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Toward unified satellite climatology of aerosol properties: What do fully compatible MODIS and MISR aerosol pixels tell us?

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ABSTRACT

Because of the global nature of aerosol effects on climate, satellite observations have been and will be an indispensable source of information about aerosol characteristics for use in various assessments of climate and climate change. There have been parallel claims of unprecedented accuracy of aerosol retrievals with the moderate-resolution imaging spectroradiometer (MODIS) and multiangle imaging spectroradiometer (MISR). These claims have been based on limited comparisons with ground-based observations which, however, are not necessarily indicative of the actual global performance of these satellite sensors. Fortunately, both instruments have been flown for many years on the same Terra platform, which provides a unique opportunity to compare fully collocated pixel-level MODIS and MISR aerosol retrievals directly and globally. Our present extensive analysis of ~8 years of the MODIS-Terra and MISR aerosol data documents unexpected significant disagreements at the pixel level as well as between long-term and spatially averaged aerosol properties. The only point on which both datasets seem to fully agree is that there may have been a weak increasing tendency in the globally averaged aerosol optical thickness (AOT) over the land and no long-term AOT tendency over the oceans. Overall our new results suggest that the current knowledge of the global distribution of the AOT and, especially, aerosol microphysical characteristics remains unsatisfactory.

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1. Introduction

Direct and, especially, indirect effects of aerosols on climate are widely recognized as being quite significant, yet poorly understood and poorly quantified [1]. Because of the global nature of aerosol climate forcings, satellite observations have been and will be an indispensable source of information about aerosol characteristics for use in various assessments of climate and climate change [2]. While the ability to retrieve aerosol parameters from the total ozone mapping spectrometer (TOMS) and advanced very high resolution radiometer (AVHRR) radiance measurements has been admittedly limited [3–5], our knowledge of the global distribution of aerosol properties has been expected to improve dramatically owing to the launch of more advanced satellite instruments. The moderate-resolution imaging spectroradiometer (MODIS) [6] and multiangle imaging spectroradiometer (MISR) [7] aerosol products have been especially popular, and their use has been increasingly frequent.

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The formal lists of retrievable aerosol characteristics in the MODIS and MISR algorithm theoretical basis documents (ATBDs) [8,9] are impressive and extend well beyond the total column aerosol optical thickness (AOT). Furthermore, the MODIS and MISR aerosol products have been validated using ground-based data from the aerosol robotic network (AERONET) [10,11], and the validation results appear to confirm the anticipated retrieval accuracy [6,12–14]. However, several recent publications (see [15–18] and references therein) have demonstrated that regional and, especially, pixel-level differences between the MODIS and MISR AOTs and Ångström exponents (AEs) can be substantial and often significantly exceed the individual retrieval accuracy claims. Since neither MODIS nor MISR can be considered *a priori* to be a significantly more accurate aerosol sensor than its counterpart, a resolution which attributes all (or almost all) differences to retrieval errors contributed by either MODIS or MISR is not warranted. These recent findings obviously pose a fundamental question regarding the actual information content of the MODIS and MISR aerosol products, especially in terms of aerosol characteristics more sophisticated than AOT and AE.

One can think of several causes of disagreement between the MODIS and MISR aerosol retrieval results, including differences in sampling and cloud screening as well as in measurement, modeling, and retrieval approaches. To quantify and mitigate all specific effects of these differences is very difficult and likely impracticable, both scientifically and logistically. Furthermore, the surprisingly large magnitude of MODIS–MISR AOT and AE differences makes it difficult to contemplate a straightforward and unequivocal unification of the MODIS and MISR datasets into a combined aerosol climatology. However, one may at least try to identify the cases of ''minimal disagreement'' and analyze their scientific implications by exploiting the fortunate circumstance of both instruments having been flown for an extended period of time on the same Terra platform. Such an analysis requires the use of pixel-level MODIS-Terra and MISR retrievals and is the main objective of this study. In contrast to the results in [17], we use here the entire ~8 years of MODIS-Terra and MISR data rather than two one-month subsets. A brief description of the MODIS and MISR datasets used in our study is given in the Appendix.

