlation coefficients for Marrakech (0.53), Santa-Cruz (0.57) and Izana (0.60). However it is performing at Dakhla. We must say that the correlation can be improved if we draw some outliers from the calculation. Except for Dakhla, the TOMS Earth Probe index signal at Marrakech, Santa-Cruz and Izana, during the period studied has very few data for November, December, January and February. The retrieval of winter and autumn AOD is limited.

The seasonal curve of the index (EP for Dakhla and OMI for the others), at all sites, presents minima corresponding to the winter and the autumn, a maximum in summer with for spring an intermediate value. The seasonal one for the AOT is different; for Dakhla, Santa-Cruz and Izana, winter, spring and autumn means are almost the same, with a pick in summer time. At Marrakech, seasonal curve of the AOT has minimum in winter and autumn and maximum in spring and summer. Since at all sites there is not linearity between AOT and AI seasonal curves, the annual relationship is not accurate enough for AOT retrievals. Seasonal relationships should be taken into account for the AOT retrieval over the past. An adjustment between the different TOMS instrument have to be done first.

Seasonal analysis is possible with TOMS OMI index because data are available throughout the year. The correlations between TOMS OMI and AERONET at Santa-Cruz and Izana (R ranges from 0.68 to 0.89) are good, whereas at Marrakech, winter and autumn gave no specific relation. Therefore, we can ask the question why TOMS OMI is performing over the Canary Islands and not that much over Marrakech? It may be that the aerosol layer over Marrakech in winter and autumn resides at low altitudes within the sensing limits of the TOMS instrument. Indeed the average single scattering albedo (SSA) is 0.81 for Dakhla, 0.85 for Santa-Cruz and Izana and is 0.91 for Marrakech. Since Marrakech has the highest SSA then its aerosol layer may reside at lower altitudes than the other sites. Another reason for that may be the topography of the pixels; Marrakech's pixel is much contrasted with mountains as high as 4000 m, whereas the pixels for Izana and Santa-Cruz have more than 75% oceanic surfaces. Homogeneous surface reflectivity increases the sensing performances of satellite remote sensors, though it have been reported that the surface reflectivity in the near UV has a negligible influence. During high AOT events in summer time, the sensing performance is increasing despite non-homogeneities in surface topography.

TOMS data have been used from astronomers; [Siher et al, 2004] found good correlation between TOMS index and light astronomical extinction over La Palma observatory, however debated [Varela et al; 2004]. We must say that the effect of the Mont Pinatubo volcano has been detected for more than two years from all observatories in the world and that the TOMS did not clearly detect such an event. TOMS (EP or Nimbus7) is not a very useful tool for site characterization , OMI , MODIS and MISR have better resolution than TOMS but not enough at particular abrupt topography sites, unless high level (smaller than 2) satellite data are used.

3-2 MISR-AERONET and MODIS-AERONET AOT correlation.

We will examine monthly values because MISR provides weekly values and MODIS TERRA provides one value every two days. The data were collected from the GIOVANNI MOVAS interface that provides monthly global level-3 products (MIL3MAE for MISR and MODO8_03 for MODIS) at 1*1 degree grid average. The MODIS AOT is at λ=550nm and the MISR one is at λ=557.5nm. The aerosol optical thickness from AERONET is at the wavelength λ=440nm because the 500 nm channel is not available in all sites. The results of linear regression analysis between the MODIS or MISR retrieved AOT and AERONET observations, in the form $AOT_{satellite}=A*AOT_{AERONET} + B$, are illustrated in Table 2; R is the correlation coefficient, N, the number of months studied and corresponding means of AOT retrieved by satellite: SAOT and measured by sun photometer: AOT.

We can see from figure 3 the good agreement between ground based AOT and both satellite AOT at Dakhla. This is confirmed by the good correlations; R=0.84 for AERONET-MISR linear relationship and R=0.92 for the AERONET-MODIS one. Both satellite instruments overestimate the aerosol optical thickness at Dakhla. The slope after adjusting the wavelengths (440 nm and 550 nm) is 1.2 for MODIS and 1.16 for MISR. The retrieval algorithms seem to have acceptable assumptions about surface reflectance and do not exhibit a significant calibration error.

