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An emerging global aerosol climatology from the MODIS satellite sensors.

Lorraine A. Remer[1], Richard G. Kleidman [1,2], Robert C. Levy [1,2], Yoram J. Kaufman [1,9], Didier Tanré[3], Shana Mattoo [1,2], J. Vanderlei Martins [1,4], Charles Ichoku [1,5], Ilan Koren[6], Hongbin Yu [1,7], and Brent N. Holben[8]

Popular Summary

The aerosol product derived from MODIS observations now includes a seven year record from Terra-MODIS and a five year record from Aqua-MODIS. We are now at a point to use this information in the manner intended, to perform a quantitative "check-up" of Earth's global aerosol system. How are aerosols distributed over the continents and oceans? How are different sizes distributed, and what are the relationships between aerosol loading and aerosol particle size in different regimes? Finally, what are the regional and seasonal characteristics of the aerosols? In this paper we will attempt to answer these questions from the data base of MODIS aerosol products.

We first evaluate the latest version of the MODIS data product and find that the retrieval of aerosol over land is substantially better than previous versions, and the ocean retrieval about the same. However, a bias has been introduced between Terra and Aqua retrievals that was not present in previous collections of MODIS aerosol data. This bias is significant, and not yet understood. Despite this unexplained bias, we do understand the MODIS retrievals well enough to describe the aerosol system as seen from space over the past 5 to 7 years.

- Global mean AOD is 0.13 over ocean and 0.19 over land
- Land shows a broader distribution of AOD than ocean. Roughly 28% of land retrievals are extremely clean and within ±0.05 of AOD = 0. Only 15% of ocean retrievals are that low.
- Global mean values are limited by sampling issues. No retrievals are made during polar night, snow, ice or bright land surfaces.

- Global mean values can vary by as much as 20% depending on how the data is aggregated, weighted and averaged. The results here are "pixel weighted". Thus, they are biased to clear skies and the reported AOD may be low.
- AOD in situations with 80% cloud fraction are twice the global mean values, although such situations occur only 2% of the time over ocean and less than 1% of the time over land.
- There is no drastic change in aerosol particle size associated with these very cloudy situations.
- The heaviest aerosol regions are North Africa, India, East and Southeast Asia. Each has its own seasonal cycle and interannual variability.
- The northern industrial economies (North America and Europe), Siberia and especially Australia have the lowest AODs.
- The three southern hemisphere biomass burning regions (South America, southern Africa and Indonesia) exhibit very similar seasonal behavior.
- Taken as a whole there is an increasing trend in southern hemisphere biomass burning AOD over the five year Aqua record.
- We find that elevated aerosol over background conditions in most oceanic regions is dominated by fine mode aerosol and not dust. This includes the Mediterranean, the north Pacific downwind of Asia and even the southern oceans. Only the Saharan outflow region in the Atlantic and the Arabian Sea area have certain months dominated by dust.
- In this analysis we did not find significant global trends of AOD either over land or ocean. A longer time series is required to identify trends.

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Abstract

The recently released Collection 5 MODIS aerosol products provide a consistent record of the Earth's aerosol system. Comparison with ground-based AERONET observations of aerosol optical depth (AOD) we find that Collection 5 MODIS aerosol products estimate AOD to within expected accuracy more than 60% of the time over ocean and more than 72% of the time over land. This is similar to previous results for ocean, and better than the previous results for land. However, the new Collection introduces a 0.015 offset between the Terra and Aqua global mean AOD over ocean, where none existed previously. Aqua conforms to previous values and expectations while Terra is high. The cause of the offset is unknown, but changes to calibration are a possible explanation. We focus the climatological analysis on the better understood Aqua retrievals. We find that global mean AOD at 550 nm over oceans is 0.13 and over land 0.19. AOD in situations with 80% cloud fraction are twice the global mean values, although such situations occur only 2% of the time over ocean and less than 1% of the time over land. There is no drastic change in aerosol particle size associated with these very cloudy situations. Regionally, aerosol amounts vary from polluted areas such as East Asia and India, to the cleanest regions such as Australia and the northern continents. In almost all oceans fine mode aerosol dominates over dust, except in the tropical Atlantic downwind of the Sahara and in some months the Arabian Sea.

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The recently released Collection 5 MODIS aerosol products provide a consistent record of the Earth's aerosol system. Comparison with ground-based AERONET observations of aerosol optical depth (AOD) we find that Collection 5 MODIS aerosol products estimate AOD to within expected accuracy more than 60% of the time over ocean and more than 72% of the time over land. This is similar to previous results for ocean, and better than the previous results for land. However, the new Collection introduces a 0.015 offset between the Terra and Aqua global mean AOD over ocean, where none existed previously. Aqua conforms to previous values and expectations while Terra is high. The cause of the offset is unknown, but changes to calibration are a possible explanation. We focus the climatological analysis on the better understood Aqua retrievals. We find that global mean AOD at 550 nm over oceans is 0.13 and over land 0.19. AOD in situations with 80% cloud fraction are twice the global mean values, although such situations occur only 2% of the time over ocean and less than 1% of the time over land. There is no drastic change in aerosol particle size associated with these very cloudy situations. Regionally, aerosol amounts vary from polluted areas such as East Asia and India, to the cleanest regions such as Australia and the northern continents. In almost all oceans fine mode aerosol dominates over dust, except in the tropical Atlantic downwind of the Sahara and in some months the Arabian Sea.

Introduction

The instruments aboard NASA's Terra and Aqua satellites have been observing the Earth since early 2000 and mid-2002, respectively. In the words of Dr. Yoram J. Kaufman, Terra Project Scientist at the time of the Terra launch, the Terra and Aqua missions were "designed for a comprehensive check-up of planet Earth" [Kaufman, 2000 http://terra.nasa.gov/Events/FirstImages/]. Similar to a check-up at the doctor's office, these missions would characterize the health of the planet. The goal was to use the vantage point of space to view the Earth's interconnected systems of atmosphere, land

and ocean, and to characterize the parameters important to sustainability of the planet and its human population.

One important feature measured by several instruments aboard Terra and Aqua is atmospheric aerosol. These small solid or liquid particles suspended in the atmosphere play a major role in the energy balance of the Earth, in modifying cloud, precipitation, and atmospheric circulation characteristics, in providing nutrients to nutrient-limited regions of land and oceans, and in affecting air quality and public health. Aerosols are highly inhomogeneous in space, time and composition, and yet, knowing the amount, composition, distribution, size and shape of these particles is necessary for any meaningful estimates of their effect, from estimating anthropogenic climate forcing to forecasting air quality and potential health effects from air pollution.

One of the instruments aboard both Terra and Aqua specifically designed to characterize atmospheric aerosols is the MODerate resolution Imaging Spectroradiometer (MODIS). The aerosol product derived from MODIS observations now includes a seven year record from Terra-MODIS and a five year record from Aqua-MODIS. We are now at a point to use this information in the manner intended, to perform a quantitative "check-up" of Earth's global aerosol system. How are aerosols distributed over the continents and oceans? How are different sizes distributed, and what are the relationships between aerosol loading and aerosol particle size in different regimes? Finally, what are the regional and seasonal characteristics of the aerosols? In this paper we will attempt to answer these questions from the data base of MODIS aerosol products.

MODIS aerosol products

The aerosol products are derived operationally from spectral radiances measured by MODIS. MODIS has 36 channels spanning the spectral range from 0.41 to 15 μm representing three spatial resolutions: 250 m (2 channels), 500 m (5 channels), and 1 km (29 channels). The aerosol retrieval makes use of seven of these channels (0.47 – 2.13 μm) to retrieve aerosol characteristics [Remer et al., 2005] and uses additional wavelengths in other parts of the spectrum to identify and mask out clouds and river sediments [Ackerman et al., 1998, Gao et al., 2002; Martins et al., 2002; Li et al., 2003]. The MODIS aerosol algorithm is actually two independent algorithms, one derives aerosol characteristics over land and the other for aerosols over ocean. The original land algorithm is based on the "dark target" approach [Kaufman and Sendra 1988; Kaufman et al., 1997; Remer et al., 2005] and therefore does not retrieve over bright surfaces including snow, ice and deserts. A more recent MODIS product, labeled "Deep Blue" does retrieve over bright surfaces [Hsu et al., 2004]. However, the climatology presented in this paper does not include the "Deep Blue" results. The ocean algorithm masks out river sediments, clouds and sunglint, then inverts the radiance at 6 wavelengths (0.55 - 2.13 μm) to retrieve aerosol optical depth (AOD) and particle size information [Tanré et al., 1996; 1997].

We will examine two types of aerosol products: aerosol optical depth (AOD) and particle size parameter. AOD is a straightforward measure of column integrated extinction. The MODIS product includes retrievals of AOD at seven wavelengths over ocean and three wavelengths over land. There are several measures of particle size included in the MODIS aerosol product. Angstrom exponent over land is defined as:

$$AngExp = -\frac{\ln(AOD470/AOD660)}{\ln(470/660)}$$

There are two Angstrom exponents over ocean, defined as

$$AngExp1 = -\frac{\ln(AOD550/AOD870)}{\ln(550/870)}$$

and

$$AngExp2 = -\frac{\ln(AOD870/AOD2130)}{\ln(870/2130)}$$

Angstrom exponent is a measure of the spectral dependence of the aerosol optical depth and a proxy for aerosol size. Larger Angstrom exponents indicate smaller particles, while smaller Angstrom exponents suggest larger particles.

There are two other measures of particle size in the MODIS aerosol product, and these are fine aerosol optical depth and fine mode/model fraction. Fine AOD is the AOD contributed by the fine mode aerosol model. Over ocean, the fine model is a single mode with effective radius spanning the range 0.10 to 0.25 μm [Tanré et al., 1997]. These are mostly submicron particles, but the tail of the mode could include particles that exceed 1 μm. Likewise, there could be submicron particles associated with the tail of the coarse mode distribution that are not included in the Fine AOD. Over land, the "fine" model is a multi-modal aerosol model that includes both fine and coarse modes [Levy et al., 2007a]. It is labeled a "fine" model because the fine mode dominates the size distribution. Therefore, fine AOD has entirely different meanings whether over ocean or land. Fine mode/model fraction is the fine AOD divided by the total AOD. We use fine "mode" to designate the parameter over ocean because the model is a single mode, and fine "model" to designate the multi-modal model over land, but abbreviate both as FMF.