2. Analysis

The analysis approach adopted for this paper is motivated by the results of [17]. Specifically, a MODIS-Terra Level-2 aerosol pixel and a MISR Level-2 aerosol pixel are defined as ''fully compatible'' if they

- are located within the narrower MISR swath;
- have been collocated spatially to ±3.3 km and temporally to ±5 min;
- have been determined to be ''cloud-free'' by both cloud-screening procedures; and
- have been identified as suitable for aerosol retrieval and have been taken through the standard MODIS and MISR retrieval routines, thereby resulting in specific AOT and AE values.

It is clear that the fully compatible pixels represent a rather small fraction of the initial set of MODIS-Terra and MISR aerosol pixels [17]. Yet they constitute the subsets of MODIS-Terra and MISR aerosol pixels that can be compared in the least ambiguous and most meaningful way.

The remaining differences between the MODIS-Terra and MISR AOTs and AEs corresponding to fully compatible pixels can still be large and systematic. This is well illustrated by Figs. 1 and 2 which depict the absolute value of the AOT and AE differences averaged over the month of July 2007 as a function of the MODIS-Terra scattering angle (i.e., the angle between the following two directions: (i) Sun→MODIS-Terra aerosol pixel and (ii) MODIS-Terra aerosol pixel→MODIS-Terra). It is seen that the AOT differences tend to increase with increasing scattering angle (cf. [19]), whereas the AE differences tend to

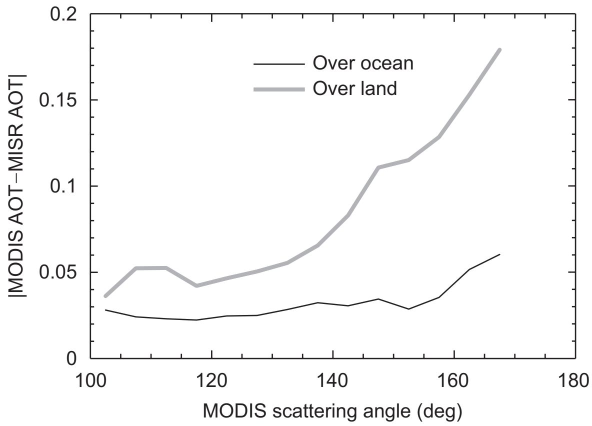

Fig. 1. MODIS–MISR differences in AOT versus MODIS scattering angle. The absolute values of the differences are averaged over the month of July 2007.

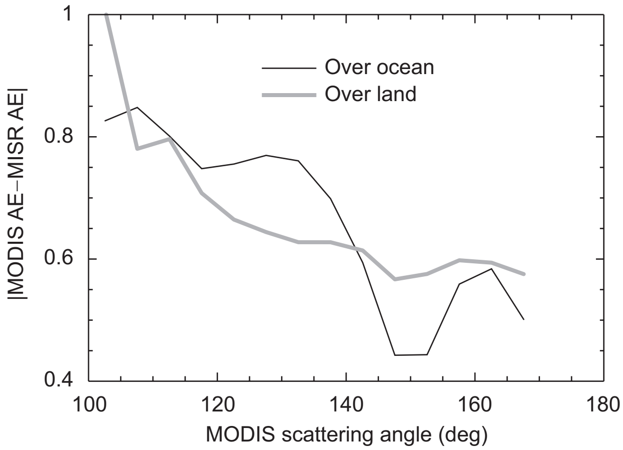

Fig. 2. MODIS–MISR differences in AE versus MODIS scattering angle. The absolute values of the differences are averaged over the month of July 2007.

increase with decreasing scattering angle. Both tendencies are quite strong and indicative of systematic biases likely inherent in both retrieval procedures.

