SATELLITE REMOTE SENSING OBSERVATIONS OF TRANS-ATLANTIC DUST TRANSPORT AND DEPOSITION: A MULTI-SENSOR ANALYSIS

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ABSTRACT

We analyze the decade-long (2007-2016) record of aerosol measurements from four distinctive sensors, namely CALIOP, MODIS, MISR, and IASI, to quantify the trans-Atlantic dust transport and deposition. These satellite sensors use different techniques to characterize particle size and shape properties; and we have developed sensor-specific methods (broadly categorized into size-based and shape-based method) to derive dust optical depth (DOD). The size-based DOD from MODIS and IASI generally agrees better with AERONET-derived DOD than the shape-based DOD from CALIOP and MISR does. Overall, the shape-based DOD is smaller than the size-based DOD by about 25%, which is consistent with distinctive ways of accounting for coarse-spherical particles of dust-pollution internal mixture. While such dust-pollution mixtures are counted as dust in the size-based DOD, they are excluded in the shape-based DOD. DOD is not a good proxy for dust deposition. Instead, the dust deposition depends strongly on the gradient of DOD on a monthly basis and can be derived by calculating the meridional and zonal dust mass flux based on the three-dimensional distributions of dust. Among the remote sensing measurements, difference in dust deposition is smaller than that of DOD, suggesting that different satellites characterize the DOD gradient more consistently than DOD itself. Satellite measurements of dust deposition and DOD also provide an accurate estimate of the dust loss frequency (LF) that measures how efficient the dust is removed from the atmosphere. We found that these remote sensing measurements yield similar LF values of 0.078 – 0.102 d^{-1}, which however is factors of 2-5 smaller than model simulations. This analysis provides valuable insights into potential deficiencies in models' emission and transport/removal processes and hence helps guide model improvement.

Index Terms— remote sensing, dust, transport, deposition, dust optical depth

1. INTRODUCTION

Dust transport and deposition is required for understanding the dust impacts on ocean biogeochemical cycles and climate change. However, in-situ observations are scarce, particularly in remote oceans. Models are very uncertain due to lack of observational constraints of major dust emission and removal processes. Satellites are a suitable platform to observe large-scale phenomenon of trans-oceanic dust transport and deposition at a range of time scales, because of their routine sampling over decadal time scales with extensive spatial coverage. It has a potential to fill data gaps. Our overarching goal is to explore the use of remote sensing observations to quantify the trans-Atlantic dust transport and deposition [1]. In this paper we focus on assessing consistency and inconsistency in dust optical depth (DOD), dust deposition rate (DDR), and dust loss frequency (LF) over tropical Atlantic Ocean among the remote sensing measurements, including MODIS, MISR, CALIOP, and IASI.

2. DESCRIPTION OF DATA

The most popular observable from satellite remote sensing is aerosol optical depth (AOD), which reflects collective contribution to the aerosol extinction by individual components. To derive the dust component or DOD, we have developed sensor-specific methods that take advantage of satellite measurements of particle size and shape information [1-4], as listed in Table 1. A fundamental assumption for these remote-sensing based methods is that dust particles are generally large in size and irregular in shape, which yields small value of fine-mode fraction and large values of depolarization ratio and non-spherical fraction. These methods can be broadly categorized into the size-based (e.g., MODIS, IASI) and shape-based (CALIOP, MISR). The two methods differ in accounting for possible dust-pollution internal mixtures that would appear as coarse-spherical particles. Although such coarse-spherical particles are counted as dust in the size-based method, they are excluded in the shape-based method. It is anticipated that the size-based DOD would be higher than the shape-based DOD. IASI DOD at 10 μm is multiplied by 1.54 to represent DOD at 0.55 μm [1], which is consistent with recent measurement of dust particle size distribution in the region [5].