The derived aerosol products undergo rigorous testing and validation. The algorithms were created before Terra launch and tested using data from airborne imagers [Kaufman et al., 1997; Tanré et al. 1997, 1999; Chu et al., 1998]. After Terra launch, the products were validated by comparison with collocated ground-based observations by the Aerosol Robotics NETwork (AERONET). The AERONET network consists of hundreds of automatic instruments that measure aerosol optical depth (AOD) to within 0.01 accuracy [Holben et al., 1998; Eck et al. 1999; Smirnov et al., 2000], and retrieve other aerosol characteristics including particle size information [Dubovik and King, 2000; O'Neill et al., 2003]. Comparison of MODIS-derived AOD with collocated AERONET-measured data showed that the MODIS AOD ocean products were accurate to within $\pm 0.03 \pm 0.05\,\tau$ over ocean, where τ is AOD [Ichoku et al, 2002; Remer et al., 2002; Levy et al., 2003, 2005; Remer et al., 2005}. Additional validation using the NASA Ames Airborne Tracking Sunphotometer confirmed these error bounds over ocean [Russell et al. 2007;

Livingston et al., 2003; Redemann et al., 2005, 2006]. Over land, the comparison yielded varying results. In some cases the over land AOD retrievals fell within expected uncertainties ($\pm0.05\pm0.15\tau$) [Chu et al., 2002; Ichoku et al., 2002; Remer et al., 2005], but in many situations there appeared to be a strong positive bias at low AOT in the over land retrieval, and a negative bias at high AOT [Ichoku et al., 2003, 2005; Levy et al., 2005; Remer et al., 2005]. The MODIS particle size information over ocean correlated well with AERONET retrievals, but tended to over predict the occurrence of small particles at the expense of large particles [Kleidman et al., 2005].

To address these lingering problems with the aerosol products, new codes were developed. The land algorithm underwent significant change, while maintaining the basic dark target approach [Levy et al. 2007ab]. The ocean algorithm remained almost the same with changes made only to three of the nine aerosol models in the Look Up Table [Remer et al., 2007]. These new algorithms were applied operationally to the complete record of calibrated radiances to generate a new "Collection" of aerosol products resulted. These reprocessed data are known as Collection 5, which is available for both the Terra and Aqua records. Collection 5 provides us with a consistent data set created from a single set of algorithms applied identically to an uninterrupted data stream of calibrated radiances. Collection 5 aerosol products exist for both Terra and Aqua records.

Data for the Climatology

Two types of MODIS data will be used in this paper: Level 2 (L2) and Level 3 (L3). MODIS L2 aerosol data are ungridded 10 km retrievals of various aerosol parameters available at the time of satellite overpass. These data represent the fundamental MODIS aerosol product. The product consists of geophysical parameters such as aerosol optical depth and aerosol particle size information, as well as a quality assurance (QA) flag that indicates the level of reliability of each retrieved pixel. QA flags range from 0 (lowest quality) to 3 (highest quality). Comparison of the L2 data, collocated in time and location with high quality ground measurements provide the 'validation' of the basic product.

MODIS L3 data are an aggregation of the L2 data onto a gridded $1^{\circ} \times 1^{\circ}$ global grid and represent the statistics including the mean and weighted means of the L2 product contained within the grid square. L3 data are available on a daily basis, as well as 8 day and monthly means. The global gridded data of L3 will provide the basic set of data for the climatology presented here.

Creating daily L3 from L2, and further processing the data to achieve global and regional monthly means requires decisions as to how to aggregate and average the data at each step. Depending on what processing is chosen variations in the final values can vary by as much as 20% [Levy et al., submitted]. In this work we start with high quality daily L3 data, weight by the number of L2 retrievals in the 1 degree grid square (pixel-weighted) and calculate monthly means and other statistics. The reason for this decision is to minimize the contribution of retrievals in cloud fields, where artificially enhanced AOD occurs frequently. It is incongruous for the monthly mean of a particular grid square determined by just one 10 km retrieval on one day of the month to count equally with another grid square that consisted of hundreds of 10 km retrievals in that month. On the other hand, we want global representation of the data without contributions from QA=0 data. Pixel-weighting the quality weighted product in this manner introduces some inconsistencies detailed in Levy et al. [submitted], and is not the same as making the same calculations directly from the 10 km L2 data.

Comparison of Collection 5 Against AERONET Observations

We evaluate the Collection 5 aerosol products by comparing with collocated AERONET observations. A preliminary evaluation was performed and reported in Levy et al., [2007b] and Remer et al. [2007], but that evaluation was confined to a test bed of MODIS radiance granules. We note that while the test bed produced a substantial number of collocations, it was still limited in time and space. Furthermore, the test bed consisted of saved Collection 4 radiances. When Collection 5 was processed, not only were the aerosol retrieval algorithms upgraded to Collection 5, but the basic calibration coefficients were changed as well. Thus, the radiances used to create Collection 5 aerosols are different than those used for Collection 4. When we compare MODIS aerosol products to AERONET now, we evaluate simultaneously both the changes we made to the aerosol algorithms and the changes made to the calibration that affect the aerosol retrieval.

Figure 1 shows the results of collocating MODIS aerosol optical depth retrievals with AERONET for the ocean retrieval following the spatio-temporal technique of Ichoku et al. [2002]. Two wavelengths and both Terra and Aqua are shown. The ocean comparison is made for any island or coastal AERONET station within 25 km of the ocean. The only station eliminated from this analysis is Mauna Loa because of its high elevation in comparison to the ocean surface. Because the ocean retrieval quality flags are regarded as 'conservative' [Russell et al., 2007] we include data of all quality in the comparison. The plots show data that were sorted according to AERONET AOD, grouped into 25 bins of near equal samples and then mean and standard deviation were calculated. The regression equations plotted and correlation coefficients indicated were calculated from the full cloud of collocated points before binning and averaging. The data used in this plot spans the length of the mission from the beginning to the end of 2006.

MODIS aerosol optical depth retrieved over ocean is strongly correlated to the corresponding AERONET values for both wavelengths and both satellites. Expected error for ocean retrievals is $\pm 0.03 \pm 0.05\tau$. AOD retrievals at the 870 nm channel fall within expected error more than 2/3 of the time. Retrieval results for shorter wavelengths are less consistently accurate, falling within expected error only 60% of the time at 550 nm. These results for Collection 5 are similar to those reported for Collection 4 [Remer et al., 2005].

Figure 2 shows the results of comparing Collection 5 retrievals over land with AERONET AOD. Again these are "global" plots making use of all AERONET stations except COVE and Venise, which are both located on stand alone ocean platforms far from shore. Unlike the ocean validation exercise, for land we use those retrievals with the highest quality labels (QA = 3). Over land, the inclusion of lower quality retrievals will make significant difference in the validation plots, lowering the correlation and decreasing the percentage of retrievals within expected error. We recommend to users to check quality flags over land and to use caution when using retrievals with QA < 3. Similar numbers of collocations are available for both land and ocean despite the fact that there are many more AERONET stations over land than near ocean. The requirement on the land quality flag eliminates many collocations from the analysis. Thus, while there are more opportunities to compare with AERONET over land, there are fewer locations where a high quality land retrieval is possible. The plots in Figure 2 are prepared in the same manner as in Figure 1, although only one channel is shown.

MODIS aerosol optical depth over land in Collection 5 is a strong improvement of the results from Collection 4 [Remer et al., 2005]. More than 72% of retrievals fall within expected error over land at 550 nm. In Collection 4, 68% of retrievals fell within expected error at that wavelength. More importantly there was an overall positive mean bias in Collection 4 of +41%. In Collection 5 we see insignificant bias, with 0 mean bias in Terra and -7% bias in Aqua. Note that the expected error over land is greater than over ocean ($\pm 0.05 \pm 0.15\tau$).

The comparison of AOD retrievals over land and ocean show that the Collection 5 retrieval is producing results either as accurate as Collection 4 (ocean) or much improved (land), at least in a global sense. There appears to be little difference between Terra and Aqua. Validation efforts beyond the scope of this paper continue. Individual regions will be examined, and we will include ship board measurements as well as AERONET observations as the "ground truth". However, for now, we see that the MODIS Collection 5 aerosol product can be used to examine the state of the aerosol system.

Comparison of Collection 5 with Collection 4

By comparing MODIS retrieved AOD with collocated AERONET observations on a day by day basis we established that the Collection 5 retrievals are a true representation of the Earth's aerosol system, to within specified accuracies. Even if both Collection 5 and Collection 4 [Remer et al., 2005] aerosol optical depth match AERONET observations within MODIS specifications, there could still be systematic offsets. In this section we compare mean results of the two Collections.

Over ocean, the only difference between Collection 4 and Collection 5 aerosol algorithms is that three of the aerosol models were modified. The new aerosol optical models are given in Table 1. AERONET retrievals of aerosol optical properties available only after Terra-MODIS launch suggested that the real part of the refractive index for coarse mode sea salt particles was smaller than the 1.43 used in the original algorithm. Changing the three coarse mode 'sea salt' aerosol models in the algorithm to a real part refractive index of 1.35 in accordance with Dubovik et al., [2002 and personal communication] was tested by applying the new aerosol models to our test bed of saved Collection 4 radiances. The results are shown in Figure 3. The changed aerosol models reduced the positive bias in the fine mode fraction retrieved by Collection 4 [Kleidman et al., 2005], while not making any significant changes to the AOD retrieval. Both Aqua and Terra data were used during testing. The mean AOD using either software was 0.15, but the mean fine mode fraction changed from 0.47 to 0.39. Thus we did not expect any changes to the AOD from Collection 4 results, but did expect reduced fine mode fraction.

Figure 4 shows a comparison of monthly global mean AOD over oceans between Collection 4 and Collection 5, separated by satellites. Unlike Figure 3 the data used to create Figure 4 do not come from our saved test bed of radiances. These data, instead, come directly from the operational data base available to all users. The Collection 4 AOD values were processed with Collection 4 radiances as input, while the Collection 5 AOD values were processed with Collection 5 radiances as input. Note, that updates in calibration cause Collection 5 radiances to differ from Collection 4. The data plotted include only the period of overlap of all four data sets, from August 2002 when Aqua began processing data to August 2005 when Collection 4 production ended. In Figure 4 we see that for the Aqua satellite global mean AOD is basically the same for both Collections, as expected, but for Terra Collection 5 it is approximately 0.015 higher than Collection 4. Note that 0.015 is well within the expected uncertainty of $\pm 0.03 \pm 0.05\tau$. Further analysis shows that Terra Collection 4 matches both Aqua Collections and that Terra Collection 5 is an outlier when compared to the other three data sets.

The 0.015 offset in AOD between Terra Collection 5 and the other three data sets is not yet understood. Algorithm changes were applied equally to the software run for Terra and Aqua. If an AOD offset was introduced by modifying the aerosol models as described above, then we would see AOD changes equally in both satellites. Because the offset has been introduced to Terra and not Aqua, we suspect this offset is due to updates to the Terra-MODIS calibration constants that altered the Collection 5 input radiances. Investigation continues. However, in this paper we will concentrate on Aqua retrievals over ocean, and leave the evaluation of Terra ocean retrievals until a time when the calibration changes to Terra have been carefully evaluated.

