Response to reviewer #1

The goal of this paper is to correct for AOD retrieval biases in GOES ABI AOD product using an empirical approach. The surface reflectance in the current GOES AOD algorithm is estimated based the relationship between 0.47 and 2.2 um and 0.64 and 2.2 um since most aerosols are 'transparent' in the 2.2 um. This is based on the Kaufman et al (1997, IEEE) paper that many MODIS algorithms use to estimate surface reflectance. In this paper, the authors look for 'clear days' (based on AERONET AOD values less than 0.05) to assess the GOES AOD (for both high and medium quality retrievals) for a few selected sites. They report that the GOES AOD is biased since the GOES AOD is much larger than the AERONET AOD for these clear days. The authors note that the biases appear to be centered around 1700 UTC and it is due to surface reflectance parametrizations at various sun-satellite viewing geometries. The authors then attempt to correct this bias based on the premise that it is the surface reflectance that is the issue in the GOES algorithm. Then they use a 30-day composite of GOES AOD to estimate the minimum AOD and subtract that with the background AOD (a fixed value of .025) to correct for the bias. They use two polynomial fitted relationships to estimate biases. They then correct the AOD using these relationships and then validate the results with AERONET AOD and show improvement in these biases.

First I need to note that the paper needs to go through some editorial clean up since several sentences are awkward; key references (Kondragunta et al 2020) are missing;and some references are really old.

We removed several old references and checked the references.

I find several problems with the paper and most importantly it is the use of AOD to make these corrections rather than working with the reflectances. The algorithm retrieves AOD based on apriori assumptions of aerosol model, surface parametrizations based on NDVI , cloud clearing approaches and a host of thresholds for cloud cover, inhomogeneity, etc (ATBD, 2018). Now this paper indicates that the surface parametrizations are a problem and then to remove the biases the authors use the retrieved AOD to make bias adjustments. The original algorithm uses reflectance ratios to arrive at surface values and now this paper goes back to the older GASP approach to obtain the 30-day composite minimum (not reflectance) AOD values. Looking at this from an algorithm perspective it is not the correct solution for an operational algorithm to go through retrieval using one set of processes, retrieve AOD's and then use the retrieved AOD values to make corrections for parameters that are part of the original retrieval process (in this case surface reflectance). The authors need to think about having the correct algorithm as part of the retrieval process rather than adjusting it after the retrieval is done.

The purpose of the bias correction algorithm is to correct the bias in an already existing aerosol optical depth product. It is not intended to substitute for the original AOD algorithm. We agree, and has been fully aware of, that ideally reduction of biases should be dealt with in the AOD algorithm itself. As discussed in the paper, the deviation of the real spectral surface reflectance relationships from the parameterization used in the retrieval can cause the AOD retrieval bias. Improving the spectral surface reflectance relationships is the subject of an independent, parallel work, and thus it is not discussed in the current paper. Once such an improvement becomes available and is shown to satisfactorily reduce the AOD bias, the bias correction may be turned off. But before that happens, we plan using the bias correction algorithm to provide users an AOD product with improved accuracy and coverage. On the other hand, surface reflectance relationship parameterization is derived at AERONET sites and is assumed to be valid over all other areas. This assumption may not hold everywhere. Actually there are very few evaluations over areas other than AERONET sites. The bias correction algorithm can evaluate

AOD bias over areas other than AERONET sites and reduce the bias there. The empirical bias corrections to retrieved AODs is not new. The NASA MODIS Dark Target AOD algorithm corrects AOD using a bias correction algorithm over urban areas using post processing of AODs for areas where urban land percentage is greater than 20% (Gupta et al., Atmos. Meas. Tech., 9, 3293-3308, 2016). There are other MODIS AOD correction algorithms as well developed by users for their own applications (e.g., Lary et al. 2009). In fact, compared to these bias correction algorithms, our approach is better because it is internally consistent and does not rely on any external dataset.

The other issue is the relaxation of quality flags to allow more data. There were strong reasons for picking all the metrics for high and medium quality flags in the first place (ATBD, 2018) whether it is cloud/snow cover or inhomogeneity. Line 90 to 95 provides the various reasons for selecting the pixels for the retrievals and this paper now allows all the medium quality flags in the process but does not address cloud contamination issues.

There is always a tradeoff between better data coverage and reducing cloud contamination. From the scatter plots in Figure 4 (Figure 5 in the revised paper), the bias corrected high and medium qualities AODs have statistics close to that of the high quality alone, which suggests that once the bias correction is applied we can use data that were assigned either high or medium quality data in the original AOD without sacrificing accuracy. In other words, the expectation is that the AOD at pixels that are subjected to potential cloud/snow contamination, and thus are labeled as medium quality, are corrected (at least partly) for this contamination as a result of bias correction.

The paper needs to be more convincing that it is indeed surface issues and not cloud cover that causes these problems. The results need to be discussed in terms of scattering angles (see She et al, Remote Sensing, 2019). This will allow more quantitative analysis rather than statements like those in 160-161.

We adopted your suggestion and plotted the scattering angle dependence of the error, comparing the AOD errors before and after correction. The original ABI AOD errors have a scattering angle dependence in the plots. After applying the bias correction algorithm, the scattering angle dependence of the bias is reduced. (Figure 6 in the revised paper and corresponding discussions).

There are several reasons that the bias is not caused by cloud contamination: (1) the diurnal pattern of retrieved ABI AOD on clear days always has a peak at around noon and the peak gradually reduces away from noon; cloud contamination is not expected to produce such a pattern; (2) cloud contaminations are random errors instead of systematic errors shown in the paper. Random errors from cloud contamination won't be corrected by our algorithm. The effectiveness of our algorithm in removing systematic errors indicates that the main reason of the bias is not cloud contamination. (3) If in some cases cloudiness at a given location has its own diurnal cycle and introduces a systematic bias, the bias correction corrects it too. The bias correction algorithm does not differentiate where the bias comes from and it corrects the bias as long as the bias is systematic.

Also for Figure 1 and Figure 2 what were the histograms of actual reflectance's from the GOES channels for the various peaks. This can help explain Figure 2 better.

Instead of histogram of the surface reflectances, we plotted scatter plots of the 0.47 µm and 2.2 µm surface reflectances, surface reflectance relationship used in the ABI AOD retrieval algorithm, and the histograms of NDVI for six observations around the GSFC site (Figure 3 in the revised paper). The analysis shows that the surface reflectance relationship used in the retrieval algorithm is directly connected to the ABI AOD retrieval biases. The change of the peak ABI AOD bias amplitude is related to the different relationship used because of the differences in NDVI in the three days.

The paper uses two sets of parametrizations for adjusting the biases and then in line 255 back tracks the approach by stating that this could have large uncertainties.

We don't expect a parameterization to fit every situation. As long as it works for the majority of the locations and/or geometries, it can be used. Notice that even for the worst case in the early morning, for the University of Houston, the peak bias is reduced from 0.4 to 0.3 (Figure 1e and Figure 8e in the revised paper).

Figure 8 and Figure 9 appears as a complete afterthought since the aerosol model discussion is not complete or convincing.

We respectfully disagree with the reviewer that this is an afterthought. One of the challenges of aerosol remote sensing is the representation of aerosol optical and physical properties in the models used to generate Look-up-Tables for retrievals. Aerosol model selection over land is a known problem in MODIS/VIIRS type sensors. We don't expect to be able to solve it with the bias correction algorithm either. Here we just want to point out that the problem exists.

I have no idea why the PM2.5 discussions (Figure 9) is relevant for this paper.

One of the main reasons why NOAA generates near real time AOD retrievals is for user applications related to air quality monitoring and forecasting. Users use AOD as a proxy for surface PM2.5 and among many things that impact this relationship, accuracy of AOD itself is very important. Better AOD retrieval means better PM2.5 estimates from satellite, which is an important application of satellite AOD product.

The AERONET data used is from 2018 and the authors need to be using Level 2 not 1.5. This data should be available.

Some sites still don't have Level 2 data yet. For example, as of April 20 2020, GSFC still does not have level 2 data available for the days after September 2018. In our daily work, we routinely do our analysis with both Level 2 and Level 1.5 data and we are quite comfortable in using Level 1.5 data.

Other issues. Define accuracy and precision and be quantitative rather than merely stating that one product is better than the other.

We added the corresponding numbers into the places where we discuss the accuracy and precision.

Line 50, Deemed to have quality sufficient is rather vague.

Sentence removed.

Line 73: The word transparent to most aerosols is rather vague. Describe why this is possible briefly based on aerosol size and extinction

We removed this sentence. This is the assumption of the original MODIS algorithm. It was abandoned later on so that the retrieval is more accurate. 2.2 µm band is approximately transparent to small sized particles such as smoke, urban aerosols, but it is not as transparent to large particles such as dust. The extinction is determined by the ratio between the wavelength and the particle size. Based on Mie theory, the larger the ratio, the smaller the extinction.

Line 74. Again, poor phrasing. It is not linear reflectance BETWEEN channels if it is three channels. Be specific.

Changed to "The algorithm assumes linear relationships exist between the surface reflectance of 0.47 µm band and 2.2 µm band, and between those of 0.64 µm band and 2.2 µm band."

Line 75-80 is awkward phrasing. The algorithm does not make retrievals? Describe the algorithm clearly but briefly. Line 81-84 is not clear at all.

While I understand how the algorithm works this type of writing will not help all readers understand the algorithm and methods used in this paper.

Revised the paragraph as follows.

Over land, three ABI channels are used in the retrieval, i.e. 0.47 µm, 0.64 µm, and 2.2 µm. The algorithm assumes linear relationships exist between the surface reflectance of 0.47 µm band and 2.2 µm band, and between 0.64 µm band and 2.2 µm band. The coefficients of the relationships are functions of NDVI (between 0.86 and 0.64 µm channel) and solar zenith angle (GOES-R ABI AOD ATBD, 2018). Other atmospheric and geographic parameters needed for the retrieval are also inputted, such as surface pressure, surface height, total column ozone, etc. The algorithm only retrieves AOD over dark surface, when the TOA reflectance in the 2.2 µm band is less than 0.25. The retrieval algorithm contains two steps. In the first step, one of four aerosol models is assumed, i.e. dust, smoke, urban, and generic, and AOD for each of the aerosol model is retrieved using the 0.47 µm and the 2.2 µm bands. The algorithm uses a Look-up-Table (LUT) to perform radiative transfer calculation. The LUT stores reflectances, transmittances and other quantities for discrete states of atmosphere and Sun-satellite geometries. For each AOD in the LUT, the algorithm performs atmospheric correction in 2.2 µm band to obtain surface reflectance in that band, and uses the 0.47 µm and the 2.2 µm band relationship to obtain 0.47 µm band surface reflectance. TOA reflectance in the 0.47 µm band can then be calculated using the LUT. The AOD for the assumed aerosol model is obtained through interpolation of the two AODs that give TOA reflectances in the 0.47 µm band closest to the satellite measurement. At the end of this step, there are four AOD solutions from the 0.47 µm band and 2.2 µm band, one for each aerosol model. In the second step, one of the four solutions is then selected as the final retrieval using the 0.64 µm channel by looking for the aerosol model that gives a TOA reflectance in that channel that is the closest to the observed TOA reflectance. In this step, 0.64 µm band TOA reflectance is calculated with 2.2 µm band surface reflectance from last step, relationship between 0.64 µm band and 2.2 µm band and AOD of corresponding aerosol model. The algorithm does not make retrievals over bright land pixels, pixels covered by cloud or snow, etc. The AOD retrieval range is [-0.05,5] and any retrievals greater than 5 are marked as out of range.

Line 89: Usually very small? What does that mean? Need some numbers.

Added: "For example, the ratio between the number of the top 2 qualities and the high quality matchup with AERONET is about 2 (see the following section), while the ratio is 1.2 for VIIRS AOD (Laszlo and Liu, 2016). "

Lines 89-94 needs to be clearer with brief discussion rather than listing the problems.

They are just a list of criteria used to degrade AOD quality in the current algorithm. The starting sentence was revised as: "Following criteria are used to degrade a pixel from high quality to medium quality: …"

The problem is the standard deviation test. We did discuss it in the next sentences.

The reasons for the other criteria are out of the scope of this paper and are not discussed in the paper. Following are the reasons about the cloud/snow adjacency criteria:

Pixels close to clouds or snow can be potentially impacted by radiation scattered from them into the cloud-free and snow-free columns (e.g. Marshak and Davis, 2005; Lyapustin and Kaufman, 2001). For clouds, there is also the issue of transition from clear to cloudy, which is gradual. Cloud detection may not label these pixels as cloudy because they are not bright enough. At the same time these pixels have cloud droplets mixed with aerosol, and/or a humidity that results in aerosols, if they are hygroscopic, which are not well represented by any of the models in the LUT (e.g. Jia et al., 2019; Tang et al., 2019) .

Line 98: If the surface reflectance issues are so different between 0.41 and 0.47 micron then the authors need to show or discuss this for certain land types. Otherwise these statements are vague.

Added: Over CONUS region, from VIIRS data, the 0.41 µm surface reflectance is 0.3-0.4 times the 0.67 µm band surface reflectance and the 0.47 µm surface reflectance is 0.5-0.6 times the 0.67 µm surface reflectance (Zhang et al., 2016). Therefore, 0.41 µm surface reflectance is 20%-50% lower than 0.47 µm surface reflectance.

115-120 discussion is not "technical" enough. What does air mass movements mean? You need to then state what wind speeds at what height provide the 27.5 km radius.

We removed "the air mass movements" in the sentence. For this matchup, we did not do temporal matchup with AERONET and just plotted the time series of ABI AOD and AERONET AOD. To our knowledge, the air mass movements argument first appeared in Ichoku et al. (2002) as follows: " the average travel speed of an aerosol front is of the order of 50 Km/h. This was visually estimated from animated daily sequences of TOMS aerosol index images (http://jwocky.gsfc.nasa.gov/aerosols/aermovie.html) for July to September 1988, where aerosol fronts are seen crossing the Atlantic from the west coast of Africa to the East coas t of America (approximately 6000 Km) in about five or six days. Therefore, the 50x50 Km window would match a 1-hour sunphotometer data segment. All references to MODIS spatial statistics in the rest of this paper imply those based on the 50x50 Km (5x5 pixel) subset grid". They did not mention the height of the aerosol layer.

Line 140+: How about retrieval biases due to sun-satellite viewing geometry in radiative transfer code?

We are not aware of any report in the literature of AOD retrieval errors with magnitude $\geq$ 0.1 due to radiative transfer model within the range of ABI AOD retrieval geometry. Errors may be present at the edge of the disk due to plane parallel assumption but those retrievals are not recommended for even qualitative use, and they were excluded from the current analysis.

Line 147: We need to see these relationships between two channels for the solar geometries.

They are added in the paragraph of case studies at GSFC site.

I find the two reasons in 152-155 to be problematic. Why should the test position issue matter if these relationships are established for certain solar viewing geometries/NDVI?

The parameterization is a simplified model that assumes the relationships depend only on solar zenith angle and NDVI. However, in reality, the relationships depend on all the angles, i.e. solar zenith angle, satellite zenith angle, solar azimuthal angle and satellite azimuthal angle, and surface type (not only NDVI). In addition, NDVI is also a function of those angles. When the satellite moved, the satellite angles changed. Unless the relationships and NDVI are independent of satellite angles, the relationships should change.

Plus there are reasons why the quality flags were established for high, low, medium in the first place (cloud cover, snow cover etc). Of course one would use the best quality flags for establishing surface reflectance relationships because of contamination issues. Now if you are using medium quality flags to get more data into the analysis then of course your surface reflectance relationships are going to be different.

This is the problem of surface reflectance relationships parameterization: they cannot be generalized to other pixels without losing AOD retrieval accuracy. With bias correction, we can correct those biases caused by this problem.

Since this paper is about surface reflectance issues the authors need to show these relationships that currently exist for various angles/NDVI first to make their case stronger.

We understand what you are saying but we think the paper is not about surface reflectance issues. It is about correcting the bias that, we think, happened to be caused primarily by deficiencies in the way we parameterize the relationship between spectral surface reflectances. The detailed surface relationships are available in GOES-R ABI AOD ATBD (2018) and is out of the scope of the paper.

But for your information, following is a summary of the relationships:

The surface reflectance relationships used in the above retrieval algorithm are derived through studies of ABI pixels near AERONET sites, where AODs are accurately measured from the ground and are considered as ground truth. A set of stringent pixel selection rules are applied to build a matchup dataset between ABI pixels and AERONET AOD in order to reduce cloud contamination and uncertainties in aerosol models (GOES-R ABI AOD ATBD, 2018). If AERONET AOD is less than 0.2 of a matchup dataset, surface reflectance of the pixels at the three channels are retrieved through atmospheric correction. With surface reflectance of all such pixels, the relationships are then derived and parameterized as functions of the solar zenith angle for different ranges of the normalized difference vegetation index (NDVI, between 0.86 and 0.64 μm channel) through linear regression analysis of the spectral surface reflectance. The current surface reflectance relationships are derived from ABI full disk matchup dataset in the time period of 04/29/2017 – 01/15/2018.

