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Global aerosol remote sensing from MODIS

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Abstract

Global aerosol concentration and size parameters derived from MODIS sensors onboard the Terra and Aqua satellites are continuously being evaluated with ground-based measurements and used for various aerosol studies. These parameters have enabled a two-year assessment of aerosol loading and seasonal trends over several important regions on land and ocean, based on $5 \times 5°$ monthly averages. Similar studies were conducted at higher spatial (50×50-km) and temporal (daily) resolutions over selected sites representative of pollution, smoke, dust, and sea-salt aerosol types. Also, a two parameter clustering technique has been employed successfully for categorizing the predominant aerosol types and events affecting selected locations over the Atlantic and Pacific Oceans. In addition, results of regional aerosol radiative forcing calculations over a few regions are reported.

Keywords: Aerosol remote sensing; MODIS; Aerosol concentration and size parameters; Regional aerosol radiative forcing

1. Introduction

The study of atmospheric aerosols is a very important element to understanding the earth's solar radiation budget, water cycle balance, and climate change dynamics. Aerosol particles in the atmosphere scatter and/or absorb earth-bound solar radiation as well as emitted and reflected radiation from the earth, to different degrees, depending on their chemical and physical properties. Also, certain aerosol types interact with cloud droplets, modifying their microphysical properties, thereby influencing their radiative properties and precipitation processes.

As a crucial step toward the understanding of the complex effects of aerosols in the atmosphere, aerosol properties and distribution should first be quantified accurately. Aerosol parameters can be measured in situ or by remote sensing from the ground, aircraft, or satellite. All these methods are important and complementary. However, this study employs satellite remote sensing, which offers the advantage of providing the most extensive coverage in the shortest time interval, thereby allowing for better tracking of regional and global distribution of aerosols, which are extremely dynamic in nature. Since the last several years, many attempts have been made to retrieve certain aerosol properties from satellite data, with some limitations (see Kaufman et al., 1997a for detailed review). Recently, Kaufman et al. (2002) published a treatise on the important role of satellite sensors in providing the much needed aerosol information for global climate studies.

The physical characteristics, composition, abundance, spatial and temporal distribution, as well as the dynamics of global aerosols are still not well known, and new data from satellite sensors can be used to improve current understanding and to give a boost to the effort in future climate predictions. The derivation of aerosol parameters from the MODerate resolution Imaging Spectro-radiometer (MODIS) sensors onboard the Earth Observing System (EOS) Terra and Aqua polar-orbiting satellites ushers in a new era in aerosol remote sensing from space. Terra and Aqua were launched on December 18, 1999 and May 4, 2002, respectively, with

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daytime equator crossing times of approximately 10:30 am and 1:30 pm, respectively. MODIS acquires data globally at 36 spectral bands, which range from the visible to the thermal infrared wavelengths. The data for each band are acquired in one of three spatial resolutions (250, 500, and 1000 m). Numerous parameters describing various properties of physical features on land and ocean surfaces as well as in the atmosphere are retrieved operationally from MODIS data at different spatial and temporal resolutions. Several aerosol parameters are retrieved at 10-km spatial resolution from MODIS daytime data. The MODIS aerosol algorithm employs separate approaches to retrieve parameters over land (Kaufman et al., 1997b) and ocean (Tanré et al., 1997) surfaces, because of the inherent differences in the solar spectral radiance interaction with these surfaces. The parameters retrieved include: aerosol optical thickness (AOT or $\tau_{a\lambda}$) at several wavelengths (λ) and Ångstrom exponent (Aexp or α) over land and ocean; and effective radius (r_{eff}), and the proportion of AOT contributed by the small mode aerosols over ocean. To assess the quality of these parameters, a substantial part of the Terra-MODIS aerosol products acquired in 2000 were validated globally and regionally, as reported in Chu et al. (2002), Ichoku et al. (2002), and Remer et al. (2002). The validation process has been continuously developed, in order to ensure high quality for the products. Similar validation programs are being implemented for the Aqua-MODIS aerosol products as well. The MODIS 10-km resolution aerosol products are operationally aggregated to generate global daily, eight-day (weekly), and monthly products at 1° spatial resolution.

MODIS aerosol data are useful for detailed studies of local, regional, and global aerosol loading, distribution, and temporal dynamics, as well as for radiative forcing calculations. Ichoku et al. (2003) reports the result of MODIS aerosol studies applied to the southern African region within the context of the Southern African Fire-Atmosphere Research Initiative (SAFARI) 2000 campaign. Levy et al. (2003) conducted a detailed study of Saharan dust transport to the Caribbean, based on the combination of ground-based, airborne, and MODIS data acquired over Puerto Rico and surrounding areas during the 2001 Puerto Rico Dust Experiment (PRIDE-2001). In addition, MODIS data featured very prominently in the studies reported by Kaufman et al. (2002).