Figs. 3a and b show the global distribution of the absolute differences |MODIS AOT−MISR AOT| and |MODIS AE−MISR AE| averaged over the 24 summer months (June, July, and August) of 2001–2008 and over $1^\circ \times 1^\circ$ areas. These plots illustrate again large disagreements between the MODIS-Terra and MISR aerosol retrievals even for the fully compatible pixels. The AOT differences are especially pronounced over the land, whereas significant AE differences can be found over both land and ocean areas. The largest AOT differences, often exceeding 0.2, can be found in areas affected by dust transport and biomass burning in sub-Saharan Africa, Middle East, India, and China. In addition, one can easily identify systematic discontinuities across coastal lines indicative of the failure of the algorithms to retrieve consistent aerosol parameters over contiguous land and ocean areas. Also obvious are systematic latitudinal biases in the AE retrievals, especially over the Southern Hemisphere. Data for the other three seasons are not shown here since they exhibit quite similar traits.

Since even averaging over 24 months and $1^\circ \times 1^\circ$ areas does not reduce the magnitude of MODIS–MISR differences to acceptable levels [20], the next logical step is to look at global monthly averages of AOT and AE computed for the fully compatible MODIS-Terra and MISR aerosol pixels. These are depicted in Fig. 4, separately for retrievals over the oceans and over the land. This figure also shows the AOT and AE standard deviations (STDs). Either STD is defined as the square root of the variance divided by one half of the sum of the MODIS-Terra and MISR mean monthly averages. The variance is the sum of the squares of the MODIS–MISR pixel-level differences minus the mean divided by the number of pixels minus one.

Fig. 4 turns out to be quite instructive. First of all, the STD plots demonstrate that pixel-level MODIS–MISR differences in both AOT and AE remain large and, on average, virtually constant over the entire duration of the MODIS-Terra and MISR observations. The AOT differences are systematically larger over the land than over the ocean, whereas the AE differences are roughly the same over the oceans and over the land. These results should be helpful in the interpretation of the busy plots in Figs. 1 and 3 of [17].

Second, the differences between the MODIS-Terra and MISR global monthly AOT averages are much smaller than the pixel-level differences. The MISR average AOT is systematically larger than the MODIS-Terra average AOT over the oceans by about 0.01–0.03. This systematic difference may, perhaps, be attributed to a relative radiance calibration offset. The MODIS-Terra and MISR AOT averages over the land do not show a similar systematic disagreement.

Third, the MISR global monthly AE average is systematically and significantly greater than the MODIS-Terra global monthly AE average, especially over the oceans. The only exception is the beginning of 2003, in which case our decision to use only version 16 and later MISR products resulted in a very small and statistically insignificant number of fully compatible MODIS-Terra and MISR pixels. Although the seasonal behavior of the MODIS-Terra and MISR AEs over the land is the same, over the oceans, where one might expect the least impact of surface albedo uncertainties, the MODIS-Terra and MISR seasonal oscillations are systematically antiphased. Also, the amplitude of the MODIS-Terra seasonal oscillations over the oceans is significantly smaller. There is no obvious explanation for this behavior.

Fourth, both MODIS-Terra and MISR show larger average AEs (and thus smaller particles) over the land than over the oceans.

Fifth, both the MODIS-Terra and the MISR average AOTs show virtually no long-term tendency over the oceans and oscillate around the long-term average values 0.12 and 0.13, respectively. On the other hand, both satellite products exhibit a weak increasing AOT tendency over the land, although it remains unclear whether this tendency is statistically significant owing to the relatively short duration of both datasets (cf. [21]). The MISR AE curves show no discernable tendencies, whereas the MODIS-Terra AE record over the land appears to exhibit a weak decreasing tendency. Again the statistical significance of the latter is rather uncertain.