The surface reflectance relationships obtained are described in the following equations:

$$\rho_{0.47}[\rho_{0.64}] = (c_1 + c_2\theta_s) + (c_3 + c_4\theta_s)\rho_{2.2} \quad (1)$$

Where $\rho_{0.47}$, $\rho_{0.64}$, $\rho_{2.2}$ are surface reflectance at the three bands, c_1, c_2, c_3, c_4 are constants depending on NDVI as shown in Table 3-12 of the ATBD (shown in the following), θ_s is the solar zenith angle. NDVI is defined by red (0.67 μm) and NIR (0.86 μm) bands at TOA as

$$\mathrm{NDVI} = \frac{\rho_{0.86}^{TOA} - \rho_{0.64}^{TOA}}{\rho_{0.86}^{TOA} + \rho_{0.64}^{TOA}} \quad . \quad (2)$$

Table 3-12. Coefficients in the spectral surface reflectance relationship for different ranges of NDVI.

Channels (µm)	c_1	c_2	c_3	c_4
		$NDVI \geq 0.55$		
0.47 vs. 2.25	1.436330E-02	2.060893E-04	1.749239E-01	-2.859502E-03
0.64 vs. 2.25	1.374160E-02	-5.128175E-05	2.761044E-01	1.034823E-03
		$0.3 \leq NDVI < 0.55$		
0.47 vs. 2.25	4.163894E-02	-2.147513E-04	1.598440E-01	7.401292E-04
0.64 vs. 2.25	2.990101E-02	-1.873911E-04	4.602174E-01	9.658934E-04
		$0.2 \leq NDVI < 0.3$		
0.47 vs. 2.25	5.154307E-02	5.679386E-05	2.048702E-01	-7.064656E-04
0.64 vs. 2.25	5.179930E-02	-1.043257E-04	4.937035E-01	4.310074E-04
		$NDVI < 0.2$		
0.47 vs. 2.25	-4.990575E-02	2.138207E-03	8.498076E-01	-1.179596E-02
0.64 vs. 2.25	-3.397737E-02	1.640336E-03	1.087497E+00	-9.538776E-03

In the revised paper, we provide a detailed analysis and the surface reflectance relationships used over the GSFC site.

The authors should also show the reflectance values on these plots so we can interpret the results better.

We added them in the surface reflectance discussion for GSFC case study.

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Response to reviewer #2

This paper evaluates the AOD retrieval from geostationary platform GOES ABI and proposed an empirical bias correction scheme to improve the AOD accuracy. The GOES AOD product is potentially very useful in radiative forcing and air quality studies, in that it offers the diurnal variability of AOD on large scale. However, the existence of bias in the diurnal cycle is a significant drawback that limits its use. Therefore, the bias correction scheme offered in this paper is both important and useful. However, I hope the authors can give more analysis proving and explaining that surface reflectance is responsible for the bias, and that the bias correction is effective under all AOD loading and surface conditions. These I think are major issues, although they should not be too difficult to address. My detailed comments are listed below.

Major comments:

I agree with the authors that surface reflectance parameterization is the most likely cause of the AOD bias. However, in the paper the authors seem very definitive on this point. For example, in the abstract, it says "ABI AOD has diurnally varying biases due to errors in the land surface reflectance relationship between the bands used in the ABI AOD retrieval algorithm". Therefore, I wonder if they can offer more detailed analysis proving this point and explain how the relationship between surface reflectance of different channels vary with geometry?

In the revised paper, we give a detailed case study at GSFC site for different geometries. Specifically, in the case study, the surface reflectance relationships used are closer to the real relationships in the afternoon than at noon, and therefore, the afternoon AODs retrieval are closer to the AERONET AODs.

The difference between the test position and the current operational position does not seem large enough to account for such high AOD bias.

We did not say it is the main reason. But it is one reason, although the effect may be small.

One possibility is that the NDVI also varies with solar zenith angle. Do the authors use MODIS NDVI? They are calculated from polar orbiting satellites and the NDVI only represent one solar zenith angle. Although NDVI should be a normalized quantity that is not affected by the angle, the large different solar position between polar orbit and geostationary orbits may cause MODIS NDVI not representative of all angles.

No, ABI AOD retrieval algorithm doesn't use MODIS NDVI. The algorithm uses ABI top of atmosphere reflectance of 0.64 μm and 0.86 μm bands to calculate it, independent from MODIS. NDVI is defined by red and NIR bands at TOA as

$$\mathrm{NDVI} = \frac{\rho_{0.86}^{\mathrm{TOA}} - \rho_{0.64}^{\mathrm{TOA}}}{\rho_{0.86}^{\mathrm{TOA}} + \rho_{0.64}^{\mathrm{TOA}}}$$

The geometry dependence of NDVI is an issue, but not so large for the main cause of the AOD bias, as shown in the case study at GSFC in the revised paper. We are aware that this NDVI is not an "aerosol-resistant" NDVI. The choice of wavelength was dictated by the availability of ABI channels. MODIS AOD algorithm uses 1.24 μm and 2.12 μm band pair, i.e.
$\mathrm{NDVI} = \frac{\rho_{2.12}^{\mathrm{TOA}} - \rho_{1.24}^{\mathrm{TOA}}}{\rho_{2.12}^{\mathrm{TOA}} + \rho_{1.24}^{\mathrm{TOA}}}$. However, ABI does not contain the 1.24 μm band. Based on the available ABI bands, we analyzed the dependence of 0.47 μm and 2.25 μm surface reflectance relationship to the NDVI from (0.64,0.86) μm pair and from (0.86,2.2) μm pair. It turned out that NDVI from (0.64,0.86) μm pair

better separates the soil-based and vegetation-based. Based on this NDVI, the surface is classified into 4 different NDVI ranges and the surface reflectance parameterization are derived using ABI reflectances (Table 3-12 in ATBD), independent from MODIS.

2. The bias correction assumes that the difference between 30-day minimum AOD and background AOD is the systematic error, and subtract this error from every AOD retrieval. I wonder if the bias also depends on AOD itself, i.e., aerosol loading, so that the systematic bias derived as above does not represent all AOD conditions?

In the revised paper, an evaluation is performed for the bias correction algorithm for different AOD loading. Figure 7 in the revised paper shows the ABI AOD error and standard deviation in different AERONET AOD bins, with equal number of matchup data in each bin. For high quality AOD, bias correction reduces bias in the highest two AOD bins, with center around 0.3 and 0.57. In the range [0.1, 0.3], bias correction over corrects and introduces negative mean bias with slightly larger magnitude than the original mean bias, around 0.01 in magnitude differences. In the range [0,0.1], AOD mean biases are close to zero both before and after correction, but the bias correction AOD error has smaller standard deviation. For the top 2 qualities ABI AOD, bias correction reduces the bias in the whole AOD range with slight over corrections of magnitude of about 0.02 when AOD is greater than 0.1.

The validation set seems somewhat small (only 6 days of data) and all days have low AOD (<0.1). I thus wonder how the bias and correction algorithm may perform for high AOD cases?

Those are for case studies. The scatter plots in Figure 5 (in the revised paper) includes all the 5 months matchup data of AERONET sites over CONUS. Figure 7 (in the revised paper) and the corresponding discussion is also added to answer your question.

Another issue is that the effect of correction is not obvious for top quality data, mostly because the bias data are already removed from top quality (see Figure 1). Is this because these retrievals have high residual error so that they are removed from top quality set? Investigating the reason may offer some clue for the causes of the bias or algorithm improvements.

A lot of them are due to the relatively large standard deviation of 3x3 box in the 0.47 µm band, which is used in the ABI AOD retrieval algorithm to remove residual cloud contamination with a standard deviation threshold 0.006 for high quality AOD retrieval. This method was adopted from VIIRS retrieval. However, VIIRS retrieval uses a different band 0.41 µm, in which surface reflectance is much lower than 0.47 µm band. As a result, the standard deviation test likely erroneously removes clear pixels with high standard deviation caused by surface. Because the standard deviation information is only available in the intermediate product, which were not archived for long term use, we examined several granules of ABI AOD retrieval from off-line algorithm run and found that 65-80% in medium quality land pixels have standard deviation of 0.47 µm band above the threshold of 0.006.

Minor comments:

1. **Section 2.1: What cloud screening scheme is used?**

ABI has a cloud mask product (ABI Cloud Mask ATBD, 2012, https://www.star.nesdis.noaa.gov/goesr/documents/ATBDs/Baseline/ATBD_GOES-R_Cloud_Mask_v3.0_July%202012.pdf , last accessed 5/3/2020), which is used in the ABI AOD retrieval algorithm. In addition, several internal tests are performed to further remove contamination from cloud(ABI AOD ATBD, 2018) : (1) internal cloud test; (2) internal cirrus test; (3) internal inhomogeneity test.

And which NDVI data is used, MODIS?

No, not MODIS NDVI. The algorithm uses ABI top of atmosphere reflectance of 0.67 µm and 0.86 µm bands to calculate it: NDVI is defined by red and NIR bands at TOA as

$$\mathrm{NDVI} = \frac{\rho_{0.86}^{\mathrm{TOA}} - \rho_{0.64}^{TOA}}{\rho_{0.86}^{\mathrm{TOA}} + \rho_{0.64}^{TOA}}$$

2. Section 2.2: Is there any quality control performed on AERONET Level 1.5 data? What is estimated AOD error?

Level 1.5 AERONET AOD data is cloud screened and quality controlled, with a + 0.02 bias and one sigma uncertainty of 0.02 (Giles et al., 2019).

3. Line 304, the following reference also points out the poor VIIRS aerosol model selection over China:

Thanks. We included this reference in the paper

4. Comparison with PM2.5 seems not very relevant, and removing it does not impair the integrity of the study. There are a lot of factors affecting the AOD-PM2.5 relationship and I think this comparison may complicate the analysis.

One of the main applications of NOAA AOD product is to operationally derive surface PM2.5 for air quality monitoring and forecasting applications. Arguably, there are many factors that affect the AOD to PM2.5 relationship (aerosol composition, aerosol layer height, relative humidity, time of observation, accuracy of AOD, etc.). It is intuitive that an accurate AOD gives a better estimate of surface PM2.5 given that other factors influencing this relationship the way they are. Therefore, demonstrating that the relationship improves with improved AOD is quite important for our studies and work we do with user community.

5. Figure 6: could the authors also compare with MODIS to demonstrate the effect of bias correction? The peak of the bias happens at 17UTC, which is 1PM US east time and is close to Aqua overpass.

The MODIS AOD from Aqua dark target and deep blue algorithm are added (Figure 9 in the revised paper). The bias corrected ABI AOD compares very well with deep blue MODIS AOD in both magnitude and data coverage.

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Response to reviewer #3

“Improving GOES Advanced Baseline Imager (ABI) Aerosol Optical Depth (AOD) Retrievals using an Empirical Bias Correction Algorithm”. Hai Zhang et al.

Submitted to AMT Discussions

Summary

Current operational retrievals of AOD from radiances measured by the ABI sensor on aboard of GOES 16 exhibit a diurnal bias (sun angle dependency) associated to the surface reflectance of the pixel under observation. This study introduces this problem and proposes an ad-hoc correction to the retrieved AOD. A correction is developed by collocating GOES AOD retrievals over selected Aeronet sites (mostly in the East of USA). Only days with low and constant (through the day) Aeronet AOD values are used to ensure that the GOES deviations are caused by the solar angle changes and not from aerosol loading variations. The differences are then assessed and a correction based on those differences (which in turn are a function of geometry and NDVI) is created. The correction is assumed to be valid through the full ABI swath and then applied to retrieved AODs. The corrected AODs are validated against Aeronet during a 6-month period. The correction successfully improves the satellite-Aeronet AOD comparison. While the improvement is clear and it may result in a more accurate operational product, this analysis does not address the actual problem the causes the bias (a non-adequate surface reflectance data base) and presents an ad-hoc correction. In addition, I find that this study has important methodological defects and I do not recommend the paper for publication in this form.

Overall there are two major concerns about this work.

First, this a very empirical approach where the root of the problem is not addressed, namely the angular dependence of the surface reflectance as a function of sun angle. Although the authors do acknowledge that this is the real issue and they are working on it, they are content to use an ad-hoc approach by forcing the retrieved AOD to match the ground truth AOD. While this may be a reasonable practical correction, it does not show any new scientific approach (alternatively the authors do not highlight what is novel in doing this) and it does not attempt a correction on the actual measurement (observed radiances) based on physical principles (such as a modeled BRF) and using radiative transfer. With this regard, the work does not offer anything new.

This is an approach in addition to the traditional approach based on physical principles. The uncertainty in BRF model is transferred to AOD. Improving AOD is the same as improving BRF. The approach in this paper solves the problem in AOD space instead of BRF space, which is different from traditional approach. The traditional approach uses AERONET matchup dataset to generate surface reflectance relationships and then assume these relationships can also be applied to surfaces at other places where AERONET stations are not present. Even at the AERONET sites, the surface reflectance relationships have large uncertainty. The bias correction algorithm proposed here can reduce those uncertainties. More importantly, it does not rely on AERONET surface and therefore can be applied anywhere else without assuming everywhere else is the same as AERONET.

The empirical bias corrections to retrieved AODs is not new. The NASA MODIS Dark Target AOD algorithm corrects AOD using a bias correction algorithm over urban areas using post processing of AODs for areas where urban land percentage is greater than 20% (Gupta et al., 2016). There are other

MODIS AOD correction algorithms as well developed by users for their own applications (e.g., Lary et al., 2009). In fact, compared to these bias correction algorithms, our approach is better because it is internally consistent and does not rely on any external dataset. Moreover, the bias correction preserves the original AOD data file, and it is "self-correcting", meaning if the physical AOD algorithm improves the bias correction will automatically adjust to the new values.

Second, the validation is carried out by comparing the corrected retrievals against observations from the same instrument used for creating the correcting term. This is not adequate and it puts an asterisk on the goodness of the correction. At least these new corrected AODs need to be validated against an independent set of observations.

The comparison is between the correction before correction and after correction to show the improvement. The 30-day AOD used is assumed to contain information of the bias. For most of the days of validation, except the first 30 days, we use the 30-day period data before the day to get the AOD bias, which is independent from the data being corrected. The following figure shows the scatter plots of the validation using the data with the first 30 day removed, and therefore the bias corrected ABI AOD data are totally independent from the data used for obtaining the AOD bias. The conclusions remain the same as in the paper.

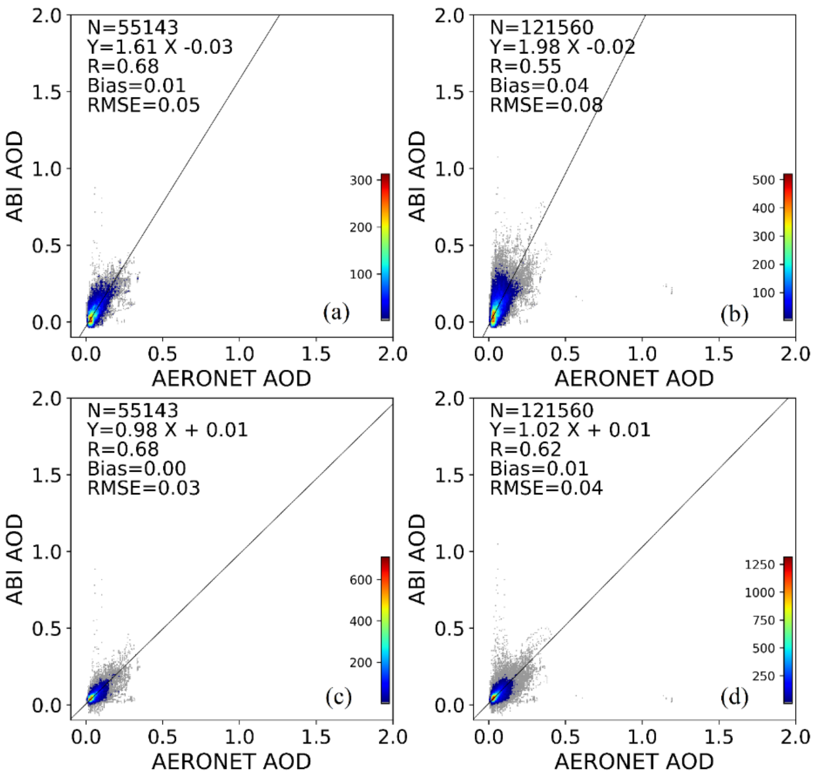

Figure A. Scatter plots of GOES-16 ABI AOD vs AERONET AOD for September 5, 2018 to December 31, 2018 across the CONUS domain: (a) high quality ABI AOD before bias correction, (b) top 2 qualities ABI AOD before bias correction, (c) high quality ABI AOD after bias correction, and (d) top 2 qualities ABI AOD after bias correction. In the plots, N is the number of matchups, R is the correlation coefficient, and RMSE is the root mean square error.

