Communications

Aerosol–Cloud Interaction—Misclassification of MODIS Clouds in Heavy Aerosol

Jessica I. Brennan, Yoram J. Kaufman, Ilan Koren, and Rong Rong Li

***Abstract*—The accuracy of the spaceborne Moderate Resolution Imaging Spectroradiometer (MODIS) cloud mask was evaluated for possible contamination by areas of heavy aerosol that may be misclassified as clouds. Analysis for several aerosol types shows that the cloud mask and products can be safely used in the presence of aerosol up to optical thickness of 0.6. Here we define as cloudy all MODIS 1–km (at nadir) pixels that were used to derive the cloud effective radius and optical thickness of water and ice clouds. The findings make it possible to study aerosol–cloud interaction from the MODIS aerosol and cloud products.**

***Index Terms*—Aerosols, clouds, Moderate Resolution Imaging Spectroradiometer (MODIS), remote sensing.**

I. Introduction

The effect of aerosol (smoke, pollution, or dust particles suspended in the air) on cloud properties and cloud cover is presently the main uncertainty regarding human impact on climate [1], [2] requiring further research. Satellites are very useful for collecting large statistics of the aerosol effect on clouds in order to distinguish between natural cloud variability and the effects of aerosol. The Moderate Resolution Imaging Spectroradiometer (MODIS) instruments on the Terra and Aqua satellites use 36 bands to collect data for remote sensing of land, ocean, and atmosphere. The MODIS data have been used for determining atmospheric properties and creating cloud and aerosol products [3]. In this communications, we make statistical analysis of MODIS cloud optical depths and aerosol optical depths retrieved with the Collection 04 operational algorithms.

II. Background

For the MODIS aerosol product, different algorithms are used over the land and ocean due to the change in reflectance properties between the two surfaces. In this analysis only aerosol retrievals over the ocean made by the Terra satellite instrument were used.

The MODIS cloud product is derived using the standard (MOD35) cloud mask that relies on spectral properties to identify pixels containing cloud and classify them according to the probability of cloudiness [4]. The main purpose of the "cloud mask" was for masking out the pixels that were obstructed between the surface and the satellite. This focus was originally in response to the MODIS ocean and land teams that wanted absolutely no contamination in the atmospheric column above the surface. After the MOD35 cloud mask is generated, the cloud product algorithms (MOD06) that determine cloud optical and microphysical properties are run on pixels determined to be cloudy. If certain physical anomalies in some pixels are present in the results, those pixels are not included in the MOD06 cloud product [5]; thus the MOD06 algorithm eliminates some pixels that the standard MOD35 cloud mask has mistakenly determined to be cloudy. This method attempts to ensure that the cloud microphysical properties are reported only for pixels confidently identified as cloudy.

The cloud screening approach for aerosol retrievals is very different from that for cloud retrievals. Martins *et al.* [6] developed a cloud screening algorithm for remote sensing of aerosols over ocean surfaces based on the difference in spatial variability between clouds and aerosols. Aerosols tend to be present in a more homogenous spatial pattern than clouds and can therefore be separated from clouds using the standard deviation of every 3×3 pixels. Any pixel that is partially cloudy or is adjacent to a cloud is classified as cloudy in an attempt to eliminate any cloud contamination and to ensure that only pure aerosol pixels are used to derive the aerosol products. Thus, the "cloud fraction" derived for aerosol retrieval purposes should be larger than the cloud fraction derived for cloud property retrievals.