Over land, in contrast to ocean, substantial differences exist between the Collection 4 and 5 algorithms [Levy et al., 2007ab]. All aerosol optical models were modified, as were surface assumptions and snow masking. A vector radiative transfer code replaced the scalar code used in Collection 4, and the overall numerics of the inversion were changed. Because of these changes we expect Collection 5 to have substantially different AOD values than Collection 4, and they do. The changes made to the aerosol land algorithm resulted in the improved comparison plots against AERONET. (See Figure 2). Mean AOD over land has decreased from 0.28 in Collection 4 to 0.19 in Collection 5. Because of the drastic changes over land, subtle changes due to calibration changes will be lost in the analysis. For the purposes of this paper, to be consistent with the analysis over ocean, we will focus on the Aqua satellite. The land Collection 5 algorithm and comparison with

Collection 4 is satisfactorily documented in the recent papers Levy et al. [2007a] and [2007b], and will not be further discussed here.

Global mean aerosol optical depth over ocean and land

Proceeding with Aqua Collection 5 we will now investigate the emerging global aerosol climatology as viewed by MODIS. Figure 5 shows the time series of monthly and global mean AOD through the Aqua record. The data are separated by ocean and land retrievals. Over ocean the global mean AOD at 550 nm is 0.13, 10% of all ocean retrievals are below 0.041 and 10% are above 0.235. The mean ocean AOD is close to the 66th percentile value showing that the distribution is skewed towards lower values. There is no significant trend in the global mean ocean AOD over the five year Aqua record. There is a significant trend in the Terra record discussed in Remer et al., [submitted]. The fine mode AOD, also plotted in Figure 5 follows the month by month variations of the total AOD. Mean fine mode AOD is approximately 0.06. Note that fine mode AOD contains fine mode contributions from marine aerosol and transported dust and pollution, and is thus not the same as the anthropogenic component.

Over land the global mean AOD at 550 nm is 0.19, 10% of all land retrievals are negative and 10% are above 0.44. Note that the land retrieval permits negative AOD retrievals in order to avoid positive bias in the large-scale statistics [Levy et al., 2007b]. The physical meaning of the negative values is that there is no difference between small negative values, zero AOD or small positive values. Approximately 20% of the AOD retrievals over land are essentially zero. Over ocean the retrieval has greater sensitivity to small values of AOD and thus there are fewer negative retrievals. The ocean retrieval 10th percentile already contains AOD values above the noise threshold. The mean land AOD is also close to the 66th percentile showing the same skewed distribution as over ocean. Similar to ocean, there is no significant trend in the global mean AOD over land in the five year Aqua record. The mean fine mode AOD is 0.10, which is larger than over ocean. Furthermore, over ocean we saw that fine mode AOD tracked with the total AOD month by month. Peaks in total AOD corresponded to peaks in fine mode AOD. Over land total AOD peaks in early Spring, while fine mode AOD peaks in late Summer and Fall, where fine mode AOD can account for almost the total mean land AOD in that season. The seasonal cycles suggest a Spring maximum due to dust transport and a Fall maximum due to southern hemisphere biomass burning. However, there is a limit to the accuracy of the retrieval of aerosol size parameter over land. The fine mode AOD shown in the land plot of Figure 5 should be considered more of a qualitative indicator, rather than a validated quantitative product.

The statistics plotted in Figure 5 are calculated from pixel weighted QA-weighted L3 daily data. Global mean values are strongly dependent on the way the data are aggregated, averaged and weighted. Resultant discrepancies in global mean values of 20% are possible [Levy et al., submitted]. The pixel-weighted method used here will produce the lowest value of global mean AOD because it is biased to cloud free conditions. Aerosol retrievals in the vicinity of clouds can be contaminated by cloud 3D effects (Wen et al, 2006; 2007) and by subpixel clouds (Zhang et al, 2006). We chose this weighting method in order to minimize the effect of clouds on the statistics, although we acknowledge that pure aerosol in the vicinity of clouds can be higher than aerosol away from cloud fields (Koren et al., 2007). The consequence of our chosen method is that the values in Figure 5 may be biased low.

Global AOD statistics in the vicinity of clouds

Figure 6 shows the global mean statistics calculated from the L3 daily data directly without first creating monthly means. The global mean AOD values calculated from the histograms are the same as those calculated from the monthly means of Figure 5. Evident are the same skewed nature of the AOD distributions, and the broader range and the negative values of the land histograms. In a global sense the fine mode fraction over ocean remains fairly constant over the range of ocean AOD values. Over land, however, the fine (model) fraction suggests that coarse aerosol dominates at low AOD, transitioning to more equal partitioning at moderate AOD. While this is physically realistic over land, one should treat the results with skepticism, due to the large uncertainty of derived size parameter over land

The histogram analysis of Figure 6 permits examination of the effect of cloud fields on the aerosol statistics. The bottom panels of Figure 6 plot the AOD distributions for those grid squares in which the cloud fraction exceeds 80%. In these cloudy situations there is a drastic shift of AOD to higher values, both over ocean and land. The mean AOD for these cloudy situations more than doubles to 0.28 over ocean and to 0.44 over land. We expected this increase in AOD to be in part caused by cloud contamination. The aerosol retrieval would interpret large cloud droplets in the field of view as being coarse mode particles. If subpixel clouds and other contaminants were the cause of the drastic increase in AOD in cloudy situations we would expect a strong decrease in fine mode fraction. There is some decrease in fine mode fraction at moderate AOD over ocean, but not as much as would be expected from cloud contamination alone. Other factors including 3D effects and increase of AOD from increased humidity around clouds are also possible and would not decrease fine fraction in the same way as subpixel cloud contamination. Such factors could help to explain the increase of AOD in the cloudy situations without decreasing fine mode fraction. Note that these cloudy situations represent only 2% of the total number of grid squares included in the overall statistics over ocean and less than 1% over land.

Regional and seasonal distribution of aerosol optical depth

Up to this point we have analyzed the global aerosol system in terms of its global mean statistics. The aerosol system is far from being well mixed and homogenous. The aerosol story is very much linked to geography and season. Figure 7 shows four months of aerosol optical depth observed from Aqua MODIS. The four months were chosen to represent seasonal changes, and each month is the mean of that month over the five years of the Aqua mission. In Figure 7 we see the strong aerosol loading over eastern China, the Indo-Gangetic Plain of India and in the eastern tropical north Atlantic during all seasons. We see the aerosol from biomass burning in Africa begin in January north of the equator and shift southward during the course of the year until it is joined by tropical biomass burning in the Amazon and Indonesia during northern Autumn. There is wide spread elevated AOD over the oceans during the Spring of each hemisphere, April in the north and October in the south. During northern Summer the Arabian Sea and India exhibit unusually high AOD values, while North America, Europe and northern Asia have their highest, though moderate, aerosol loading during the same season.

Figure 7 also shows the limits of the MODIS aerosol products to represent the global aerosol system. Large expanses of the globe are left blank during various seasons due to polar night or surfaces unsuitable for making a dark-target retrieval. The new Deep Blue product will fill in some of these spaces when combined with the standard aerosol products although that prospect is outside the scope of this study. Because of these missing regions, the global mean aerosol values described here may not be truly representative of the entire globe, particularly over land.

Aerosol optical depth of individual regions

We define 13 regions over ocean (following Remer and Kaufman 2006) and 14 regions over land to examine MODIS-derived aerosol characteristics in greater detail. Figure 8 defines these regions. Seasonal and annual mean AOD are given for each region and season in Table 2 for ocean regions and Table 3 for land. The heaviest aerosol loading can be found over India and the surrounding oceans during northern summer (JJA). East Asia also exhibits heavy aerosol loading, but during northern spring (MAM). The southern tropical Pacific shows the lowest AOD, but MODIS-observed AOD over the Australian continent is even lower, although the Australian values fall within the land algorithm's noise level.

Because the seasonal cycle is most pronounced near the aerosol source regions over land we concentrate our seasonal analysis on the land regions. Figure 9 shows the AOD time series for four categories of regions: northern industrial economies, southern biomass burning regions, dust dominated and Asia. The four regions grouped as northern industrial economies are west and east North America, north Europe and the Mediterranean Basin. These four regions track together exhibiting increased AOD in the Spring and Summer, but increasing to only moderate levels as compared to other regions of the globe. The Fall and Winter seasons have very low AOD with eastern North America surprisingly showing the lowest values of AOD during the winter. The Mediterranean region, which includes parts of North Africa and the Middle East as well as southern Europe has a longer aerosol season with higher AOD values both in summer and in winter than the other three regions.

The three southern biomass burning regions, South America, southern Africa and Indonesia, show very similar seasonal patterns, despite their widely varying locations. The biomass burning season in the southern hemisphere occurs during southern Spring (SON) on all three continents. There is a high degree of interannual variability in the AOD values at each location with an overall increasing trend when all three locations are taken as a whole. The AOD during the biomass burning season is roughly twice the AOD values of the northern industrial economies, excluding the Mediterranean. However, during the ¾ of the year with no burning, South America and southern Africa have low AOD comparable with values in North America and northern Europe.

Northern Africa and India, grouped together because both are affected by dust transported from the Sahara and Arabia, have overall higher AOD than any of the previous regions. North Africa exhibits an irregular seasonal cycle with the highest values reported in later winter (February and March) at the peak of the northern hemisphere biomass burning season, but also a secondary seasonal peak that varies but generally appears in late summer when dust is dominant. India's seasonal cycle is more regular with a single longer aerosol season. AOD begins building in the spring and extends into early summer. A small regular secondary peak also occurs late in the year. In 2006, this secondary peak was larger than in previous years.

The fourth grouping of regions in Figure 9 are the Asian regions, excluding India and Indonesia, which were previously discussed. The Asian regions include Siberia, East Asia, which is mainly China, and Southeast Asia. The AOD values in Siberia are low, especially in autumn and winter. However, snow covers much of the region in winter and therefore, MODIS does not sample much of this region in that season. Summer AOD values in Siberia are comparable to summer values in North America and northern Europe. Note that Siberia seems to track with the Asian regions to the south, although at much lower aerosol loading. This suggests some commonality in aerosol transport or similarity of sources. East Asia and Southeast Asia track together showing an extended aerosol season that spans the spring and summer seasons. The AOD during the aerosol season shows interannual variability for both regions, but can exceed values from the dust regions of northern Africa, India or the southern hemisphere biomass burning regions. AOD values remain moderately high even for the autumn and winter months.

Aerosol size characteristics of individual regions

Aerosol particle size can be described by a variety of parameters in the MODIS aerosol data product including fine mode AOD, fine mode fraction and various Angstrom Exponents. These parameters provide subtle differences, but are more or less correlated with each other. The ocean algorithm uses 6 wavelengths and benefits from a fairly homogenous background surface. Therefore, the ocean product contains inherently greater information content than the land product, which uses only three wavelengths and is sensitive to the assumptions made about the spectral surface reflectance. In short, the size parameters from the ocean algorithm are more reliable than the land. Despite this fact, in the global analysis we showed global statistics of aerosol size parameter over land (which we took as a qualitative parameter) because random errors introduced in various regions may be reduced by global averaging. We are already aware of specific regions where the land size parameter is systematically wrong [Jethva et al., 2007] and prefer to wait until full characterization of the land size parameter is available before calculating regional climatological statistics. In the regional analysis we focus the size parameter analysis solely on the ocean retrievals.