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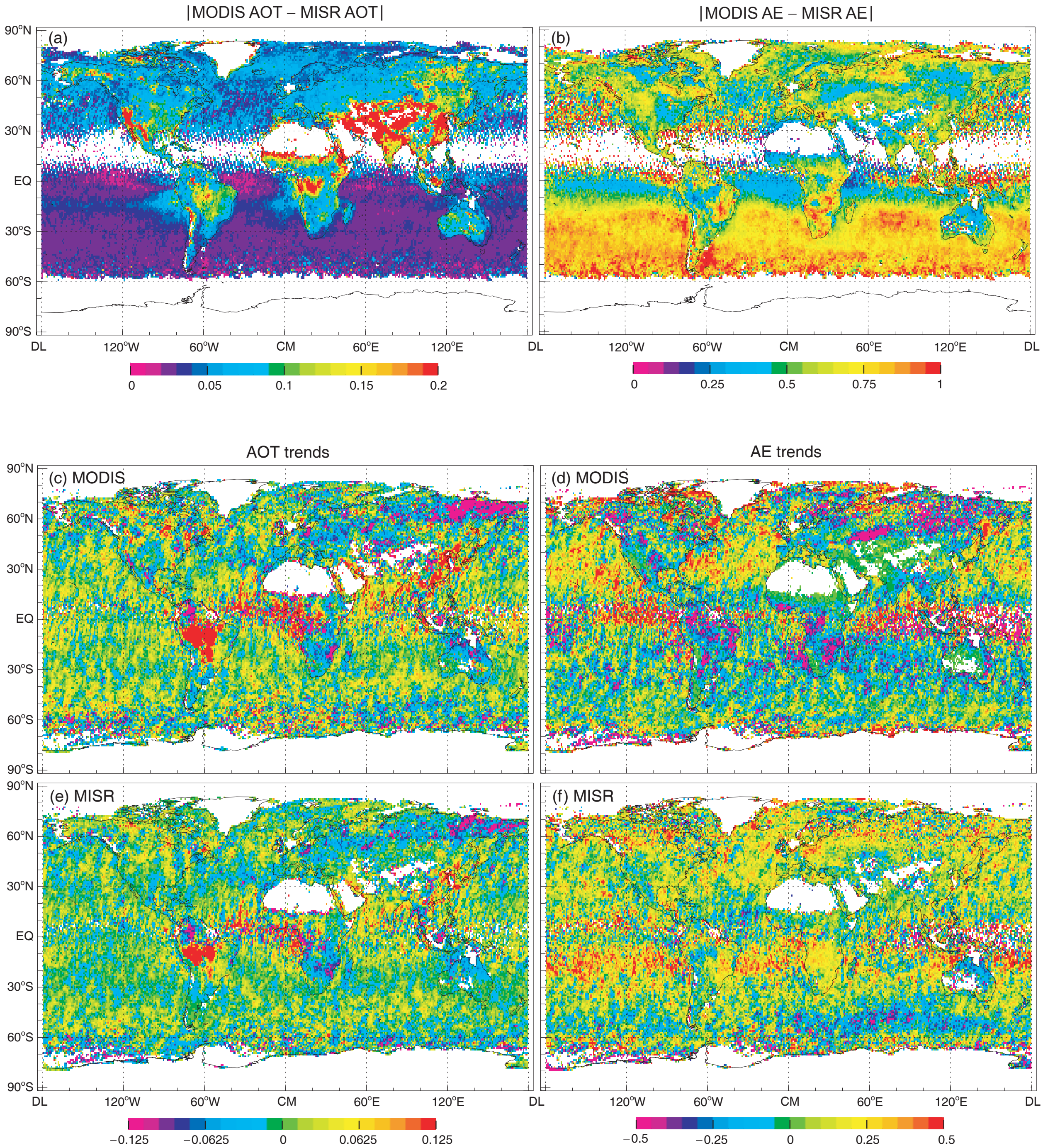

Fig. 3. Global comparisons of MODIS and MISR aerosol products. (a, b) Absolute MODIS–MISR differences averaged over the summer months (June, July, and August) of 2001–2008. (c) Differences between the MODIS-Terra AOTs averaged over two 12-month periods: March 2007–February 2008 and March 2001–February 2002. (d) As in (c), but for the corresponding MODIS-Terra AEs. (e, f) As in (c, d), but for the MISR AOTs and AEs.