This paper presents the application of MODIS data to the study of aerosol column burden and size properties at global, regional, and local scales during the two-year period from August 2000 to August 2002, approximately. We demonstrate the utility of MODIS aerosol products for studying the global aerosol distribution over land and ocean, at different spatial and temporal resolutions.

2. MODIS aerosol retrieval and validation

One of the greatest difficulties in aerosol remote sensing from space involves the isolation of the portion of the solar radiance reflected by the atmosphere (path radiance) from the total radiance observed by the satellite-sensor at the top of the atmosphere (TOA). The total radiance includes inputs from both the atmosphere and the land or water surface beneath it. Once the path radiance is recovered, radiative transfer equations are employed in deriving the aerosol size distribution and column burden, based on appropriate aerosol models. The MODIS aerosol algorithm has two components, one adapted for retrieval over land (Kaufman et al., 1997b), and the other for retrieval over ocean (Tanré et al., 1997). They both include several processes of statistical data sampling and pixel aggregation, as well as masking for clouds, snow (over land), and sun-glint (over ocean). Since the launch of the first MODIS on Terra, the algorithms have undergone slight changes to adapt better to the post-launch data quality and calibration, and to improve their ability to filter out environmental influences such as clouds (Gao et al., 2002; Martins et al., 2002), snow, ice, muddy water, and sun-glint.

2.1. Characteristics of MODIS aerosol products

In the MODIS data processing hierarchy, level 2 products are geophysical parameters derived directly from MODIS radiance data (which are categorized as level 1B). The level 2 aerosol products are operationally derived at 10-km pixel spatial resolution from MODIS radiance data daily. Table 1 shows a list of the main aerosol parameters retrieved over land or ocean. Some of the parameters are listed with their specified or achieved accuracies where available. Selected parameters of the level 2 aerosol products are further aggregated into 1° spatial resolution global products at daily, weekly (eight-day), and monthly temporal resolutions. These are referred to as the level 3 aerosol products. They are suitable for large regional or global studies.

2.2. Validation of MODIS aerosol products

MODIS level 2 aerosol products are being validated using data acquired with AErosol RObotic NETwork (AERONET) ground-based sun-photometers, located in approximately 200 continental or island sites around the world (Holben et al., 1998, 2001), although not all stations are occupied all the time. Most AERONET sun-photometers are programmed to observe AOT at several wavelengths at intervals of 15 min during the daytime, and achieve an AOT accuracy of ±0.01 to ±0.02 (Holben et al., 1998, 2001). Cloud filtered AERONET AOT data are used to validate MODIS AOT, usually by cross-correlating the spatial statistics of 50×50-km

Table 1
MODIS main aerosol parameters (10-km pixel resolution: level 2)

Parameter	Over land characteristics	Over ocean characteristics
Total column aerosol optical thickness (AOT or $\tau_{a\lambda}$)	At 470, 550, 660 nm wavelengths. Accuracy: $\pm(0.05 + 0.2\tau_{a\lambda})$ (Chu et al., 2002)	At 470, 550, 660, 870, 1200, 1600, 2100 nm wavelengths. Accuracy: $\pm(0.03 + 0.05\tau_{a\lambda})$ (Remer et al., 2002)
Fraction of small mode to total AOT	At 550 nm	At 550 and 870 nm wavelengths. Accuracy: ±0.25 (Tanré et al., 1997)
Small mode AOT	None	At 470, 550, 660, 870, 1200, 1600, 2100 nm wavelengths
Large mode AOT	None	At 470, 550, 660, 870, 1200, 1600, 2100 nm wavelengths
Aerosol particle effective radius (r_{eff})	None	At 550 nm wavelength. Accuracy: $\pm 0.3 r_{eff}$ (Tanré et al., 1997)
Ångstrom exponent (α)	At 470–660 nm (visible)	At 470–660 nm (visible), and 870–2100 nm (infrared) wavelength ranges
Reflected flux	At 470, 550, 660 nm	At 470, 550, 660, 870, 1200, 1600, 2100 nm wavelengths
Transmitted flux	At 470 and 660 nm	At 470, 550, 660, 870, 1200, 1600, 2100 nm wavelengths
Cloud condensation Nuclei (CCN)	None	At 550 nm wavelength
Aerosol mass concentration (g/cm^2)	Yes	Yes

subsets of MODIS aerosol data centered over AERONET stations against corresponding temporal statistics of AERONET data acquired within ±30 min of the MODIS data acquisition time (Ichoku et al., 2002). Data derived in this way were used to validate early Terra-MODIS data acquired over land (Chu et al., 2002) and over ocean (Remer et al., 2002).