At Marrakech, MODIS aerosol optical depth is in good agreement with AERONET AOT, the correlation coefficient is R=0.85. The MISR AOT doesn't give as good correlation coefficient; R=0.77 and underestimates the AOT especially during 2005 and 2006. The slope after adjusting wavelengths is 0.98 for MODIS and 0.83 for MISR. A slope different from unity indicates that there might be some inconsistency between aerosol microphysical and optical properties used in the retrieval algorithms and that in the real situation. Slopes slower than unity indicate an underestimation of AOT by MISR with respect to AERONET retrieval. Low intercepts suggest that there are low calibration errors. According to these results, we can deduce that MODIS is the best candidate to characterize the AOT of Marrakech.

At Santa-Cruz, we can see that unlike Marrakech, now the MISR data follow the AERONET curve better than MODIS. For MODIS, first the correlation coefficient is R=0.68, A=0.54 (for λ=550 nm) and B=0.12. This indicates an important underestimation of the AOT by MODIS retrieval algorithm, due to improper assumptions of the aerosol physical properties of that region. There is a bias for low aerosol loadings which indicates a calibration error or an improper assumption about surface reflectance. Indeed the MODIS retrieval algorithm is based on the "dark object method" [Kaufman et al 2002]. There are two key requirements associated with this method: (1) existence of large homogeneous dense vegetation in the scene, (2) stable empirical relationships of surface reflectance between band 7 and band 3 and 1. The first requirement precludes the accurate reflectance retrieval of surfaces with non-dense vegetation canopies. To meet the second requirement, dense vegetation canopies have to be distinguished from other dark objects, such as wet soil and water. The correlation coefficient for MISR is good, R=0.88, and the slope A=1.25 (λ=550 nm), it overestimates the AOT at Santa-Cruz. This instrument is suitable for sensing aerosol loading over Santa-Cruz. The aerosol optical thicknesses measured with sunphotometers at Izana and Santa-Cruz are in very good correlation as well illustrated in the section altitude effect. We expect, like at Santa-Cruz, good correlation between sun photometer and MISR signals. Izana and Santa-Cruz are in the same MISR and MODIS pixel, they have the same satellite aerosol optical thicknesses. Izana being at high altitude, its aerosol optical thickness is very low. Satellite measurements do not see the high altitude contribution as long as the pixel topography is mostly constituted by low altitude land.

MISR overestimates the AOT over ocean [Mischenko et al; 2007] and maybe underestimates the AOT over topography contrasted areas. Meanwhile MODIS seems more performing over contrasted land surfaces in North Africa. From seasonal statistics for Santa-Cruz, the MISR AOD is overestimated in summer and underestimated in winter.

4- Altitude effect

Vertical distribution of aerosol properties is not well understood; there is no systematic way of deducing aerosol microphysical and optical properties at a given height from aerosol properties measured on the ground just below. Active sensors like LIDAR can give the average position of the aerosol layer. In this section we will focus on AERONET AOT at Izana and Santa-Cruz and make regression analysis. As the AERONET data at Santa-Cruz and Izana are level 1.5 and then are not manually inspected, we remove from the statistics the days where the number of measurements is less than ten. The AOT magnitude of Santa-Cruz is always higher than the AOT at Izana. They have the same oscillation with magnitude depending on the season. The daily mean aerosol optical thickness of

Santa-Cruz and Izana exhibits a good linear correlation with a Pearson correlation coefficient of 0.92 for both years 2005 and 2006. The seasonal correlation coefficients are 0.85 for winter, 0.87 for spring, 0.91 for summer and 0.87 for autumn. The linear relationships (annual from daily means, annual from monthly means, annual from seasonal means, seasonal) are illustrated in table 3 ($AOT_{Izana}=A*AOT_{Santa\text{-}Cruz}+B$) with corresponding correlation coefficient, number of measurements and AOT means.
Like for previous regressions, as the seasonal curves of Santa-Cruz and Izana (table 3) are not strictly linear, seasonal regression analysis have to be performed for accurate estimate of the AOT. From this table we can see that the annual average of Izana is 0.08 which is very low aerosol loading, we must say that the corresponding histogram is very sharp with 75% of the frequency occurring for AOT less than 0.05. At Izana, the corresponding averages for winter, spring and autumn are respectively; 0.035, 0.06 and 0.05, exhibiting good astronomical observation qualities in term of sky transparency. Santa-Cruz annual mean is 0.21; 2.6 times higher than Izana's annual average and at 0.13 from Izana's annual average. The subtraction of the seasonal AOT at Santa-Cruz and Izana is 0.165 for winter, 0.109 for spring, 0.126 for summer and 0.129 for autumn.
The aerosol optical thickness at Santa-Cruz expressed with surface layer extinction coefficient α is:

$$AOT_{Santa-Cruz} = \int_{Ground}^{Top\ atmospher} \sigma(h)\, dh = \int_{Ground}^{h(Izana)} \sigma(h)dh + \int_{h(Izana)}^{Top\ atmospher} \sigma(h)\, dh = AOT_{background} + AOT_{Izana}$$