Table 2 shows the seasonal and annual mean fine mode fraction (FMF) for the 13 ocean regions. Values range from 0.28 – 0.35 in pristine southern hemisphere regions to 0.60 – 0.65 in the northern midlatitudes. These seasonal mean numbers conform to our expectations that pristine oceanic regions would be dominated by sea salt, a coarse mode aerosol, and therefore have smaller FMF, while northern midlatitudes would have a greater fine mode contribution from aerosol transported from land sources.

We obtain greater physical interpretation by plotting monthly mean aerosol size parameter against monthly mean total AOD, following Kaufman et al., [2005]. Figure 10 shows the results for five regions. The results fall into two classes. Regions 2, 4, and 13 fall into the first class. In this situation as aerosol optical depth is added to a baseline background value AOD of the fine mode increases as well. The slope of the regression is approximately 0.7 – 0.8. Region 6 represents the second class. Here AOD fine also increases as total AOD increases, but at a much slower rate. The slope of the class 2 regression is approximately 0.3. We interpret these two classes as the difference between adding smoke/pollution to a background marine aerosol in which the slope is the higher value, and adding dust, which results in the smaller slope.

We expect elevated AOD in Region 2 to be pollution from North America and Europe. Likewise we expect elevated AOD in Region 6 to be dust from the Sahara. However, it is somewhat surprising that the elevated aerosol in Region 13 follows the smoke/pollution curve so tightly. This suggests that elevated aerosol in the southern circumpolar ocean has a strong biomass burning component, and indeed the seasonal means in Table 2 shows that elevated AOD and FMF occur during the southern hemisphere biomass burning season. We also expected that some of the elevated aerosol in Region 4 would have a dust component from transported Asian dust. Instead we see a tight correlation following the smoke/pollution curve. Figure 10 also plots Region 7, the northern Indian Ocean. Region 7 splits its monthly means to follow both curves. This suggests that in some months the aerosol is dust and other months it is smoke/pollution.

Table 4 gives several annual mean aerosol size parameters, and the regression slope and correlation coefficients following Figure 10 for each ocean region. Note that Region 7, which contains both classes from Figure 10 has a small slope, but a relatively low R^2 value. A low R^2 gives indication that the region follows neither class. In some cases this is because some months follow the smoke/pollution curve and other months the dust curve (Regions 3 and 7), but in other cases the region remains pristine through all months and there is no elevated aerosol (Region 9).

Discussion and Conclusions

The MODIS aerosol product derived from 7 years of Terra data and 5 years of Aqua data has recently undergone reprocessing using a new algorithm labeled Collection 5. Collection 5 represents both new aerosol software and new calibration coefficients, applied consistently through the entire data records of each MODIS sensor. Comparison of Collection 5 MODIS aerosol optical depth (AOD) retrievals over ocean and land with high quality AERONET observations shows agreement as good as Collection 4 for ocean and much improved for land. In fact, in Collection 5 the land algorithm is performing as well as the ocean algorithm, with similar or smaller offsets, regression slopes close to 1.0 and similar or better correlation. Comparison with collocated AERONET products requires both MODIS and AERONET to report cloud free conditions. Situations where MODIS retrieves but AERONET does not will not be included in the analysis. Validation efforts continue, and a more comprehensive validation study is in preparation.

The differences we expected to find between Collection 4 and Collection 5 included a shift to larger particle sizes over ocean but no change to ocean AOD. In the Aqua record, indeed that is exactly what we find. However, something else has occurred in the Terra record. Not only did the particle size shift in Terra ocean, but the global ocean AOD increased by 0.015. The MODIS aerosol software is applied equally to Terra and Aqua. To have Terra oceanic AOD shift by 0.015, while Aqua AOD remain the same is impossible. The only logical answer is that MODIS calibration constants also changed between Collections. This change in Terra calibration is under investigation. In the meantime, we have focused on the Aqua record because the results are as expected. It is possible that Terra's new calibration will prove to be the more accurate and the results shown here are artificially low.

We have presented an analysis of Aqua-MODIS aerosol optical depth and particle size information, over ocean and land, globally and regionally. We have shown time series and histograms. From this analysis we conclude:

- Global mean AOD is 0.13 over ocean and 0.19 over land
- At every decision point in the processing we have taken the road leading to lower values of global mean AOD. In particular by pixel weighting and using Aqua instead of Terra, the global mean AOD is lower by 0.015 to 0.04 than if calculated without pixel weighting and by using Terra.
- We feel that the higher range of values that would be achieved without pixel weighting contain cloud artifacts. Therefore we decided to produce values that are least affected by clouds and are at the lower range of the envelope.
- Land shows a broader distribution of AOD than ocean. Roughly 28% of land retrievals are extremely clean and within ±0.05 of AOD = 0. Only 15% of ocean retrievals are that low.
- Global mean values are limited by sampling issues. No retrievals are made during polar night, snow, ice or bright land surfaces.
- Global mean values can vary by as much as 20% depending on how the data is aggregated, weighted and averaged. The results here are "pixel weighted". Thus, they are biased to clear skies and the reported AOD may be low.
- AOD in situations with 80% cloud fraction are twice the global mean values, although such situations occur only 2% of the time over ocean and less than 1% of the time over land.
- There is no drastic change in aerosol particle size associated with these very cloudy situations.
- The heaviest aerosol regions are North Africa, India, East and Southeast Asia. Each has its own seasonal cycle and interannual variability.
- The northern industrial economies (North America and Europe), Siberia and especially Australia have the lowest AODs.

- The three southern hemisphere biomass burning regions (South America, southern Africa and Indonesia) exhibit very similar seasonal behavior.
- Taken as a whole there is an increasing trend in southern hemisphere biomass burning AOD over the five year Aqua record.
- We find that elevated aerosol over background conditions in most oceanic regions is dominated by fine mode aerosol and not dust. This includes the Mediterranean, the north Pacific downwind of Asia and even the southern oceans. Only the Saharan outflow region in the Atlantic and the Arabian Sea area have certain months dominated by dust.
- In this analysis we did not find significant global trends of AOD either over land or ocean. A longer time series is required to identify trends.

We demonstrate in this work an emerging climatology of aerosol characteristics using the satellite view from MODIS. Longer records are necessary to fully characterize trends and further analysis with multiple data sets is necessary to better unravel the signatures of aerosols and clouds. However, this view from space and "check-up" of the aerosol system provides valuable information for understanding the planet now and estimating the potential consequences of global change.

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This work was first put in motion almost three years ago by our co-author, mentor and dear friend, Yoram Kaufman. He actively participated in designing several figures and in organizing the latter half of the paper. Since then, not only did tragedy take him from us, but the MODIS reprocessing to Collection 5 required a revisit to the original analysis and a discussion of new validation. We only hope that the paper in present form does justice to his original vision. We miss Yoram's guidance and inspiration almost every single day. We also wish to acknowledge the many AERONET PIs and their site managers who make the AERONET program possible. The research was supported by NASA's Radiation Sciences Program and Earth Observation System Project Office.

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Figure Captions

Figure 1. MODIS aerosol optical depth (AOD) over oceans plotted against collocated AERONET observations. Top: AOD at 550 nm. Bottom: AOD at 870 nm. Left: Collocations with the Terra satellite. Right: Collocations with the Aqua satellite. The data were sorted according to AERONET AOD, divided into 25 bins of equal observations, and statistics calculated. Points represent the means of each bin. Error bars represent the standard deviation of MODIS AOD within those bins. Highest AOD bin typically represents the mean of fewer observations than the other bins. AERONET AOD at 550 nm was interpolated on a log-log plot between observations at 500 nm and

675 nm. Stations with no 500 nm channel were not included in the upper plots, but were included in the lower plots where no interpolation was necessary. The regression line, regression equation and correlation were calculated from the full cloud of points before binning. Expected uncertainty is ±0.03±0.05*AOD, and is shown in the plots by the dashed lines.

Figure 2 Similar as Figure 1, but for collocations over land. Only AOD at 550 nm is shown. Expected uncertainty over land is ±0.05±0.15*AOD.

Figure 3. Histogram of aerosol optical depth at 550 nm (AOD) over ocean and fine mode fraction (FMF) derived from MODIS aerosol algorithms applied to a test bed of saved Collection 4 radiances. The test bed consisted of 35 granules of various oceanic aerosol scenes spread throughout 2001. Over 400,000 retrievals were used to construct the histograms. The Collection 4 results are shown in blue. Results of applying Collection 5 software to Collection 4 radiances are shown in black. Solid curves denote AOD, and dotted curves denote FMF.

Figure 4. Global and monthly mean aerosol optical depth (AOD) at 550 nm over the global oceans from operational Collection 5 processing plotted against similar produced from old Collection 4 processing. Collection 5 processing includes both updates to the aerosol algorithm and also updates to the calibration. Terra and Aqua are plotted separately. Terra Collection 5 is higher than Terra Collection 4, and also higher than both Aquas.

Figure 5 Time series of MODIS global aerosol optical depth at 550 nm over ocean (left) and over land (right) for the length of the Aqua mission. Monthly mean total AOD is plotted with a heavy black line. Contribution to the AOD from fine mode (ocean) or fine model (land) is plotted in blue. Note that unlike ocean the land fine model contains coarse mode aerosols, as well. The percentile AODs are plotted by various dotted and dashed thin black lines. The mean AOD roughly corresponds to the 66% percentile over both ocean and land, showing that 66% of the monthly mean AOD values are less than the mean. Note that the vertical axes are different in the land and ocean plots.

Figure 6. Global aerosol optical depth histograms (AOD) over ocean (left) and land (right) constructed from pixel-weighted daily 1° x 1° latitude-longitude MODIS aerosol products. Top: Calculated from all available data. Bottom: Calculated only for those grid squares with greater than 80% cloud cover. Line with solid circles shows mean fine mode (ocean) or fine model (land) AOD in each total AOD bin. Line with open circles shows mean fine mode fraction (ocean) or fine model fraction (land) in each AOD bin. Fine mode/model fraction is the fine AOD divided by the total AOD. Note that fine AOD and fine mode/model fraction are not the same quantities in the land and ocean plots. Fine model over land includes a coarse mode.

Figure 7. Five year mean global distribution of aerosol optical depth (AOD) at 550 nm for four selected months: January, April, July and October. The averages were calculated from pixel-weighted daily 1° x 1° latitude-longitude MODIS aerosol products. Negative values in purple identify where AOD is so low that it cannot be distinguished from zero, Black indicates fill value where no retrieval was attempted. Retrievals are not attempted over snow, during polar night or over bright deserts.

Figure 8 The 13 ocean regions (top) and 14 land regions (bottom).

Figure 9. Time series of regional and monthly mean aerosol optical depth (AOD) at 550 nm calculated from pixel-weighted daily 1° x 1° latitude-longitude MODIS aerosol products. Regions are defined in Figure 8.