Fig. 1 shows the validation of a much larger data set derived from MODIS over all AERONET stations around the world, from the inception of MODIS data acquisition (February 2000 for Terra-MODIS and June 2002 for Aqua-MODIS) until August 2002. To avoid undue clutter from direct scatterplots, the MODIS data were first regrouped on the basis of AERONET data bins at class intervals of 0.2 AOT (i.e., 0–0.2, 0.2–0.4, 0.4–0.6,...). For each AERONET class, MODIS data means and standard deviations were computed separately for land and ocean and for Terra and Aqua at 470 and 660 nm wavelengths. The matching AERONET AOT at 470 nm were derived by interpolation based on their 440–870 nm Ångstrom exponent (Holben et al., 2001), while the AOT at 670 nm were used directly since 670 nm is considerably close to MODIS's 660 nm. The plots in Fig. 1 show that, in all cases, well over 90% of all observations have AOT values of 0.5 or lower. Over land, at 470 nm, almost all MODIS AOT means fall within the specified accuracy limits for both Terra and Aqua, but, at 660 nm Terra-MODIS appears to have underestimated AERONET for AOT values larger than 0.5. Similar underestimation observed over southern Africa during SAFARI-2000 was attributed to the global generalization of absorption in the initial MODIS smoke aerosol model (Ichoku et al., 2003). That problem was rectified in a recent (late 2002) update of the aerosol algorithm. However, the Terra-MODIS data in Fig. 1 still includes the data set affected by underestimation. The Aqua-MODIS data are much less affected because most of it were acquired and processed after the algorithm was rectified. Other possible explanations for MODIS 660-nm AOT underestimation over land may include systematic inaccuracies in the surface reflectance assumptions and other inaccurate assumptions in the aerosol models.

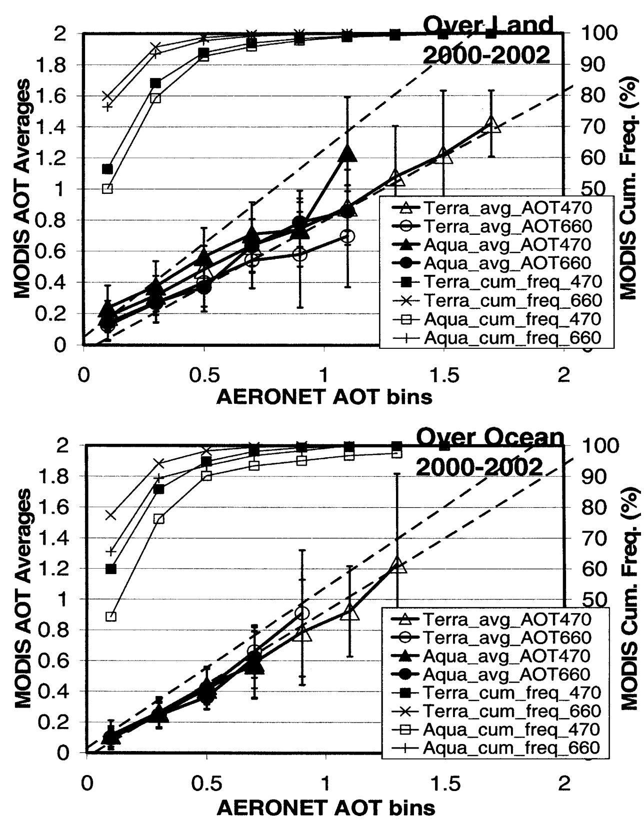

Fig. 1. Validation of MODIS aerosol optical thickness (AOT) at 470 and 660 nm, over land and ocean, for Terra and Aqua using AERONET data, from the inception of each satellite data acquisition to August 2002. Using collocated MODIS (50 × 50-km) and AERONET (1-h) data averages, the AERONET AOT were binned at 0.2 class intervals and the corresponding MODIS AOT averaged and plotted against the bin centers. The standard deviations are plotted as error bars for Terra, but not for Aqua (to avoid excessive clutter, though their values are relatively smaller than their Terra counterparts). The near-diagonal pairs of broken lines represent the boundaries of the ideal accuracy levels. The percentage cumulative frequencies of the MODIS data are also plotted.

