Collection 005 Change Summary for MODIS Aerosol (04_L2) Algorithms

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Summary:

1. Land: New algorithm implemented.

The algorithm to retrieve the aerosol optical depth over land has been completely restructured to produce the Collection 005 products. Levy et al. (2006) provide a detailed documentation of the new algorithm and the changes from previous version. Here we give a brief overview. The algorithm is now based on a true inversion that uses three pieces of information: apparent reflectance at 470 nm, 660 nm and 2130 nm to derive three products: aerosol optical depth (AOD), fraction of AOD attributed to non-dust aerosol and the surface reflectance at 2130 nm. This structure deviates from previous versions in the following ways:

- No longer are the AODs in individual wavelengths derived independently. Now all wavelengths are linked through the choice of aerosol model. The look up table is indexed by AOD at 550 nm, even though the reflectance at 550 nm is not used as input to the retrieval.
- Fitting error of inversion is output as a diagnostic SDS.

- The Look Up Table is calculated with the MieV-RT3 radiative transfer code that accounts for the effects of polarization.
- No longer does the algorithm assume that the reflectance at 2130 nm measured by satellite is the same as surface reflectance in that channel. There are still relationships between surface reflectance in the visible to surface reflectance at 2130 nm.
- No longer does the algorithm use a cascade to choose the darkest pixels in a 20 by 20 pixel box. Now all pixels with 2130 nm reflectance 0.01 to 0.25 are included.

Other changes to the land algorithm include updated aerosol models with new geographic distribution, the inclusion of negative AODs, more sophisticated relationships between surface reflectance in the various wavelengths and improved snow and cloud masking. These improvements are described below in greater detail. The net effect of these major changes to the over land algorithm is to reduce the biases previously noted in various validation studies (Remer et al., 2005; Ichoku et al., 2005; Levy et al., 2005), and also to produce more realistic aerosol particle size information, both in terms of fine model fraction and fine model AOD (a new parameter introduced for Collection 005).

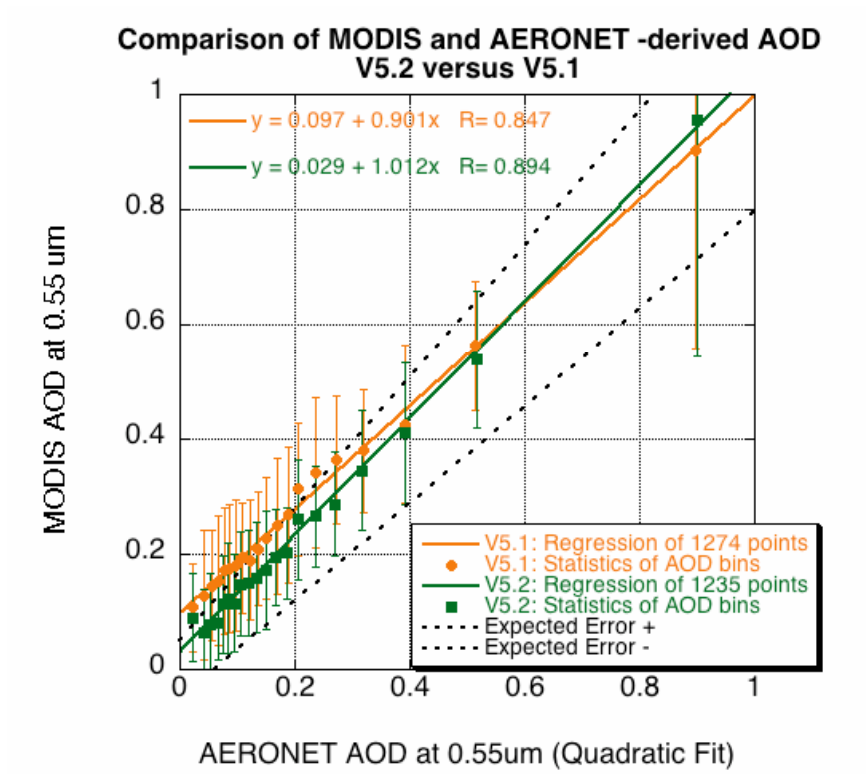

Figure 1. MODIS AOD retrievals at 550 nm plotted against collocated AERONET values in the manner described by Ichoku et al., (2002). Data has been sorted according to AERONET AOD and averaged in groups of 50 observations. Error bars refer to standard deviations within the AOD bin. The regression lines were calculated from the original points before binning and averaging. V5.1 (orange) refers to data only slightly modified from Collection 004 and V5.2 (green) refers to Collection 005. The data was extracted from approximately 45 days of observations spread over a year, and both Terra and Aqua are represented. Note that the positive bias has been cut to 1/3 of previous values and the slope is much closer to 1.