Figure 10. Monthly and regional mean fine mode AOD over ocean plotted against monthly and regional mean total AOD for five selected ocean regions. Regression lines and correlations are calculated and displayed. Regions fall into two classes defined by the slope of this regression. Most regions have slopes in the 0.7 to 0.8 range, as demonstrated by Region 4 (Asian Pacific) and denoted by the green line. However,

Region 6 (Saharan Atlantic) has a slope of 0.32 and is denoted by the blue line. Region 7 (North Indian Ocean) has a seasonal shift with the months of October through March following the green line and months April through September following the blue line.

Table 1. Aerosol models used in Collection 5 MODIS ocean retrievals.

Small Particles

	λ=0.47 to 0.86 μm	1.24 μm	1.64 μm	2.13 μm	rg	σ	reff	comments
1	1.45-0.0035i	1.45-0.0035i	1.43-0.01i	1.40-0.005i	0.07	0.40	0.10	Wet water soluble type
2	1.45-0.0035i	1.45-0.0035i	1.43-0.01i	1.40-0.005i	0.06	0.60	0.15	Wet water soluble type
3	1.40-0.0020i	1.40-0.0020i	1.39-0.005i	1.36-0.003i	0.08	0.60	0.20	Water soluble with humidity
4	1.40-0.0020i	1.40-0.0020i	1.39-0.005i	1.36-0.003i	0.10	0.60	0.25	Water soluble with humidity

Large Particles

	λ=0.47 to 0.86 μm	1.24 μm	1.64 μm	2.13 μm	rg	σ	reff	comments
5	1.35-0.001i	1.35-0.001i	1.35-0.001i	1.35-0.001i	0.40	0.60	0.98	Wet sea salt type
6	1.35-0.001i	1.35-0.001i	1.35-0.001i	1.35-0.001i	0.60	0.60	1.48	Wet sea salt type
7	1.35-0.001i	1.35-0.001i	1.35-0.001i	1.35-0.001i	0.80	0.60	1.98	Wet sea salt type
8	1.53-0.003i (0.47) 1.53-0.001i (0.55) 1.53-0.000i (0.66) 1.53-0.000i (0.86)	1.46-0.000i	1.46-0.001i	1.46-0.000i	0.60	0.60	1.48	Dust like type
9	1.53-0.003i (0.47) 1.53-0.001i (0.55) 1.53-0.000i (0.66) 1.53-0.000i (0.86)	1.46-0.000i	1.46-0.001i	1.46-0.000i	0.50	0.80	2.50	Dust like type

Table 2 Seasonal and annual aerosol optical depth at 550 nm (AOD) and fine mode fraction (FMF) for each ocean region of Figure 8

	MAM		JJA		SON		DJF		annual	
	AOT	FMF	AOT	FMF	AOT	FMF	AOT	FMF	AOT	FMF
1	0.20	0.53	0.13	0.62	0.11	0.44	0.13	0.33	0.14	0.49
2	0.17	0.52	0.15	0.62	0.11	0.44	0.12	0.36	0.14	0.49
3	0.20	0.60	0.19	0.65	0.15	0.58	0.15	0.48	0.17	0.58
4	0.32	0.60	0.22	0.65	0.16	0.58	0.18	0.50	0.22	0.59
5	0.14	0.45	0.11	0.42	0.10	0.47	0.11	0.46	0.12	0.45
6	0.23	0.40	0.26	0.39	0.16	0.45	0.17	0.44	0.20	0.42
7	0.26	0.44	0.43	0.38	0.22	0.53	0.23	0.59	0.28	0.47
8	0.18	0.48	0.12	0.47	0.12	0.54	0.15	0.50	0.14	0.50
9	0.09	0.40	0.09	0.39	0.10	0.35	0.10	0.33	0.10	0.37
10	0.11	0.46	0.12	0.47	0.13	0.49	0.12	0.42	0.12	0.46
11	0.10	0.46	0.14	0.48	0.14	0.48	0.11	0.37	0.12	0.44
12	0.09	0.45	0.10	0.43	0.14	0.51	0.11	0.37	0.11	0.44
13	0.10	0.30	0.09	0.28	0.13	0.42	0.13	0.47	0.11	0.39

Table 3. Seasonal and annual aerosol optical depth at 550 nm for each land region of Figure 8.

	MAM	JJA	SON	DJF	annual
1 West N. Am.	0.17	0.16	0.09	0.10	0.13
2 East N. Am.	0.13	0.17	0.06	0.05	0.10
3 Central Am.	0.25	0.15	0.12	0.10	0.15
4 S. Amer.	0.07	0.11	0.22	0.12	0.13
5 N. Europe	0.18	0.15	0.10	0.10	0.13
6. Mediter. Basin	0.22	0.25	0.16	0.13	0.19
7. N. Africa	0.38	0.34	0.24	0.29	0.31
8. S. Africa	0.11	0.21	0.21	0.14	0.17
9. Siberia	0.22	0.15	0.08	0.08	0.13
10. India	0.36	0.42	0.29	0.29	0.34
11. East Asia	0.46	0.35	0.24	0.27	0.33
12. SE Asia	0.39	0.28	0.24	0.21	0.28
13. Indonesia	0.17	0.19	0.28	0.19	0.21
14. Australia	0.03	0.01	0.07	0.07	0.04

Table 4. Annual mean aerosol optical depth at 550 nm (AOD), fine mode AOD, fine mode fraction (FMF), Angstrom Exponent defined by 550 nm and 870 nm, slope of the regression between AOD fine and AOD, and correlation of the regression.

Region	AOD	AOD fine	FMF	Ang1	slope	R^2
1	0.14	0.07	0.49	0.65	0.72	0.79
2	0.14	0.07	0.49	0.66	0.81	0.80
3	0.17	0.1	0.58	0.87	0.69	0.77
4	0.22	0.13	0.59	0.84	0.71	0.94
5	0.12	0.05	0.45	0.60	0.49	0.83
6	0.20	0.09	0.42	0.52	0.32	0.90
7	0.28	0.13	0.47	0.65	0.22	0.58
8	0.14	0.07	0.50	0.67	0.57	0.84
9	0.10	0.04	0.37	0.45	0.30	0.40
10	0.12	0.06	0.46	0.60	0.64	0.81
11	0.12	0.06	0.44	0.59	0.70	0.88
12	0.11	0.05	0.44	0.59	0.65	0.83
13	0.11	0.04	0.39	0.44	0.76	0.91

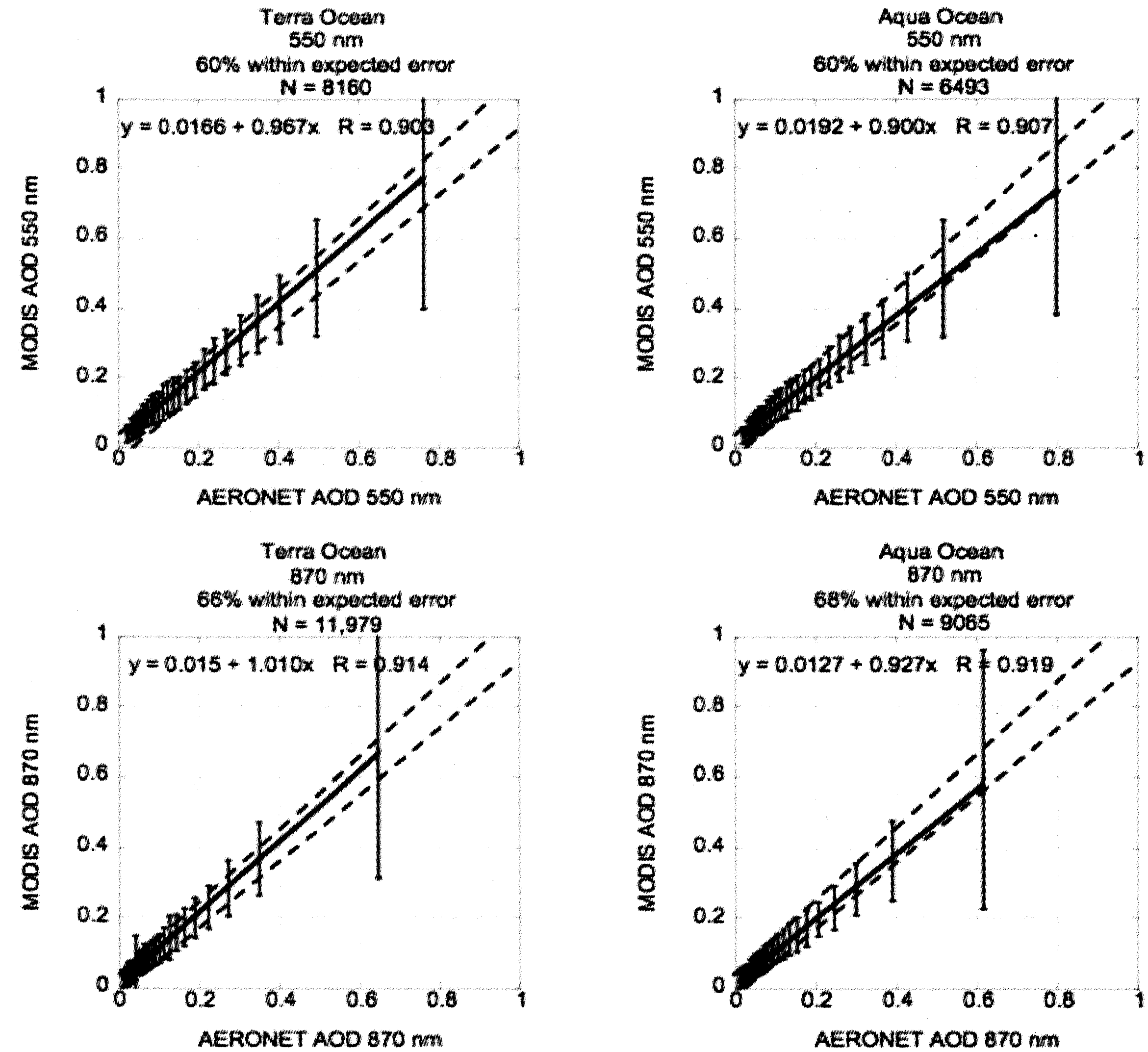

Figure 1. MODIS aerosol optical depth (AOD) over oceans plotted against collocated AERONET observations. Top: AOD at 550 nm. Bottom: AOD at 870 nm. Left: Collocations with the Terra satellite. Right: Collocations with the Aqua satellite. The data were sorted according to AERONET AOD, divided into 25 bins of equal observations, and statistics calculated. Points represent the means of each bin. Error bars represent the standard deviation of MODIS AOD within those bins. Highest AOD bin typically represents the mean of fewer observations than the other bins. AERONET AOD at 550 nm was interpolated on a log-log plot between observations at 500 nm and 675 nm. Stations with no 500 nm channel were not included in the upper plots, but were included in the lower plots where no interpolation was necessary. The regression line, regression equation and correlation were calculated from the full cloud of points before binning. Expected uncertainty is ±0.03±0.05*AOD, and is shown in the plots by the dashed lines.