Over ocean, although the accuracy specifications are more stringent (narrower space between the pair of near-diagonal broken lines), all class means are either within or very close to the accuracy limits. This is because the over-ocean algorithm has less uncertainty in surface-reflectance and other assumptions. The larger variation (longer error bars) at higher AOT is caused by much larger uncertainty in dust aerosol retrieval due to the complexity of the dust non-sphericity problem, as highlighted previously (Remer et al., 2002; Levy et al., 2003).

3. Aerosol concentrations and size distributions

Like no other existing satellite aerosol products, MODIS aerosol products provide tremendous opportunities to study the characteristics and distribution of aerosols at different spatial and temporal scales over land and ocean. Indeed, MODIS on Terra and Aqua together provide the possibility to observe the aerosols over any given location twice a day and even at a higher frequency for higher latitude locations. Furthermore, because of their wide spectral coverage, MODIS instruments are the first satellite sensors capable of distinguishing coarse and fine aerosol modes, especially over ocean. At visible and near infrared (Vis/NIR) wavelengths (below 900 nm) most aerosols produce significant backscattering, whereas between 1000 and 2200 nm the fine particles are almost transparent while the coarse mode still gives strong signal. MODIS uses this spectral dependence of the fine mode to estimate the proportion of AOT contributed by it. This offers a vast scope for identifying different aerosol types (pollution, smoke, dust, sea-salt), thereby providing the potential to distinguish natural and anthropogenic aerosols and to attain higher accuracy in quantifying aerosol effects on climate (Kaufman et al., 2002).

3.1. Global analysis

Fig. 2 shows a global composite of MODIS level 3 coarse and fine mode AOT at 550 nm, derived using an 11-day Gaussian-weighted mean centered on 11 August 2001. Greenish and reddish colors depict coarse and fine mode aerosols, respectively. By associating these MODIS-derived size modes with external knowledge of typical aerosol source regions and circulation patterns (Husar et al., 1997), it is possible to identify regions dominated by different aerosol types. As an illustration, in Fig. 2, large boxes are used to roughly show the areas dominated by pollution, smoke, and dust aerosols. Apparently, the northern hemisphere mid-latitude belt is mostly affected by pollution, the low-latitude belt by

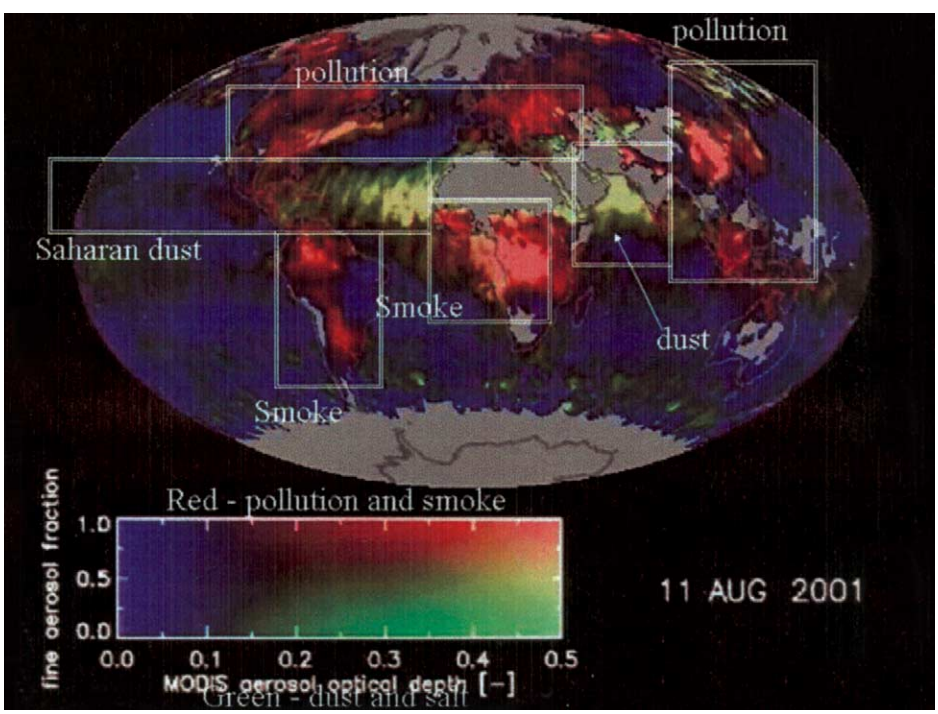

Fig. 2. Global composite of MODIS level 3 (1° spatial resolution) daily coarse and fine mode aerosol optical thickness (AOT) data at 550 nm. The composite is an 11-day Gaussian-weighted mean centered on 11 August 2001. Greenish tints represent areas dominated by the coarse particle mode (dust and/or sea-salt) aerosols, while the reddish tints represent those dominated by fine particle mode (pollution and/or smoke) aerosols. Gray areas do not contain aerosol retrieval during the composited period because the surface (mainly land) is too bright for aerosol retrieval or because the area experiences persistent cloud cover. The boxes are used to roughly indicate the different aerosol-type dominated zones, and do not represent accurate boundaries in any way.