III. Methodology

In studying the aerosol interaction with clouds, problems can arise if in some cases pixels are classified as aerosol pixels in the aerosol algorithm and as cloud pixels in the cloud algorithm, causing artificial correlation between aerosols and clouds. This analysis examines the relative performance of both cloud screening methods described previously, but concentrates on cases where aerosols are mistakenly identified as clouds. An example of the discrepancy between the two cloud masks is clearly shown in Fig. 1, which displays six partial images created from the granule data collected on April 10, 2001 over the Sea of Japan. A plume of dust is easily identifiable in the top left image in Fig. 1. While the aerosol product reports high aerosol optical thickness values for the dust plume, the MOD06 (Collection 04) cloud product classifies the dust plume as cloud and derives cloud radius as shown in the middle right image in Fig. 1. In addition to the large dust plume, cloud radius is also derived in areas of pollution near North Korea. The images in Fig. 1 clearly show that the misidentification of aerosols as cloud occurs for the MODIS Collection 04 cloud retrieval algorithm. This analysis is intended to clarify when these misidentifications occur.

The need for the study of aerosol contamination effects on cloud retrievals is demonstrated by the histograms in Fig. 2. Here, the MOD06 cloud fraction data were taken at a resolution of 1° longitude by 1° latitude for the months of June through August, 2002 for stratiform clouds over the Atlantic Ocean in a region dominated by dust (5°N–30°N) and smoke (20°S–5°N). Fig. 2(a) and (c) are histograms for data with AOT values from 0.2 to 0.45 and show fairly consistent distribution of

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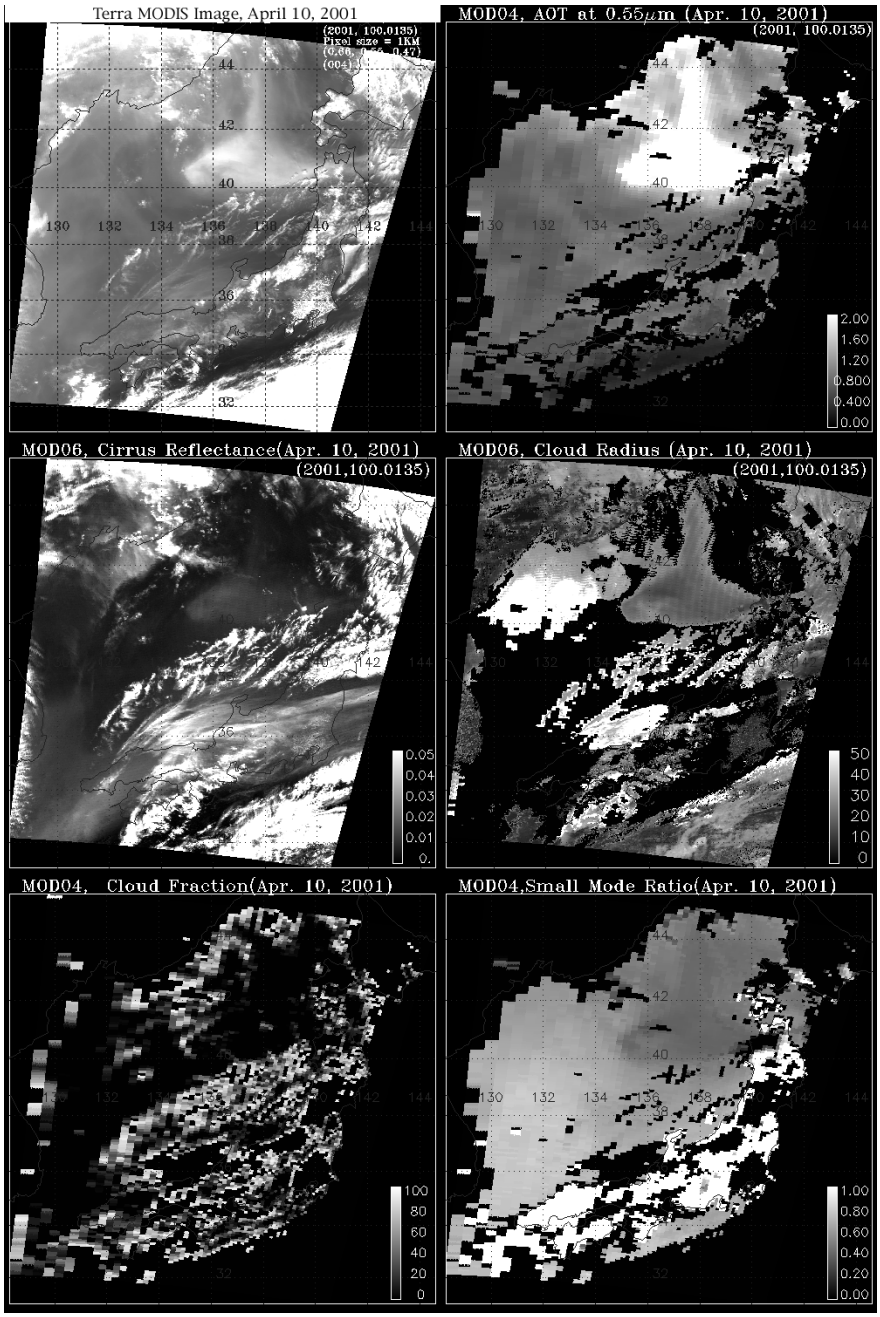