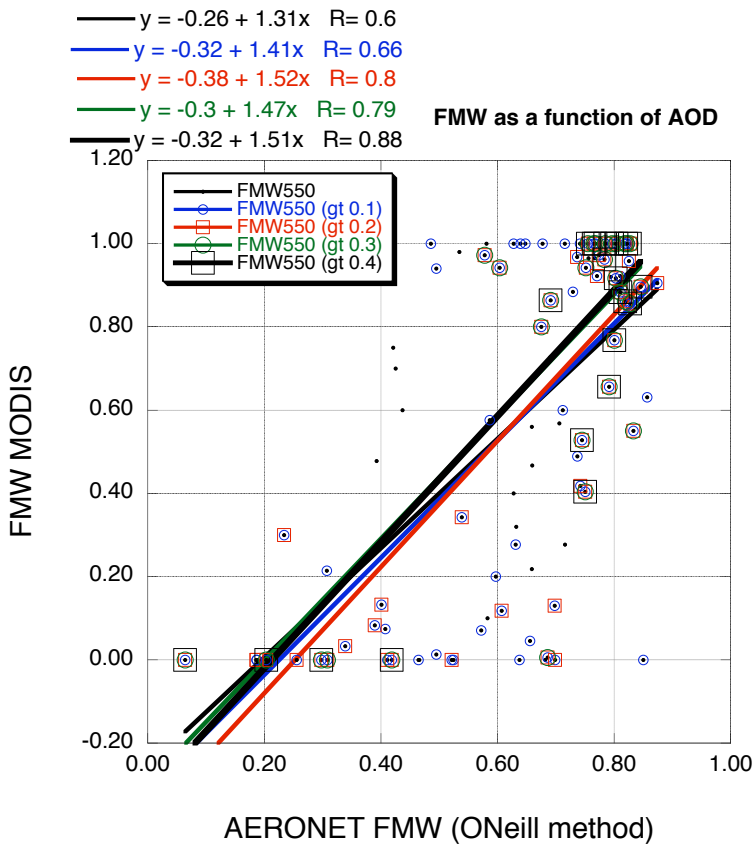

Figure 2. Aerosol fine model weighting – fmw (Optical_Depth_Ratio_Small_Land) derived from MODIS data plotted against collocated values derived from AERONET sun observations using the O'Neill method (O'Neill et al., 2003). Note that the two quantities are not identical, and more information is given in Levy et al (2006). Points are designated as to amount of aerosol loading. Small black points are all data in this data base, blue are for AOD > 0.10, red for AOD > 0.20 and large black boxes for AOD greater than 0.40. Accuracy of fmw increases with increasing AOD. Collection 005 algorithm reports Optical_Depth_Ratio_Small_Land only when AOD_550 > 0.20.

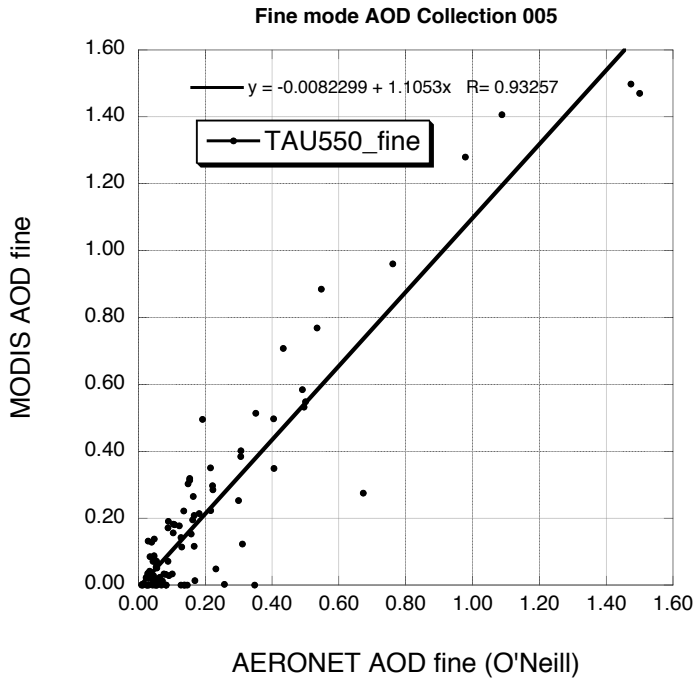

Figure 3. Fine model AOD at 550 nm over land, a new product in Collection 005. Fine model AOD may be calculated from multiplying total AOD (Figure 1) by fine model weighting (fmw in Figure 2). Fine model AOD is reported for all ranges of AOD.