$AOT_{background}$ represents the subtraction of the aerosol optical depths at Santa-Cruz and Izana; its annual average is about 0.13; with a higher average of 0.16 in winter and a lower one of 0.11 in spring.
Steady AOT values often occurs at Izana during winter and autumn and high AOT events often occur in summer time. Santa-Cruz seems to see more AOT events during all the year with a magnitude depending on the season. The plume altitude distribution should have its maximum higher than Izana's altitude in summer time and lower in winter. Figures (4-a and 4-b) shows the behaviour of the monthly and seasonal mean AOT values respectively; we can see clearly very low values at Izana compared to Santa-Cruz. Seasonal behaviour is also clear with low AOT values in winter time, increasing in spring time to a maximum in the early summer and decreasing during summer and autumn to a minimum value in the following winter. Inter annual variability in the seasonal shape is visible with lower 2006 spring AOT means than winter ones. The ratio $AOT_{Santa\text{-}Cruz}$ /AOT_{Izana} has seasonal variation from 2 in summer time to 4.5 in winter.

5- Retrieval of Aerosol optical thickness and light extinction coefficient at Oukaïmeden observatory.

First, we want to confront long term satellite aerosol loading previsions from different instruments. Figure 5 illustrates the average aerosol optical thicknesses of MODIS and MISR instruments from 2000 until 2006. These images (MODIS and MISR) were acquired using the GES-DISC Interactive Online Visualization and Analysis Infrastructure (Giovanni) as part of the NASA's Goddard Earth Sciences (GES) Data and Information Services Center (DISC). MISR AOT forecast for the Canary Islands and the Moroccan coasts is between 0.2 and 0.3, and between 0.1 and 0.2 for the interior of Morocco. However, MODIS forecasts values between 0.2 and 0.3 for most of the Moroccan territories except a small area (AOT between 0.1 and 0.2) included between 7° to 5° W and 31.5° to 33.5° N corresponding to a part of the Atlas mountains. In order to compare all the satellite data we have to convert the TOMS EP index into aerosol optical depth; SAOT. Figure 6 shows the scattergramm of all the AERONET data in this area and their corresponding TOMS EP index. The corresponding linear relationship is:
$SAOT= 0.11(\pm0.01)*AI\_EP + 0.11(\pm0.02)$ The correlation coefficient is R=0.61
The mean retrieved SAOT from 1997 to 2005 is illustrated in figure 7 (a). Figure 7 (b) shows the inter-annual variability of the SAOT during the period 1997-2005
From figure 7, the mean SAOT during 1997-2005 in the Canary Islands and north Morocco is below 0.2 and greater than 0.15 with an inter-annual variability approximately of 0.04 for the Canary Islands and 0.06 for north Morocco.
Now we will try to retrieve the AOT at Oukaimeden; a Mororccan observatory, near Marrakech city at 2760 m of altitude. To retrieve monthly values from MODIS and MISR measurements, we can use the relationships related to Izana:
$AOD_{AERONET}= 0.35(\pm0.16)AOD_{MODIS} - 0.006(\pm0.035)$
$AOD_{AERONET}= 0.22(\pm0.08)AOD_{MISR} + 0.02(\pm0.02)$
Retrieved monthly values from AERONET measurements at Marrakech are extracted from relationships in table 3 related to monthly means. Daily values can be retrieved from AERONET and from TOMS index .To have better estimation of daily values we can use seasonal relationships. From figure 7 (a), we can see that MODIS and AERONET retrievals are in good agreement. We have already noticed that the MISR signal underestimates the AOT around Marrakech (section 3-2), whereas the MODIS signal gives a better estimation. Figure 7 (b) illustrates daily retrievals from TOMS OMI and from AERONET for the year 2005. We can notice the good agreement of the two signals for spring and summer time as previously reported. Daily values relation overestimates the AOT because the