Fig. 1. Images created from the MODIS data showing (top left) a visible band image (top right) AOT, (middle left) cirrus reflectance, (middle right) cloud radius, (bottom left) aerosol product cloud fraction, and (bottom right) aerosol small mode ratio. Note the dust plume in the top left image is given cloud radius values in the middle right image. The middle left image does not indicate cirrus clouds in the area of the dust plume.

the cloud fractions. However, when the AOT is increased by 0.1 to include data with values from 0.2 to 0.55, a significant increase in cloud fractions for the bin from 0.99 to 1 occurs in both the dust and smoke cases. This demonstrates that there are aerosol contaminations in cloud retrievals. Pixels in which aerosols are present have been classified as completely cloudy by the MOD06 cloud product and used to derive cloud microphysical parameters. This contradiction highlights the importance of determining the AOT at which contamination begins to appear. Although these histograms indicate that the contamination starts to appear at an AOT of approximately 0.5, we decided to use higher resolution data to find the AOT threshold in the following analysis.

Using both the cloud and aerosol products derived from entire granules, images such as the ones displayed in Fig. 1 were created for the visible bands, aerosol optical thickness (AOT), cloud fraction, cirrus reflectance derived from the 1.38- and 0.66-μm bands [7], aerosol small mode ratio—the fraction of the AOT due to submicron particles, and several other parameters. Since the MOD06 cloud product is produced at a resolution of 1 km and the MOD04 aerosol product is produced at a resolution of 10 km, the cloud fraction was averaged on a 10 km $\times$ 10 km grid. Once these images were generated, specific cases were selected in different locations with different aerosol types. Beginning with all the data in a 2000 km $\times$ 2000 km granule, the data were sorted so that only the pixels where cloud effective radius was derived were used. In several of the chosen cases there was more than one type of aerosol present in the granule. When this occurred, the data were grouped by small mode ratio to be analyzed separately.