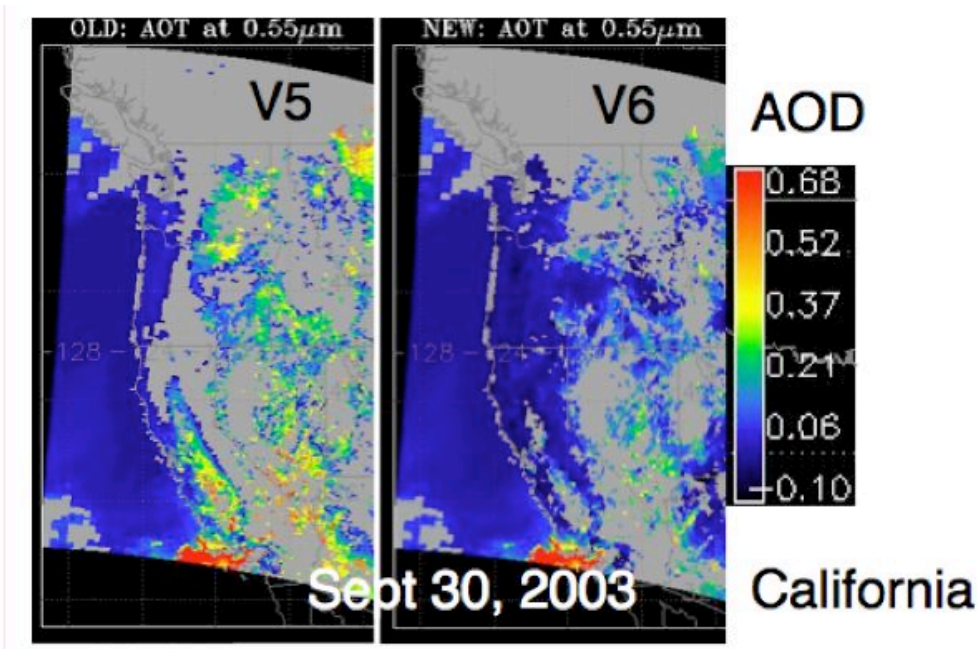

Figure 4. An example of a region that will be much improved in Collection 005. V5 refers to Collection 004 and V6 to Collection 005. Both 004 and 005 properly retrieve the high AOD values caused by an actively burning smoke plume in Southern California. However, V6 (Collection 005) returns overall much lower AOD and more retrievals that were previously discarded because of negative values.

2. Land: Valid range of AOD extended to -0.1

The expected uncertainty of the land retrievals is $\pm 0.05 \pm 0.15 * \tau$, where τ is the aerosol optical depth. For small values of τ we expect equal probabilities of retrieving a small negative value as a small positive one. Thus, to avoid a positive bias in the long-term statistics of AOD we must include the possibility of small negative values when AOD is low. In Collection 005, all retrievals of $-0.05 < \tau < 0$, are reported just as retrieved. All retrievals of $-0.10 < \tau < -0.05$ are reported as -0.05. All retrievals < -0.10 are determined to be unrealistic, and are not reported.

The net effect is to contribute to reducing the positive bias previously seen at low AOD. (Figure 1)

3. Land: Aerosol models now based on Dubovik (2002) and new geographic distribution

Five aerosol models are used in Collection 005 and described in Levy et al. (2006). These are continental, dust, non-absorption, moderate absorption and heavy absorption. Models are based on Dubovik et al. (2002) with some modification. This is a departure from all previous collections in which the aerosol models were based on the work of Remer in the 1990's. The inversion chooses between dust and one of the fine mode dominated models, which are designated by geography and season. The continental model is used only in special cases where the surface is too bright for the standard retrieval. The distribution of the fine mode dominated models was determined from cluster analysis and is shown in Figure 5. All fine mode dominated models are multi-modal and contain both fine and coarse modes. Fine model weighting (FMW) from Figure 2 is a weight between non-dust and dust models, not a weight between fine and coarse modes.

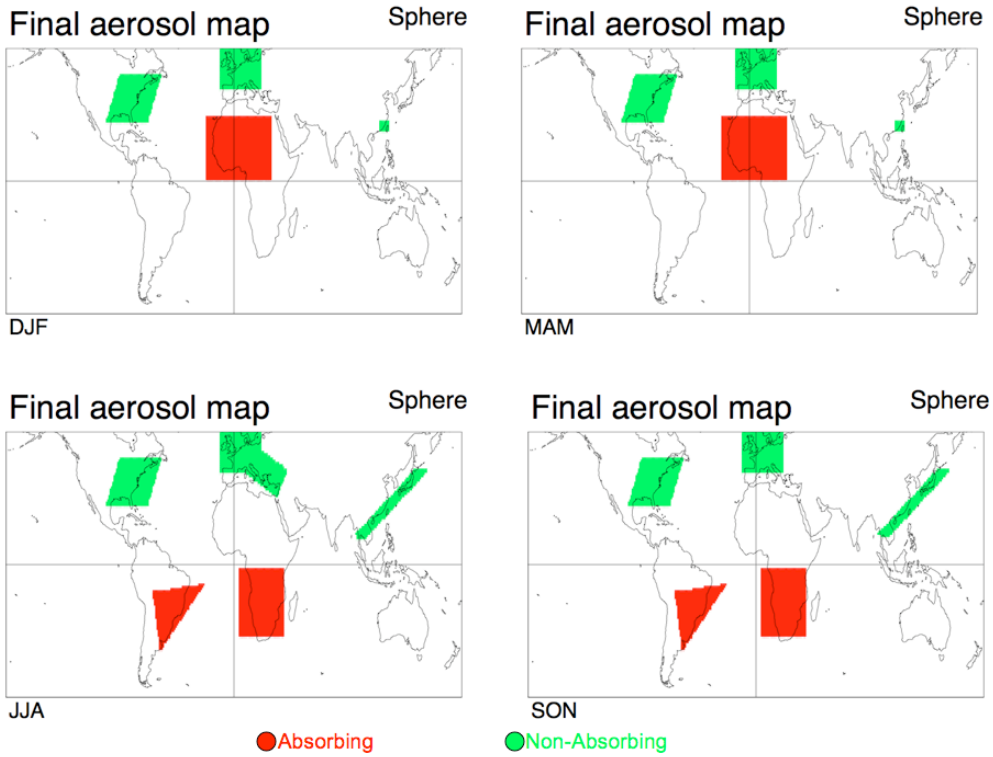

Figure 5. Distribution of the 3 non-dust models used by the primary retrieval. Red is absorbing aerosol with $\omega_o = 0.85$, green is the non-absorbing aerosol (formerly called urban/industrial) with $\omega_o = 0.95$. The uncolored regions use a moderately absorbing aerosol of $\omega_o = 0.90$. Further information on the aerosol models is given in Levy et al. (2006).