dust, while the southern hemisphere low-latitude belt appears to be dominated by smoke, and the most southerly belt probably by sea-salt.

3.2. Regional analysis

Fig. 3 shows monthly mean AOT at 550 nm derived from the Terra-MODIS level 2 (10-km spatial resolution) aerosol data covering the 2-year period from November 2000 to September 2002. The data represent averages over $5 \times 5°$ regions across different parts of the world's land and ocean, broadly categorized into western and eastern hemispheres. The curves enable a clear quantitative perception of the regional aerosol concentrations and temporal trends. For instance, in the western hemisphere over land, there appears to be very obvious seasonality in aerosol concentrations over the Amazon, West Africa, southern Africa, and the eastern United States. For the Amazon,the peak season is in the August–November time frame, probably due to the intense biomass burning activity which takes place in that region during that time of year. Over West Africa, there appears to be a minor peak around September–October, perhaps, due to the influence of the seasonal biomass burning activities all across the central African sub-region (also perceptible in the mid-August global image in Fig. 2), but the major peaks occur around January–February, probably caused by the intrusion of the Saharan dust into West Africa, a phenomenon referred to as the 'harmattan' (Pinker et al., 1994). Over the eastern United States, the peak pollution season is seen to occur during the summer months (June–August). In the eastern hemisphere, over land, there is also appreciable seasonality over eastern China, eastern Mediterranean, Moscow and surrounding areas, as well as Siberia. The seasonal peak over eastern China is broad, stretching from mid-winter to late summer, the lowest aerosol concentration being in fall. Similarly the seasonal peak over the eastern Mediterranean is broad, portraying the frequent spring-to-summer dust storms prevalent in that region, although the overall concentration is lower than that of eastern China. The Moscow peak is relatively sharp and occurs around early spring (March/April), while the Siberian peak shows up in late spring, probably when biomass-burning is most frequent in that region. Over ocean, the western hemisphere appears relatively clean because of distance from main continental aerosol sources. However, over the western Atlantic, the influence of the Saharan dust is perceived as peaks around June–July over Puerto Rico, while the