Also, note that in comparing figures 4c and 4d, there is a clear improvement in high AODs (~>0.5) whereas for lower AODs values, the scattering increases in figure 4d.

Figure 4c and 4d are both after correction AOD. One is high quality and the other is high and medium quality. Figure 4d has more data points than 4c and they don't have one-to-one correspondence. Therefore, they should not be compared for improvement of bias correction. The correct comparison is between Figure 4a and Figure 4c, and between Figure 4b and Figure 4d. (Figure 4 changes to Figure 5 in the revised paper).

This raises the question on whether the correction should be applied across the board to all aerosol loadings. This is relevant to AQ studies given that the vast majority of aerosol loadings are below AODs ~< 0.5, it is very desirable to have those levels of loading well characterized.

We plotted comparisons of AOD errors vs AERONET AOD for different AOD loadings in Figure 7 in the revised paper. The bias corrected AOD are shown to have reduced bias for all the AOD ranges for the top 2 (high and medium) qualities AOD. For high quality AOD, bias correction reduces bias in the highest two AOD bins, with center around 0.3 and 0.57. In the range [0.1, 0.3], bias correction over corrects and introduces negative mean bias with slightly larger magnitude than the original mean bias, around 0.01 in magnitude differences. In the range [0,0.1], AOD mean biases are close to zero both before and after correction, but the bias correction AOD error has smaller standard deviation.

It should be noted that this critique does not preclude or advise against the application this correction to the operational product. However, the material here presented does not have the depth required for a scientific report.

The algorithm is an effective tool to evaluate and correct the AOD bias from geostationary satellites. If you agree that the algorithm works, we should have it published so the other researchers can benefit from the improvements and use this data in their studies/applications. For example, apply it on AOD product from other geostationary satellite platform or other retrieval algorithm.

We hope the new results added to the revised paper also adds more depth to the material presented. We believe that even though an empirical "technique" for correcting biases in a specific product is presented, the approach and its evaluation presented do have merits in its application to other AOD products as well, and thus others could benefit from its publication.

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Improving GOES Advanced Baseline Imager (ABI) Aerosol Optical Depth (AOD) Retrievals using an Empirical Bias Correction Algorithm

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Abstract. The Advanced Baseline Imager (ABI) on board the Geostationary Operational Environmental Satellite-R (GOES-R) series enables retrieval of aerosol optical depth (AOD) from geostationary satellites using a multi-band algorithm similar to those of polar-orbiting satellites' sensors, such as the Moderate Resolution Imaging Spectroradiometer (MODIS) and Visible Infrared Imaging Radiometer Suite (VIIRS). ~~Therefore, ABI AOD is expected to have accuracy and precision comparable to MODIS AOD and VIIRS AOD.~~ However, this work demonstrates that the current version of GOES-16 (GOES-East) ABI AOD has diurnally varying biases due to errors in the land surface reflectance ~~relationship~~relationships between the ~~bands~~0.47 µm band and the 2.2 µm band and between 0.64 µm band and 2.2 µm band used in the ABI AOD retrieval algorithm, which vary with respect to the Sun-satellite geometry~~.~~ and NDVI (Normalized Difference Vegetation Index). To reduce these biases, an empirical bias correction algorithm has been developed based on the lowest observed ABI AOD of an adjacent 30-day period and the background AOD at each time step and at each pixel. The bias correction algorithm improves the performance of ABI AOD compared to AErosol RObotic NETwork (AERONET) AOD, especially for the high and medium (top 2) quality ABI AOD. AOD data for the period August 6 to December 31, 2018 are used to validate the bias correction algorithm. For the top 2 qualities ABI AOD, after bias correction, the correlation between ABI AOD and AERONET AOD improves from 0.87 to 0.91, the mean bias improves from 0.04 to 0.00, and root mean square error (RMSE) improves from 0.09 to 0.05. These results for the bias corrected top 2 qualities ABI AOD are comparable to those of the ~~uncorrected~~corrected high-quality ABI AOD. ~~Thus, by~~By using the top 2 qualities of ABI AOD in conjunction with the bias correction algorithm, the ~~area~~areal coverage of ABI AOD is ~~substantially~~ increased by about 100% without loss of data accuracy.

1 Introduction

Aerosols in the atmosphere such as dust, smoke, pollutants, volcanic ash, and sea spray can affect climate through scattering and ~~absorbing~~absorption of radiation directly, and through interaction with clouds indirectly (~~McCormick and Ludwig, 1967; Charlson and Pilat, 1969; Atwater, 1970; Mitchell Jr., 1971; Coakley et al., 1983; Twomey, 1977;~~ Albrecht, 1989; Rosenfeld and Lensky, 1998; Mahowald, 2011). In addition, aerosols impact air quality and thus affect human health (e.g. Pope and Dockery 2006). Satellite retrieved aerosol optical depth (AOD), a quantitative measure of the amount of aerosols present in the atmosphere, is useful for evaluating aerosols' effect on climate change (e.g. Yu et al. 2006) and for estimating and forecasting ambient $PM_{2.5}$ concentrations (particulate matter with ~~diameters~~median diameter ≤ 2.5 μm; e.g. Hoff and Christopher, 2009).

AOD from polar-orbiting satellite sensors, such as the Moderate Resolution Imaging Spectroradiometer (MODIS) and Visible Infrared Imaging Radiometer Suite (VIIRS), is retrieved using multi-channel algorithms (Levy et al., 2007; Levy et al. 2010; Sayer et al., 2014; Jackson et al., 2013; Liu et al., 2014; Laszlo and Liu, 2016). As a result, AOD from MODIS and VIIRS has high accuracy, e.g. MODIS dark target AOD has an expected error of ±(0.05 +15 %) over land (Levy et al. 2013) and VIIRS AOD has a bias of 0.02 and standard deviation of error of 0.11 (Laszlo and Liu, 2016), but the low temporal resolution of polar-orbiting satellites limits the availability of observations for a given location. In contrast, geostationary satellites such as the United States' Geostationary Operational Environmental Satellites (GOES) provide an opportunity for nearly continuous AOD retrievals during daylight over a hemispheric domain. The GOES Aerosol and Smoke Product (GASP) retrieved at the National Oceanic and Atmospheric Administration (NOAA) from the legacy GOES imagers, however, was not as accurate as the MODIS or VIIRS AOD due to limitations imposed by a single channel retrieval (Prados et al., 2007; Green et al., 2009). GASP AOD was reported to have a correlation of 0.79 and RMSE of 0.13 compared with AERONET AOD over CONUS (Prados et al., 2007). The Advanced Baseline Imager (ABI) on the new generation GOES-R series of satellites ~~provides~~are expected to provide AOD retrievals with accuracies similar to MODIS and VIIRS due to similar instrument design and algorithm science, combined with high temporal resolution. NOAA launched the first and the second satellites in the GOES-R series, GOES-16 and GOES-17, in 2016 and 2018, respectively (Schmit et al., 2017; https://www.nesdis.noaa.gov/content/goes-17-now-operational-here%E2%80%99s-what-it-means-weather-forecasts-western-us accessed 6/12/2019). Each satellite carries an ABI, which has 16 spectral bands ranging from the visible to infrared wavelengths. GOES-16 is located at 75.2°W and GOES-17 is located at 137.2 °W. Both satellites observe the continental United States (CONUS) region every 5 minutes and the full hemispheric disk every 10 minutes or every 15 minutes, depending on the scan mode (Schmit et al., 2017).

The ABI AOD product has a spatial resolution of 2 km at nadir, compared to 3 km from MODIS Collection 6 and 750 m from VIIRS. The GOES-16 ABI AOD product~~, deemed having a quality sufficient to be used in applications and research (provisional maturity),~~ was released on July 25, 2018, while the GOES-17 ABI AOD product reached provisional maturity (EOSDIS Glossary, https://earthdata.nasa.gov/learn/user-resources/glossary, accessed May 14, 2020) on January 1, 2019.

The accuracy and precision of VIIRS and MODIS AOD is well documented for use in various decision support systems (Laszlo and Liu, 2016; Levy et al., 2013). The geometries of observations from a geostationary satellite are quite different from ~~those~~

~~from~~ a polar-orbiting satellite; this can lead to differences in the quality of retrieved AOD despite the similarity of the AOD retrieval algorithms. It is therefore very important to evaluate the new ABI AOD product and demonstrate its accuracy and precision at daily and sub-daily time scales. This should allow users to interpret the ABI AOD product correctly and apply it appropriately in research and operational applications.

In this study, we compare GOES-16 ABI AODs to AERONET AODs for a five-month period in 2018 and document a diurnal bias in the ABI AOD due to deficiencies in the land surface reflectance relationship currently applied in the retrieval algorithm. The presence of the bias is consistent across the CONUS but its magnitude varies by location~~ and aerosol composition.~~. We describe a novel method that corrects the bias for each AOD pixel and time step. The resultant corrected ABI AOD shows little to no diurnal bias over a variety of surface types (e.g., urban, rural).

2 Data

2.1 GOES-16 ABI AOD

The GOES-16 ABI AOD data used in this work is from the period of August 6 to December 31, 2018, over the CONUS region. The ABI AOD data have 2 km spatial resolution at nadir and 5 minutes temporal resolution. Similar to MODIS and VIIRS AOD, ABI AOD are retrieved using separate algorithms over ocean and over land, due to the different surface characteristics of ocean and land (Kondragunta et al., 2020; GOES-R AOD ATBD, ~~2012,~~ 2018). Over land, three ABI channels are used in the retrieval, i.e. 0.47 μm, 0.64 μm, and 2.2 μm. ~~The 2.2 μm channel is transparent to most aerosols, so it is used to estimate the surface reflectance in the visible bands using prescribed functions. The algorithm assumes linear relationships exist between the surface reflectances in these three channels. With the help of LUT, AODs are retrieved using 0.47 μm and 2.2 μm for four types of aerosol models, i.e. dust, smoke, urban, and generic. The aerosol model is then selected using 0.64 μm channel by looking for the aerosol model that gives closest top of the atmosphere (TOA) reflectance at the channel.~~The algorithm assumes linear relationships exist between the surface reflectance of 0.47 μm band and 2.2 μm band, and between 0.64 μm band and 2.2 μm band. The coefficients of the relationships are functions of NDVI (between 0.86 and 0.64 μm channel) and solar zenith angle (GOES-R ABI AOD ATBD, 2018). Other atmospheric and geographic parameters needed for the retrieval are also inputted, such as surface pressure, surface height, total column ozone, etc. The algorithm only retrieves AOD over dark surface, when the TOA reflectance in the 2.2 μm band is less than 0.25. The retrieval algorithm contains two steps. In the first step, one of four aerosol models is assumed, i.e. dust, smoke, urban, and generic, and AOD for each of the aerosol model is retrieved using the 0.47 μm and the 2.2 μm bands. The algorithm uses a Look-up-Table (LUT) to perform radiative transfer calculation. The LUT stores reflectances, transmittances and other quantities for discrete states of atmosphere and Sun-satellite geometries. For each AOD in the LUT, the algorithm performs atmospheric correction in 2.2 μm band to obtain surface reflectance in that band, and uses the 0.47 μm and the 2.2 μm band relationship to obtain 0.47 μm band surface reflectance. TOA reflectance in the 0.47 μm band can then be calculated using the LUT. The AOD for the assumed aerosol model is obtained through interpolation of the two AODs that give TOA reflectances in the 0.47 µm band closest to the satellite measurement. At the end of this step, there are four AOD solutions from the 0.47 µm band and 2.2 µm band, one for each aerosol model. In the second step, one of the four solutions is then selected as the final retrieval using the 0.64 µm channel by looking for the aerosol model that gives a TOA reflectance in that channel that is the closest to the observed TOA reflectance. In this step, 0.64 µm band TOA reflectance is calculated with 2.2 µm band surface reflectance from last step, relationship between 0.64 µm band and 2.2 µm band and AOD of corresponding aerosol model. The algorithm does not make retrievals over bright land pixels, pixels covered by cloud or snow, ~~sun-glint pixels over water,~~ etc. The ~~valid~~ AOD retrieval range is [-0.05,5~~].~~] and any retrievals greater than 5 are marked as out of range.

~~The surface reflectance relationships between the three bands are derived through studies of surfaces close to AERONET sites, where AOD are accurately measured from the ground and are considered as ground truth. Surface reflectances at the three channels are first retrieved with the help of AERONET AOD for the ABI pixels if AOD is less than 0.2. The relationships are then parameterized as functions of the solar zenith angle for different ranges of the normalized difference vegetation index (NDVI, between 0.86 and 0.64 µm channel) through linear regression analysis of the spectral surface reflectances.~~

The retrieval algorithm assigns the pixel level AOD to one of three qualities: high, medium and low. AOD quality is determined on conditions of the pixels, such as solar/satellite zenith angle, cloud/shadow adjacency, standard deviation of measured reflectance at a specific band; the full set of criteria is listed in Table 1. High quality AOD is the most accurate and most recommended for scientific applications. However, the ABI AOD retrieval algorithm uses such strict criteria to remove potential erroneous pixels that the number of pixels with high quality AOD is usually very small. ~~Several criteria can cause a pixel be degraded to medium quality instead of high~~For example, the ratio between the number of the top 2 qualities and the high quality matchup with AERONET is about 2 (see the following section), while the ratio is 1.2 for VIIRS AOD (Laszlo and Liu, 2016). Following criteria are used to degrade a pixel from high quality to medium quality: (1) adjacent to a cloudy pixel; (2) adjacent to a snow pixel within 3 pixels distance; (3) 3x3 standard deviation of 2 km 0.47 µm TOA reflectance is greater than 0.006; (4) retrieval residual is greater than 0.4; (5) external cloud mask is "probably clear". Out of these five criteria, the standard deviation test tends to remove a large number of pixels that are potentially high quality~~.~~, i.e about 65-80% in medium quality land pixels have standard deviation in the 0.47 µm band above the threshold of 0.006. This test is used to remove pixels that are inhomogeneous in TOA reflectance due to the existence of undetected cloud or snow by the cloud mask algorithm. A similar test is used in the VIIRS AOD algorithm but with the 0.41 µm band instead of the 0.47 µm band (e.g. Huang et al., 2018). The surface reflectance in the 0.41 µm channel is usually low and therefore does not have much influence in the standard deviation at the TOA for VIIRS AOD. Over CONUS region, from VIIRS data, the 0.41 µm surface reflectance is 0.3-0.4 times the 0.67 µm band surface reflectance and the 0.47 µm surface reflectance is 0.5-0.6 times the 0.67 µm surface reflectance (Zhang et al., 2016). Therefore, 0.41 µm surface reflectance is about 20%-50% lower than 0.47 µm surface reflectance. However, the ABI does not have a 0.41 µm channel and the algorithm ~~must~~has to use the 0.47 µm channel instead. The surface can have a noticeable influence on the standard deviation in the 0.47 µm channel, especially in urban regions where surface reflectance variations are large. To include more retrieval pixels that are otherwise omitted due to the very conservative screening process for high quality pixels, both high quality and medium quality pixels are included in this analysis.

2.2 AERONET AOD

The AErosol RObotic NETwork (AERONET) is a global ground-based aerosol remote sensing network (Holben et al., 1998). It uses CIMEL sun photometers to measure spectral sun irradiance and sky radiances. The measurements are then used to calculate and retrieve aerosol properties. Among them, AOD is one of the main products; it is measured at 22 different wavelengths from ultraviolet to infrared, i.e. 340, 380, 400, 412, 440, 443, 490, 500, 510, 531, 532, 551, 555, 560, 620, 667, 675, 779, 865, 870, 1020, and 1640 nm. Angstrom Exponent (AE) can be calculated from the multibandmultispectral AOD. Besides AOD, AERONET also retrieves other aerosol properties, such as volume size distribution, refractive index, phase function, and single scattering albedo (SSA). AERONET AOD is considered ground truth for satellite AOD (Holben et al., 1998) and is used to evaluate the ABI AOD retrievals. AERONET AOD at 550 nm is obtained through interpolation from other spectral bands so that it can be compared against ABI AOD, which is reported at 550 nm. In this work, AERONET AOD version 3 level 1.5 is used. Although level 2.0 data have higher quality, they have time delays such that the latest data were not available during the analysis period. Level 1.5 AERONET AOD data is cloud screened and quality controlled, with a + 0.02 bias and one sigma uncertainty of 0.02 (Giles et al., 2019).