4. Land: Surface reflectance relationships a function of vegetation index and scattering angle.

In previous versions of the algorithm, we used a fixed relationship between the visible surface reflectances (470 nm and 660 nm) and the 2130 nm reflectance measured at top of atmosphere. These were:

$\rho_{470} = 0.25\ \rho_{2130}$
$\rho_{660} = 0.50\ \rho_{2130}$

In Collection 005 these relationships are now

$\rho_{660} = f_1(\mathrm{MVI}, \Theta)\ \rho_{2130}$
$\rho_{470} = f_2(\mathrm{MVI}, \Theta)\ \rho_{660}$

Where $\mathrm{MVI} = (\rho_{1240} - \rho_{2130})/(\rho_{1240} + \rho_{2130})$ which is sensitive to vegetation and Θ is the scattering angle. These new dependencies permit different relationships depending on the degree of vegetation of the surface. They also account for some of the scatter introduced by BRDF. Note that the 660 nm channel relates to 2130 nm, but now the 470 nm channel relates to the 660 nm.

5. Land: Subpixel snow mask implemented.

Aerosol retrieval from satellites requires assumptions about surface reflectance in order to separate the radiance signal originating in the atmosphere from that originating from the Earth's surface. Over ocean the uniformity of the surface makes this relatively easy. Over land it is much more difficult. The MODIS aerosol retrieval over land is limited to pixels where our assumptions about the land surface reflectance will hold. These tend to be dark, vegetated pixels. The over land algorithm does not work over bright deserts or over snow. Since launch, the aerosol algorithm has relied on a snow mask based on other MODIS products and ancillary data that is passed to us through the MOD35 product. This snow mask effectively identifies fully snow covered pixels, such as that can be seen in Figure 6 as the black regions in the most northerly latitudes of the northern hemisphere in April 2004. However, just south of the properly masked snow fields lies a band of bright colors representing aerosol optical thicknesses greater than 0.60. These high aerosol values are not real, but an artifact caused by snow-contaminated pixels slipping through the standard snow mask.

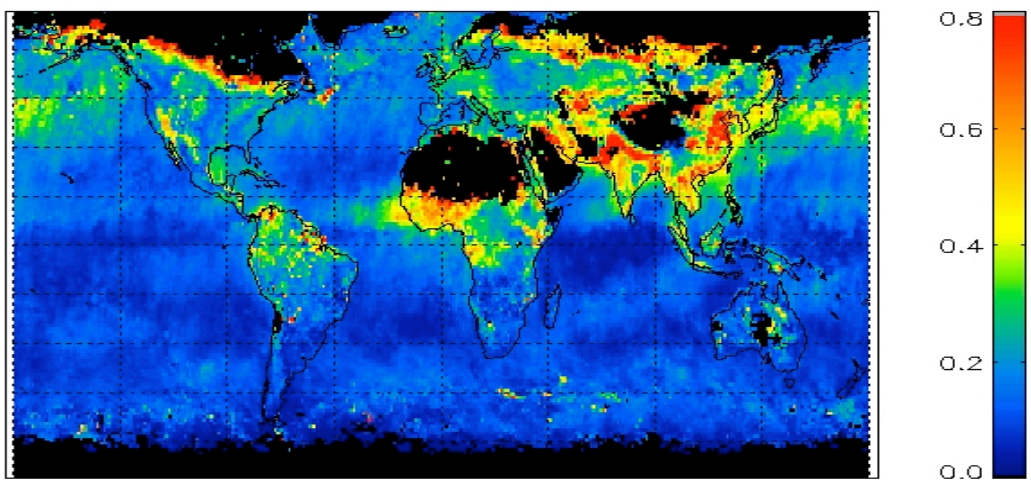

Fig. 6. A sample Collection 004 Level 3 monthly-mean global aerosol optical depth image retrieved from the Terra MODIS data for April 2004.

We have developed a new method that is sensitive to pixels only partially filled with snow. The method is based on the fact that snow is darker at 1.24 µm than at 0.86 µm, but almost all other surface types exhibit the reverse spectral dependence. We apply the normalized difference ratio,

$$R = [\rho^*_{0.86} - \rho^*_{1.24}] \;/\; [\rho^*_{0.86} + \rho^*_{1.24}], \qquad (1)$$

and couple the ratio to a threshold of the 11 μm channel brightness temperature to identify snow-contaminated pixels. This ratio was previously suggested for remote sensing of liquid water content of vegetation canopies (Gao, 1996). The result effectively eliminates snow contamination in the aerosol land product without accidentally masking out perfectly good pixels in other regions. An

example is shown below in Figure 7. The method is described in full, and other examples given in Li et al. (2005).