Normally one would expect it to be easier to identify possible regional long-term tendencies since they are likely to be (much) stronger than those in the global AOT and AE averages [5,22,23]. Comparison of Figs. 3c and e shows that this can indeed be the case. For example, both datasets are indicative of a significant AOT increase over much of Brazil and Southern Asia as well over much of the Equatorial Atlantic Ocean and Equatorial Africa. They also show a significant AOT decrease

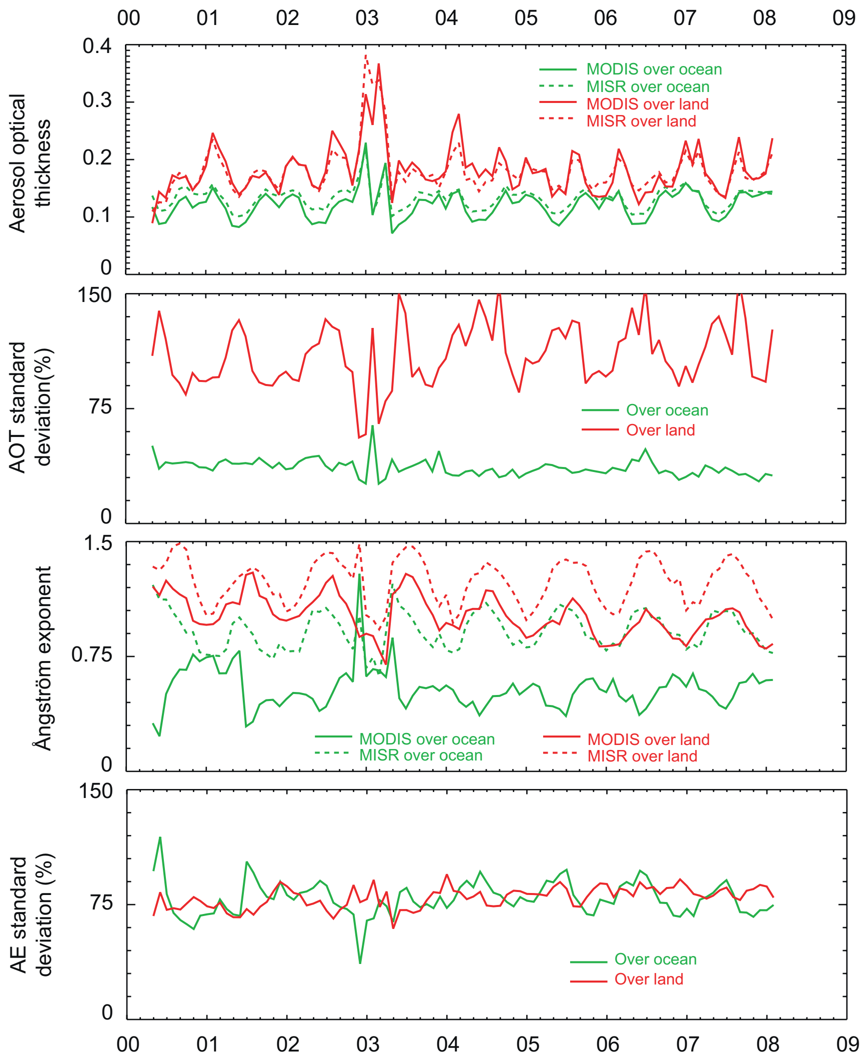

Fig. 4. Global monthly averages of the MODIS-Terra and MISR AOTs and AEs and their standard deviations over land and oceans.

over much of Europe and the Former Soviet Union. On the other hand, the corresponding long-term tendencies in the MODIS-Terra and MISR AEs are quite different over most of the globe, even to the extent of having different signs (Figs. 3d and f).

3. Conclusions

We reiterate that our approach in this study has been not to modify the MODIS-Terra and MISR Level-2 products but rather to create subsets of these products that can be expected to have a minimal amount of *a priori* disagreement. In doing so, we may have introduced a bias with respect to the global and regional average AOTs and AEs corresponding to the full Level-2 datasets, and it remains unclear whether this potential bias makes our averages more accurate. However, our strategy appears to be the only direct way of comparing MODIS and MISR products without having to analyze and address the potentially strong effects of the differences between the MODIS-Terra and MISR swaths and cloud-screening approaches. One can, of course, think of an even more conservative strategy wherein one keeps only the fully compatible MODIS-Terra and MISR pixels with AOTs agreeing to, for example, $\pm$10% over the ocean and $\pm$15% over the land. However, this approach is likely to result in an even more substantial yet less understood bias in terms of average AOT and AE values and is beyond the scope of this study.