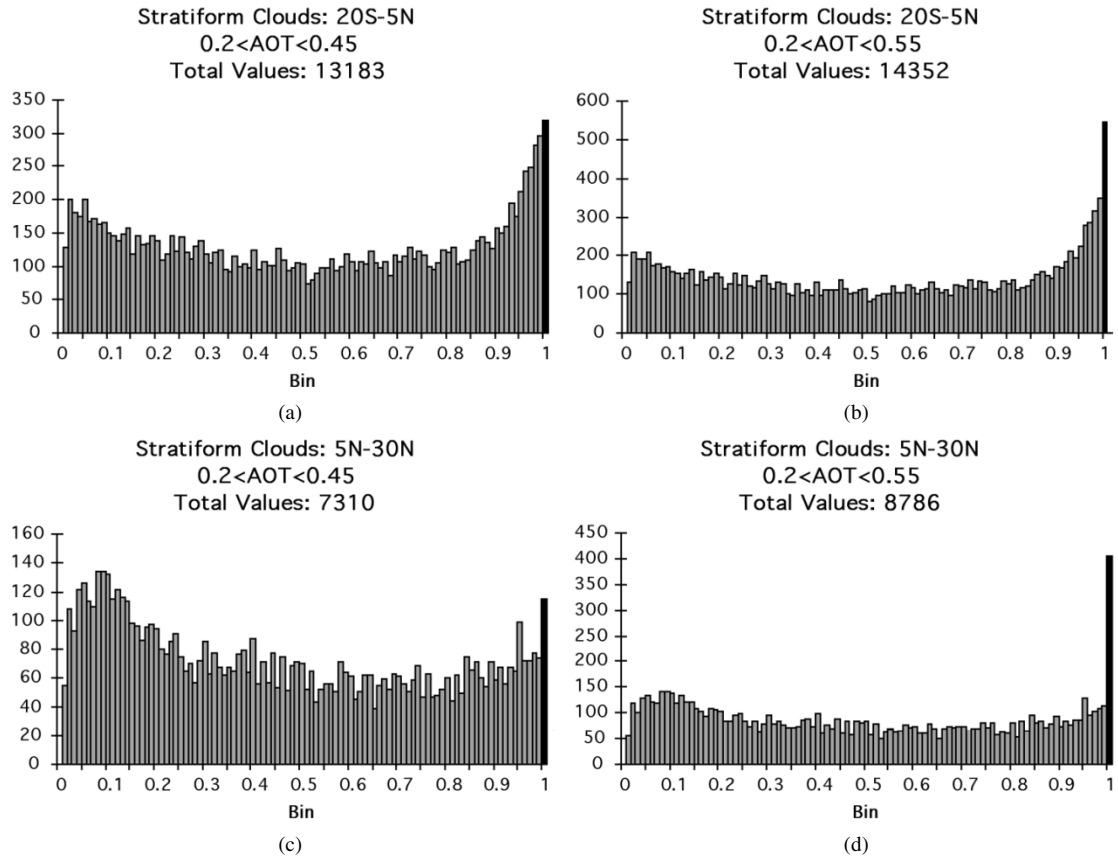

Fig. 2. Histograms of cloud fraction data taken at 1° longitude by 1° latitude resolution for stratiform clouds over the Atlantic Ocean for June through August 2002. (a) and (b) are histograms for a region of the Atlantic dominated by smoke (20°S to 5°N), while (c) and (d) are from a region dominated by dust (5°N to 30°N). (a) and (c) display data for which AOT from 0.2 to 0.45 were derived, while (b) and (d) show data with AOT from 0.2 to 0.55. The total values in the title show the number of data values used in the histogram. The bins are at increments of 0.01 AOT with the black bar highlighting the last bin which contains the number of data with cloud fractions from 0.99 to 1.

For this analysis, we assume that the aerosol (MOD04) cloud mask does not underestimate the cloud fraction. The assumption is based on extensive evaluation of the aerosol cloud mask [6] and can be seen visually by comparing the visible band images, such as the top right image in Fig. 1, with the MOD04 cloud fraction and the AOT images, such as the bottom left and top right images of Fig. 1. They show that areas with clouds generally have larger cloud fractions. Also, the AOT image does not have higher values of AOT around the identified clouds (gray areas) as is characteristic of contamination in the aerosol product.

Therefore, the cloud mask used for the MOD06 cloud product should show equal or smaller cloud fraction than the aerosol cloud mask. From this observation, two parameters were determined to best display possible aerosol contamination of the cloud product with increasing AOT. By adding the ice cloud fraction and water cloud fraction from the cloud product, defined as the fraction of water clouds or ice clouds for which the cloud microphysical properties were derived by MOD06, a combined cloud fraction (cf_c) comparable to the cloud fraction produced by the aerosol algorithm (cf_a) was created. If a negative difference $(cf_a - cf_c < 0)$ was found then aerosol contamination of the cloud product was likely. Fraction of successful identifications was defined as the number of successes, or positive differences between the cloud and aerosol masks, out of the number of data values in a given AOT range.