To evaluate the satellite-based monthly DODs over ten-year period (12/2006 to 11/2016), we use the ground-based AERONET coarse-mode AOD at 0.55 μm from the spectral de-convolution algorithm (SDA) [6] in seven stations in the coast of North Africa (Dakar, Tenerife, Izana, La Laguna) and in the Caribbean Basin (Ragged Point, La Parguera, and Tudor Hill), as illustrated in Fig. 1. It is important to note that Izana with an elevation of 2400 m will only sample the dust in the free atmosphere, while Tudor Hill, located in the northmost fringe of trans-Atlantic dust plumes, mainly samples dust in summer on an event basis and hence could show large variability.

Table 1: Satellite sensors used to derive DOD.

Sensor	Relevant observables used to derive DOD	References
MODIS	AOD, particle size	[2], [3]
IASI	AOD at 10 µm, layer height	[1]
CALIOP	Profiles of backscatter and depolarization ratio	[4]
MISR	AOD, non-spherical fraction	[1]

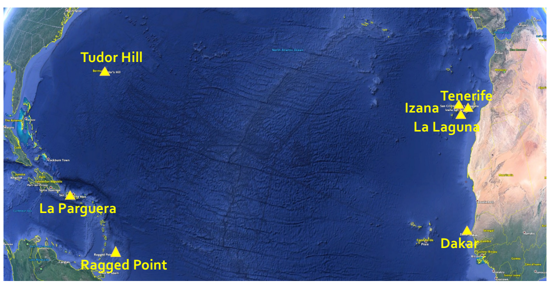

Fig. 1: Illustration of seven AERONET stations with multi-year SDA data that are used to evaluate satellite-derived monthly DOD.

Satellite snapshots of DOD for a specific day is not a good proxy for the dust deposition. Instead, on a basis of monthly average, the dust deposition depends strongly on the gradient of DOD along the transport route without dust sources. We have developed a "mass balance" approach to calculate dust deposition based on the three-dimensional (3-D) distribution of dust in the atmosphere [1]. The dust deposition into ocean is the divergence of dust mass fluxes in the meridional and zonal directions. This approach only applies to the region without dust sources, such as oceans and the Amazon Basin. Although CALIOP provides 3-D distribution of dust that can be used directly to calculate dust deposition, DOD from MODIS, MISR, and IASI has been distributed in the vertical using the vertical profile information from CALIOP. Thus, difference in the dust deposition results from that in DOD. We further calculate the dust loss frequency (LF) as a ratio of dust deposition rate to dust mass loading (related to DOD through dust mass extinction efficiency or MEE), which measures how efficient that the dust is removed from the atmosphere. The estimate of LF is more accurate than the dust deposition itself, because uncertainties associated with the assumption of dust MEE are largely cancelled out.

3. EVALUATION OF SATELLITE-BASED WITH AERONET MEASUREMENTS

Fig. 2 shows comparisons of monthly DOD derived from MODIS, MISR, CALIOP, and IASI against the AERONET DOD over Tenerife in Canary Island and Ragged Point in Barbados. It shows that, in general, the satellites capture well the seasonal and interannual variations of DOD. For all sites, we calculate the correlation coefficient (R) and bias (B) with respect to the AERONET observation, as shown in Table 2. These statistics show that, for the first stations, MODIS and sometimes IASI generally agree better (higher R and B closer to 1) with AERONET observations than MISR and IASI do. The better agreement of MODIS and IASI may have resulted from two facts: (a) more frequent sampling by MODIS and IASI is necessary to capture episodic dust events; and (b) DODs from MODIS, IASI, and AERONET are all size-based, while those from MISR and CALIOP are shape-based. The bias depends on season, which is generally greater in off-dust seasons than peak-dust season. At Izana, although satellites show high correlation with AERONET, the average bias falls into a range of 3.08 to 4.92, suggesting that AERONET observed DOD in the free atmosphere accounts for about 20-30% of satellite-observed columnar DOD. In the northmost fringe of dust plumes (at Tudor Hill), only MODIS shows very limited capability of capturing the dust variability.