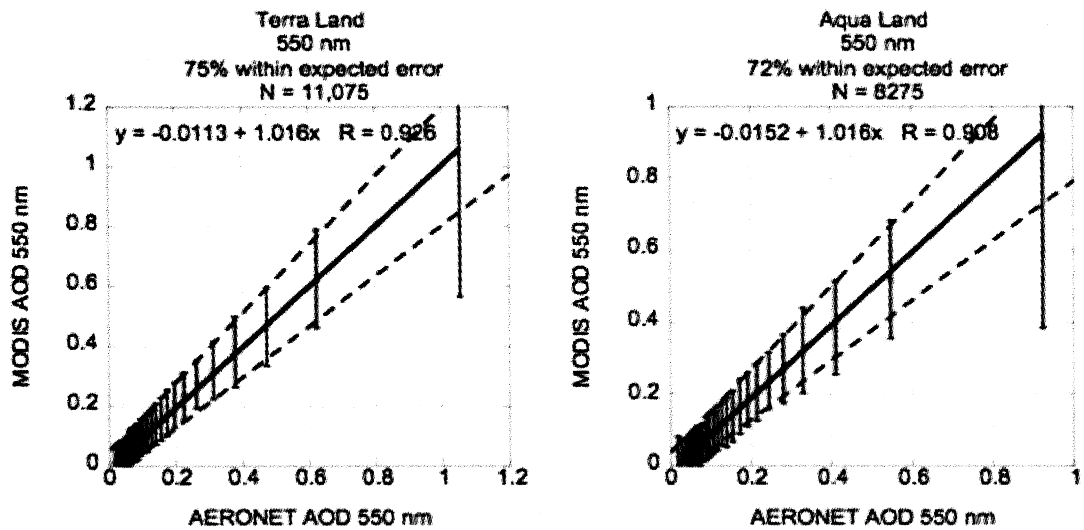

Figure 2 Similar as Figure 1, but for collocations over land. Only AOD at 550 nm is shown. Expected uncertainty over land is ±0.05±0.15*AOD.

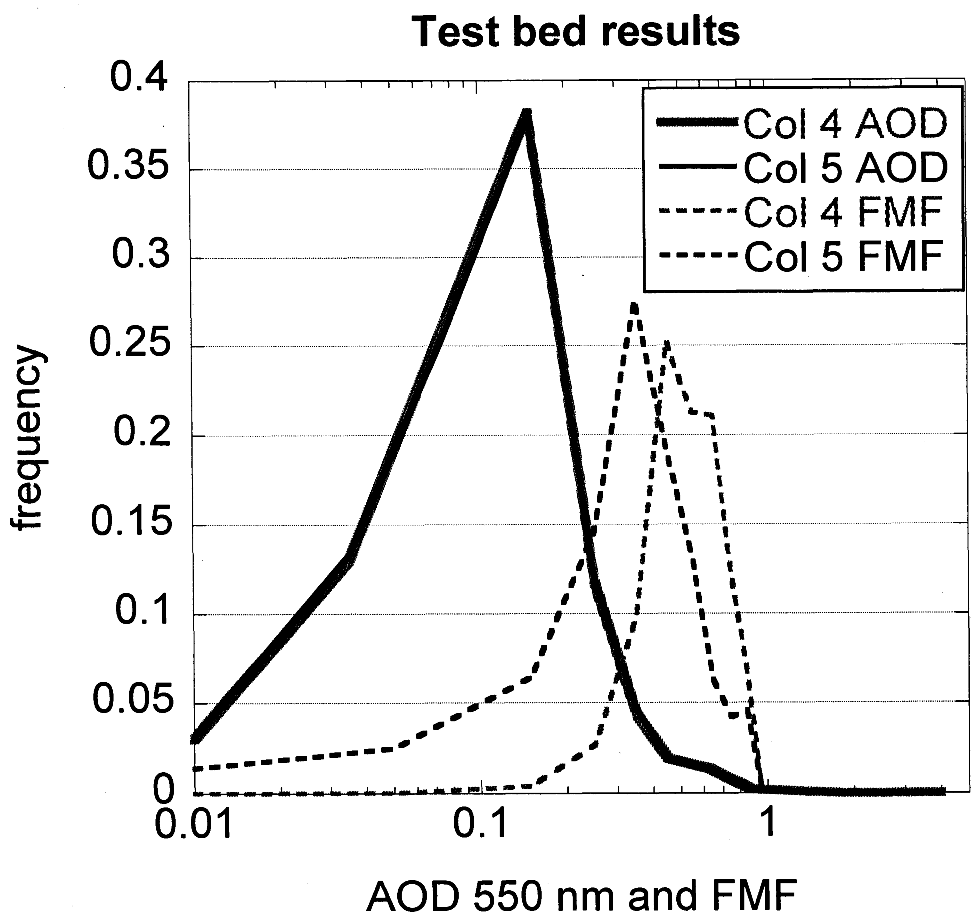

Figure 3. Histogram of aerosol optical depth at 550 nm (AOD) over ocean and fine mode fraction (FMF) derived from MODIS aerosol algorithms applied to a test bed of saved Collection 4 radiances. The test bed consisted of 35 granules of various oceanic aerosol scenes spread throughout 2001. Over 400,000 retrievals were used to construct the histograms. The Collection 4 results are shown in blue. Results of applying Collection 5 software to Collection 4 radiances are shown in black. Solid curves denote AOD, and dotted curves denote FMF.

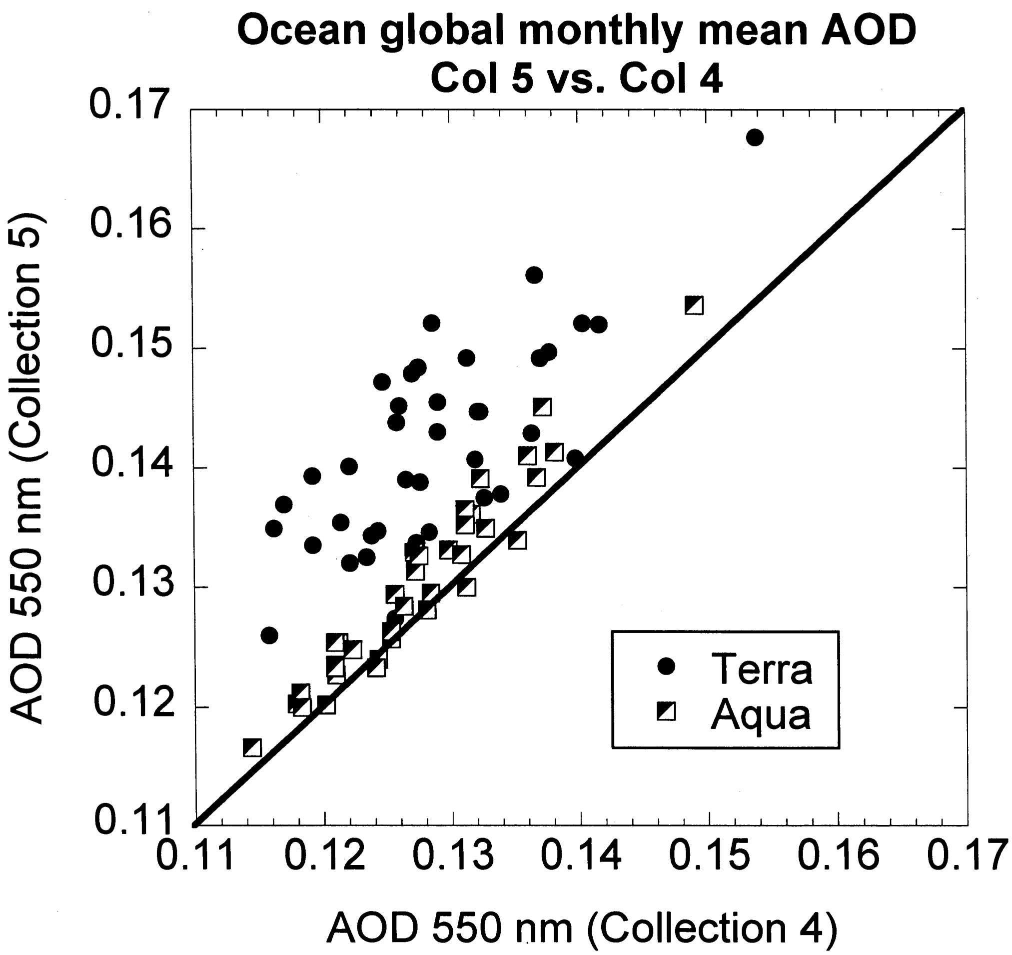

Figure 4. Global and monthly mean aerosol optical depth (AOD) at 550 nm over the global oceans from operational Collection 5 processing, plotted against similar produced from old Collection 4 processing. Collection 5 processing includes both updates to the aerosol algorithm and also updates to the calibration. Terra and Aqua are plotted separately. Terra Collection 5 is higher than Terra Collection 4, and also higher than both Aquas.

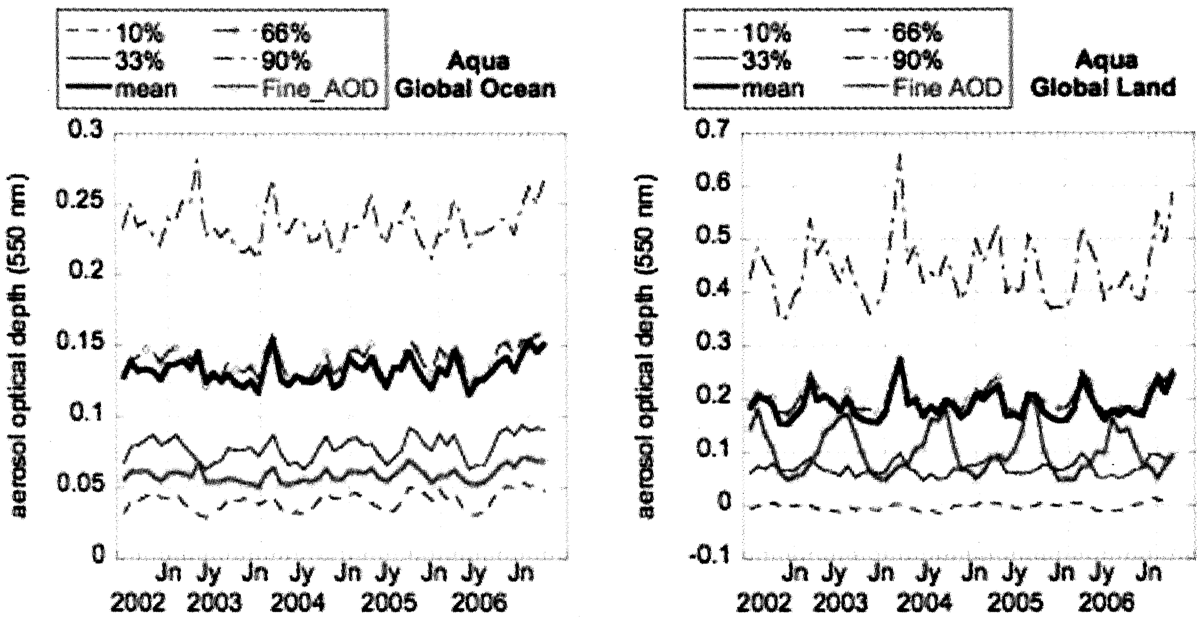

Figure 5 Time series of MODIS global aerosol optical depth at 550 nm over ocean (left) and over land (right) for the length of the Aqua mission. Monthly mean total AOD is plotted with a heavy black line. Contribution to the AOD from fine mode (ocean) or fine model (land) is plotted in blue. Note that unlike ocean the land fine model contains coarse mode aerosols, as well. The percentile AODs are plotted by various dotted and dashed thin black lines. The mean AOD roughly corresponds to the 66% percentile over both ocean and land, showing that 66% of the monthly mean AOD values are less than the mean. Note that the vertical axes are different in the land and ocean plots.