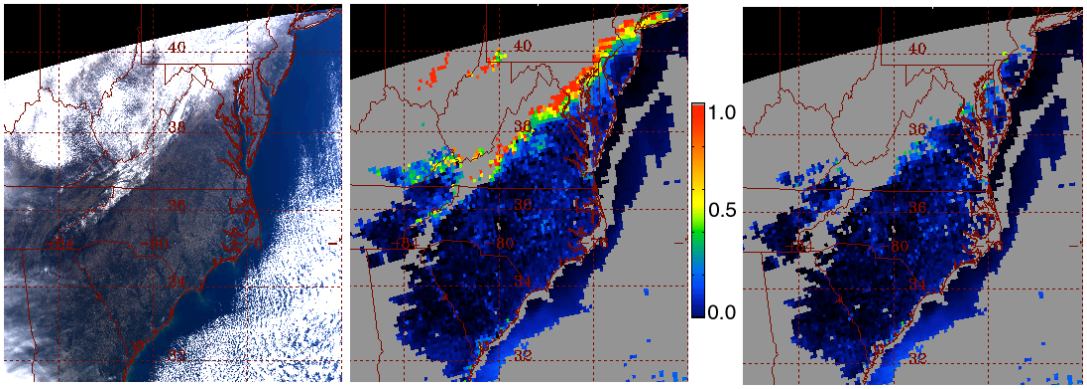

Fig. 7. (a) – An Aqua MODIS image over North America on February 8, 2004; (b) the derived aerosol optical depth image using the Collection 004 MODIS aerosol algorithm; and (c) the Collection 005 aerosol optical depth image with improved snow masking.

6. Land: Cloud mask adjusted and QA flag set to 0 in some situations.

Masking clouds without masking aerosol events remains one of the most challenging issues faced by the aerosol retrieval algorithms. At Terra launch, the aerosol retrievals relied on the standard cloud mask products available in MOD35. Almost immediately we realized that these products were not going to be adequate. A new cloud mask based on a spatial variability test, supplemented by cirrus tests using the 1.38 μm channel and a few remaining MOD35 products, was implemented in the over *ocean* aerosol algorithm (Martins et al., 2002). The mask proved to be very successful, especially after adjustments to the cirrus identification part of the algorithm (Gao et al. 2002). All of Collection 004 data over ocean, both from Terra and Aqua, were produced using this cloud mask.

A separate but similar cloud mask for masking clouds over land was developed later and not implemented until November 2002. The spatial variability cloud mask over land improved the aerosol retrievals, especially when it came to confusing heavy aerosol with cloud. However, isolated, residual cloud contamination in the product remained. For Collection 005, we have made a few adjustments to the technique, but maintained the general philosophy and structure of using spatial variability tests coupled with threshold tests only in the 1.38 μm channel. This seems to remove isolated artifacts in the retrieval. For example, in Figure 8, the red spots associated with clouds over India in a relatively clean area are removed with the new cloud logic.

For the record, the new logic of the cirrus part of the cloud mask for over land aerosol retrievals is as follows:

If stdev(1.38)* refl_1.38 >= 0.025 then CLOUD
  If refl_1.38 > or = 0.025 then CLOUD
  If refl_1.38 < 0.025 then NOT CLOUD

If 0.01 < refl_1.38 < 0.025 then NOT CLOUD but Quality is set to 0

where stdev(1.38) is the standard deviation of the 1.38 μm reflectance of the 3x3 array of pixels centered on the pixel of interest, and refl_1.38 is the reflectance of the pixel at 1.38 μm. A refl_1.38 < 0.0025 threshold will allow cirrus contamination into the land aerosol retrieval. However, those retrievals will have Quality parameter set to zero. Checking the Quality of every land retrieval is essential to understanding the final products.

