CHANGES TO MODIS DEEP BLUE AEROSOL PRODUCTS BETWEEN COLLECTION 6 AND COLLECTION 6.1

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1. Introduction and purpose of document

This document provides a brief summary of changes in the MODIS Deep Blue aerosol products between Collection 6 (C6) and Collection 6.1 (C6.1). It is intended primarily for those users who are already familiar with the MODIS Deep Blue data products. If you are not already familiar with these data products, you may find the overview webinars freely available from https://aerocenter.gsfc.nasa.gov/ext/c6/ to be of use.

These aerosol products are those distributed by the NASA Level 1 and Atmospheres Data Service (LAADS) from https://ladsweb.modaps.eosdis.nasa.gov/; specifically, those contained within the Level 2 M*x*D04_L2 and M*x*DATML2 and Level 3 M*x*D08_D3, M*x*D08_E3, and M*x*D08_M3 products, where *x* is O for MODIS Terra products and Y for MODIS Aqua products. MODIS Dark Target land/ocean aerosol data sets are also contained within the above data products. However, Dark Target is maintained by a separate algorithm team. This document only covers Deep Blue changes, and focused on examples of retrieved aerosol optical depth (AOD) at 550 nm, which is the primary data product.

Users with questions about this or other aspects of Deep Blue are strongly encouraged to get in touch with Andrew Sayer (andrew.sayer@nasa.gov). We like hearing from data users, and are happy to help!

More information about the Deep Blue aerosol project is also available from our project website, https://deepblue.gsfc.nasa.gov. Users may also be interested in the Aerosol portion of the MODIS Atmospheres web portal, https://modis-atmos.gsfc.nasa.gov/products/aerosol.

2. Deep Blue updates, and their impacts on the data set

1.1. Radiometric calibration (level 1)

Both MODIS sensors have now been in operation for around a decade longer than their design lives. While both continue to function well, continual effort is required by the MODIS Characterization Support Team (MCST) to maintain and improve the quality of MODIS' radiometric calibration. MCST are producing a C6.1 Level 1b (calibrated radiance) product to replace the previous C6 L1b product. Information about L1b changes can be found at https://modis-atmosphere.gsfc.nasa.gov/documentation/collection-61.

The NASA Ocean Biology Processing Group (OBPG) develop additional calibration corrections to be applied on top of the MCST L1b products, due to the very tight radiometric requirements of the Ocean Color discipline (e.g. Meister *et al.*, 2014). From the previous MODIS Collection 5 onwards, we have been implementing the OBPG corrections for MODIS bands 3 and 8 (centred near 470 and 412 nm respectively) into Deep Blue processing for MODIS Terra (cf. Jeong *et al.*, 2011; Sayer *et al.*, 2015). For C6.1, we continue to use the OBPG's latest corrections for MODIS Terra. We now also apply the OBPG's corrections for MODIS Aqua as well.