3 GOES-16 ABI AOD Diurnal Bias

The diurnal bias of ABI AOD is evident when it is compared to coincident measurements of AERONET AOD. The diurnal bias is most apparent on "clear" days, when AERONET AOD is ≤ 0.05 during an entire day. Comparisons are made on clear days at six representative AERONET sites, listed in Table 2. These sites include a range of geographic locations across the CONUS and different surface types (e.g., urban, suburban, rural), most of which are urban or surfaces with little vegetation. Matchups at the AERONET sites were made by averaging ABI AOD pixels within a circle of 27.5-km radius surrounding the site; a minimum of 120 pixels are required to have an effective matchup, which is about 20% of all the pixels within the circle. These criteria are adopted from the traditional satellite and AERONET AOD matchup procedure through the consideration of the air mass movements (e.g.(e.g. Ichoku et al., 2002; Huang et al., 2016).

To illustrate the problem of the diurnal bias of ABI AOD the time series of ABI AOD and AERONET AOD for clear days are plotted at the representative AERONET sites in Figure 1. As demonstrated in the figure, the number of the ABI top 2 qualities (high and medium quality) data points are much larger than that of the high quality AOD. For example, on October 18, 2018 at the CCNY site (Figure 1a), which is located in New York City, New York, no high quality ABI AOD data matchup data are available, but top 2 qualityqualities AOD matchup points exist at nearly all time steps.

The diurnal variation of the ABI AOD bias is observed at all six sites, but the magnitude of the bias varies, with higher bias observed at the urban/suburban sites (Figures 1a, 1c, 1d, and 1e) compared to the rural sites (Figures 1b and 1f). For all sites, the bias peaks around 17:00 UTC, when the Sun moves from the east of the satellite to the west of the satellite, as determined by the location of the satellite, i.e. 75.2°W for GOES-16. The bias curves are nearly symmetric at the two sites with longitudes close to that of the satellite (Figures 1a, 1b, and 1c), while the bias curves are asymmetric at the sites to the west of the satellite (Figures 1d, 1e, and 1f).

There are several potential causes of the diurnal bias observed in ABI AOD, including known sources of uncertainty associated with calibration, cloud/snow contaminations, aerosol models, and errors in surface reflectance retrievals (Li, et al., 2009). In the cases shown in Figure 1, all days have low AOD values and continuous AOD measurements from AERONET, indicating that the influences of the aerosol model selection and cloud contamination are small. Snow contamination is not an issue because the analysis days are mostly in September and October, before it was cold enough for widespread snowfall. The one case in December (University of Houston) was not contaminated by snow through visual inspection of the true color (RGB) images of VIIRS or GOES, which are available on the AerosolWatch website (https://www.star.nesdis.noaa.gov/smcd/spb/aq/AerosolWatch/~~).~~, accessed May 5, 2020) It is not likely that the diurnal patterns of biases are caused by calibration error, because calibration errors are constant and do not change as a function of time of day. Therefore, the most probable reason for the observed diurnal patterns of the ABI AOD biases is errors in surface reflectance retrievals. In the ABI AOD retrieval algorithm, the land surface reflectance relationships between the 0.47 µm~~,~~ and the 2.2 µm band and between the 0.64 µm and the 2.2 µm ~~bands~~band were parameterized, as described in Section 2.1, and assumed to be functions of solar zenith angle and NDVI. Errors in these parameterizations are most likely responsible for the observed diurnal pattern of the ABI AOD biases. They can cause errors in surface reflectance retrieval, and therefore influence the retrieval of AOD. When the deviation of parameterization from the actual relationship is large, the AOD retrieval error will also be large. One reason that causes the land surface relation error is that current surface relationships were derived from the dataset when GOES-16 was located at the test position (89.5°W) instead of the current operational position (75.2 °W), and so the relationship does not adequately represent the current observation geometry. The other reason is that the relationships are derived using pixels that have high AOD quality and therefore the medium quality pixels are not represented by the training set.

The diurnal pattern of biases is also found to be different on different days. As an example, Figure 2 shows the diurnal bias at GSFC on two additional days in October 2018, the 18th and the 30th. Although the peak of the bias occurs at approximately the same time on both days, around 17:00 UTC, the magnitudes of the peaks are different. On October ~~12~~12th (Figure 1a) the maximum ABI AOD is about 0.25, while it is 0.2 on October ~~15~~18th (Figure 2a) and only 0.1 on October ~~30~~30th (Figure 2b). ~~The magnitude difference of the peaks is caused by the difference in the geometry between the two days. Because surface~~

reflectance relationships depend on the geometry, if the surface reflectance relationships are not correctly parameterized for the geometry dependence, they can cause the retrieval error in AOD as observed.

To further illustrate the reasons that cause the diurnal variation of the ABI AOD biases, atmospheric corrections were performed to obtain the surface reflectance at different times and days for the pixels near GSFC site, i.e. at 17:02 UTC and 20:02 UTC on October 12th, October 18th, and October 30th. The atmospheric correction uses the LUT from the ABI AOD retrieval and the input of the TOA reflectance from ABI, geometries, and AERONET AOD, along with the assumptions of standard column ozone, water vapor and surface pressure. Because there are four aerosol models in the LUT, the four surface reflectance were averaged. In the ABI AOD retrieval algorithm, 0.47 µm and 2.2 µm bands are used to obtain AOD and 0.64 µm band is used to select aerosol model. Therefore, in this analysis, only the surface reflectance of the 0.47 µm and the 2.2 µm bands are obtained to illustrate the problem. Figure 3 shows the scatter plots of 0.47 µm vs 2.2 µm of the pixels (high and medium quality) of the six occasions, along with the corresponding NDVI histograms.

In the scatter plots, the average of the three days' solar zenith angle is used to calculate the coefficients of the linear relationships for each time step for illustration purpose, because the solar zenith angles are close in value for the three days at each time step with about ±2° differences. Here only two lines are plotted because the majority of the pixels have NDVI in these two categories, as shown in Figure 3 (c) and (d).

At 17:02 UTC, on October 30th 2018, nearly all the pixels fall into the category of $0.3 \leq NDVI < 0.55$ and the corresponding relationship line (orange) passes through nearly the center of the pixel groups. Therefore, the AOD retrieval at this time on October 30th uses a relationship close to the reality and the AOD retrieved is close to AERONET AOD. On the other two days, about half of the pixels fall into $0.3 \leq NDVI < 0.55$ and another half into $NDVI \geq 0.55$. Although the pixels with $0.3 \leq NDVI < 0.55$ uses close to reality relationship, the pixels with $NDVI \geq 0.55$ uses a relation far away from reality and therefore the retrievals have large bias, i.e. about 0.2. Of these two days, October 12th has more fraction of pixels in the category with wrong relationship and therefore it has slightly higher bias.

Comparing the two time steps, pixels have lower NDVI at 20:02 UTC than those at 17:02 UTC on the same days. The surface reflectance is significantly lower at 20:02 UTC, i.e. with mean surface reflectance reduced from 0.06 to 0.04 in 0.47 µm band. Again, October 30th at 20:02 UTC, the pixels use surface reflectance relation of $0.3 \leq NDVI < 0.55$, which is also close to the reality. Although the other two days also use both relationships, both relationships are closer to the reality than the one with $NDVI \geq 0.55$ at 17:02 UTC. Therefore, all three cases at 20:02 UTC have retrievals close to AERONET AOD.

The change in NDVI from October 12th, 18th to October 30th is most likely due to the change in the colors of the vegetation during fall, when leaves of trees turn reddish. Within the same day, due to the change in geometry, NDVI changed. It should be pointed out that even though at 20:02 UTC the surface relationships used are close to reality, there is still a lot of scattering in individual pixels. This can introduce pixel level uncertainty which cannot be observed when averaged over the area around AERONET site.

4 Bias Correction Algorithm

Now that the diurnal bias in ABI AOD has been identified, the next step is to develop an algorithm to correct it by taking advantage of the special characteristics of geostationary satellites. Because the GOES-16 satellite is stationary, the locations of the image pixels are fixed and the satellite zenith azimuthal angles remain unchanged. In addition, the solar zenith azimuthal angles at a given time of day change little during a relatively short time period, on the order of one month. These features, common to geostationary satellites, were used to design an AOD retrieval algorithm for the legacy GOES, e.g. the GOES aerosol/smoke product (GASP) (Knapp, 2002a; Knapp et al., 2002b; Knapp et al., 2005; Prados, et al., 2007). Unlike the GOES-R series satellites, the legacy GOES had only one visible channel that could be used for AOD retrieval. In the GASP retrieval algorithm, to obtain the surface reflectance at the visible channel at each time step, a composite TOA reflectance was generated such that the second lowest reflectance was chosen from a time period of the previous 28 days. This reflectance was then used to retrieve the surface reflectance assuming a background AOD of 0.02.

We designed a GOES-16 ABI AOD bias correction algorithm similar to the GASP AOD retrieval algorithm. However, instead of the reflectance space, the composite bias correction algorithm works in the AOD space. The flowchart of the algorithm is shown in Figure ~~3~~4. GOES-16 ABI AOD top 2 qualities, i.e. high quality and medium quality, are used to generate the bias curves in the algorithm, because they have much larger area coverage than the high quality data alone. For example, it is not possible to build a bias curve for pixels near CCNY using high quality AOD data as there are too few data points, as seen in Figure 1.

In the algorithm, ABI AOD (top 2 qualities) over the CONUS with 5 minutes temporal resolution ~~are~~is first aggregated into 15 minutes temporal resolution. This is because that GOES can operate in different modes and the observation times are different for different modes, even though the time interval between the time steps stays the same for CONUS region. Averaging AOD into 15 minutes interval reorganizes the AOD data into regular time steps. In addition, averaging AOD also increases data coverage at each time step. At each time step, the algorithm loops through a 30-day period to look for the lowest AOD for each pixel. In this work, the 30-day time period was selected based on the experience developing the GASP algorithm. For real-time bias correction, the most recent past 30 days are used, because future AOD observations, after the date of interest, are not yet available. If the bias correction is being done as part of reprocessing, such that all the AOD data after the date of interest are available, a 30-day period is used with the date of interest placed at the center; this period may estimate the AOD bias more accurately. As shown in Knapp et al. (2005), the optimal time period to obtain a clear day background is not fixed and is dependent on seasons.

Once the optimum 30-day period has been selected, the bias at each pixel and at each time step is estimated using the lowest AOD during the 30-day period minus the background AOD. The background AOD over the CONUS area is obtained through an analysis of multi-year AERONET AOD data using the method described in Zhang et al. (2016). The main steps are summarized here for reference. At each AERONET site i, the lowest 5^{th} percentile of AOD over a 5-year (2012-2016) period is obtained and is set as the estimate of the background AOD (τ_i) at the site. Then the background AOD at each site is interpolated to provide continuous values across the globe using:

$$\tau_b = \frac{\sum_i w_i \tau_i}{\sum_i w_i}, \quad (1)$$

where τ_b is the interpolated background AOD, and τ_i is the background AOD at site i. The weighting factor w_i is defined as a function of the distance (d_i) between the site i and the interpolation point as:

$$w_i = exp(-d_i/d_0), \quad (2)$$

where the constant d_0 is set as 500 km. Using this method, a global map of background AOD is obtained. The background AOD over the CONUS is found to be low and the variation is also small, i.e. the average background AOD over CONUS is 0.025 and the range is [0.019, 0.033]. Therefore, instead of using various background AOD values at different places in the bias correction algorithm, a constant background AOD of 0.025 is used, which is similar in magnitude as that used in GASP algorithm. After the bias at each 15-minute time step is obtained for each pixel, the bias data are fitted to two curves of polynomial of second order, separated at 17:00 UTC, which is about the time when the bias peaks. This step is used to obtain estimates of the bias at each 5-minute AOD observation time step and also helps to further smooth the diurnal curve of the bias. The use of a smoothed curve removes potential random noise from factors such as cloud shadow contamination and deviations from background AOD at the lowest AOD retrieval. Subsequently, the bias corrected AOD is calculated by subtracting the bias at each pixel for each time step from the original AOD.

The basic idea to derive the ABI AOD bias is that the minimum of the 30-day ABI AOD at each time step should be close to the background AOD. Therefore, deviation of the minimum of ABI AOD retrievals during the 30-day period from the AERONET-derived background AOD are assumed to represent a systematic bias. Background AOD may change over time in case some extreme events happen, in which the bias correction algorithm may not work well.

5 Bias Correction Algorithm Validation

GOES-16 ABI AOD data and AERONET AOD data for the time period from August 6, 2018 to December 31, 2018 are used to validate the bias correction algorithm. The diurnal bias of ABI AOD data across the CONUS domain was corrected using the algorithm described in Section 4 and compared to coincident AERONET AOD. The original ABI AOD and the bias corrected ABI AOD were matched with AERONET AOD using the following criteria: (1) ABI AOD are averaged within the circle of 27.5 km radius around an AERONET site, requiring at least 120 valid AOD pixels within the circle; (2) AERONET AOD are averaged within ±30 minutes of the satellite observation time and at least 2 AERONET AOD data points exist within the hour. These are the same criteria that were used to validate the VIIRS AOD product (Liu, et al., 2014; ~~Zhang~~Huang et al., 2016).

For the first 30 days of the validation period (August 6 to September 4), the bias correction curves are derived from the same 30 day period. For the remainder of the validation period, the bias correction curves are derived from the 30-day period immediately prior to the day of interest.

Figure ~~4~~5 shows scatter plots of GOES-16 ABI AOD vs AERONET AOD for high quality and top 2 qualities of ABI AOD, before and after bias correction, averaged over the entire validation period and across the CONUS domain. Scatter plots for both high quality and top 2 qualities are shown, although the bias curves were derived using the top 2 qualities data. In order for a valid comparison, the AOD pixels in the plots have one-to-one correspondence before and after bias corrections, i.e. the quality flag does not change and all the pixels are kept even though some of them may be below the lower bound of the operational GOES-16 ABI AOD product (-0.05) after bias correction. As seen in the scatter plots, the bias correction improves the performance of the top 2 qualities ABI AOD more than the high-quality ABI AOD, which indicates that the ABI AOD algorithm does a good job identifying high quality retrievals. Therefore, the ABI AOD retrieval algorithm does a good job identifying high quality retrievals, but with ~~too few~~limited data coverage ~~comparing~~compared to the top 2 qualities. For the top 2 qualities ABI AOD, after bias correction, the correlation between ABI AOD and AERONET AOD improves from 0.87 to 0.91, the total bias improves from 0.04 to 0.00, and RMSE improves from 0.09 to 0.05. The high-quality ABI AOD shows a small decrease in RMSE, which improves from 0.06 to 0.05 after bias correction. The results in Figure ~~4~~5 demonstrate that by applying the simple bias correction, the top 2 qualities ABI AOD perform as well as the high-quality ABI AOD, but with twice the number of matchups. In this way, the ~~area~~spatial coverage of ABI AOD is substantially increased, without loss of data accuracy, by using top 2 qualities in conjunction with the bias correction.

Table 3 shows validation statistics for GOES-16 ABI AOD vs AERONET AOD at the 6 representative AERONET sites listed in Table 2. After applying the bias correction, most of the statistics for ABI AOD improve at the six sites, demonstrating the success of the bias correction algorithm. For example, 5 out of 6 sites have RMSE improved to 0.05 or below. The exception is the University of Houston site, where the RMSE is still as high as 0.08 after correction, although it is improved from 0.19. This result may indicate there is still some bias left uncorrected at this site due to its complicated surface with respect to geometries. The sites in the eastern US have a geometry symmetric to the local noon and therefore the AOD biases are symmetric to the local noon. The sites in the western US do not have such symmetry and therefore the splitting of parameterization at noon and using second order polynomials may introduce ~~larger~~some errors. The complexity of surfaces over University of Houston can be seen in Figure 1 (e), where two AOD bias peaks are observed, one in the morning and the other at noon, indicating that the diurnal variation of surface reflectance relationship is different from the other sites, such as GSFC, CCNY, etc, where AOD biases only peak at noon.