probability distribution of AOT at higher altitudes is sharp whereas it is broad at lower altitudes. Linear relationship from lower altitudes to higher altitudes does not give sharp AOT distribution.
Now we will try to retrieve the astronomical light extinction coefficient over the observatory where in-situ measurements have been achieved there; in 1997 [Benkhaldoun et al; 1998; Siher et al; 2002]. The only way we have to go back in time is the TOMS EP index. We have already said that it gave the lowest correlation coefficients and that winter and autumn retrievals are not accurate. TOMS EP stops functioning at the end of 2005 because of calibration problems. We transformed the TOMS EP index to aerosol optical thickness first using the relation related to Izana in order to account for altitude contribution. Then, since the measurement at the observatory have been done at 589 nm wavelength, we transformed the 440 nm AOT retrieved to 589 nm AOT using climatology table of Izana from AERONET database. The result is illustrated in figure 9 where we added the astronomical light extinction coefficient of La Palma for the same year. The measurements of the light astronomical extinction coefficient have been done at La Palma using stellar photometry and at Oukaimeden using daytime photometry from IRIS (International Research of the Interior of the Sun) database. The value corresponding to September is very low, we think it is a bad data; the corresponding number of days of measurements is 9. The average of the retrieved extinction coefficient is 0.14 mag/air mass; the same as the measured one at La Palma. The average value at Oukaimeden is 0.1mag/air mass.

6- Conclusion and perspectives

In this work we have characterized sky transparency by means of aerosol optical properties trough the aerosol optical thickness parameter in the area of Morocco and the Canary Islands. Ground based measurements are provided by the AERONET Network in four locations: Dakhla, Marrakech, Santa-Cruz and Izana. TOMS Earth Probe aerosol index have been used to have long term aerosol cover in the four AERONET stations. Seasonal effects of aerosol cover have been clearly demonstrated through ten years of aerosol index variations. A relationship involving all AERONET data and their corresponding TOMS Earth Probe index have been used to transform the TOMS EP index into 'SAOT' satellite aerosol optical thickness. The area of Morocco and the Canary islands have been mapped with inter-annual variations for a long term study. We also used other satellite products like TOMS OMI aerosol index, MODIS and MISR aerosol optical thicknesses. A set of linear relationships have been established between ground measurements and satellite data, individually in every station, for all available ground measurements. Then an inter-comparison of satellite products was conducted. The Pearson correlation coefficient for TOMS OMI, MISR and MODIS vary from 0.68 to 0.92 and from 0.54 to 0.74 for TOMS Earth Probe. Izana is very close to Santa-Cruz (30 km), but 2300m higher in altitude. Their corresponding ground aerosol optical thickness are in very good correlation (R=0.92), however AOT Izana have small value with a very sharp histogram around 0.05 and AOT Santa-Cruz has wider histogram. Izana is the key station for this paper as we will use its relationships to extrapolate AOT values at elevated places. We retrieve the AOT parameter at Oukaimeden; a Moroccan observatory near Marrakech city, at 2760 m above sea level. We also retrieved light extinction coefficient for the year 1997 and compare with in-situ measurements achieved at the observatory at that time. The discrepancies between the measured and calculated light extinction coefficient in the autumn and winter months can be explained in terms of the seasonal behaviour of dust distribution and the poor spatial resolution of the TOMS EP. Satellite data with larger spatial and spectral resolutions are required to derive a reliable AOT for pre-selected ELT sites.

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Figure 1: map showing sites under study (red arrow).

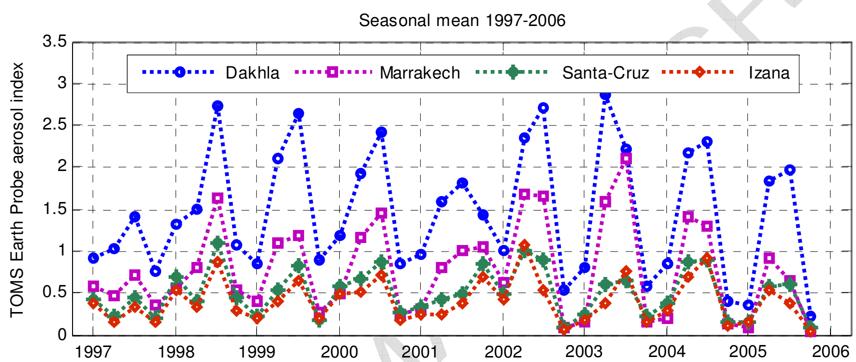

Figure 2: seasonal aerosol index values at Dakhla, Marrakech, Izana and Santa-Cruz, since 1997 until the end of 2005.