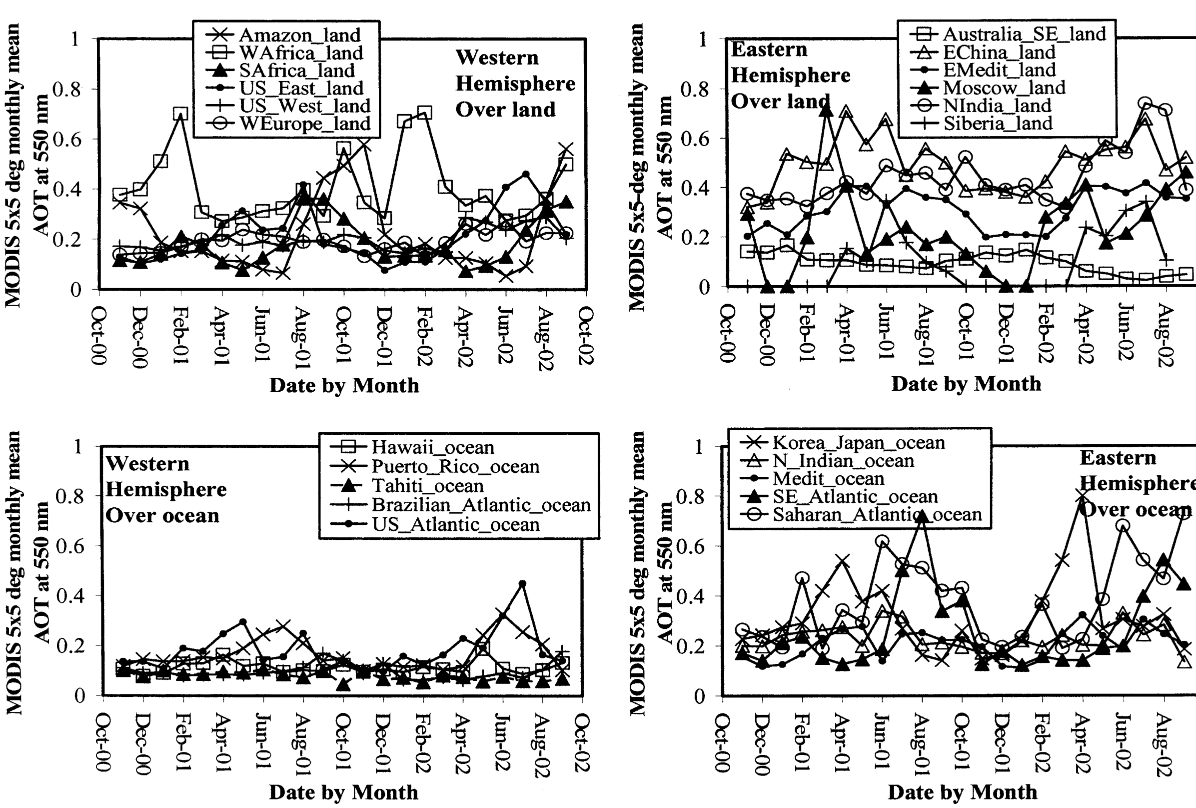

Fig. 3. Time series of monthly averages of level 2 (10-km resolution) aerosol optical thickness (AOT) data extracted from $5 \times 5°$ areas distributed over various important land (upper pair) or ocean (lower pair) locations, roughly categorized into the Western (left pair) or Eastern (right pair) hemispheres. On the eastern hemisphere over land, the segments of the Moscow and Siberia curves touching the date axis should be ignored because the data points do not represent zero AOT, but are rather caused by lack of aerosol retrieval due to persistent snow cover during and around the winter months.

outflow of pollution from the US East coast and, in particular, the early July 2002 Quebec fires, show up as a sharp peak on the US Atlantic region. The Eastern hemisphere oceanic regions are very close to land masses where the main aerosol sources are located, the impacts of which are obvious. The Korea–Japan oceanic region shows prominent peaks due to the impact of the Asian dust in early spring, as in East China (already described above). The Saharan Atlantic shows the impacts of the Saharan dust in late spring to late summer, while the SE Atlantic reflects the effect of the southern African intensive biomass-burning activity and transport across the Atlantic during summer.

3.3. Local analysis

A close-up view of the typical temporal distribution of the principal aerosol types (pollution, smoke, dust, sea-salt) can be appreciated by examining the daily time series of AOT over selected individual locations. Fig. 4