~~Figure 5~~Figure 6 demonstrates the scattering angle dependence of the ABI AOD errors for high quality and top 2 qualities. It can be seen that the errors before bias correction have strong scattering angle dependency: AODs have positive bias when the scattering angle greater than 110° and negative bias otherwise; The bias increases with scattering angle, with the highest bias at 175° bin; top 2 qualities AOD has higher bias than high quality AOD, as expected. The scattering angle dependence of AOD retrieval bias may be caused by many reasons, in which surface reflectance modeling error is one of the main reasons (She et al., 2019). After applying the bias correction, the positive biases in both high quality and top 2 qualities for scattering angle greater than 110° are removed. The standard deviations of the errors are also smaller in most of the bins. The bias correction does not have much improvements in bias for the scattering angle less than 110° as large as those greater than 110°.

To evaluate the performance of the algorithm for different AODs, Figure 7 shows the ABI AOD error and standard deviation in different AERONET AOD bins, with equal number of matchup data in each bin. For high quality AOD, bias correction reduces bias in the highest two AOD bins, with center around 0.3 and 0.57. In the range [0.1, 0.3], bias correction over corrects and introduces negative mean bias with slightly larger magnitude than the original mean bias, around 0.01 in magnitude differences. In the range [0,0.1], AOD mean biases are close to zero both before and after correction, but the bias correction AOD error has smaller standard deviation. For the top 2 qualities ABI AOD, bias correction reduces the bias in the whole AOD range with slight over corrections of magnitude of about 0.02 when AOD is greater than 0.1.

Figure 8, analogous to Figure 1, shows the time series comparisons between bias corrected ABI AOD and AERONET AOD for clear days at the same representative AERONET sites used in Figure 1. Almost all of the large biases in Figure 1 are reduced to a magnitude < 0.05 after the bias correction procedure. The exception is in the early morning at the University of Houston site, where large biases remain. This is probably because the second order polynomial fit of the bias correction does not accurately describe the shape of the AOD biases in this area, which may be the reason why the RMSE of the bias-corrected ABI AOD is still high at the University of Houston site (Table 3).

Figure ~~6~~9 shows maps of the top 2 qualities of ABI AOD over the Northeast US at 17:42 UTC on October 18, 2018 before (Figure ~~6a~~9a) and after (Figure ~~6b~~9b) bias correction, illustrating the effects of the bias correction on observed ABI AOD. The black areas in the figures are locations where no AOD was retrieved, primarily caused by cloud coverage. This is a clear day, with no major sources of ambient atmospheric aerosols. However, before the bias correction, Figure ~~6a~~9a shows that the ABI AOD field is noisy, due to the effects of the surface reflectance on the AOD retrievals. For example, over New York City, NY area, uncorrected ABI AOD values are as high as 0.5, while the coincident AERONET AOD measurement at the CCNY site is only 0.02. After the bias correction, Figure ~~6b~~9b shows that the ABI AOD field is mostly cleared from the surface effects. Some isolated pixels of slightly higher ~~AOD~~AODs are still observed in the bias corrected ABI AOD map, which are likely originated from cloud contamination, with a few due to incomplete bias correction caused by outliers in fitting the bias correction with a second order polynomial. ~~-~~For comparison, Figure 9 (c) and (d) show MODIS AOD dark target and deep blue retrievals from Aqua for this day, with overpassing time 17:55 UTC. The bias corrected high and medium quality ABI AOD compares well with MODIS deep blue AOD in both magnitude and data coverage. MODIS dark target AOD has much less data coverage, but ABI AOD also compares well in magnitude in the areas with MODIS dark target AOD data.

Figure ~~7~~10 shows histograms of original (uncorrected) and bias corrected ABI AOD pixels over the areas within a 27.5 km radius circle around the CCNY AERONET site (Figure ~~7a~~10a) and the Wallops AERONET site (~~Figure7b~~Figure 10b) at 17:42 UTC on October 18, 2018 (the same observation time as the AOD data shown in Figure ~~6~~9). At the urban CCNY site, ABI AOD before bias correction ranges from 0 to 0.5, with an average of 0.25, which is much higher than the AERONET AOD value of 0.02. After correction, the ABI AOD distribution narrows down to a very small range with a peak and average at 0.02 - the same value as AERONET. Wallops is a rural site and therefore its surface is darker and more favorable for AOD retrievals. Figure 7b shows that uncorrected ABI AOD at the Wallops site ranges from -0.05 to 0.2, with an average of 0.05, much closer to AERONET AOD (0.03) compared to the matchups at the CCNY site. After the bias correction, the average ABI AOD is 0.03, identical to the AERONET AOD measurement, and the distribution of AOD is narrower than before the bias correction.

The results ~~in Figures 1 and 5~~discussed thus far suggest that the surface reflectance parameterizations in the ABI AOD algorithm is the main source of the diurnal bias when ABI AOD is close to zero. When AOD is higher, such as during periods of high aerosol concentration, the aerosol model in the ABI AOD algorithm becomes a larger source of bias. As an example, a case with a moderate aerosol ~~load~~loading is examined. On August 15-16, 2018, smoke aerosols were transported to the New York City, NY metropolitan area from wildfires burning in the western US and Canada, resulting in AERONET AODs in the range of 0.4-0.7 at the CCNY site. As shown in Figure ~~8~~11, the bias corrected ABI AOD is very close to the AERONET AOD on August 15 (Figure ~~8a~~11a), but much lower than the AERONET AOD on August 16 (Figure ~~8b~~11b). To investigate the reason for this discrepancy in the bias corrected ABI AOD, the statistics of the ABI AOD retrievals were examined for the 18:12 UTC time step. These statistics are listed in Table 4 for the original ABI AOD pixels within a 27.5 km radius circle of the CCNY AERONET site, which are involved in the average of the matchup with AERONET AOD. AERONET AOD increases from 0.35 on August 15 to 0.55 on August 16, but the uncorrected ABI AOD ~~decreases from 0.82~~remains the same on August 16 as on August 15~~ to 0.80 on August 16.~~. The reason for this discrepancy is that the ~~ABI AOD algorithm used different~~ aerosol models ~~in different percentages on each day.~~retrieved within the 27.5 km circle are not the same between the two days. Table 4 indicates that on August 15, the dust model was ~~used~~retrieved primarily (46%), but on August 16, the urban aerosol was predominant. This aerosol event in August 2018 was dominated by smoke, so it is surprising that the ABI AOD algorithm did not select the smoke model a majority of the time on these days. The results for ABI AOD in this case are not unprecedented. The selection of the aerosol model in AOD retrievals over land ~~has been known to~~sometimes does not perform ~~poorly~~very well in the VIIRS AOD retrieval ~~too~~either, e.g. over China (Huang et al., 2016; Wang et al., 2020). The ABI retrieval uses only four aerosol models for retrieval over land and the real model may be different from every one of them. Wagner et al. (2018) showed that smoke often carries dust and therefore the aerosol may be a mixture of smoke and dust, which makes the aerosol selection in the AOD retrieval algorithm more challenging.

Uncertainties in the bias correction algorithm can also be caused by the geometry change within the 30 day period. During 30-day period, the position of the Sun and therefore the solar geometry does change for a given time step. Hence, the surface reflectance relationship and AOD bias are not constant in the time period. The magnitude of AOD bias variation during the time period determines the magnitude of the uncertainty of the algorithm. Besides the change in solar geometry, the surface vegetation color change during seasonal variation may also be a source of uncertainty through its influence on surface reflectance ~~relationship between bands.~~relationships.

The bias correction of ABI AOD can also improve its correlation with measurements of fine particles, PM2.5 (particulate matter with diameter ≤ 2.5 μm). PM2.5 is a “criteria” pollutant designated by the US Environmental Protection Agency (EPA) as harmful to public health and the environment. Satellite AOD can be used to estimate ambient PM2.5 concentrations at the surface. Figure ~~9~~12 shows scatter plots of the correlation between hourly PM2.5 concentration measurements from EPA’s ground-based monitor station at Queens College in New York City and GOES-16 ABI AOD before (Figure ~~9a~~12a) and after (Figure ~~9b~~12b) bias correction. The correlation between PM2.5 and ABI AOD improves from 0.58 to 0.68 after the bias correction. These results suggest that applying the bias correction to ABI AOD data will improve its use in air quality monitoring and research applications.

6 Summary and Conclusions

In this paper, a diurnal bias in the GOES-16 ABI AOD bias is identified. Analysis shows that the bias is caused by errors in the land surface reflectance relationship between the spectral bands used in the ABI AOD retrieval algorithm. To remove the biases, an empirical algorithm is developed that utilizes the lowest AOD in a recent 30-day period in conjunction with the background AOD to derive a smooth bias curve at each ABI AOD pixel. ABI AOD are then corrected by subtracting the derived bias curves at each time step.

The bias correction algorithm is validated for five months of GOES-16 ABI AOD data through comparison against coincident AERONET AOD. The results demonstrate that the bias correction algorithm works successfully: for the top 2 qualities of ABI AOD, the correlation with AERONET AOD, average bias, and RMSE all improve. As a result of the bias correction, top 2 qualities ABI AOD performs as well as uncorrected high-quality ABI AOD. Therefore, bias corrected top 2 qualities ABI AOD data are recommend for use in research and operations, since they cover twice the area as high-quality ABI AOD data alone with the same accuracy.

The ABI AOD bias correction process is most effective when AOD is low because under those conditions, the surface reflectance relationship is the main source of uncertainty in the ABI AOD retrieval. When AOD is higher, the uncertainty from the aerosol model selection in the ABI AOD retrieval algorithm becomes as large as or larger than that from the surface reflectance relationship, and therefore the bias correction for high AOD conditions is not as effective as that for low AOD conditions.

The surface reflectance relationships in the ABI AOD retrieval algorithm will be improved when more GOES-16 data are accumulated and analyzed. However, these relationships are based on AERONET sites and they are statistical models. Therefore, individual AOD pixels will always suffer to some degree from deviation in the statistical relationship and some bias will always exist, although it may be reduced by a more accurate surface reflectance relationship. Hence, future versions of the GOES ABI AOD product may still benefit by applying the bias correction algorithm, unless the AOD retrieval algorithm uses pixel level surface reflectance relationships. On the other hand, in the bias correction algorithm, background AOD assumption may also fail in some extreme cases, even with small likelihood.

GOES-17 is located at 137.2°W, observing the western US. A lot of areas in the western US with low quality AOD in GOES-16 due to high satellite zenith angle can be retrieved with high or medium quality with GOES-17 data. Therefore, ABI AOD from GOES-17 can complement those from GOES-16. ABI AOD from GOES-17 will be analyzed and the bias correction algorithm will be applied. The results are expected to be similar to those from GOES-16.

Data Availability

GOES-16 ABI AOD can be obtained at NOAA CLASS (https://www.avl.class.noaa.gov/ ; accessed on 5/29/2020). AERONET AOD can be obtained at https://aeronet.gsfc.nasa.gov/ (accessed on 5/29/2020). The data produced from the bias correction algorithm can be requested by contacting Hai Zhang (hai.zhang@noaa.gov).

Author Contributions

HZ worked on the developing and analyzing activities described and led the manuscript writing. SK and IL supervised the work. SK, IL and MZ reviewed the algorithm and the results analysis, and contributed to the paper revisions. MZ and IL provided the AOD retrieval code that is used in the atmospheric correction for the surface reflectance analysis.

Competing interests

The authors declare that they have no conflict of interest.

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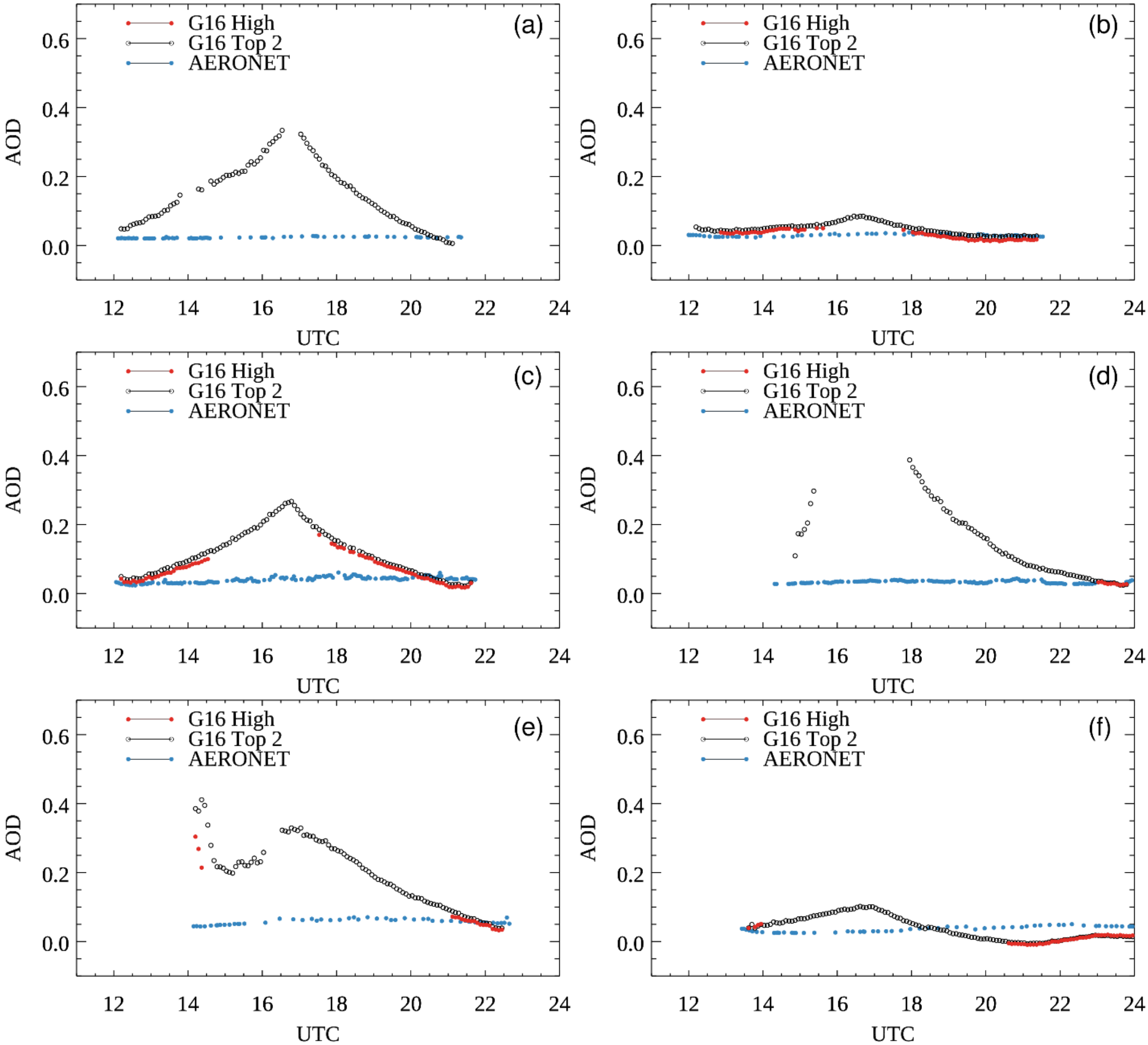


Figure 1: Time series of GOES-16 ABI AOD and AERONET AOD at 6 representative AERONET sites: (a) CCNY on October 18, 2018, (b) Wallops on October 18, 2018, (c) GSFC on October 12, 2018, (d) Tucson on October 25, 2018, (e) University of Houston on December ~~12~~22, 2018, and (f) Table Mountain on September 12, 2018, showing the diurnal variations in the ABI AOD bias. Details about the AERONET sites are listed in Table 2. Clear days are selected such that AERONET AOD are ≤ 0.05 throughout the entire day. "G16 High" represents GOES-16 high quality AOD and "G16 Top 2" represents GOES-16 high quality and medium quality AOD.