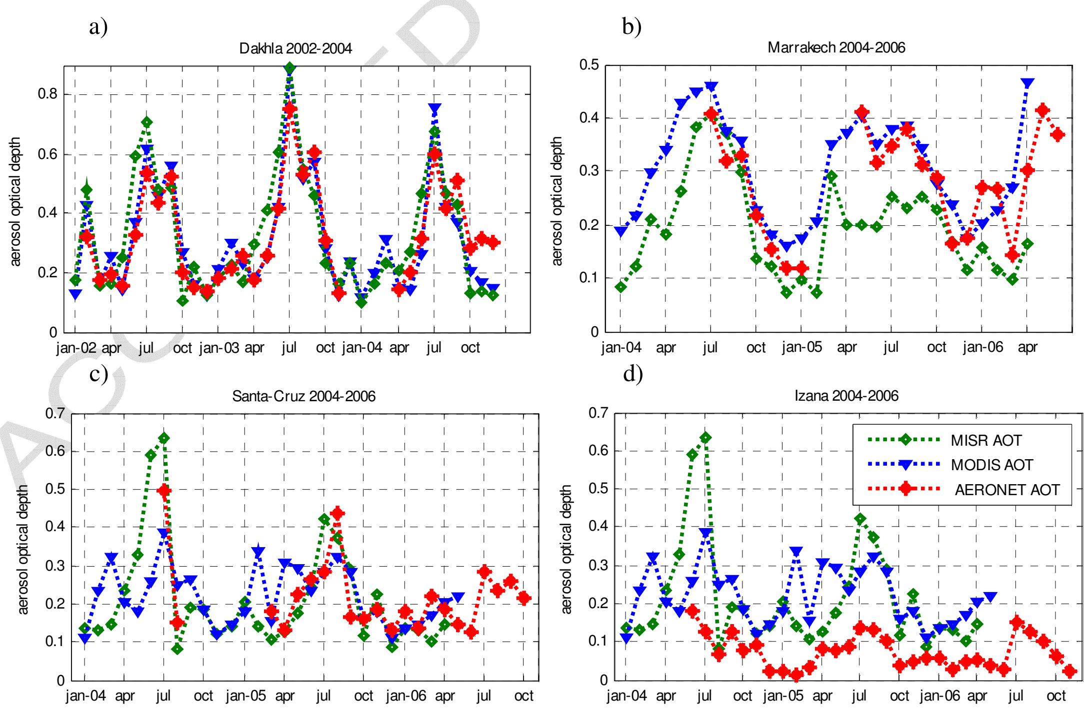

Figure 3: AERONET, MODIS and MISR aerosol optical thicknesses at a) Dakhla, b) Marrakech, c) Santa-Cruz, and d) Izana.

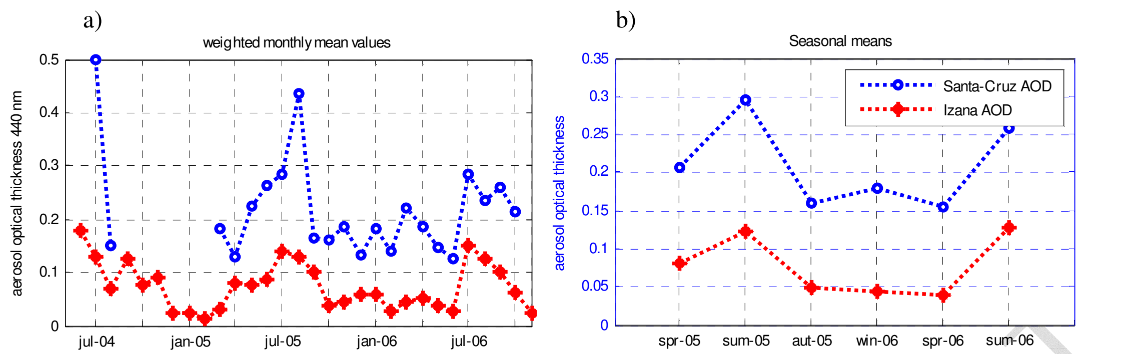

Figure 4: Time evolution of the monthly mean (a) and seasonal AOD values at Santa-Cruz and Izana (b).