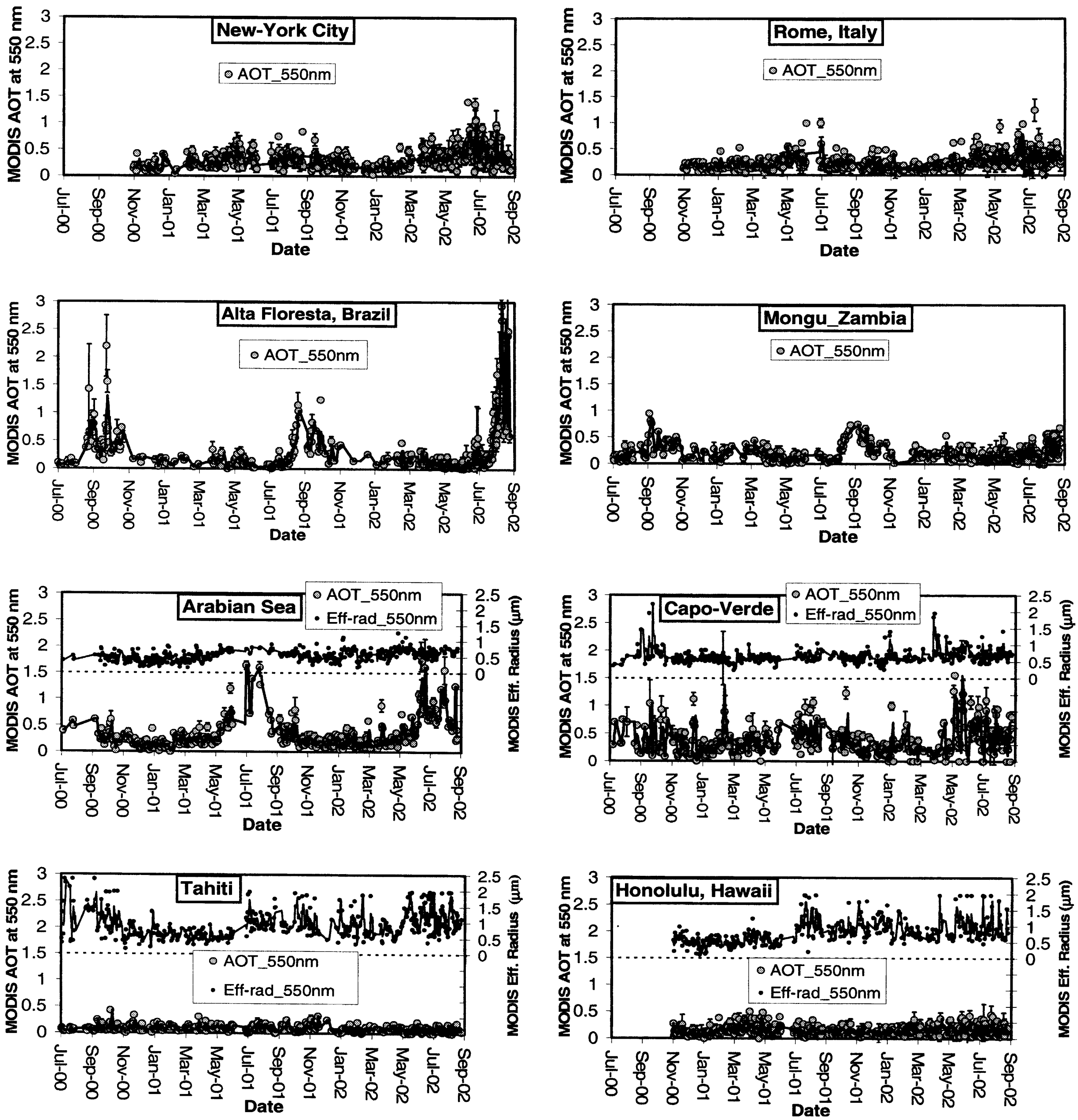

Fig. 4. Time series of daily 50 × 50-km spatial averages of MODIS level 2 (10-km resolution) aerosol optical thickness at 550 nm (AOT_550 nm) over important individual locations, dominated by different aerosol types: urban/industrial (top pair) and smoke (second pair) over land or dust (third pair) and sea-salt (last pair) over ocean. Standard deviations are plotted as error bars. The ocean plots also show time series of corresponding effective radius (r_{eff}) at 550 nm (denoted as 'Eff-rad_550 nm', with scale on right side). A five-point moving average line is superimposed on each data set to designate the trend.

shows plots of the local (50 × 50-km spatial mean AOT at 550 nm wavelength derived from MODIS level 2 (10-km spatial resolution) data. Local standard deviations are plotted as error bars, while the trend curves are based on 5-point moving averages. New York and Rome represent urban pollution, which appears to be cyclic in both cities with highs in summer and lows in winter. Although New York appears to experience a slightly higher overall aerosol concentration than Rome, it is amazing how similar the trends in the two cities seem, despite the fact that they are located in two unconnected continents far from each other. Alta–Floresta (Brazil) and Mongu (Zambia) represent smoke aerosols, which show prominent peaks during the late summer biomass burning seasons in both places, although the concentration appears to be significantly higher over Alta–Floresta than over Mongu, mirroring the relationship, in Fig. 3, between the Amazon and southern Africa. The time series representing dust and sea-salt aerosols are based on over-ocean retrievals. Each of these also shows their corresponding effective radii (r_{eff}). The Arabian Sea and Capo–Verde sites show strong influences of dust from the Arabian and Sahara deserts. Over the Arabian Sea, the dust events are markedly seasonal, with the most prominent peaks occurring in summer. On the other hand, the peaks are less obvious for Capo–Verde because of the more sporadic tendency of Saharan dust generation and transport across the Atlantic. In contrast to the three aerosol types (pollution, smoke, and dust) just described in this paragraph, sea-salt aerosols practically always maintain low concentration and never portray any noticeable seasonality. This is obvious from the time series for Tahiti and Honolulu, both island locations in central Pacific, which are farthest away from continental aerosol sources than all previously discussed locations. Nevertheless, the Honolulu site shows a slightly higher aerosol concentration due to the urban influence. It is pertinent to observe that these sea-salt dominated sites show a larger range of r_{eff} than the dust sites. This could be partly because of the elevated uncertainty associated with the retrieval of r_{eff} for large particles, especially at low AOT (Tanré et al., 1997), and partly because sea-salt aerosols actually occur at a wide range of sizes (Murphy et al., 1998).