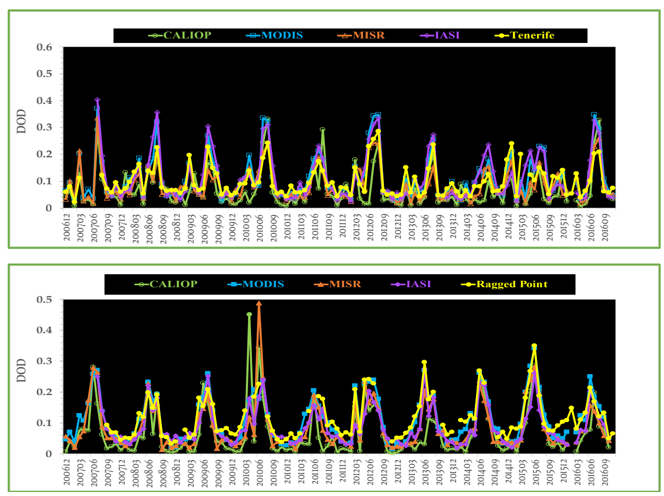

Fig. 2: Comparisons of monthly DOD from MODIS, CALIOP, MISR, and IASI with AERONET measurements over Tenerife in Canary Island (top panel) and Ragged Point in Barbados (bottom panel).

Table 2: Correlation coefficient (R) and bias (B, mean ± standard-deviation) of satellite DOD with respect to AERONET observations at 7 stations on a monthly basis over the 10-year period.

Site	MODIS		CALIOP		MISR		IASI	
	R	B	R	B	R	B	R	B
Dakar	.93	0.97	.76	0.88	.85	0.68	.88	1.02

		±0.25		±0.43		±0.23		±0.25
Tenerife	.92	1.06 ±0.33	.73	0.63 ±0.42	.85	0.84 ±0.31	.83	1.04 ±0.44
La Laguna	.85	1.32 ±0.45	.74	0.76 ±0.43	.83	1.06 ±0.44	.85	1.30 ±0.52
Ragged Point	.96	0.86 ±0.24	.79	0.43 ±0.32	.85	0.66 ±0.27	.89	0.75 ±0.26
La Parguera	.95	0.96 ±0.35	.92	0.43 ±0.26	.93	0.68 ±0.25	.95	0.79 ±0.28
Tudor Hill	.53	0.85 ±0.33	.20	0.37 ±0.28	.15	0.51 ±0.31	.26	0.59 ±0.34
Izana	.92	4.92 ±2.97	.76	3.08 ±4.43	.84	3.99 ±2.71	.95	4.57 ±2.48

4. MULTI-SENSOR COMPARISONS OF BASIN-SCALE DOD AND DUST DEPOSITION

We further examine consistency and inconsistency among satellite observations of DOD and dust deposition rate on the basin scales. Fig. 3 shows scatterplots of shape-based monthly DOD (MISR and CALIOP) versus MODIS size-based DOD. Each data point in the figure represents monthly average over the 5° (longitude) x 2° (latitude) grid. It shows that these satellite-based DOD correlates well with each other, with R = 0.88 (MISR vs MODIS) and 0.80 (CALIOP vs MODIS). The higher correlation for MISR presumably results from more frequent sampling by MISR than CALIOP. On average, the shape-based DOD from MISR and CALIOP is 25-28% smaller than the MODIS size-based DOD. This difference is consistent with the different treatments of the dust-pollution mixtures in the size-based and shape-based approaches of deriving DOD, as discussed earlier.

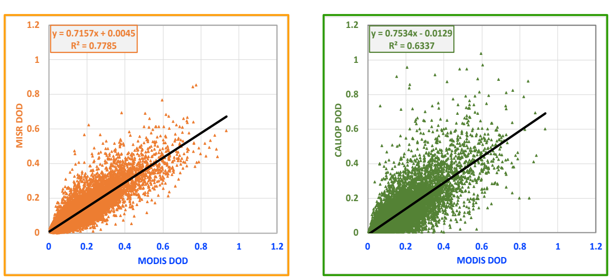

Fig. 3: Comparison of the shape-based DOD (MISR, left panel; CALIOP, right panel) against the MODIS size-based DOD in eastern North Atlantic Ocean.