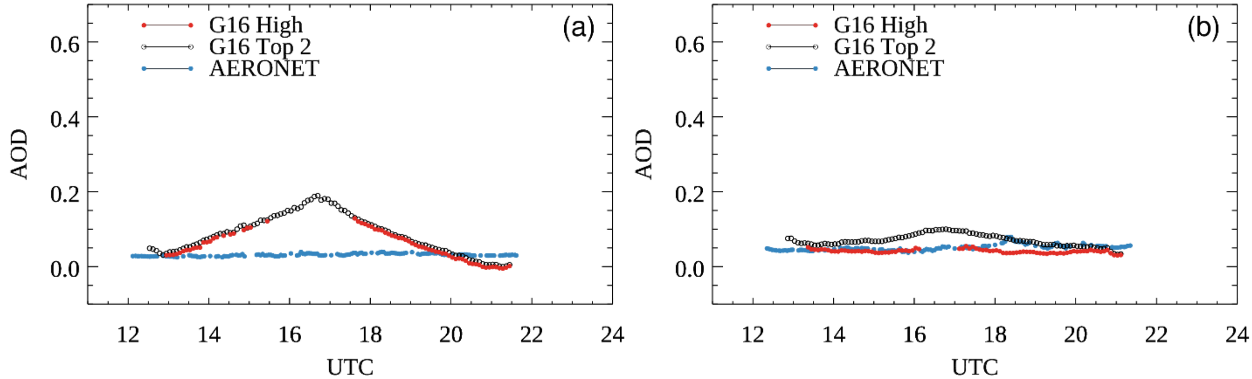
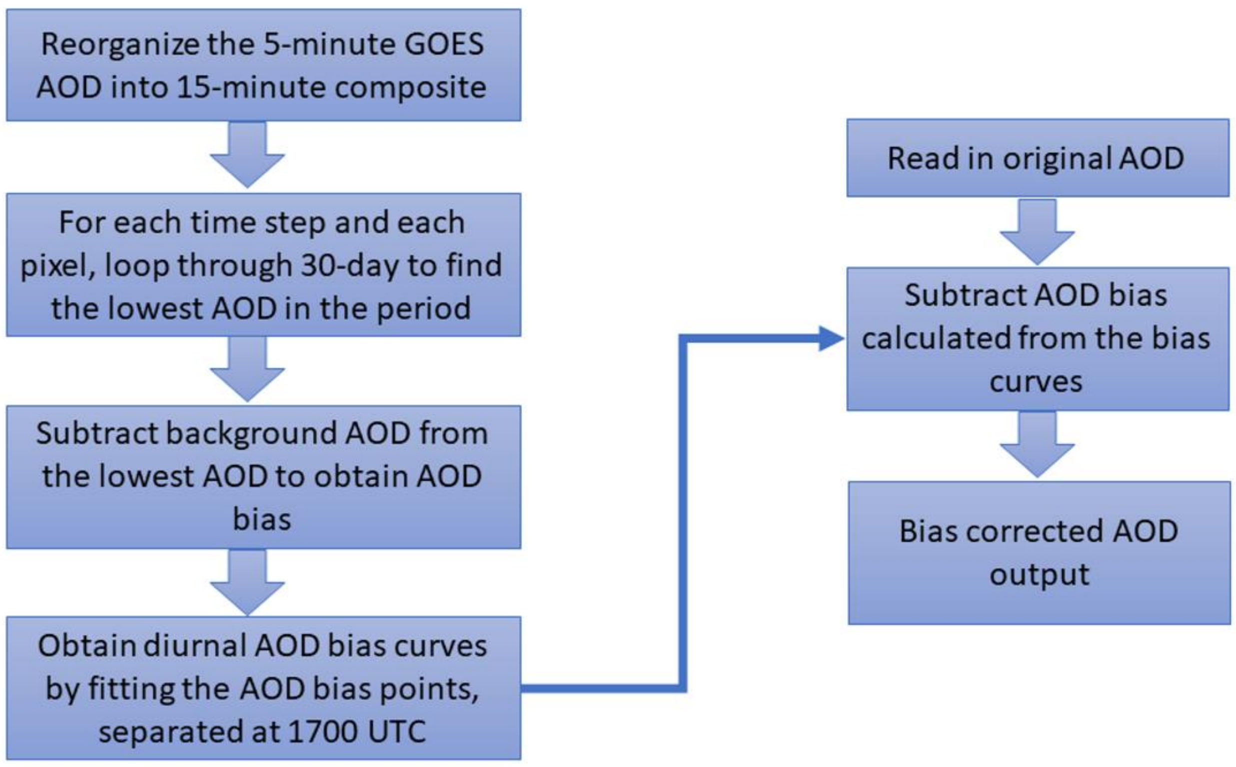


Figure 2. The diurnal pattern of biases in GOES-16 ABI AOD at GSFC on two additional clear days: (a) October 18, 2018 and (b) October 30, 2018, showing the difference in the magnitude of the bias.



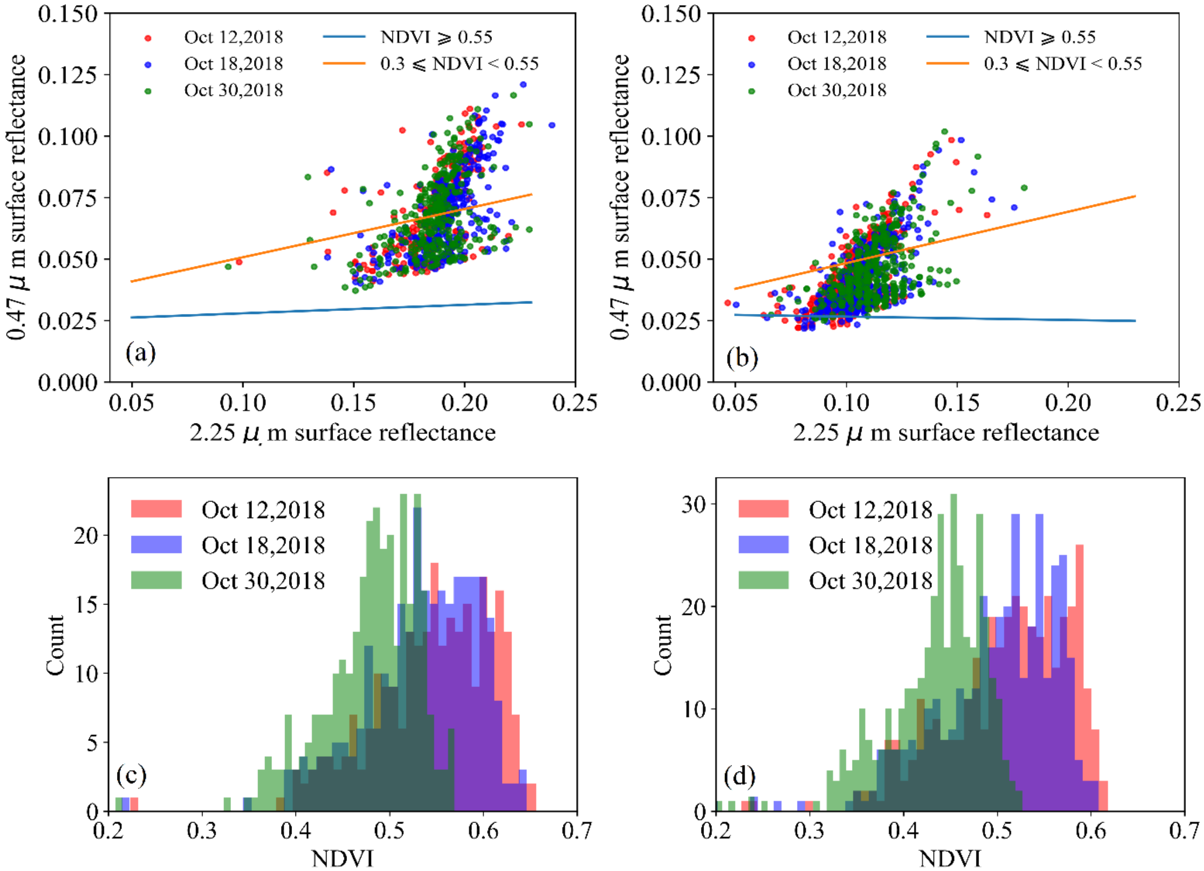


Figure 3. Scatter plots of surface reflectance on 0.47 µm band and 2.2 µm band for three days, i.e. October 12th, October 18th, and October 30th 2018, at GSFC at (a) 17:02 UTC and (b) 20:02 UTC, and histograms of NDVI for the three days at (c) 17:02 UTC and (d) 20:02 UTC. The lines on the scatter plots are the surface reflectance relationship between 0.47 µm band and 2.2 µm band used in the ABI AOD retrieval algorithm.

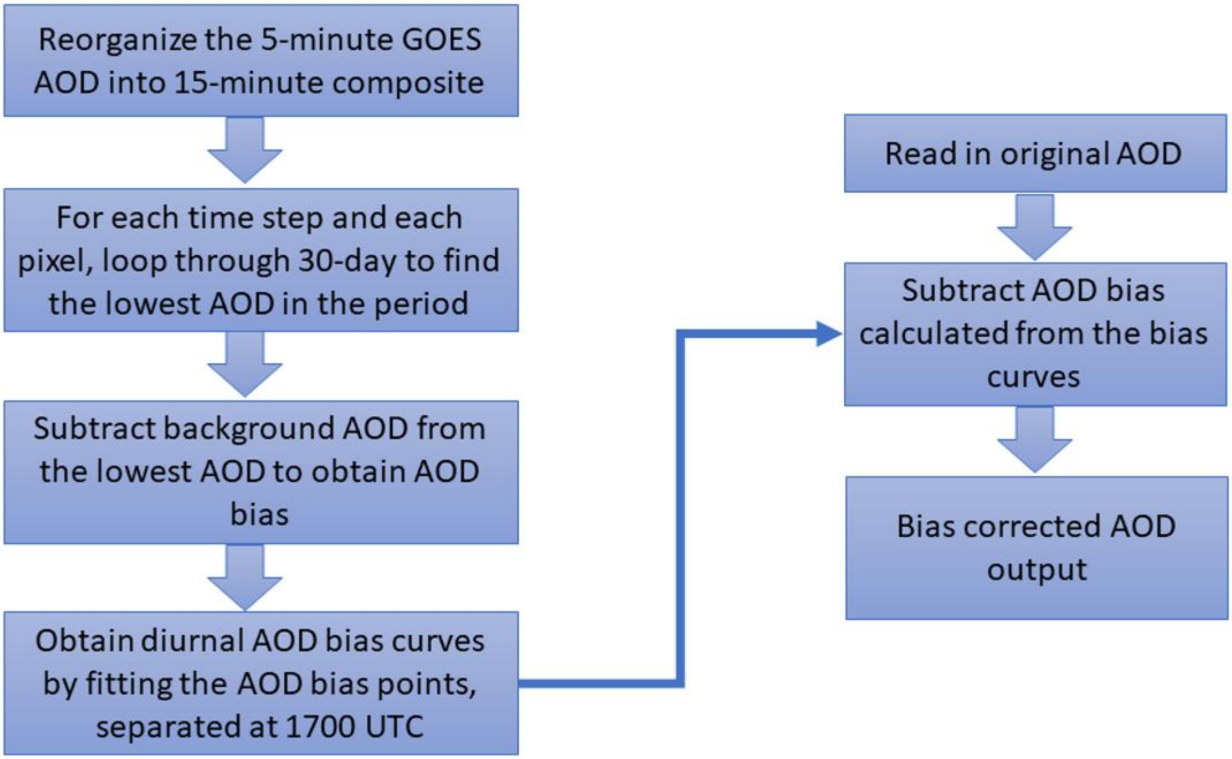
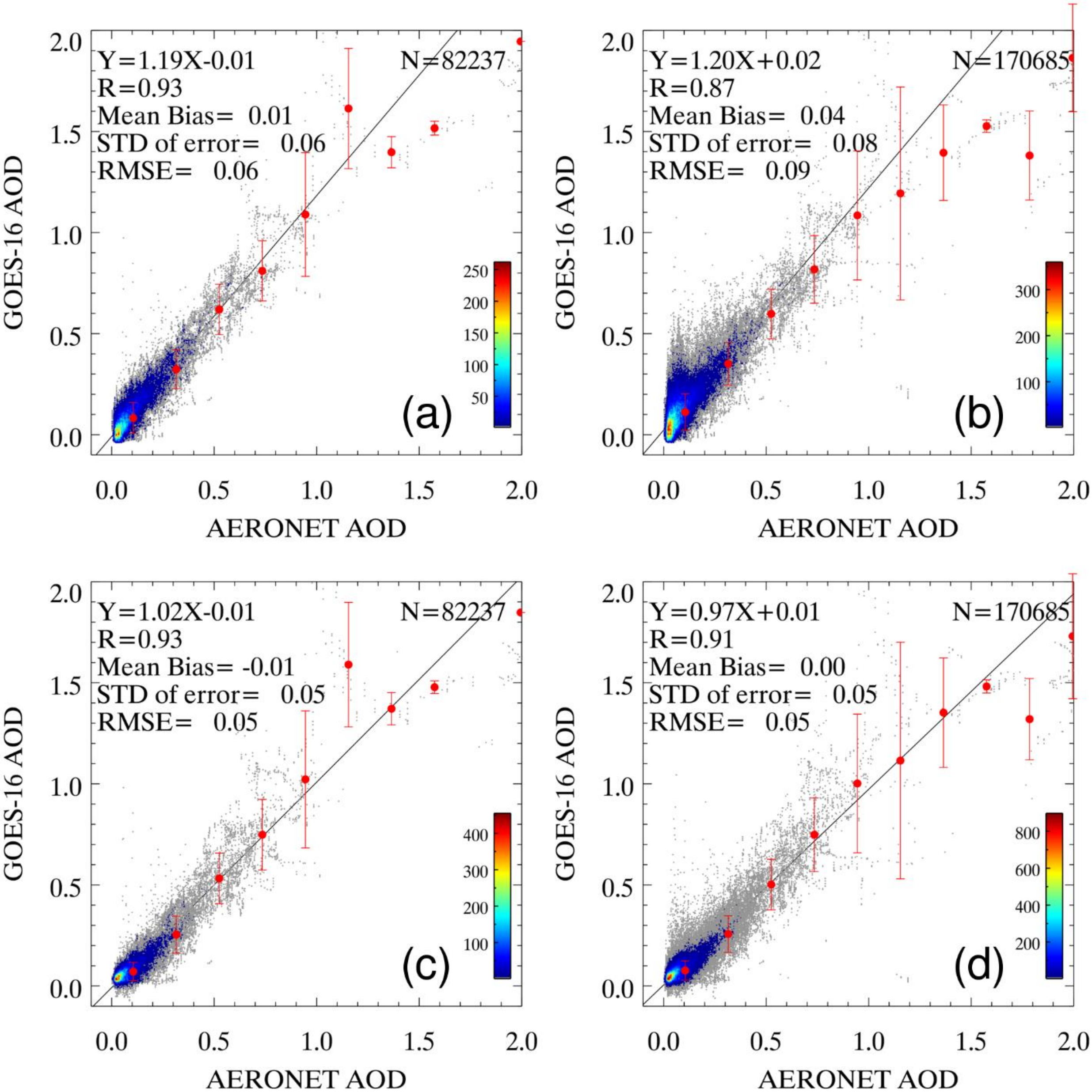


Figure 4. Flow chart of the ABI AOD bias correction algorithm.