In summary, the above comparative analysis of ~8 years of MODIS-Terra and MISR aerosol data is cause for concern. The differences even between the fully compatible MODIS-Terra and MISR aerosol pixels are often so large that it is hard to recommend the use of either Level-2 aerosol dataset without some kind of prior averaging. Indeed, the upper panel of Fig. 4 is perhaps the only reassuring outcome of our study, with Figs. 3c and e demonstrating some marginal usefulness. In order to yield meaningful results, however, exactly the same averaging approach must be applied to both Level-2 datasets, which by itself necessitates the use of the fully compatible MODIS-Terra and MISR aerosol pixels.

The AE is usually considered to be the easiest semi-microphysical aerosol characteristic to retrieve from space [4,24]. Therefore, the large disagreements between the MODIS-Terra and MISR AE datasets are likely indicative of even poorer retrieval accuracies for the other microphysical parameters listed in the MODIS and MISR ATBDs. All in all, our analysis demonstrates that existing retrievals of global aerosol characteristics from current satellite data remain unsatisfactory and that a major improvement of the MODIS and MISR aerosol products is needed. Unfortunately, the long history of inadequate satellite aerosol retrievals appears to provide ample evidence of the inherent inability of radiance-only instruments to yield aerosol characteristics with requisite accuracy and specificity (cf. [20,25]).

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Appendix

The MODIS instrument has a viewing swath width of 2330 km and a moderate spatial resolution (250–1000 m). Its detectors yield radiance measurements in 36 spectral bands ranging in wavelength from 400 to 14,400 nm, seven of which (nominal wavelengths 470, 550, 660, 870, 1240, 1640 and 2130 nm) are used to characterize aerosol optical properties. MODIS includes on-orbit calibration.

A detailed description of the aerosol retrieval algorithm can be found in [8,26–28]. In this study, we use the MODIS collection 5 Level-2 aerosol products available from the NASA Goddard Space Flight Center's Atmosphere Archive and Distribution System (http://ladsweb.nascom.nasa.gov). The MODIS Level-2 standard aerosol product reports AOT on a 10 km grid of 10×10 1-km pixels, along with the AE, effective radius, and fine mode fraction retrieved over both land and ocean. Each MODIS orbit is separated into 5-minute granules. The size of each granule is about 2030 km (about 203 scans of 10 km) along the orbital path.

The MISR instrument consists of nine pushbroom cameras that view the Earth in nine different directions (four forward, four backward, and nadir) at four wavelengths (446, 558, 672, and 866 nm) and also includes in-flight radiance calibration. MISR has a 360-km-wide swath.

The aerosol retrieval methodologies used with MISR data have been described in [7,9,29]. The MISR product, downloadable through the NASA Langley Research Center's Atmospheric Sciences Data Center (http://eosweb.larc.nasa.gov), consists of the AOT, AE, and aerosol type retrieved over both land and ocean. MISR Level-2 products are in swaths, each derived from a single MISR orbit, where the imagery is 360 km wide and approximately 20,000 km long. The MISR Level-2 standard aerosol product reports the AOT and the other aerosol parameters on a 17.6 km grid of 16×16 1.1-km pixels.

In this paper, we refer to MODIS 10 km resolution or MISR 17.6 km resolution Level-2 grids as pixels. The MODIS and MISR data are written as scientific data sets (SDSs) in the HDF format. The SDSs that we used in this study include the following:

For MODIS:
- Corrected_Optical_Depth_Land
- Angstrom_Exponent_Land
- Quality_Assurance_Land
- Cloud_Fraction_Land
- Effective_Optical_Depth_Average_Ocean
- Angstrom_Exponent_1_Ocean
- Quality_Assurance_Ocean
- Cloud_Fraction_Ocean
- Scattering_Angle

For MISR:
- RegBestEstimateSpectralOptDepth
- RegBestEstimateAngstromExponent
- RetrAppMask

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