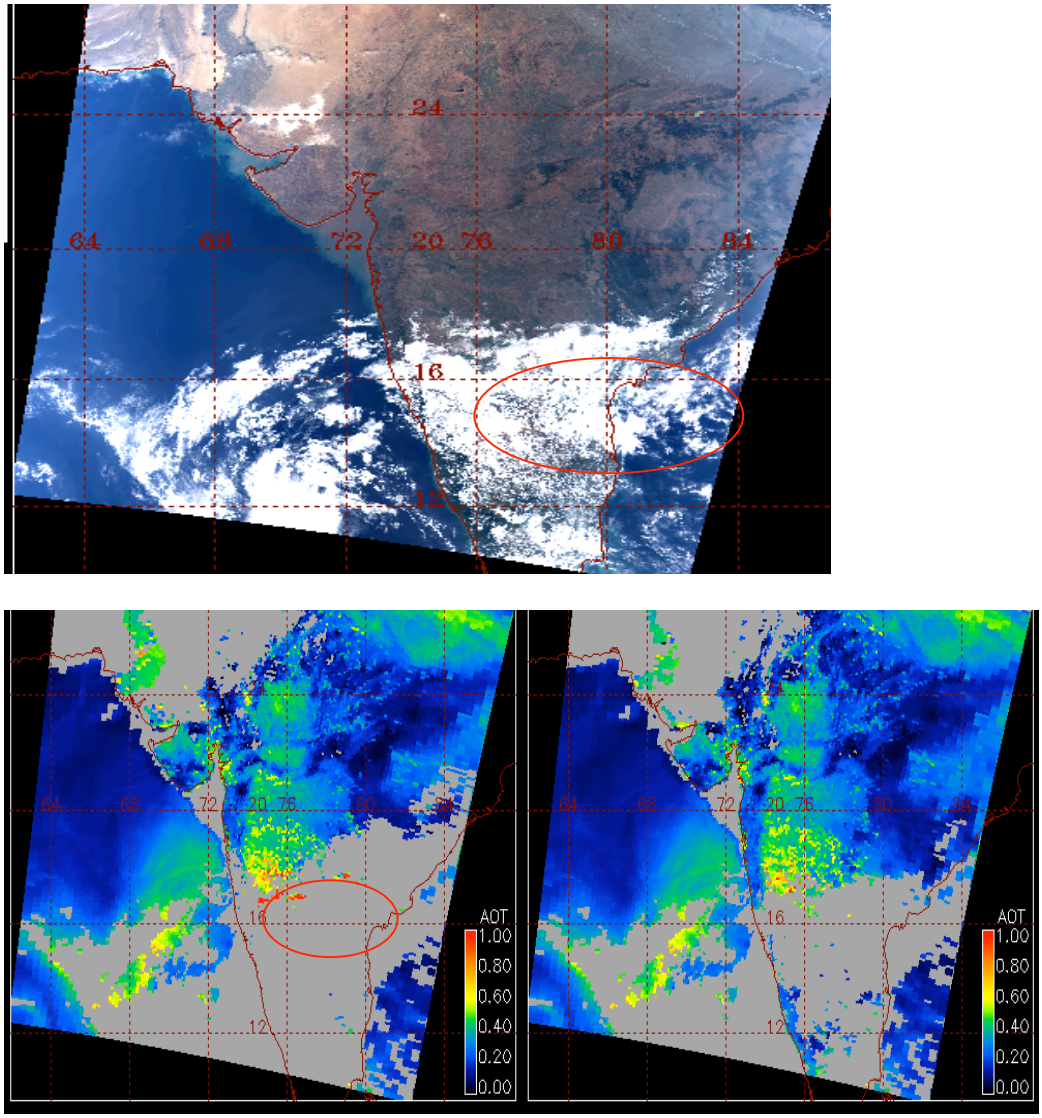

Figure 8. Images from MOD04 from year 2000, day 337, time 0555 located over India. The top image is a true color rgb with the red oval highlighting the edge of a cloudy area. The same area is identified by the oval in the lower left image, which shows aerosol optical thickness retrieval available in Collection 004. The bright red spots are artifacts of cloud contamination. These are eliminated in the lower right image, which was produced with Collection 005 software and improved cloud masking logic over land. The increased number of retrievals in the Collection 005 image result from permitting negative values in the 1.38 µm channel, as described in Section 13 below.

7. Land: Mass concentration now multiplied by exp(4.5σ)

The land mass concentration is now multiplied by exp(4.5_σ) where σ is the width of the lognormal mode of the aerosol model. This factor was erroneously omitted in previous versions.

8. Ocean: Real and imaginary refractive indices changed for 3 of the 5 coarse modes in the Look Up Table

The Look Up Table has identical values for the four fine modes (modes 1-4) and also for coarse modes 8 and 9. The change was made for only modes 5, 6 and 7, where the refractive indices are now 1.35-0.001i for all wavelengths. The change was made based on Dubovik retrievals of marine aerosol (personal communication from Oleg Dubovik). The results do not change retrievals of AOD at 550 nm, but do change the retrieval of aerosol model and fine mode weighting (fmw – Aerosol_Optical_Depth_Ratio_Small_Ocean). In dusty situations fmw decreases to more realistic values, but in smoke or pollution dominated situations fine particles are still retrieved.