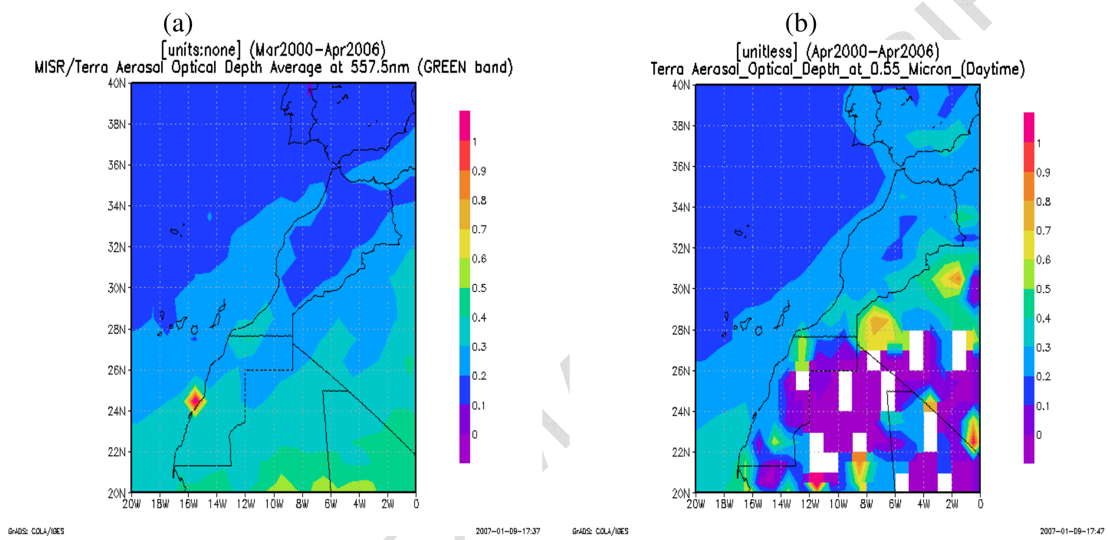

Figure 5: MISR (a) and MODIS (b) mean aerosol optical thickness during the period 2000-2006.

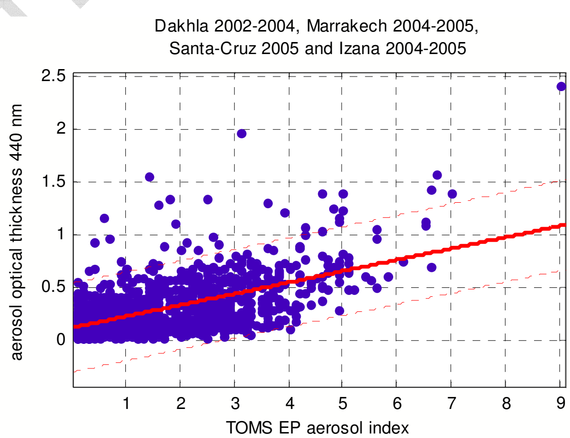

Figure 6: scattergramm of all the AERONET AOT and the corresponding TOMS EP AI in Morocco and the Canary Islands

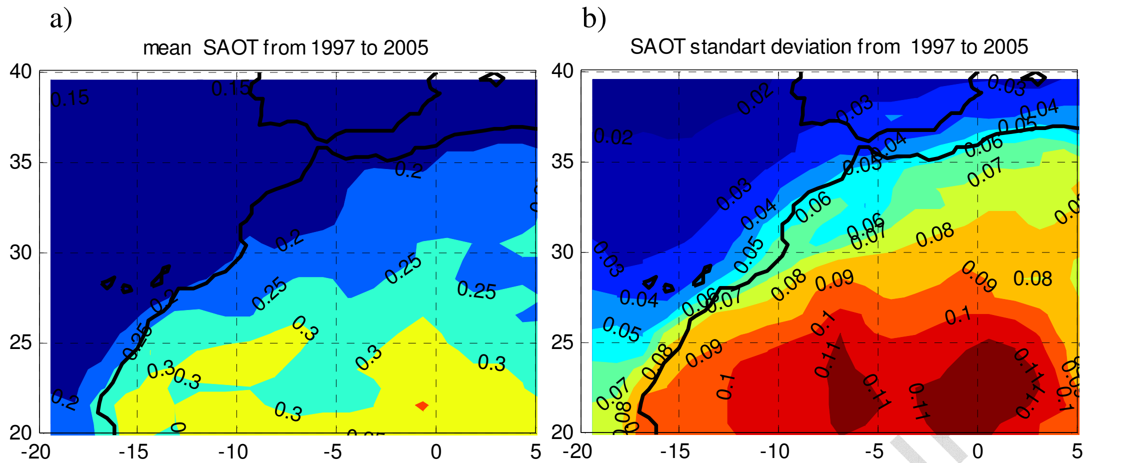

Figure 7: TOMS EP mean retrieved aerosol optical thickness SAOT from 1997 to 2005 (a) and the inter-annual variability of the SAOT during that period.