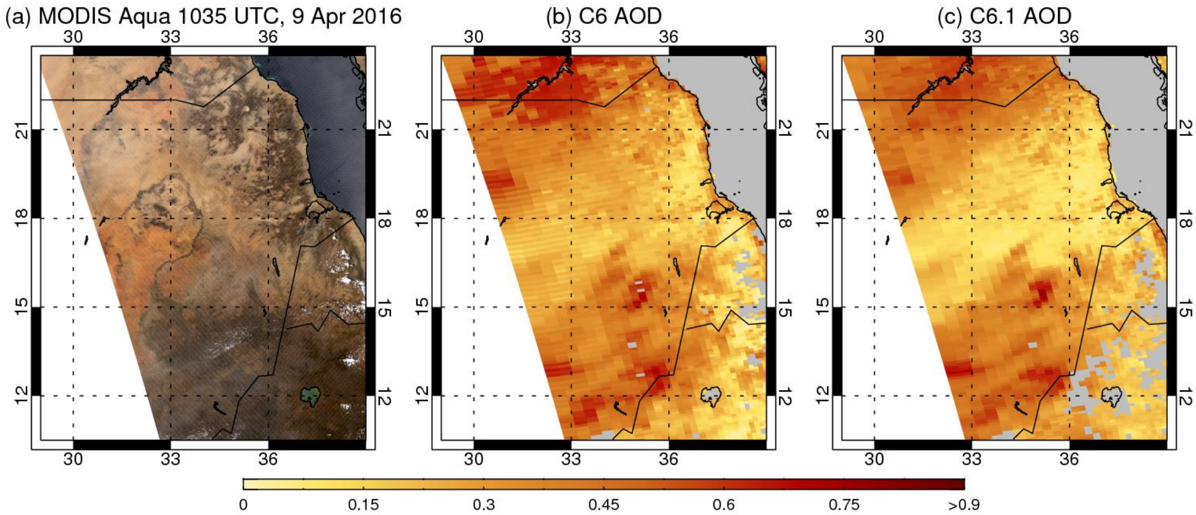

Figure 1. MODIS Aqua (a) true-colour image over eastern Africa, and corresponding (b) C6 and (c) C6.1 retrieved AOD at 550 nm. Pixels without valid retrievals are shaded in grey.

The MCST and OBPG corrections affect the radiometric gain, sensor response vs. scan angle (RVS), and polarization sensitivity, which depend on band/detector, scan mirror side, scan angle, and time. When these (particularly RVS and polarization sensitivity) are not as well-characterised as would be hoped, apparent 'striping' between adjacent scan lines is a common artefact. Figure 1 shows an example of a scene where such striping in the retrieved AOD field was particularly severe in C6 (it tends to be most notable near the edge of the scan, and over bright targets), but is much less evident in C6.1. Note that some of the differences between Figure 1(b) and 1(c) are due to algorithm improvements discussed below.

The effects of L1b changes tends to be largest for most recent years (~2013 onwards), although MCST and OBPG regenerate the L1b and additional corrections for the whole MODIS record. Thus, in the same way as previous MODIS Collections, C6.1 uses a consistent (continuous) calibration across the whole time series. Retrieval quality should also remain stable over the whole MODIS missions to date (for both Terra and Aqua). Continual monitoring and correction of further calibration degradation is also performed by MCST and OBPG.

1.2. Level 2 algorithm updates and bug fixes

The general principles behind the C6.1 Deep Blue data set remain the same as the second-generation (aka 'enhanced' Deep Blue) algorithm from C6, described by Hsu *et al.* (2013). However for C6.1 some improvements have been made, and some bugs identified in the code have been fixed. As this document is intended to provide a brief overview for the data user, a summary of the main areas of improvement follows, but technical details are omitted for brevity.