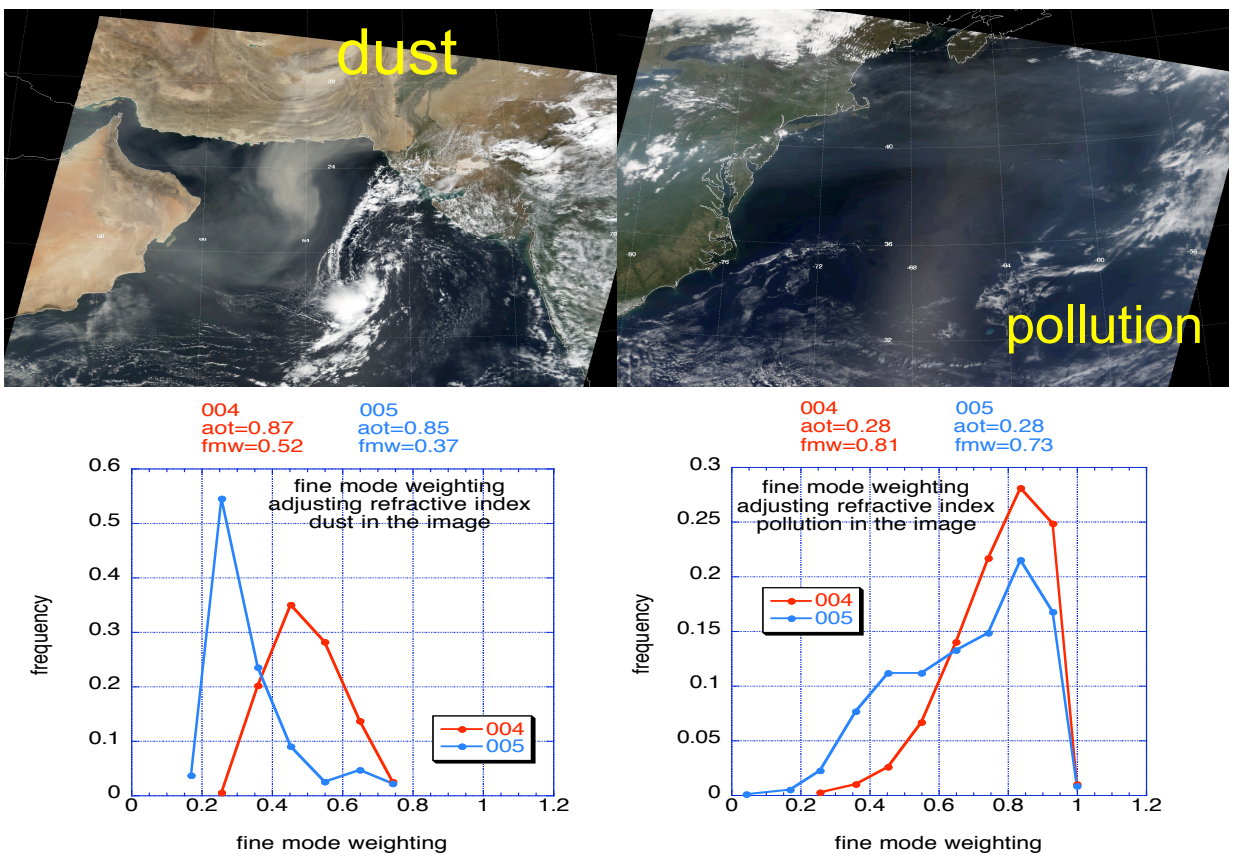

Figure 9. In dusty situations the Collection 004 (red) data reported a too high proportion of fine mode aerosols with average fmw of ~0.5. In smoke or pollution aerosols it retrieved roughly the correct fmw of ~0.8. Using the new refractive indices in the three coarse modes, the Collection

005 (blue) retrievals report less fine mode particles in the dust (fmw reduces to ~0.3), but there is still a high frequency of predominately fine mode particles retrieved in the pollution episode. Note that the mean aerosol optical thickness (AOT) remains the same in the two collections.

9. Ocean: CCN units corrected.

The units of the cloud condensation nuclei (CCN) are supposed to be number/cm^2. The over land algorithm reported the correct units, but the ocean algorithm reported values off by 10^6. The Collection 005 product will be reported in the correct units, number/cm^2, over both land and ocean.

10. Ocean: Mass concentration now multiplied by 4*pi/3

The Mass_Concentration_Ocean parameter was missing a factor of (4/3)pi. It has been corrected.

11. Land and Ocean: Original SDS now contains only land products with QA = 3. New "Image" SDS introduced to display all data of all levels of QA

The MODIS aerosol products are designed to be used with careful consideration of the associate Quality Assurance (QA) parameters. We make retrievals in situations where we anticipate that the quantitative value of the retrieval diminishes to near uselessness. However, there remains a qualitative value in producing images of the AOD retrieval in those regions. At Level 3, a user who desires high quality, quantitative AOD information can use the QA weighted mean values over land. However, if the user chooses the Land_And_Ocean product, there is no associated QA-weighted mean value for this combined product. In order to guide our users towards better decisions at Level 3 we now only permit the highest quality land data (QA=3) to go into the Land_And_Ocean product at Level 2. We have introduced a new product Image_Optical_Depth_Land_And_Ocean, which contains all land retrievals, even those retrievals where QA=0. This "Image" product is equivalent to Collection 004's regular Land_And_Ocean product.

12. Land and Ocean: Cloud fraction redefined.

Since launch, both the over land and over ocean aerosol retrievals have reported a parameter called "cloud fraction" (Cloud_Fraction_Land and Cloud_Fraction_Ocean). These parameters were used as a diagnostic and included ALL pixels not included in the retrieval. Over ocean, not only clouds, but glint and sediments would be included in the "cloud fraction". Over land, "cloud fraction" included clouds, inland water, and bright surfaces that did not fall within acceptable range of the retrieval. In Collection 005 we are changing the definitions of these parameters to include only clouds identified by the MOD04/MYD04 internal cloud masks based on spatial variability. Those pixels identified only as thin cirrus will NOT be included in this new "cloud fraction". Those

pixels not used because of sediment, glint, internal water or bright surfaces also will NOT be included in this new "cloud fraction".

These new "cloud fraction" parameters continue to be diagnostic and experimental in nature, and may still not correspond to a true cloud fraction.