While the fraction of successful identifications is a good preliminary test, used alone it cannot determine definitively whether there is contamination or not. Even when the difference between the two cloud fractions is positive, one or both cloud masks could mistake aerosol for cloud or vice versa. To supplement the fraction of successful identifications defined above, a second parameter of average relative difference was used. The relative difference was calculated as follows:

$$\mathrm{RD} = \frac{cf_a - cf_c}{cf_a}$$

where RD is the average relative difference, cf_a is the aerosol product cloud fraction, and cf_c is the cloud product cloud fraction. These values were then averaged over a range of AOT. If the aerosol cloud mask indicated zero cloud cover it was not included in the calculation. When used together these two parameters complement each other to aid in determining the threshold value for the granule data used.

IV. Results

The results of the analysis for nine granules are summarized in Table I. The threshold values specified in the table are defined as the values of AOT after which contamination was indicated on graphs such as Fig. 3(a)–(d). For the fraction successful parameter, the values were invariably equal to 1 for the lowest ranges of AOT. As the AOT increased, the fraction successful parameter would occasionally decrease slightly to around 0.99 or 0.98. The large reduction in success rate generally started between an AOT of 0.5 and 0.7 but was found to occur at an AOT as low as 0.4. The threshold value indicates where the

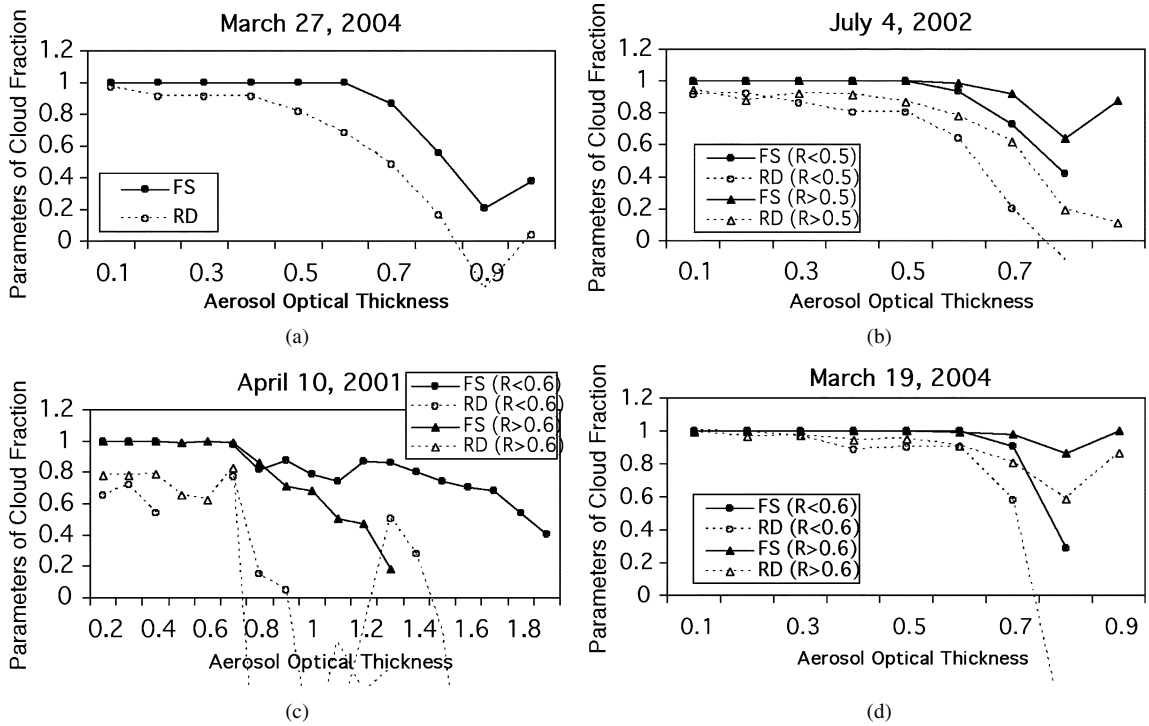

Fig. 3. Graphs of the parameters fraction successful (FS)—the number of values where $cf_a - cf_c > 0$ out of the total in a given AOT range—indicated by solid lines and average relative difference (RD)—$(cf_a - cf_c)/cf_a$ averaged over a given AOT range—indicated by dashed lines with increasing AOT. (b), (c), and (d) have been separated by small mode ratio (R) to distinguish between two different types of aerosols.