Heavy smoke detection

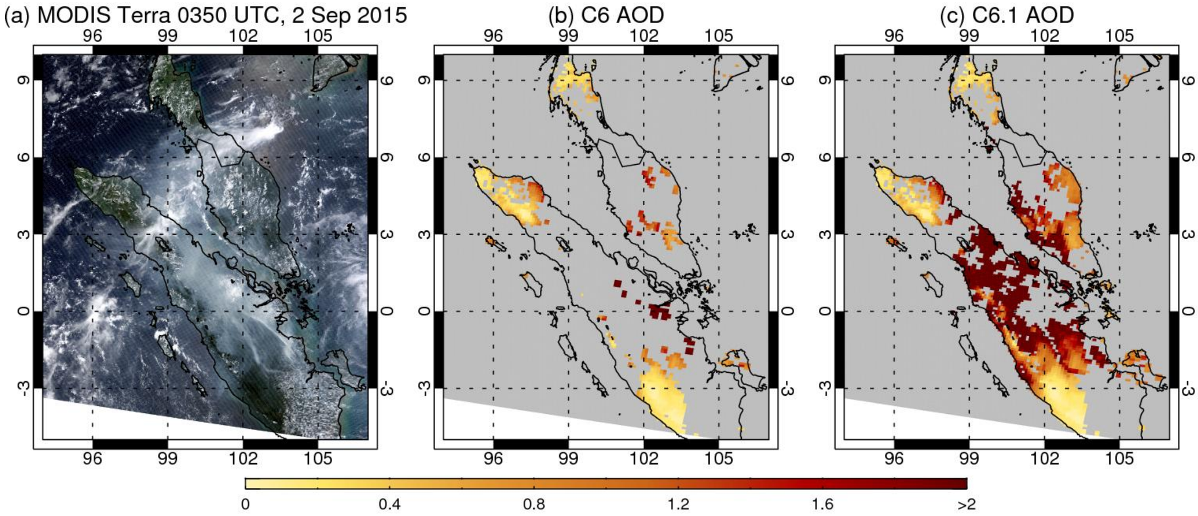

Figure 2. MODIS Terra (a) true-colour image over Indonesia and Malaysia, and corresponding (b) C6 and (c) C6.1 retrieved AOD at 550 nm. Pixels without valid retrievals are shaded in grey.

In C6, thick, homogeneous smoke events could sometimes be falsely identified as cloud and consequently not processed by the retrieval algorithm. This led to systematic sampling gaps in the data set, particularly for weakly-absorbing smoke (which looks like cloud in some spectral bands). In C6.1 we have improved our internal smoke detection masks, and have been able to address some of this overscreening while minimising true cloud contamination. Figure 2 shows an example comparing C6 and C6.1 for a typical case of this type, where a strong El Niño led to extremely strong peat burning in Indonesia in 2015.

Artefact reduction in heterogeneous terrain

In C6, rugged terrain (i.e. mountains and valleys on similar spatial scales to the MODIS pixel size) could sometimes lead to artificial hotspots in retrieved AOD in certain conditions. This is due to factors such as the surface data base not being able to resolve the heterogeneity of the terrain in these surfaces, as well as geometric effects such as shadowing which cannot be modelled with 1D radiative transfer codes.

As they were linked to the underlying terrain, these hotspots were only an issue in certain parts of the world, western North America being the main example. Figure 3 shows one example. For C6.1, extensive effort has gone into improving the surface reflectance modelling for these surface types, as well as fixing some code bugs and improving QA tests to identify and flag affected pixels. Figure 3 illustrates that in C6.1, the artefacts are smaller, fewer, and removed more effectively by QA tests. Incidentally, this granule also contains an example (around 40° N, 121° W) of a smoke plume absent in C6 but reclaimed in C6.1 due to the improved smoke tests mentioned above.