13. Land and Ocean: Negative reflectances in 1.38 µm channel permitted.

The aerosol retrieval algorithms continually check incoming data before using the L1B radiances to derive aerosol. Pixels identified as containing bad data in specific channels are discarded and fill values placed in the final product. One important channel contains the 1.38 µm reflectance, which is used to identify cirrus in the pixel. This channel is especially sensitive to cirrus clouds because in the absence of particles high in the atmosphere the channel returns reflectances near zero due to the strong water vapor absorption at this wavelength. As it turns out, near zero reflectance could either be slightly positive or slightly negative. The aerosol algorithm required incoming reflectances in this channel to be non-negative. If negative values were found, no aerosol retrieval was attempted. The result was that in cirrus free conditions when the 1.38 µm was slightly negative the aerosol algorithm would often fail make an aerosol retrieval. Many retrieval opportunities were lost. We have adjusted the checking of incoming data to permit slightly negative values. The result is the recovery of many additional retrievals, especially over land. Figure 10 illustrates the increased number of retrievals.

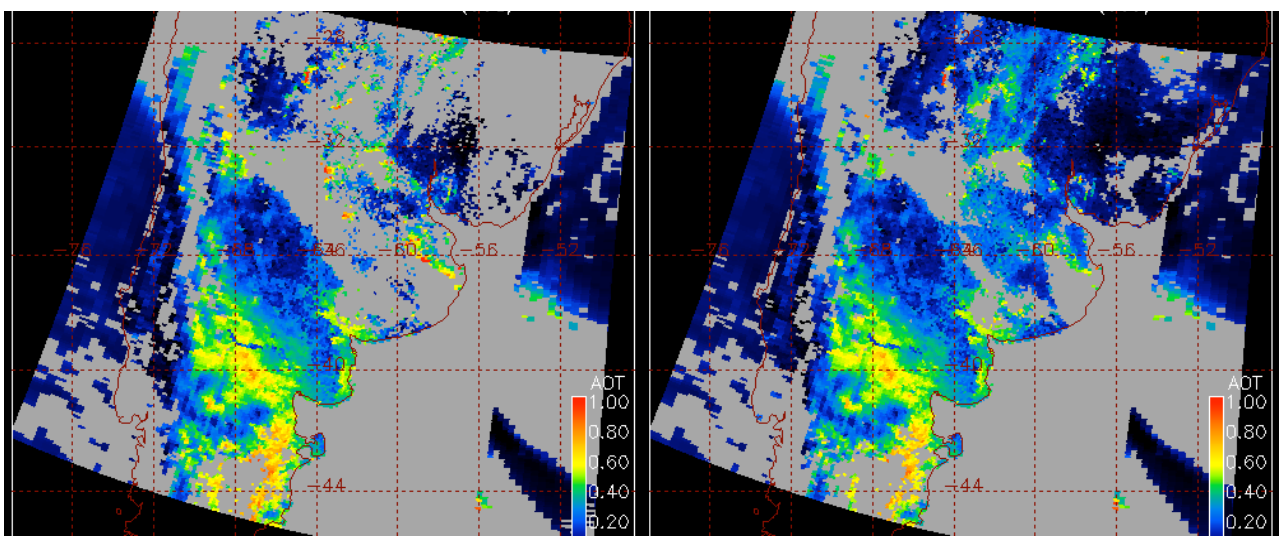

Fig.10 Image of aerosol optical thickness from MOD04 from year 2000, day 337, time 1425 located over South America. On the left is the retrieval from the 004 collection, while on the right, from the 005 collection. Note the increased range of the aerosol retrieval in Brazil. The extended range of retrieval is due simply to permitting slightly negative values of 1.38 µm reflectance to be processed. Note that the image on the right also benefits from the adjusted cloud mask logic over land described in Section 6, and therefore several patches of high aerosol optical thickness associated with cloud contamination are eliminated.

14. Land and Ocean: New SDS introduced to hold diagnostic information on the cloud mask.

Separating aerosols from clouds continues to be one of the most challenging aspects of remote sensing of aerosol. We have introduced new SDSs Aerosol_Cldmask_Byproducts_Land and Aerosol_Cldmask_Byproducts_Ocean to hold additional diagnostic information on different aspects of the internal cloud mask. For the time being these new SDSs will contain fill values. We expect to submit a software patch in the near future to fill the SDSs with useful diagnostic information that can inform us of the spatial variability statistics, detection of thin cirrus, etc. for every aerosol retrieval.

15. Land and Ocean: Removal of unnecessary SDSs and general clean up of code.

The definitions of the family of SDSs called "Fluxes", which are the hemispherical irradiances, have been changed several times since launch, never satisfactorily. At this point it is unclear how to make use of them, and so, we have decided to eliminate the following SDSs:

Reflected_Flux_Land_And_Ocean
Estimated_Uncertainty_Land
Reflected_Flux_Land
Transmitted_Flux_Land
Reflected_Flux_Best_Ocean
Reflected_Flux_Average_Ocean
Transmitted_Flux_Best_Ocean
Transmitted_Flux_Average_Ocean

In addition, the Collection 005 software has undergone a general housecleaning, without making significant changes to the products.

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Papers on algorithm development or validation.

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