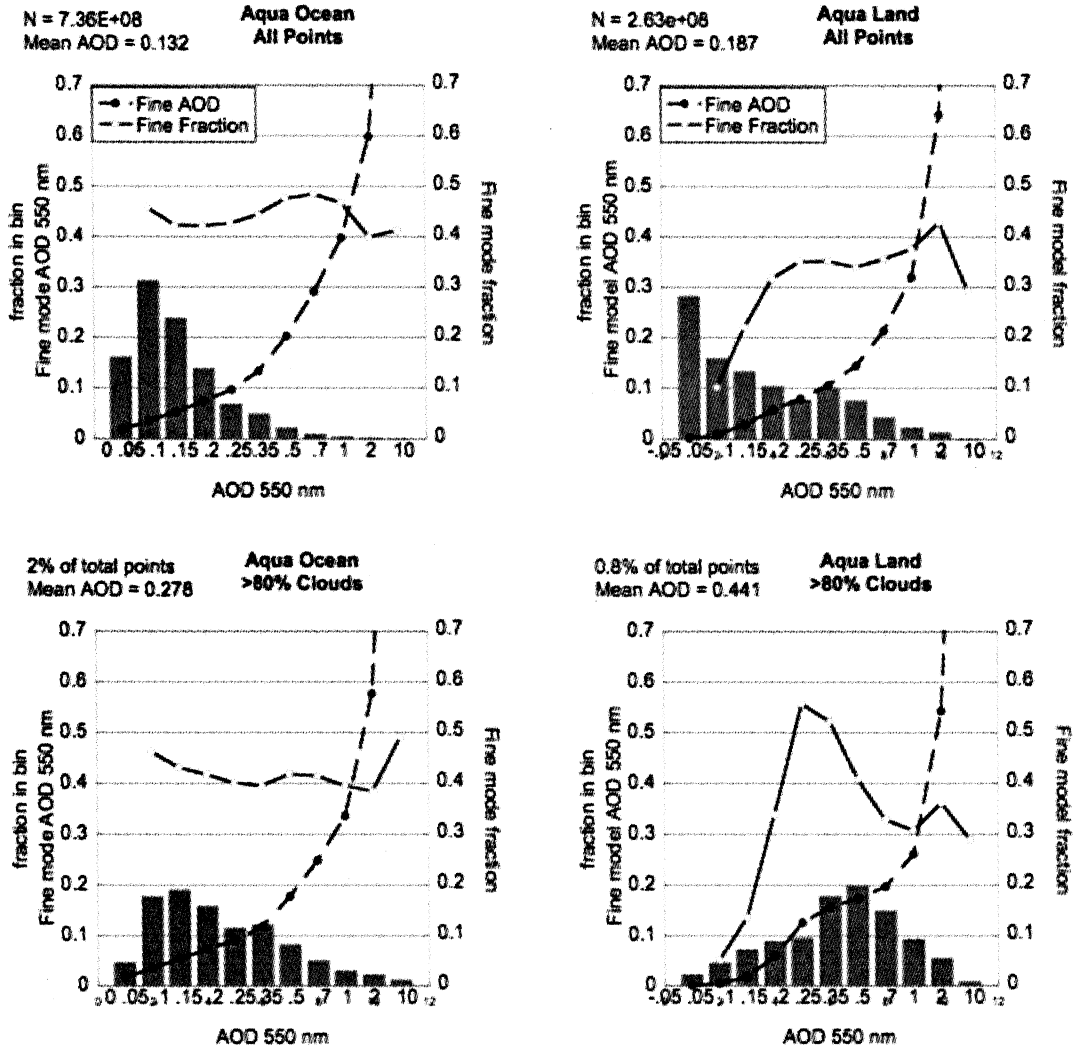

Figure 6. Global aerosol optical depth histograms (AOD) over ocean (left) and land (right) constructed from pixel-weighted daily 1 ° x 1° latitude-longitude MODIS aerosol products. Top: Calculated from all available data. Bottom: Calculated only for those grid squares with greater than 80% cloud cover. Line with solid circles shows mean fine mode (ocean) or fine model (land) AOD in each total AOD bin. Line with open circles shows mean fine mode fraction (ocean) or fine model fraction (land) in each AOD bin. Fine mode/model fraction is the fine AOD divided by the total AOD. Note that fine AOD and fine mode/model fraction are not the same quantities in the land and ocean plots. Fine model over land includes a coarse mode.

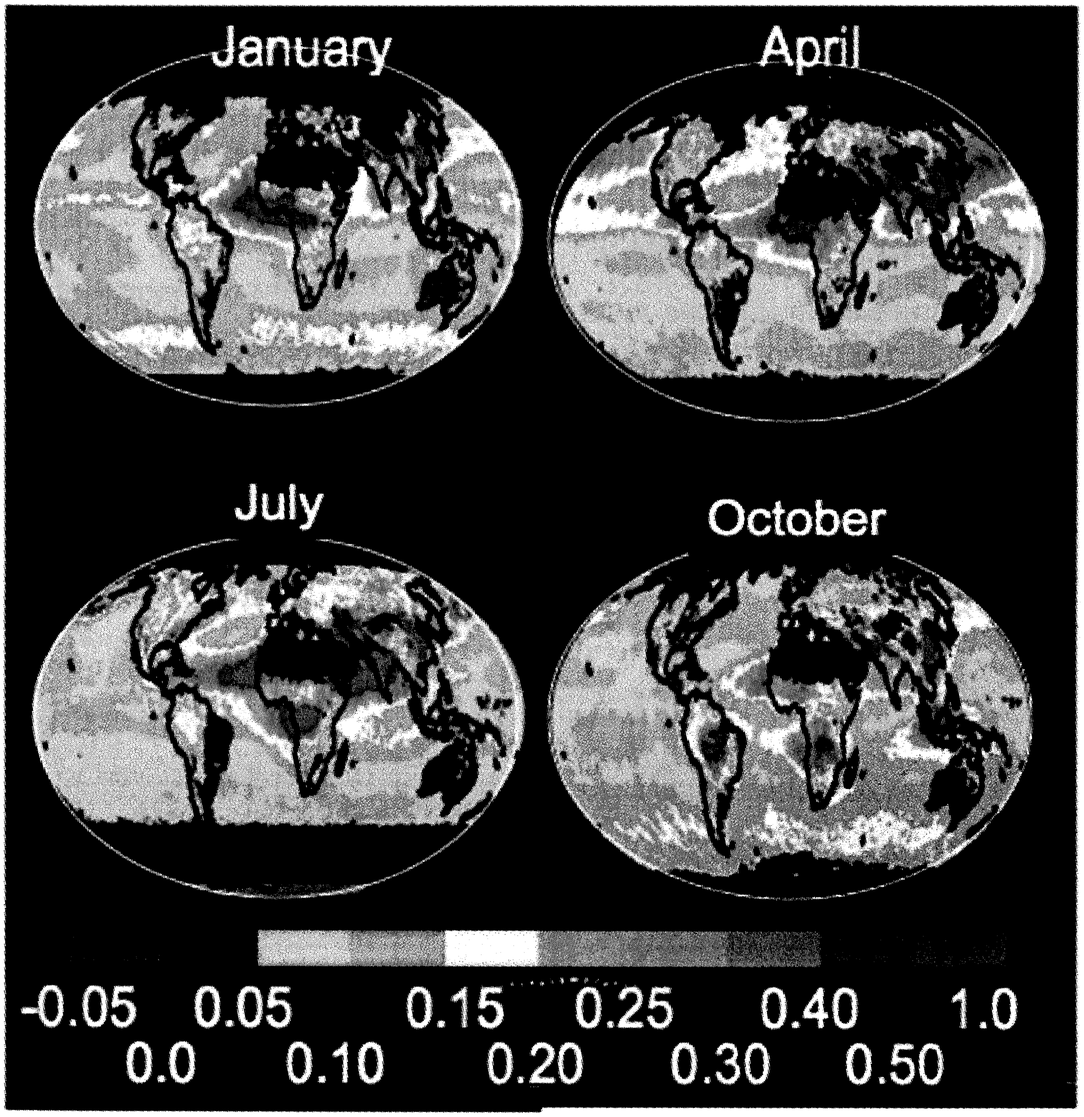

Figure 7. Five year mean global distribution of aerosol optical depth (AOD) at 550 nm for four selected months: January, April, July and October. The averages were calculated from pixel-weighted daily 1 ° x 1° latitude-longitude MODIS aerosol products. Negative values in purple identify where AOD is so low that it cannot be distinguished from zero, Black indicates fill value where no retrieval was attempted. Retrievals are not attempted over snow, during polar night or over bright deserts.