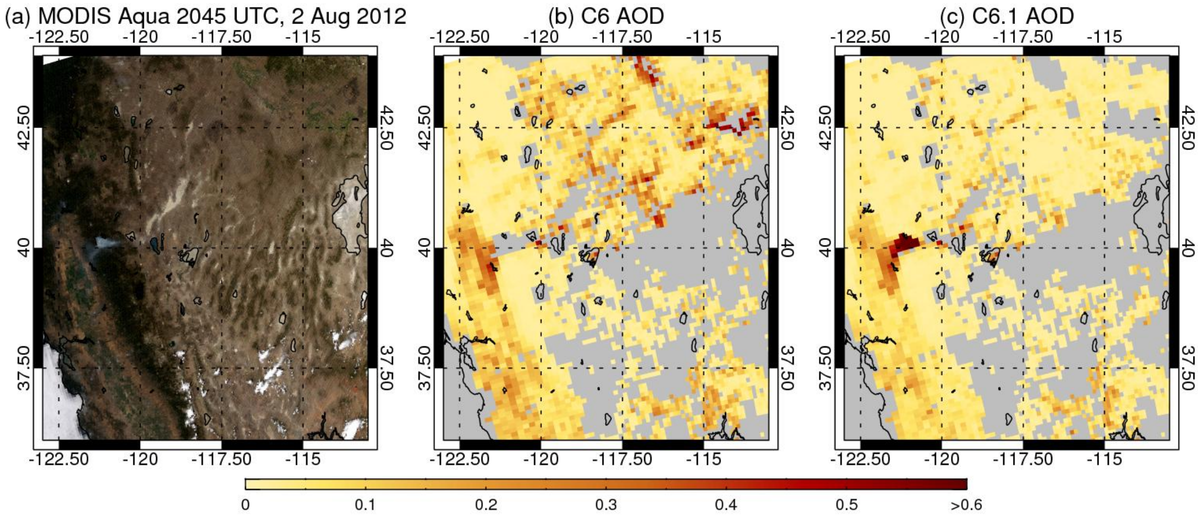

Figure 3. MODIS Aqua (a) true-colour image over western North America, and corresponding (b) C6 and (c) C6.1 retrieved AOD at 550 nm. Pixels without valid retrievals are shaded in grey.

Improved surface modelling in elevated terrain

Elevated terrain (whether mountainous or plateaus) presents difficulties for AOD retrieval from most algorithms and sensor types. In addition to issues of scene heterogeneity, the nonlinear interaction between Rayleigh scattering and aerosol absorption means that complex scene-dependent uncertainties arise, and assumptions about effective land surface reflectance can be in error.

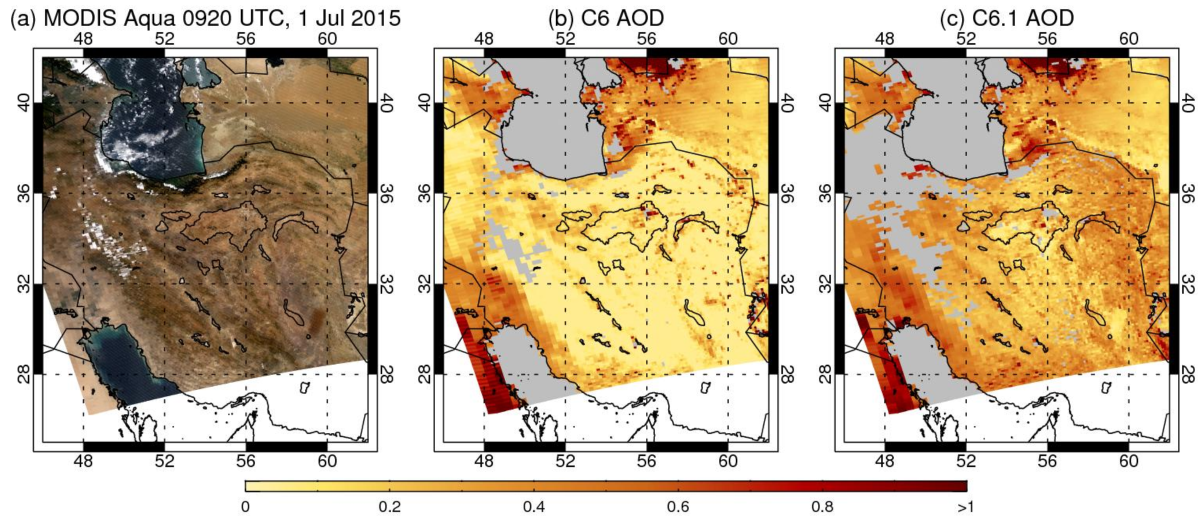

Figure 4. MODIS Aqua (a) true-colour image over Iran, and corresponding (b) C6 and (c) C6.1 retrieved AOD at 550 nm. Pixels without valid retrievals are shaded in grey.

In C6, these difficulties meant that in some parts of the world, particularly elevated areas of the Middle East and Central Asia, frequently retrieved near-zero AOD under certain conditions, whether the true AOD was small or not. In C6.1, we have developed new surface reflectance models for these terrain types which remove these systematic biases. Our internal tests are also more capable of identifying and removing pixels where such biases remain, which results in a slight decrease in spatial coverage compared to C6 in these areas. Figure 4 shows an example over Iran.