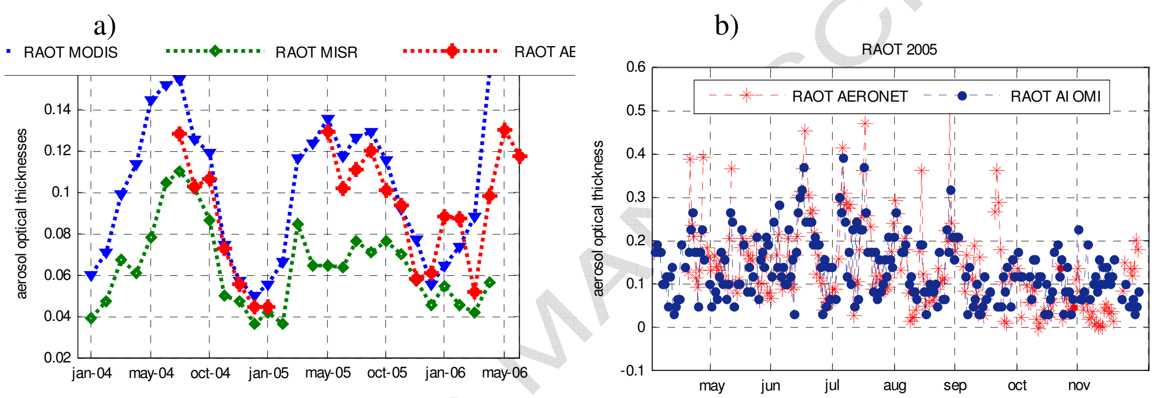

Figure 8: Retrieval of monthly values near Marrakech (a) from monthly values MODIS, MISR and AERONRT, (b) from daily values from TOMS OMI index and AERONET (year 2005).

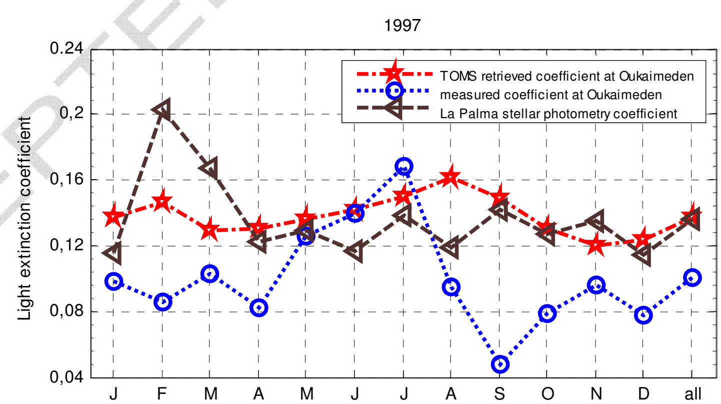

Figure 9: light extinction coefficient measured and retrieved at Oukaimeden observatory, with comparison with La Palma measured coefficient.