As discussed in [1], the 65-83% of satellite-based estimates of dust deposition agree with the in-situ climatology (23 sites) within a factor of 2. Here we examine the time series of dust deposition into sub-basins from the four satellites. Fig. 4 shows the satellite-estimated monthly dust deposition rate (DDR) into the eastern North Atlantic Ocean (ENA, top panel) and the Caribbean Basin (CAR, bottom panel) over the 10-year period. Fig. 5 shows the seasonal variation of DDR averaged over the 10-year period. It shows that in general the individual sensor follows each other closely in capturing the seasonal and interannual variations of dust deposition, in particular in CAR. On the basis of monthly dust deposition, correlation coefficient between the satellite sensors falls into 0.93-0.95 in CAR and 0.75-0.91 in ENA. Over ENA, all the satellite measurements show consistently double peaks of the dust deposition in August and February, although MODIS-based DDR is much higher than IASI-based estimate, particularly in spring. Over CAR, the four satellites yield similar magnitude of dust deposition throughout year and the peak in July-August.

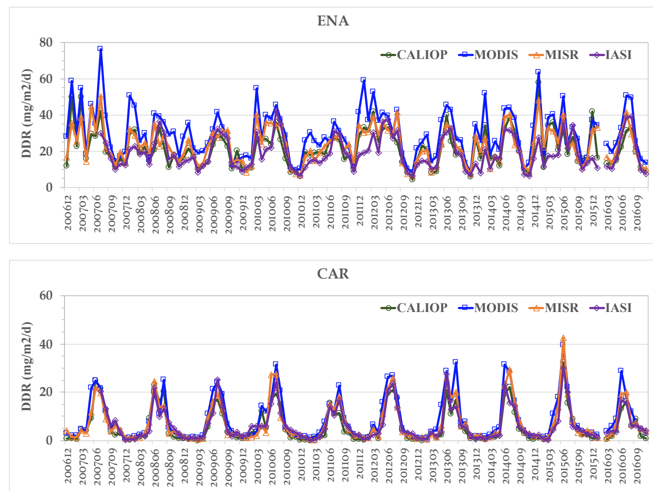

Fig. 4: satellite-estimated monthly dust deposition rate (DDR) into the eastern North Atlantic Ocean (ENA, top panel) and the Caribbean Basin (CAR, bottom panel) over the 10-year period.

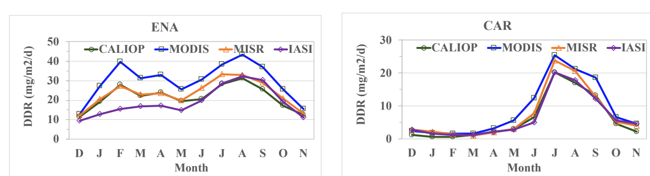

Fig. 5: Seasonal variation of basin-scale dust deposition rate (DDR) into ENA (left) and CAR (right).

We then compare the biases of DDR and DOD from CALIOP, MISR, and IASI, with respect to the corresponding MODIS value, as shown in Fig. 6. For all satellite observations and in both ENA and CAR, the average bias for DDR is smaller (closer to 1) than the DOD bias. This suggests that the satellite observations are more consistent in characterizing the gradient of DOD than the DOD itself. This is likely the case when satellite retrieval is subject to a relatively uniform bias of DOD, resulting from, for example, cloud contamination, imperfect aerosol models, and some inherent assumptions in deriving DOD from AOD and particle properties.