3.4. Importance of the aerosol size parameter

Indeed, MODIS aerosol r_{eff} can be used in conjunction with AOT to identify different aerosol types and events. Fig. 5 shows a scatter-plot of these two parameters for three sites in the northern, middle, and southern segments of the Atlantic, and a fourth site in southern Pacific. The plot reveals appreciable clustering in the scatter point space. This has enabled a rough classification of different aerosol types and events de-

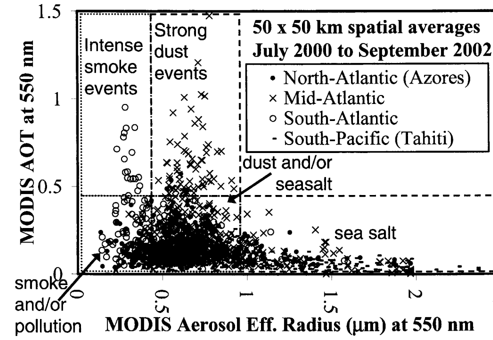

Fig. 5. Scatterplots of daily 50 × 50-km spatial averages of MODIS level 2 (10-km resolution) aerosol optical thickness (AOT) against effective radius over three individual locations in the northern, middle, and southern Atlantic Ocean, plus a fourth location in the southern Pacific. The point clusters enable broad identification of signatures of different aerosol types (pollution, smoke, dust, and sea-salt) and events.

limited with the rectangles in dotted or broken lines. The lower left box shows that regular concentrations (AOT < 0.5) of small mode aerosols (r_{eff} < 0.5 μm) are mostly represented in the north and south Atlantic, which are dominated, respectively, by European pollution and southern African smoke. The lower middle box shows substantial representation of all four sites in regular concentrations (AOT < 0.5) of midsize range ($0.5 \leqslant r_{eff} < 1$ μm), which is probably dust in the mid-Atlantic site, sea-salt attenuated by pollution and smoke in north and south Atlantic, respectively, and mostly sea-salt in the southern Pacific. The lower right box shows representations of all four sites in regular concentrations (AOT < 0.5) and larger effective radii ($r_{eff} \geqslant 1$ μm), which in the Atlantic cases, are probably sea-salt aerosols occurring during the off seasons of the other aerosol types, but in the case of southern Pacific are just sea-salt aerosols in their dominant nature. The upper boxes show a clear separation between high concentrations (AOT ⩾ 0.5) of small aerosol particles in the south (signaling southern African smoke) and larger particles (represented by Saharan dust) in mid Atlantic, with limited influence in north Atlantic. Such events obviously have not affected the southern Pacific.

4. Aerosol effects on climate

In addition to their usefulness in monitoring aerosol concentrations, the MODIS aerosol products have been found very useful for calculating aerosol climate forcing. This is enhanced by the capability of MODIS to separate coarse and fine aerosols. Using MODIS and AERONET data complementarily, Kaufman et al. (2002) calculated the clear-sky monthly mean forcing of climate for September 2000, both at the top of the atmosphere and close to the surface, over four regions representative of different aerosol types. For pollution aerosols, they obtained the top-of-the-atmosphere/surface forcing value pairs of 8/10 Wm^{-2} over North Atlantic and 10/23 Wm^{-2} over Southeast Asia. Over southern Africa, the predominantly smoke aerosols produced TOA/surface forcing values of 10/30 Wm^{-2}, while the dust predominating over the West African coast yielded 17/23 Wm^{-2}. Ichoku et al. (2003) performed similar calculations, also for September 2000, but only over the southern African part of the Atlantic Ocean in connection with SAFARI-2000, and obtained similar results for that region.

5. Conclusions

MODIS is a truly versatile sensor operating onboard both the EOS Terra and Aqua satellites, and collecting data suitable for aerosol remote sensing. The aerosol properties retrieved from MODIS include total column AOT and the fraction contributed by coarse and fine mode aerosols, Ångstrom exponent, and effective radius, among other parameters. The MODIS aerosol parameters have been validated, and have been used to accomplish aerosol mapping at global, regional, and local resolutions and at different time scales. Time trends have enabled the tracking of the intensity and seasonality of different aerosol events in different locations and regions. The effective radii also have been used in conjunction with AOT to separate different aerosol types as well as to distinguish high intensity events involving the fine aerosol types (mainly smoke) from those of the coarse aerosol types (mainly dust). In addition, the MODIS aerosol products have proven useful for estimating the regional aerosol radiative forcing both at the top of the atmosphere and close to the surface.

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