TABLE I
RESULTS OF ANALYSIS FOR THRESHOLD OF AEROSOL CONTAMINATION OF THE CLOUD PRODUCT. LAT/LONG IS THE APPROXIMATE CENTRAL LOCATION OF AEROSOL RETRIEVALS IN THE GRANULE. CF IS THE AVERAGE MOD06 CLOUD FRACTION (IN PERCENT) FOR THE PIXELS USED IN THE ANALYSIS. τ_{FS} IS THE AOT THRESHOLD, OR LAST ACCEPTABLE VALUE OF THE PARAMETER FRACTION SUCCESSFUL BEFORE THE REDUCTION IN SUCCESS RATE OCCURS. V IS THE VALUE OF THE PARAMETER FRACTION SUCCESSFUL AFTER THE THRESHOLD AOT. BT IS THE APPROXIMATE NUMBER OF DATA VALUES BEFORE THE THRESHOLD. AT IS THE APPROXIMATE NUMBER OF DATA VALUES AFTER THE THRESHOLD. τ_{RD} IS THE THRESHOLD AOT VALUE AFTER WHICH THE AVERAGE RELATIVE DIFFERENCE BEGINS TO DECREASE, AND D IS THE DIFFERENCE BETWEEN THE AVERAGE RELATIVE DIFFERENCE AT THE THRESHOLD AOT AND THE NEXT VALUE OF AVERAGE RELATIVE DIFFERENCE. ND REPRESENTS A NONDETERMINABLE VALUE

Date	Location	Lat/Long	CF (%)	Aerosol Type	Small Mode Ratio	τ_{FS}	V	BT	AT	τ_{RD}	D
10 April 2001	Japan	40N, 136E		pollution	R>0.6	0.7	0.86	870	780	0.7	2.32
			35	dust	R<0.6	0.8	0.81	140	1000	0.8	0.63
19 March 2004	Indian Ocean	17N, 86E		pollution	R>0.6	0.7	0.86	1520	270	0.6	0.1
			6	dust/sea salt	R<0.6	0.6	0.91	1140	20	0.6	0.32
27 March 2004	Indian Ocean	16N, 76E	14	pollution		0.6	0.87	3370	500	0.4	0.09
30 July 2002	Caribbean	25N, 64W		dust	R<0.6	≥0.8	--------	3510	--------	ND	--------
			10	pollution	R>0.6	0.5	0.83	3410	100	0.5	0.34
26 and 28 August 2003	Atlantic off Africa (S)	4S, 8E	21	smoke		≥1.2	--------	3820	--------	ND	--------
23 July 2002	Atlantic off Africa (N)	26N, 20W		non-dust	R>0.4	0.6	0.91	1740	680	0.6	0.5
			28	dust	R<0.4	0.4	0.92	780	440	0.6	1.42
7 July 2002	Atlantic off S. America	12N, 42W		dust	R<0.5	0.5	0.93	880	420	0.5	0.18
			24	pollution	R>0.5	0.6	0.93	760	330	0.6	0.15
4 July 2002	Atlantic off S. America	16N, 56W		dust	R<0.5	0.5	0.94	3440	270	0.5	0.16
			10	smoke/ pollution	R>0.5	0.6	0.92	4520	140	0.4	0.04
17 July 2002	N. Amer. Coast	32N, 72W	9	pollution		0.6	0.93	4065	490	0.6	0.27

decrease begins, which does not necessarily correspond to the most dramatic decrease in successful identification of clouds.