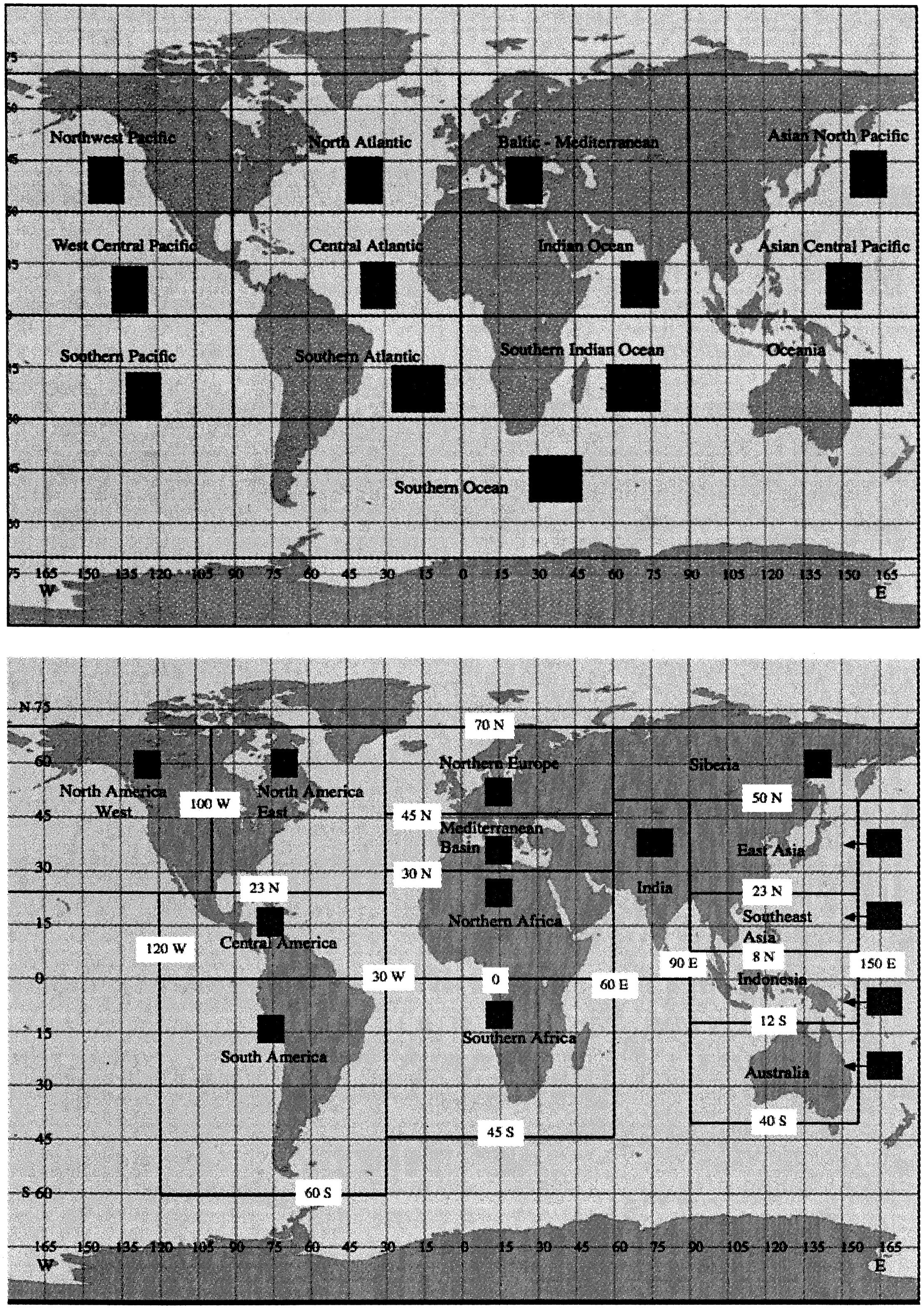

Figure 8 The 13 ocean regions (top) and 14 land regions (bottom).

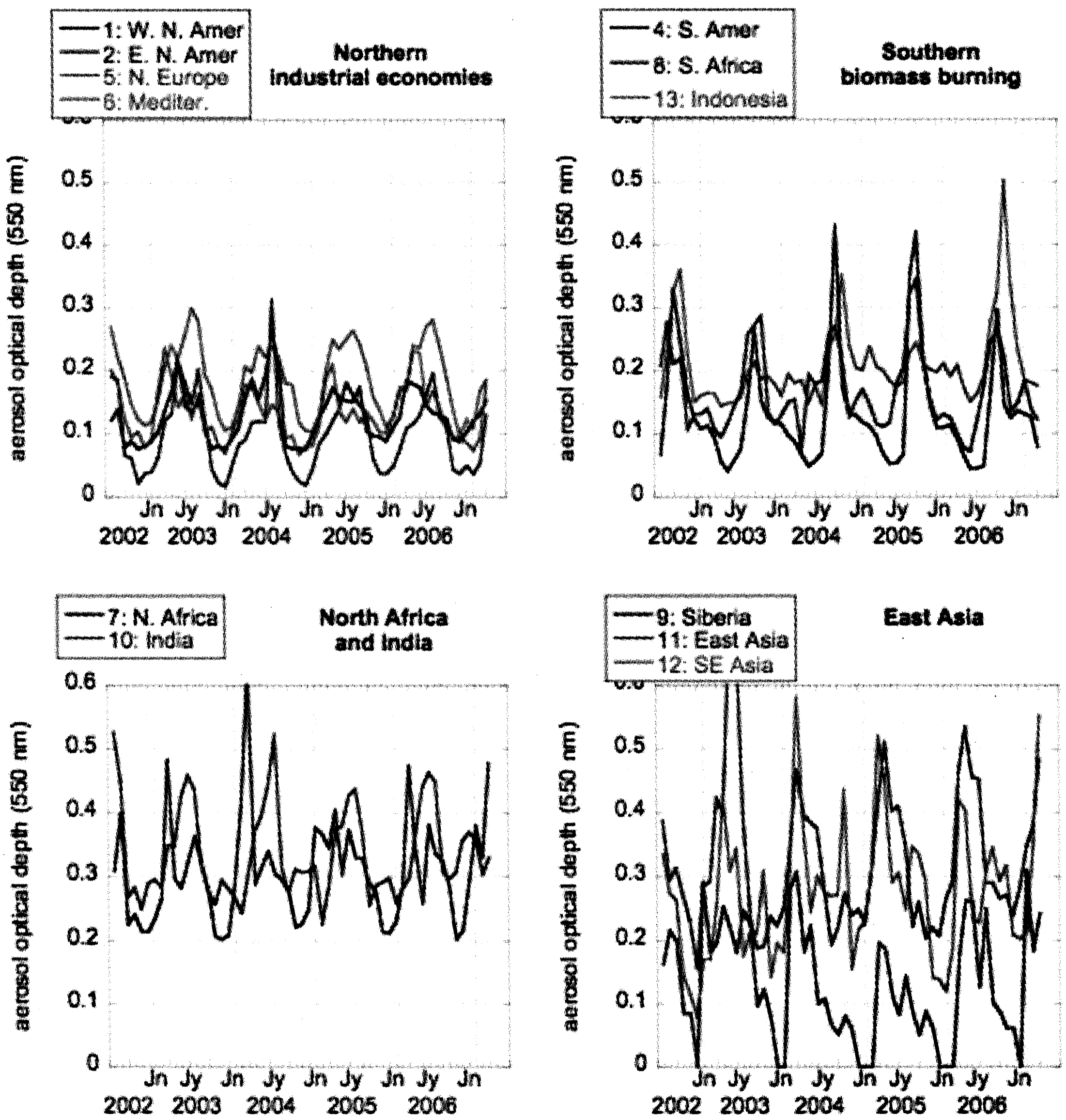

Figure 9. Time series of regional and monthly mean aerosol optical depth (AOD) at 550 nm calculated from pixel-weighted daily $1^{\circ} \times 1^{\circ}$ latitude-longitude MODIS aerosol products. Regions are defined in Figure 8.

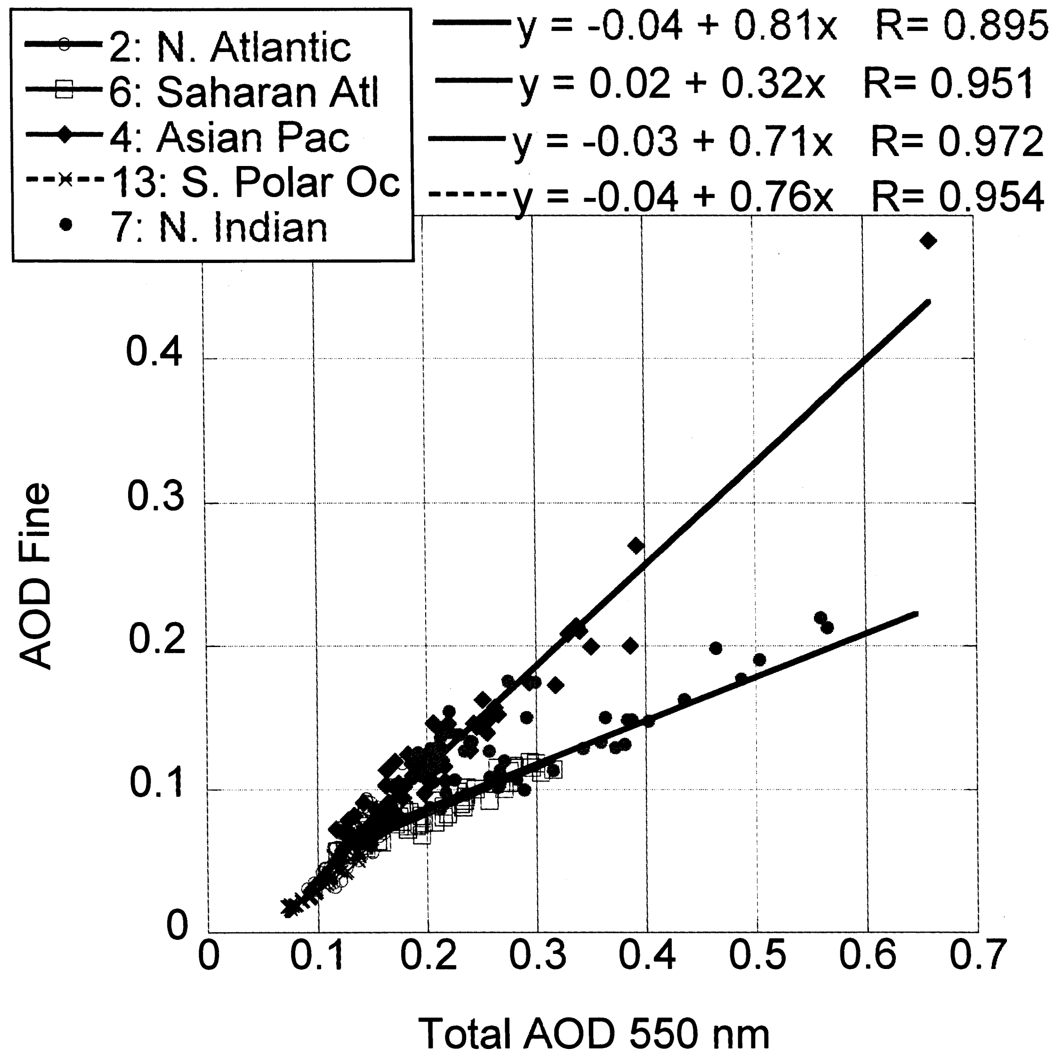

Figure 10. Monthly and regional mean fine mode AOD over ocean plotted against monthly and regional mean total AOD for five selected ocean regions. Regression lines and correlations are calculated and displayed. Regions fall into two classes defined by the slope of this regression. Most regions have slopes in the 0.7 to 0.8 range, as demonstrated by Region 4 (Asian Pacific) and denoted by the green line. However, Region 6 (Saharan Atlantic) has a slope of 0.32 and is denoted by the blue line. Region 7 (North Indian Ocean) has a seasonal shift with the months of October through March following the green line and months April through September following the blue line.