There are unfortunately few AERONET sites in these areas to quantify the retrieval performance in these conditions. The IASBS site in northwestern Iran is one example; Figure 5 shows both the tendency to underestimate AOD in C6, as well as the improvement in C6.1.

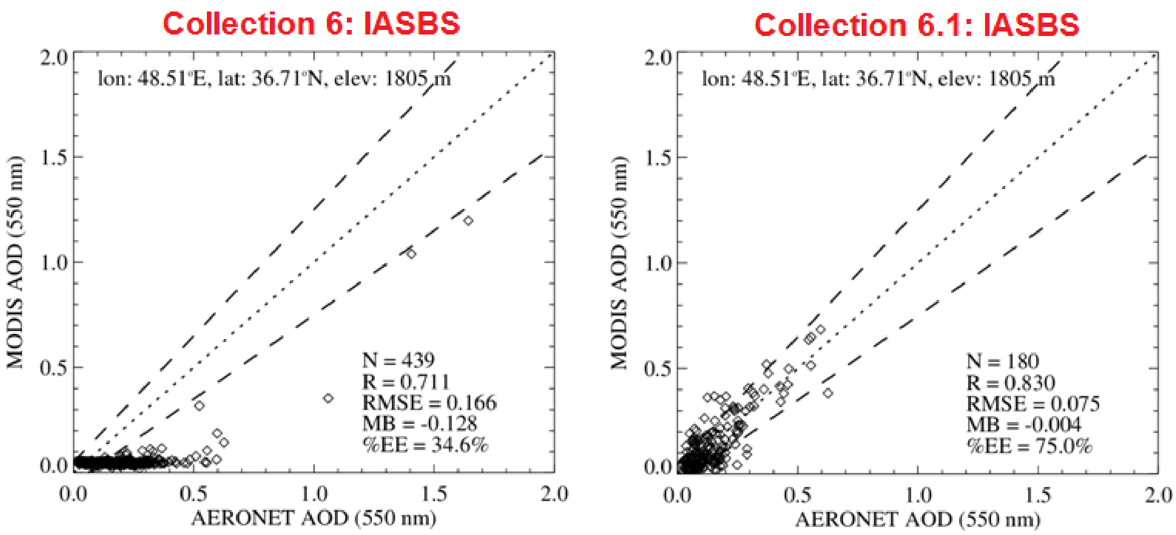

Figure 5. MODIS vs. AERONET AOD at 550 nm at IASBS, Iran for (left) C6 and (right) C6.1. Statistics show N, the number of matchups, R, Pearson's correlation coefficient, the root mean squared error (RMSE), MB the median bias, and %EE the percentage of points in agreement with AERONET within ±(0.05+20%).

Bug fixes and updated regional/seasonal aerosol optical models

In addition to the above, several miscellaneous bugs were found and fixed, and assumed aerosol optical models in some areas were updated based on biases identified from our C6 validation work (e.g. Sayer *et al.*, 2013, 2014, 2015).

1.3. Level 2 metadata updates

An issue identified in the C6 data files was that the Deep Blue Ångström Exponent data set's *long_name* attribute did not mention which wavelengths this quantity was calculated over. This information is now included in this attribute. Specifically, the Ångström Exponent is calculated over the 412-470 nm spectral range over bright scenes where the surface data base method is used to model surface reflectance, and over the 470-650 nm spectral range where the dynamic (vegetation) method is used.