The average relative difference tends to be more variable than the fraction successful parameter, but it can also strongly indicate the threshold value. Often, the threshold value is the same for both

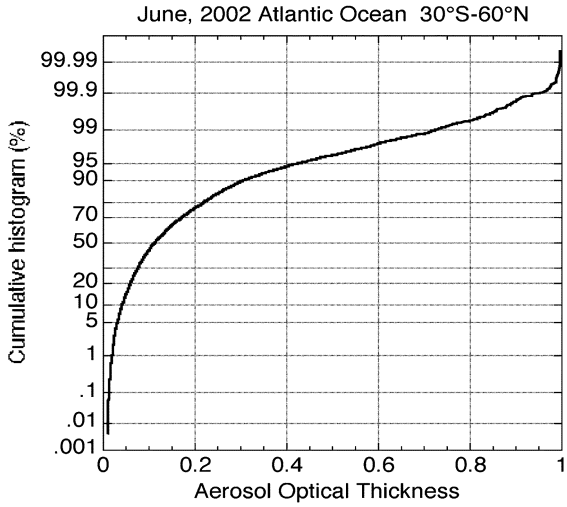

Fig. 4. Cumulative histogram of AOT for the month of June 2002 over the Atlantic Ocean, for 30°S–60°N. The Atlantic Ocean is an ideal region to study the aerosol interaction with cloud, due to flux of dust, smoke, and pollution from Africa, North America, and Europe. Only 2% of the AOT values were greater than 0.6, while only 6% were greater than 0.4 for this time period.

parameters. For the remaining cases, the relative difference threshold is smaller than the fraction successful threshold in all but one instance. This can be clearly seen in Fig. 3(a) where the average relative difference begins to fall before the fraction successful indicating that the accuracy of the data begins to decrease even before negative differences are occurring, while in Fig. 3(b)–(d), the contamination seems to occur at the same point for both parameters.

Using Figs. 1–3, we demonstrated that cloud optical depths were contaminated by aerosols when aerosol optical depths are 0.6 or greater. In order to examine how often the situations of AOT > 0.6 occur, we

made studies of AOTs for the month of June 2002 over the Atlantic Ocean in the latitude range of 30°S–60°N. The Atlantic Ocean is an ideal region to study the aerosol interaction with cloud, due to fluxes of dust, smoke and pollution from Africa, North America and Europe. Fig. 4 shows the cumulative histogram of the aerosol optical thickness for the month of June over the Atlantic Ocean. Only 2% of the AOT values were greater 0.6 and 6% were greater 0.4 for the month. Therefore, the situations of high AOTs (>0.6) do not occur frequently.

V. Summary and Conclusion

The results from this study indicate that aerosol contamination of the MOD06 Collection 04 cloud product occurs when AOT values are larger than about 0.6. The contamination can hinder the study of aerosol and cloud interactions. Possible contaminations can start to occur in certain cases when AOT values as low as 0.4. No apparent trends were detected by either parameter based on aerosol type or geographical location. The histograms in Fig. 2 indicate a threshold value that is slightly lower at 0.5 AOT. This is most likely a result of the difference in resolution, with the 1° longitude by 1° latitude resolution using averages that include a few of the higher AOT pixels that are contaminated as well as the pixels with lower AOT. It should be noted that in most cases the aerosol optical thickness is smaller than 0.4. Despite the heavy dust and pollution over the Atlantic Ocean, AOT > 0.6 occurs only 2% of the time and AOT > 0.4 only 6%.

In summary, the MODIS detailed measurements of aerosol and clouds make it possible to study cloud-aerosol interaction. However, the Collection 04 cloud data products must be used cautiously, especially for the cases of AOT above the thresholds indicated by this analysis. The cloud masking technique in the recently updated Collection 05 cloud retrieval algorithm has been improved, and the Collection 05 cloud products available in the near future will largely eliminate the aerosol contamination effect.

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