We further calculate the dust loss frequency (LF, with a unit of d^{-1}) as a ratio of the dust deposition rate (DDR) to dust mass loading (=DOD/MEE). Given that the uncertainty associated with an assumption of dust MEE is largely cancelled out, estimated LF is likely to be more accurate than DDR. Fig. 7 shows the seasonal and annual averages of dust LF for trans-Atlantic dust transport derived from the four satellites. All the satellite-based estimates suggest a significant higher LF in winter than in other seasons. In each season, MODIS-based LF is the lowest. On the basis of annual average, the satellite-based estimates of dust LF fall into a range of 0.078 to 0.102 d^{-1}, which are up to factors of 2-5 greater than model simulations as documented in [7]. This finding suggests that models currently have too efficient dust removal mechanisms than the satellite observations indicate. LF is a useful parameter that isolates uncertainty associated with transport/removal processes from that of emissions and hence offers better insights into model deficiencies that can help guide the model improvement.

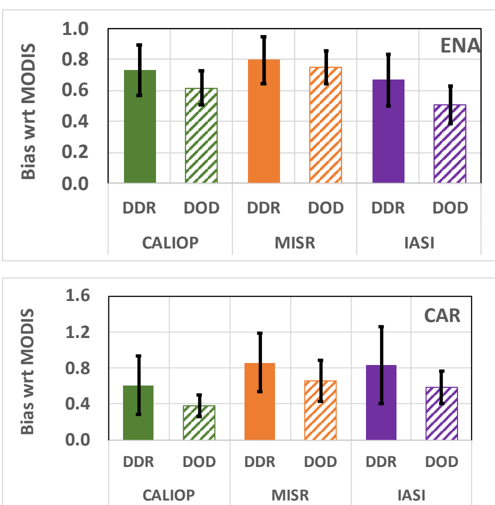

Fig. 6: Bias (mean ± standard-deviation) of monthly DDR and DOD with respected to MODIS-based values in ENA (top panel) and CAR (bottom panel).

5. CONCLUSIONS

We have evaluated the decade-long estimates of dust optical depth over tropical Atlantic Ocean from MODIS, IASI, MISR, and CALIOP against the AERONET observations. We found the size-based DOD from MODIS and IASI generally agrees better with AERONET-derived DOD than the shape-based DOD from CALIOP and MISR does. On average, the shape-based DOD is smaller than the size-based DOD by about 25%, which is consistent with distinctive ways of accounting for coarse-spherical particles in dust-pollution internal mixture. While such dust-pollution mixtures are counted as dust in the size-based DOD estimate, they are excluded in the shape-based DOD due to the spherical shape of these particles.

Although satellite observed snapshots of DOD doesn't tell how much dust is removed, an aggregation of these snapshots over a period of month can yield a map of DOD, in which the gradient of DOD along the transport route reflects how much dust is removed along the transport. We found that among the remote sensing measurements from MODIS, MISR, CALIOP, and IASI, difference in dust deposition is smaller than that of DOD, suggesting that these satellites characterize the DOD gradient more consistently than DOD itself. The remote sensing measurements also yield similar dust LF values of 0.078 ~ 0.102 d^{-1}, which is, however, factors of up to 2-5 smaller than model simulations. This suggests that models remove dust from the atmosphere too efficiently. This analysis provides valuable insights into potential deficiencies in models' emission and transport/removal processes and hence helps guide model improvement.

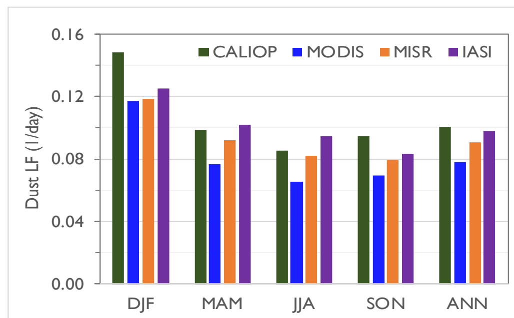

Fig. 7: Satellite-derived seasonal (DJF, MAM, JJA, SON) and annual (ANN) loss frequency (LF, d^{-1}) for the trans-Atlantic dust transport

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