1.4. Validation and AOD uncertainty updates

Starting in C6, we provide an estimate of the uncertainty on the retrieved AOD at 550 nm for each retrieval in the level 2 files (Sayer *et al.*, 2013, 2015). These uncertainty estimates, often referred to as 'expected error' (EE) envelopes, should be interpreted as one-standard-deviation Gaussian confidence intervals around the retrieval solution. So, with respect to a ground-truth, one standard deviation (~68%) of retrievals should lie within the EE, two standard deviations (~95%) within twice the EE, and so on. In C6, EE calculations were of the form:

$$EE = \frac{a+b\tau}{\frac{1}{\mu_0}+\frac{1}{\mu}} \quad (1)$$

In the above *a*, *b* are coefficients determined by comparison against AERONET data at 60 sites, τ the retrieved AOD at 550 nm, and μ_0, μ the cosines of solar and viewing zenith angles respectively. The quantity ($1/\mu_0+1/\mu$) is also referred to as the geometric air mass factor (AMF). This expression was found to be a useful representation based on physical reasoning and empirical evidence, as uncertainty generally increases in high-AOD conditions and when the atmospheric path length is short.

In C6 one set of coefficients a,b was calculated for each quality assurance (QA) value from 1 to 3 (Sayer *et al.*, 2013). That and subsequent analyses revealed that due to the differences in wavelengths used and surface characteristics, whether a pixel was processed with either the arid or vegetated algorithm paths (cf. Hsu *et al.*, 2013) was also a relevant factor. Therefore, in C6.1, coefficients are computed stratifying the data both by algorithm path flag and QA flag. Terra coefficients are provided in Table 1 for user reference; Aqua coefficients are presently being calculated and will be implemented prior to the C6.1 MODIS Aqua reprocessing.

Table 1: coefficients a, b from Equation 1 used in AOD uncertainty estimates provided in C6.1 Terra data.

Surface type	**QA value**	***a***	***b***
Vegetated	3	0.085	0.49
	2	0.088	0.67
	1	0.078	0.97
Arid	3	0.094	0.61
	2	0.12	0.72
	1	0.11	0.92

Note that in C6.1 implementation, the total uncertainty for QA=1 retrievals is doubled from that computed in Equation 1 and shown in Table 1. This is because the validation by its nature may underestimate the error due to cloud contamination, and because applications such as data assimilation are very sensitive to high-magnitude outliers, both of which are expected to be more common in QA=1 data (which is why QA=1 retrievals are not generally recommended for most scientific applications). This change was therefore made to err on the side of caution and decrease the risk of a user over-interpreting QA=1 data in an analysis, if they choose to use that subset of retrievals.

For a typical AMF of ~2.8, and for QA=3 data, Terra EEs in C6.1 are therefore approximately 0.03+21% for 'arid' path retrievals and 0.03+18% for 'vegetated' path retrievals. These are slightly better than C6 results (cf. Sayer *et al.*, 2015 for Terra), although the reader is reminded that in C6 results were not stratified by surface type.

3. Merged Deep Blue/Dark Target product

No changes have been made to the logic used to create the combined (aka 'merged') MODIS Deep Blue/Dark Target data set, which is described by Sayer *et al.* (2014). However, changes have been made to the Level 1 radiance data used as inputs, and the Level 2 Deep Blue and Dark Target aerosol retrieval algorithms. As a result this combined product is also different in C6.1. The main results and general tendencies as shown in Sayer *et al.* (2014) are likely to still hold. However, C6.1 results for the merged product have not yet been evaluated in detail.

4. Level 3 aggregation changes

Although not a change in the Deep Blue algorithm *per se*, it is worth noting that in C6.1 the logic for the monthly level 3 (L3) product (M*x*D08_M3) has been changed to require valid retrievals from at least 3 days from the month for a grid cell to be populated. This change applies only to the monthly product (i.e. not the daily or 8-day products), for both Deep Blue and Dark Target.