Y=1.19X-0.01
N=82237
R=0.93
Mean Bias= 0.01
STD of error= 0.06
RMSE= 0.06
(a)
Y=1.20X+0.02
N=170685
R=0.87
Mean Bias= 0.04
STD of error= 0.08
RMSE= 0.09
(b)
Y=1.02X-0.01
N=82237
R=0.93
Mean Bias= -0.01
STD of error= 0.05
RMSE= 0.05
(c)
Y=0.97X+0.01
N=170685
R=0.91
Mean Bias= 0.00
STD of error= 0.05
RMSE= 0.05
(d)
GOES-16 AOD
AERONET AOD

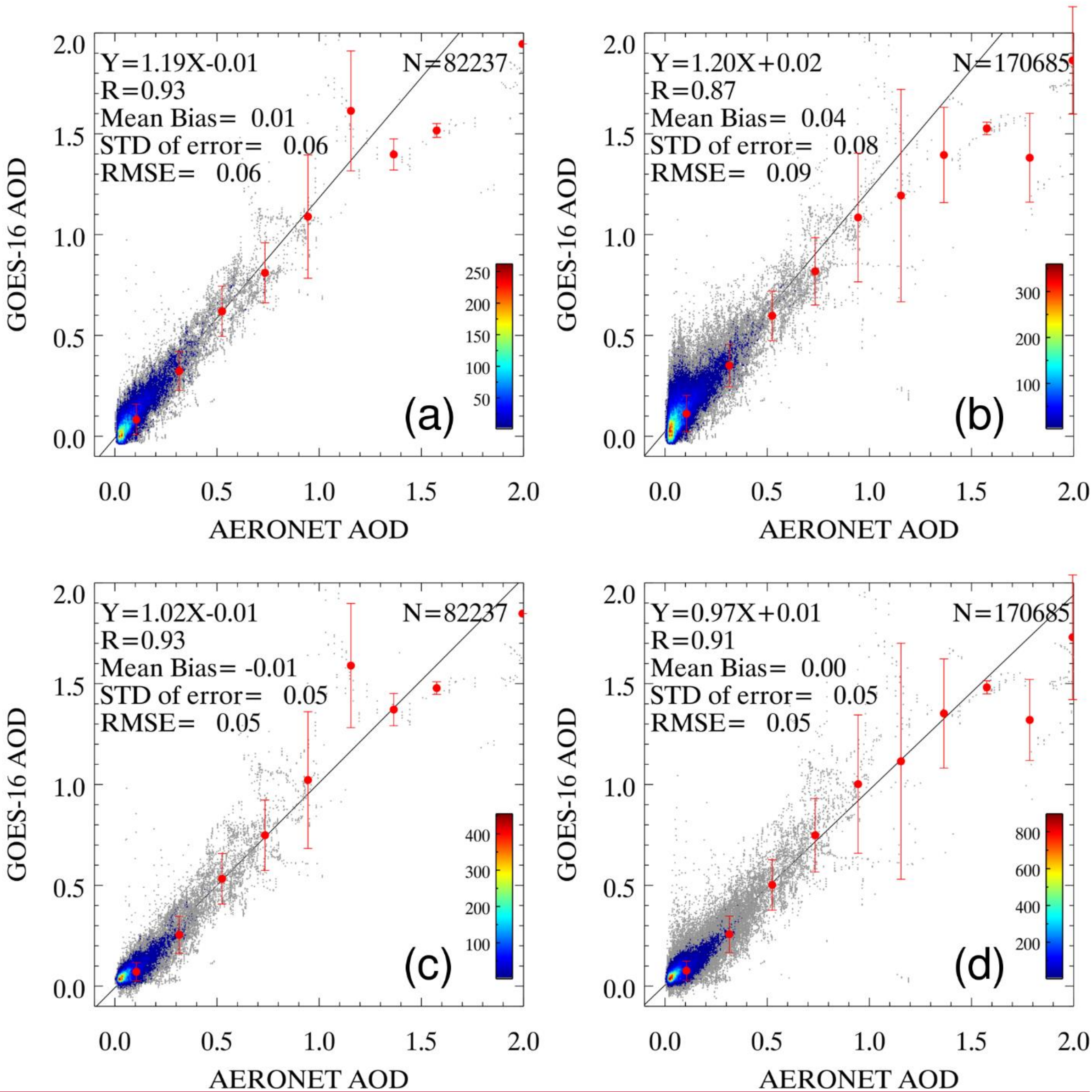
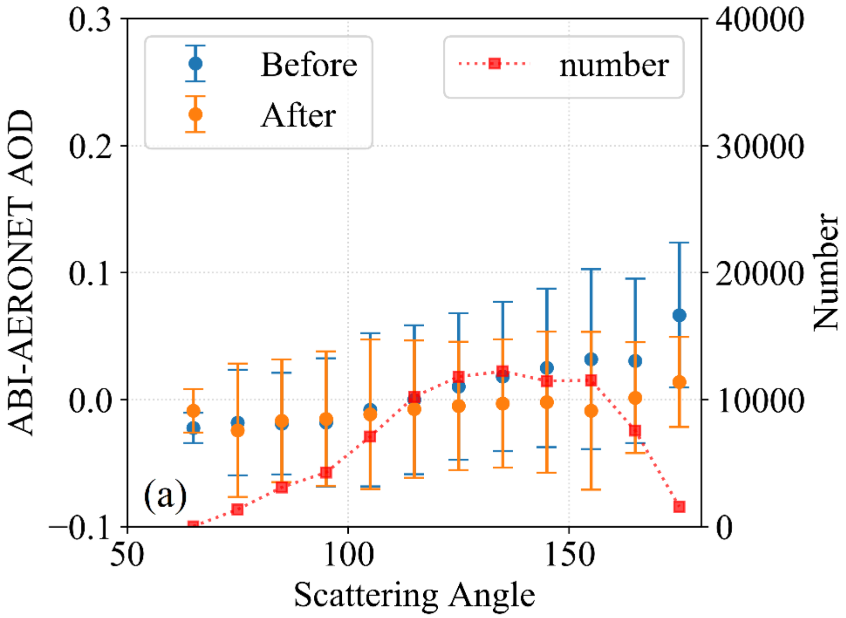
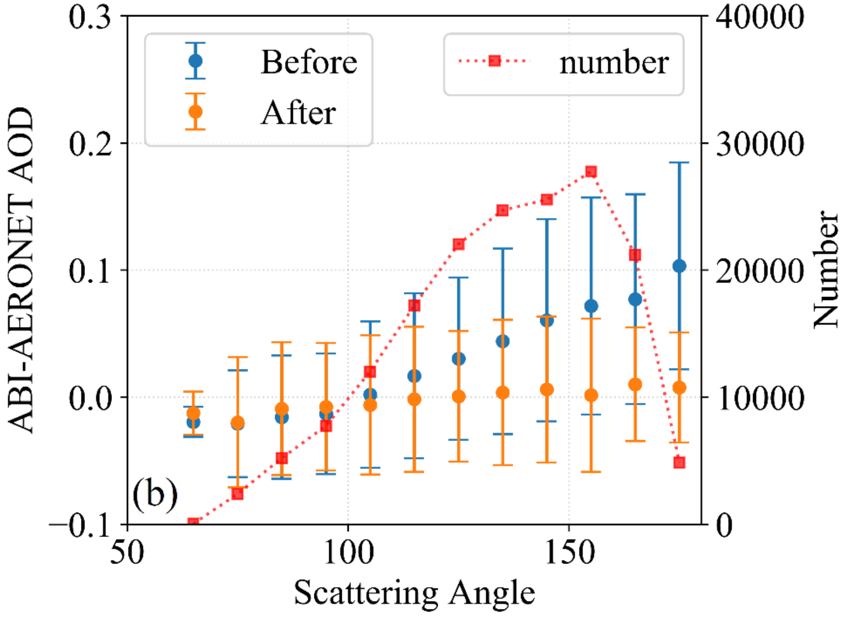


Figure 45. Scatter plots of GOES-16 ABI AOD vs AERONET AOD for August 6, 2018 to December 31, 2018 across the CONUS domain: (a) high quality ABI AOD before bias correction, (b) top 2 qualities ABI AOD before bias correction, (c) high quality ABI AOD after bias correction, and (d) top 2 qualities ABI AOD after bias correction. The red circles and vertical bars are the mean ABI AOD and the standard deviation of errors of data points falling in the bins with size of 0.2. In the plots, N is the number of matchups, R is the correlation coefficient, and RMSE is the root mean square error.





595

Figure 6.

Comparisons of ABI AOD error vs scattering angle between before and after bias correction for (a) high quality and (b) high and medium quality.

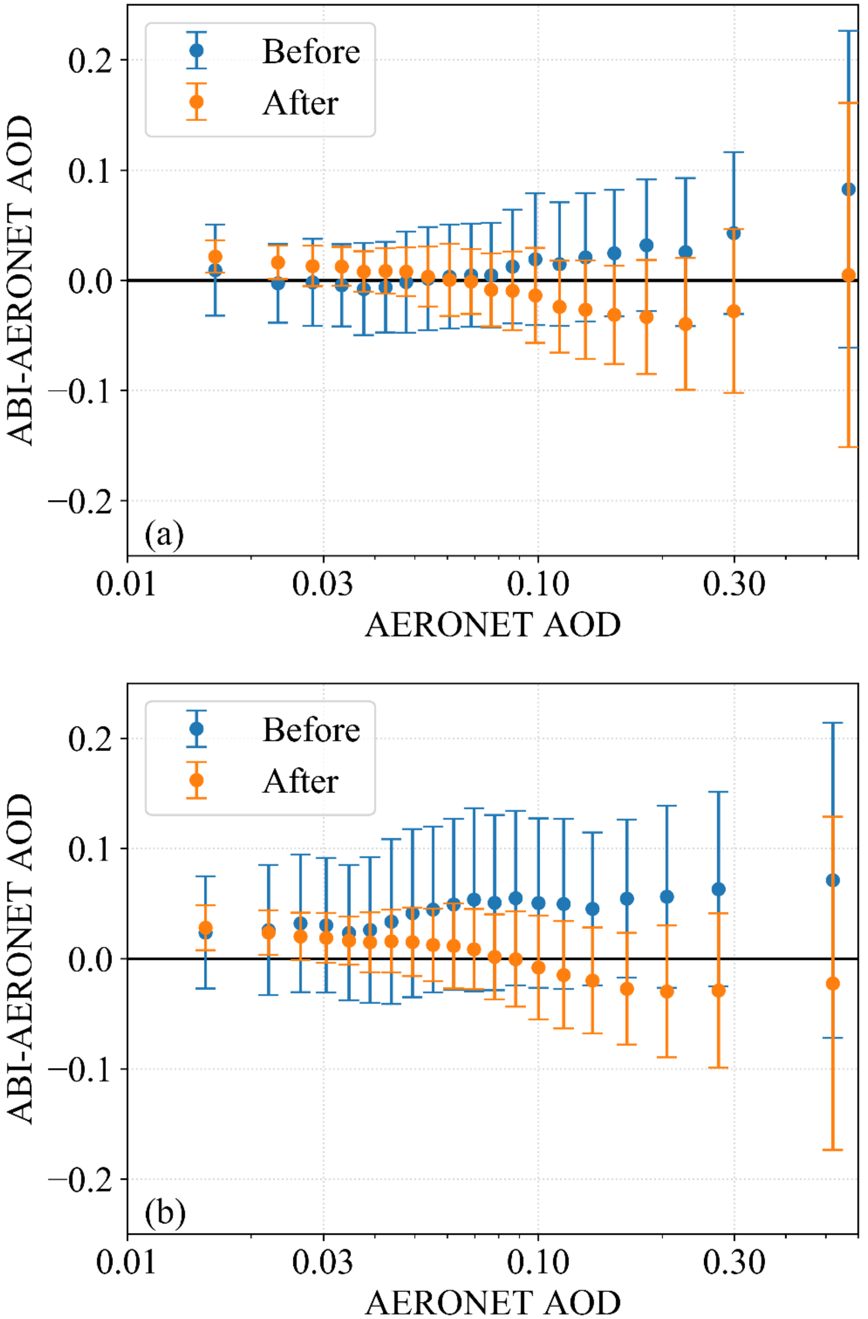


Figure 7. Comparisons of ABI AOD error vs AERONET AOD between before and after bias correction for (a) high quality and (b) high and medium quality. Each bin contains equal number of matchup data.

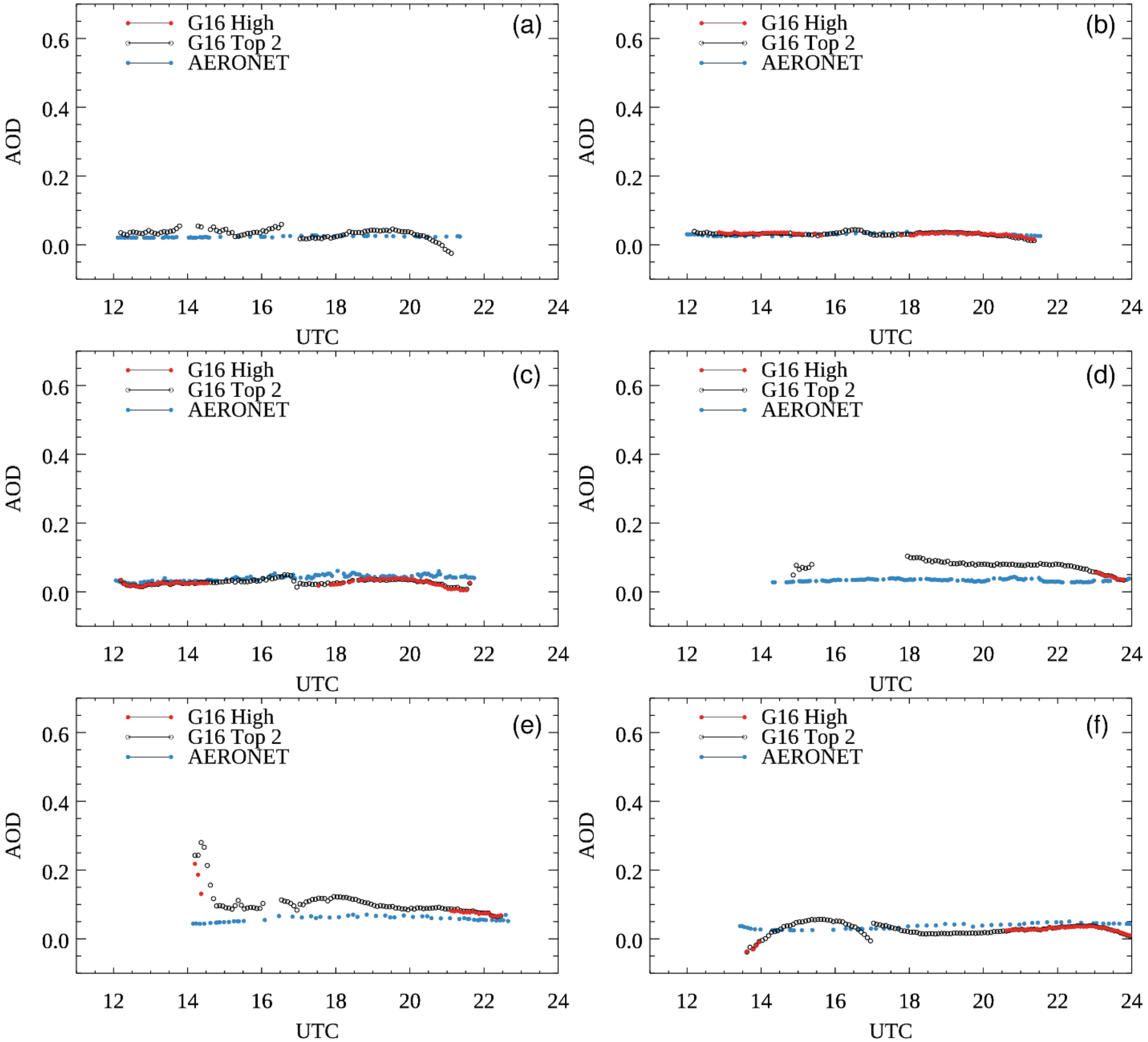
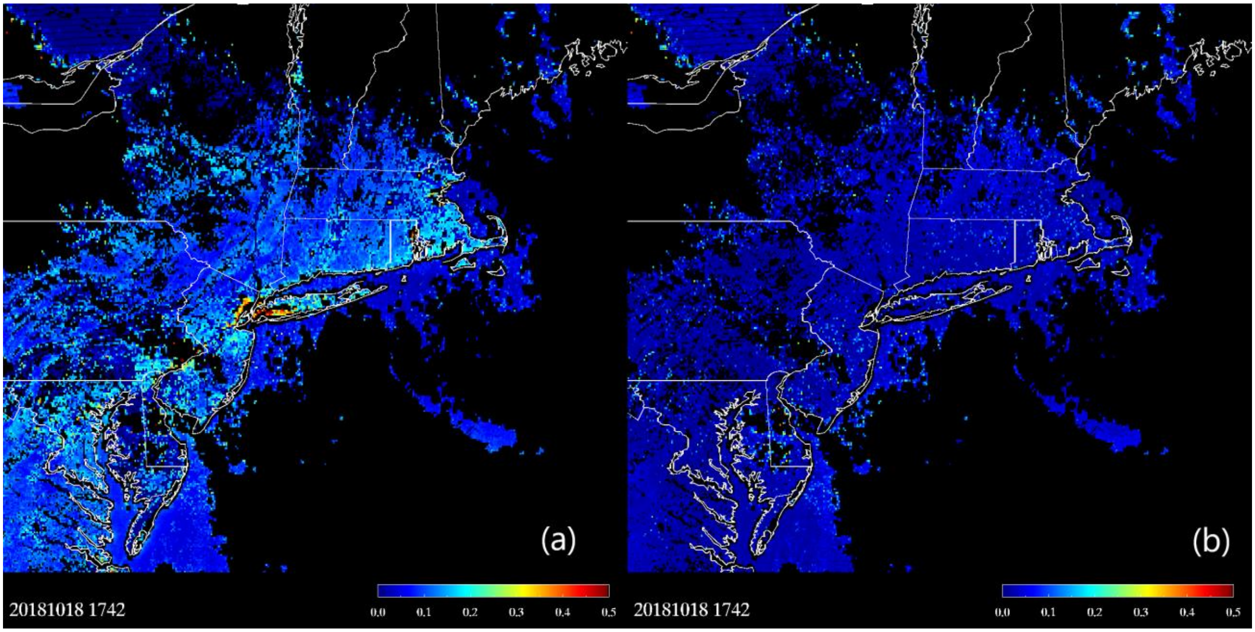


Figure ~~5~~8. Same as in Figure 1, but after correcting the GOES-16 ABI AOD for the diurnal bias.