	Dakhla (2002-2003-2004)						Marrakech (2004-2005-2006)					
	A	B	R	N days	AI mean	AOT mean	A	B	R	N days	AI mean	AOT mean
Annual (TOMS EP)	0.12(±0.01)	0.04(±0.03)	0.68	660	1.90	0.34	0.07(±0.02)	0.25(±0.03)	0.53	205	1.03	0.27
Annual (TOMS OMI)	No data	No data					0.23(±0.03)	0.13(±0.02)	0.68	303	0.67	0.28
Winter (TOMS OMI)	0.10(±0.04)	0.08(±0.05)	0.41	114	0.99	0.22	No relation	No relation		63	0.38	0.19
Spring (TOMS OMI)	0.11(±0.02)	-0.07(±0.04)	0.70	224	2.60	0.25	0.22(±0.06)	0.18(±0.05)	0.65	86	0.67	0.35
Summer (TOMS OMI)	0.15(±0.02)	0.04(±0.08)	0.68	197	3.12	0.56	0.29(±0.06)	0.09(±0.05)	0.73	88	0.94	0.35
Autumn (TOMS OMI)	0.16(±0.03)	0.09(0.03)	0.71	126	0.79	0.24	No relation	No relation		66	0.48	0.20
	Santa-Cruz (2005-2006)						**Izana** (2004-2005-2006)					
	A	B	R	N days	AI mean	AOT mean	A	B	R	N days	AI mean	AOT mean
Annual (TOMS EP)	0.12(±0.05)	0.15(±0.03)	0.57	28	0.82	0.22	0.07(±0.02)	0.05(±0.04)	0.60	149	0.82	0.09
Annual (TOMS OMI)	0.24(±0.03)	0.09(±0.03)	0.85	130	0.79	0.21	0.18(±0.01)	0.01(±0.01)	0.88	211	0.64	0.08
Winter (TOMS OMI)	0.24(±0.12)	0.14(±0.10)	0.82	11	0.55	0.19	0.09(±0.04)	0.02(±0.02)	0.68	25	0.47	0.035
Spring (TOMS OMI)	0.19(±0.09)	0.15(±0.08)	0.68	24	0.80	0.17	0.18(±0.03)	0.006(±0.02)	0.89	48	0.58	0.061
Summer (TOMS OMI)	0.25(±0.03)	0.08(±0.04)	0.87	66	1.03	0.26	0.18(±0.05)	0.03(±0.02)	0.89	99	0.85	0.134
Autumn (TOMS OMI)	0.24(±0.07)	0.06(0.04)	0.83	28	0.54	0.18	0.13(±0.04)	0.01(±0.02)	0.72	39	0.48	0.051

Table 1: AERONET aerosol optical thickness and TOMS (EP and OMI) index linear relationship from daily values AOT=A*AI+B with corresponding correlation coefficient R, number of data N with coincident AOT and AI, average index and average AOT for the corresponding full range of data. Each station has its own time domain indicated on the corresponding header.

	Dakhla (2002-2003-2004)						Marrakech (2004-2005-2006)					
	A	B	R	N months	AOTS	AOT	A	B	R	N months	AOTS	AOT
MODIS	1,14(±0.18)	-0.02(±0.06)	0.92	31	0.33	0.32	0.89(±0.28)	0.06(±0.08)	0.86	19	0.30	0.26
MISR	1,10(±0.27)	-0.01(±0.09)	0.85	31	0.35	0.32	0.75(±0.32)	-0.005(±0.09)	0.77	19	0.19	0.26
	Santa-Cruz (2005-2006)						**Izana** (2004-2005-2006)					
	A	B	R	N months	AOTS	AOT	A	B	R	N months	AOTS	AOT
MODIS	0.50(±0.30)	0.12(±0.07)	0.68	17	0.23	0.21	1.49(±0.66)	0.11(±0.05)	0.73	24	0.073	0.22
MISR	1,16(±0.36)	-0.04(±0.09)	0.88	16	0.21	0.22	2.69(±1.38)	0.02(±0.12)	0.77	23	0.072	0.21

Table 2: AERONET AOT with MODIS AOT and MISR AOT linear relationships from monthly values $AOT_{satellite}=A*AOT_{AERONET}+B$ with corresponding correlation coefficient R, number of months N, and corresponding average SAOT satellite AOT and average AERONET AOT.

	Santa-Cruz/Izana AERONET AOT relationships (2005-2006)					
	A	B	R	N	<AOT> Santa-Cruz	<AOT> Izana
Annual daily values	0.59(±0.03)	-0.04(±0.01)	0.92	255 days	0.21	0.08
Monthly values	0.29(±0.13)	0.01(±0.03)	0.71	22 months	0.22	0.07
Seasonal values	0.67(±0.28)	-0.06(±0.06)	0.96	6 seasons	0.21	0.08
Winter	0.39(±0.09)	-0.02(±0.02)	0.85	33 days	0.20	0.035
Spring	0.46(±0.06)	-0.02(±0.01)	0.87	83 days	0.17	0.061
Summer	0.64(±0.06)	-0.03(±0.02)	0.91	100 days	0.26	0.134
Autumn	0.50(±0.09)	-0.03(±0.03)	0.87	39 days	0.18	0.051

Table 3: Linear relationships between AERONET AOT Santa-Cruz and Izana from daily values $AOT_{Izana}=A*AOT_{Santa\text{-}Cruz}+B$ with corresponding correlation coefficient R, number of data N, and corresponding average AOT.