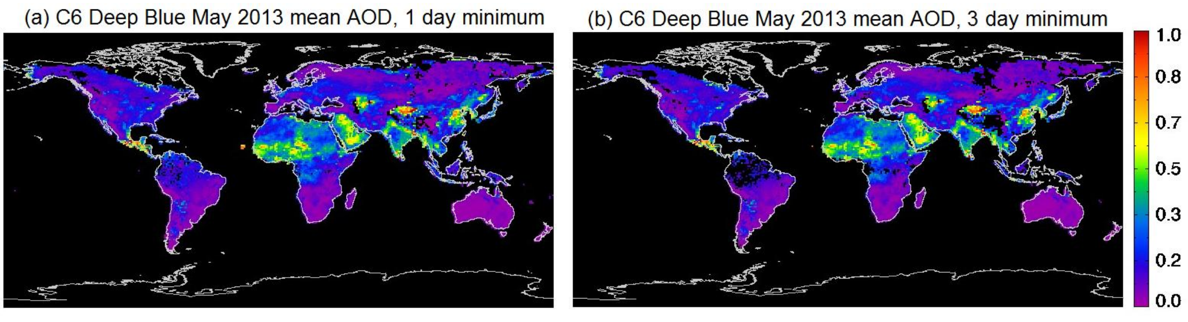

Figure 6. Monthly mean Deep Blue AOD for May 2013, with (a) 1-day minimum (as in C6) and (b) 3-day minimum (as in C6.1). Images courtesy Paul Hubanks.

Figure 6 shows an example of the effects of the change for May 2013. Note that both panels used the C6 L2 products as a basis so the only change is to the L3 aggregation. The reason for the change was that in some cases (typically highly-cloudy environments such as monsoonal tropical regions, high-latitude ocean storm tracks, or regions near the day/night boundary) the number of retrievals contributing to a monthly grid cell could be very small. These results could potentially be highly unrepresentative, due to sampling error, and were more likely to contain artefacts. A 3-day threshold was found empirically to remove the small number of affected grid cells, but not significantly decrease coverage of the resulting data fields.

5. References

Hsu, N. C., M.-J. Jeong, C. Bettenhausen, A. M. Sayer, R. Hansell, C. S. Seftor, J. Huang, and S.-C. Tsay (2013), Enhanced Deep Blue aerosol retrieval algorithm: The second generation, *J. Geophys. Res. Atmos.*, 118, 9296–9315, doi:10.1002/jgrd.50712.

Jeong, M.-J., N. C. Hsu, E. J. Kwiatkowska, B. A. Franz, G. Meister, and C. E. Salustro (2011), Impacts of cross-platform vicarious calibration on the Deep Blue aerosol retrievals for Moderate Resolution Imaging Spectroradiometer Aboard Terra, *IEEE Trans. Geosci. Remote Sens.*, 49(12), 4877–4988, doi:10.1109/TGRS.2011.2153205.

Meister, G., R. E. Eplee, and B. A. Franz (2014), Corrections to MODIS Terra calibration and polarization trending derived from ocean color products, *Proc. SPIE 9218, Earth Observing Systems XIX*, 9218V, doi:10.1117/12.2062714.

Sayer, A. M., N. C. Hsu, C. Bettenhausen, and M.-J. Jeong (2013), Validation and uncertainty estimates for MODIS Collection 6 “Deep Blue” aerosol data, *J. Geophys. Res. Atmos.*, 118, 7864–7872, doi:10.1002/jgrd.50600.

Sayer, A. M., L. A. Munchak, N. C. Hsu, R. C. Levy, C. Bettenhausen, and M.-J. Jeong (2014), MODIS Collection 6 aerosol products: Comparison between Aqua's e-Deep Blue, Dark Target, and “merged” data sets, and usage recommendations, *J. Geophys. Res. Atmos.,* 119, 13,965–13,989, doi:10.1002/2014JD022453.

Sayer, A. M., N. C. Hsu, C. Bettenhausen, M.-J. Jeong, and G. Meister (2015), Effect of MODIS Terra radiometric calibration improvements on Collection 6 Deep Blue aerosol products: Validation and Terra/Aqua consistency, *J. Geophys. Res. Atmos.*, 120, 12,157–12,174, doi:10.1002/2015JD023878.