(a)
20181018 1742
0.0
0.1
0.2
0.3
0.4
0.5
(b)
20181018 1742
0.0
0.1
0.2
0.3
0.4
0.5

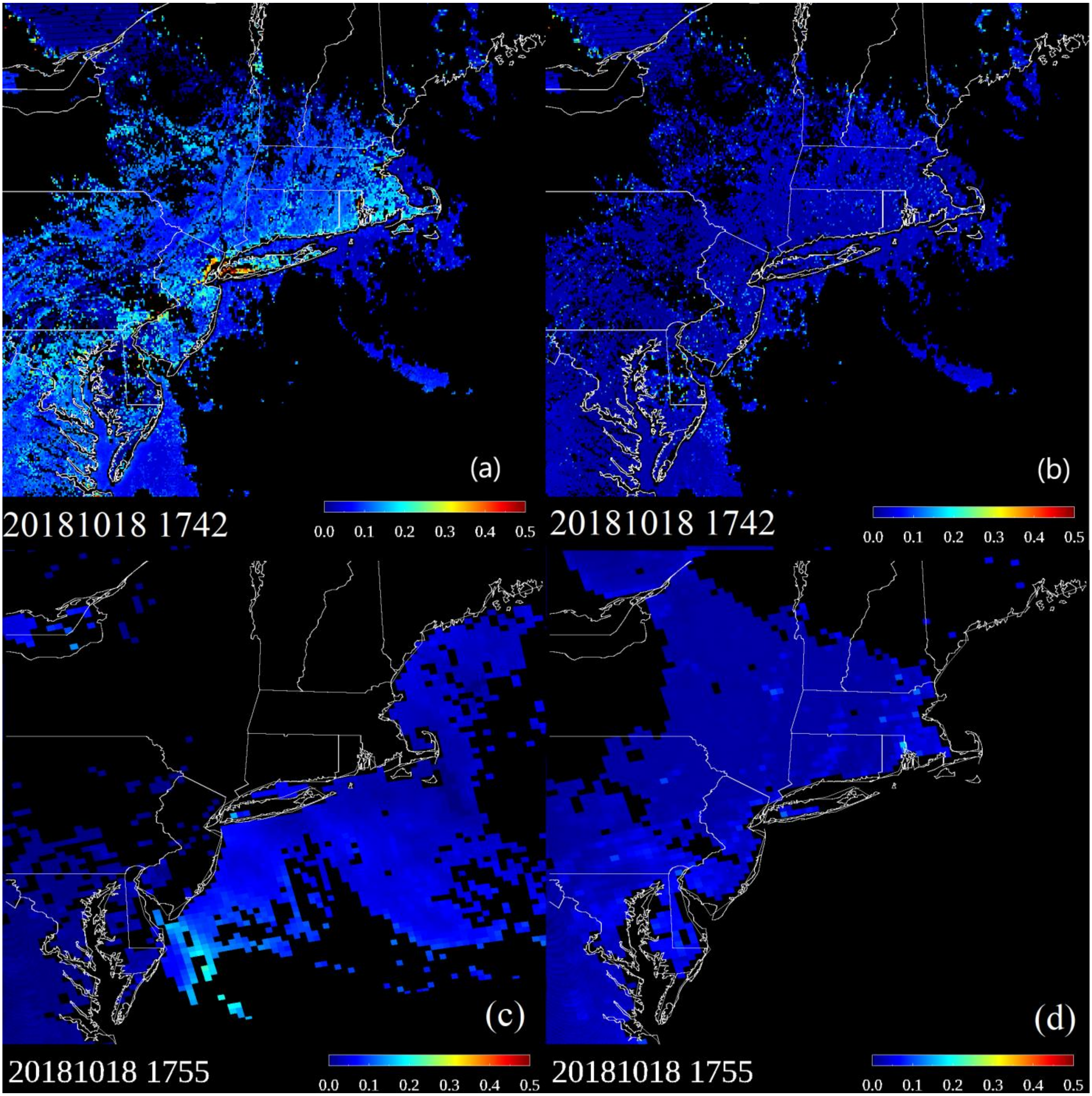


Figure 9.~~Figure 6.~~ Maps of GOES-16 ABI AOD, top 2 qualities (high and medium), over the Northeast US at 1742 UTC on October 18, 2018: (a) before bias correction and (b) after bias correction, and high quality MODIS Aqua AOD (c) dark target product and (d) deep blue product.

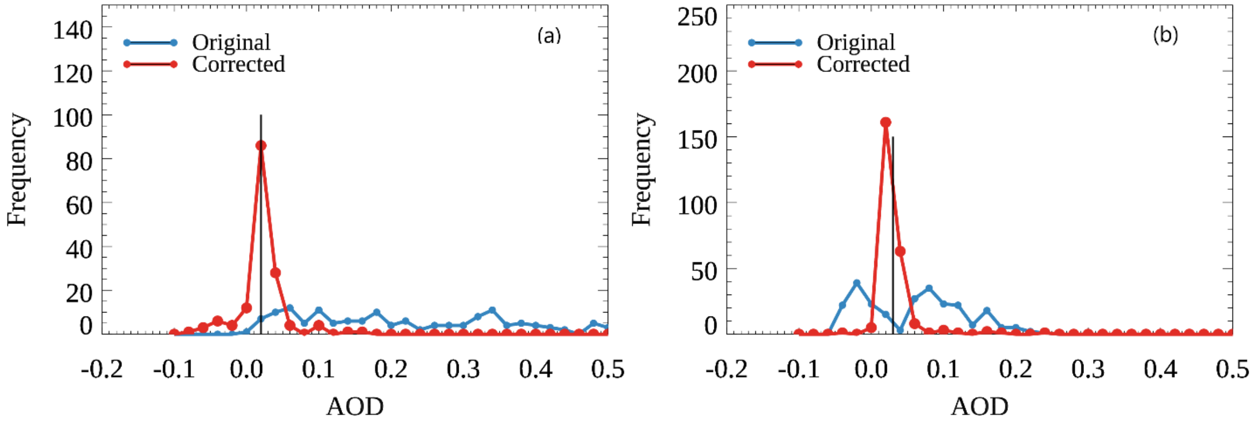


Figure ~~7~~10. Histograms of original (uncorrected) and bias corrected GOES-16 ABI AOD at the (a) CCNY and (b) Wallops AERONET sites, at 17:42 UTC on October 18, 2018. The black vertical lines in the figures represent AERONET AODs.

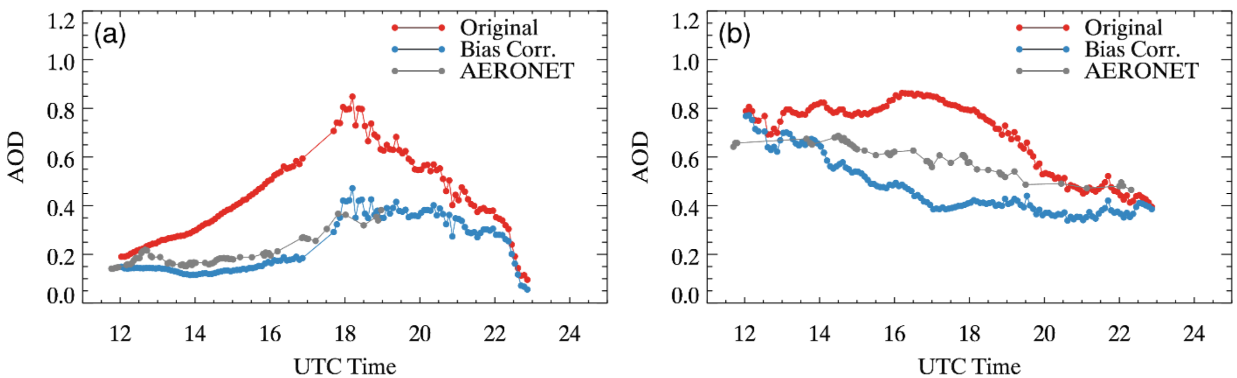
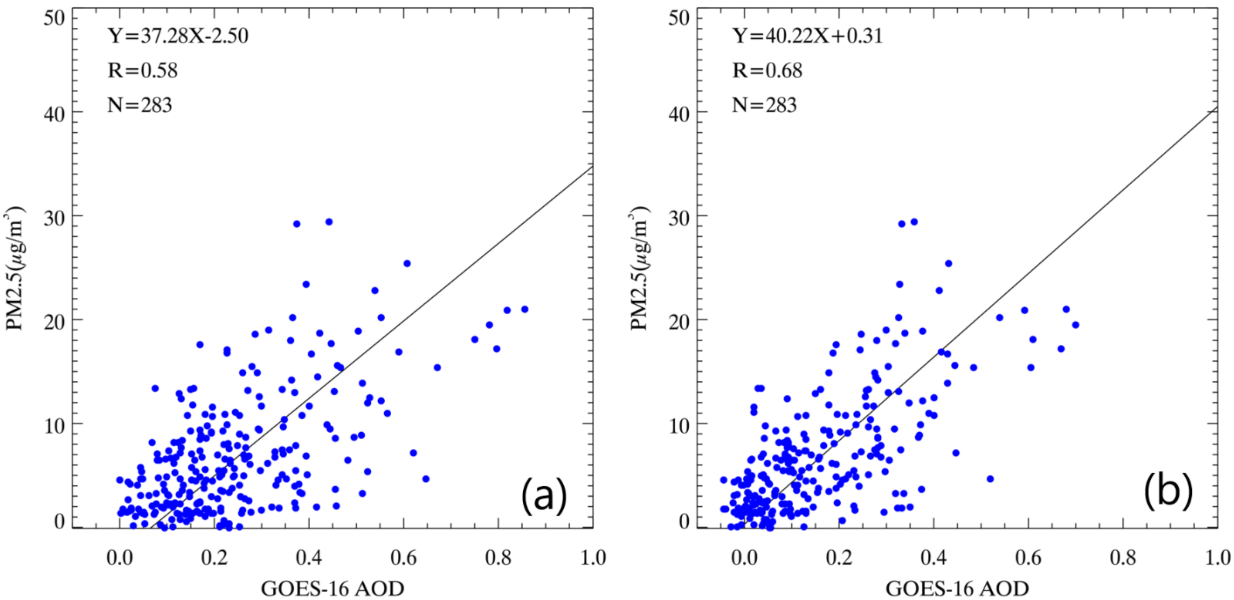


Figure ~~8~~11. Time series of original (uncorrected) GOES-16 ABI AOD, bias corrected ABI AOD, and AERONET AOD at the CCNY AERONET site on (a) August 15, 2018 and (b) August 16, 2018, showing the difference in bias corrected ABI AOD relative to AERONET AOD on two consecutive days with moderate aerosol loading.


Y=37.28X-2.50
R=0.58
N=283
PM2.5(μg/m³)
GOES-16 AOD
(a)
Y=40.22X+0.31
R=0.68
N=283
PM2.5(μg/m³)
GOES-16 AOD
(b)

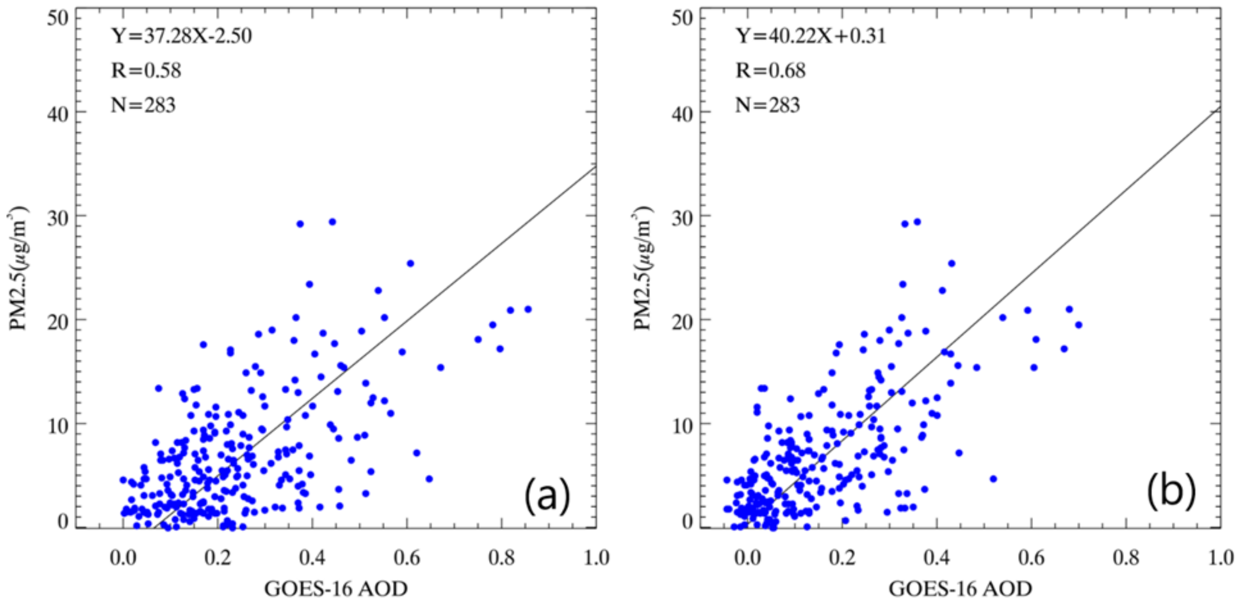


Figure ~~9~~12. Scatter plots of hourly PM2.5 vs GOES-16 ABI AOD at an EPA station at Queens College in New York City during August 6 – December 31, 2018: (a) GOES-16 ABI AOD before bias correction; (b) GOES-16 ABI AOD after bias correction.

Quality Level	Condition
No retrieval	Invalid input data, Cloud, Snow/ice, Bright land surface, Sun glint over ocean
Low	External and internal cloud tests contradict, Low satellite (satellite zenith angle > 60°), Low sun (solar zenith angle > 80°), AOD out of range, Coastal, Shallow inland water, High residual, High inhomogeneity
Medium	Cloud/Snow adjacency, Shallow ocean, Probably clear, Medium inhomogeneity, Medium residual
High	Remaining

Table 1. Conditions for quality levels of ABI AOD pixels.

Site Name	**Location**	**Coordinates**	**Type**
City College of New York (CCNY)	New York City, NY, USA	40.821°N, 73.949°W	Urban
Wallops	Wallops, MD, USA	37.933°N, 75.472°W	Rural
Goddard Space Flight Center (GSFC)	Greenbelt, MD, USA	38.992°N, 76.839°W	Suburban
Tucson	Tucson, AZ, USA	32.233°N, 110.953°W	Urban
University of Houston	Houston, TX, USA	29.717°N, 95.341°W	Urban
Table Mountain	Longmont, CO, USA	40.125°N, 105.237°W	Rural

Table 2. Details about the representative AERONET sites used as examples to illustrate the range of the observed diurnal bias in GOES-16 ABI AOD.

Site	N	R		Slope		Intercept		Bias		RMSE	
		Before	After	Before	After	Before	After	Before	After	Before	After
City College of New York (CCNY)	2810	0.81	0.89	1.40	0.78	0.07	0.01	0.12	-0.01	0.15	0.05
Wallops	4267	0.95	0.89	1.16	0.74	0.02	0.02	0.04	-0.01	0.05	0.04
Goddard Space Flight Center (GSFC)	3972	0.86	0.90	1.33	0.91	0.02	0.00	0.06	-0.01	0.09	0.04
Tucson	4507	0.47	0.66	3.64	1.22	-0.01	0.02	0.11	0.03	0.16	0.04
University of Tucson	2197	0.57	0.52	1.95	1.10	0.05	-0.02	0.15	-0.01	0.19	0.08
Table Mountain	3695	0.92	0.94	1.19	1.06	0.01	0.01	0.03	0.02	0.07	0.05

Table 3. Validation statistics for comparisons between GOES-16 ABI AOD (top 2 qualities) and AERONET AOD at the 6 representative AERONET sites listed in Table 2 for August 6, 2018 to December 31, 2018 across the CONUS domain, both before and after bias correction. N is the number of matchups, R is the correlation coefficient, and RMSE is the root mean square error.

	Average GOES-16 AOD	Total number of pixels	AERONET AOD	Dust		Generic		Urban		Heavy smoke	
				N (%)	AOD	N (%)	AOD	N (%)	AOD	N (%)	AOD
20180815	0.82	41	0.35	19 (46%)	0.87	3 (7%)	0.84	10 (24%)	0.51	9 (21%)	1.05
20180816	0.80	246	0.55	50(20%)	1.04	28 (11%)	0.74	101 (41%)	0.60	67 (27%)	0.94

Table 4. Statistics of original (uncorrected) ABI AOD and AERONET AOD retrievals at the CCNY AERONET site on August 15 and 16, 2018 for the 4 aerosol models used in the ABI AOD algorithm.