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GLOBAL VALIDATION OF THE 1998 TRMM/CERES-SSF AEROSOL DATA WITH AERONET SUN-PHOTOMETER OBSERVATIONS

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1. INTRODUCTION

A new set of Earth radiation balance data is now being provided to the science community by the National Aeronautics and Space Administration (NASA) CERES (Clouds and the Earth's Radiant Energy System) instrument aboard the Tropical Rainfall Measurement Mission (TRMM) satellite for eight months from 1998 (Wielicki et al., 1996). Satellite radiation from CERES, cloud and aerosol from VIRS (Visible/Infrared Scanner), and assimilated meteorological fields have been merged in the TRMM/CERES Single Satellite Footprint (SSF) data set for convenient applications in radiation and climate studies. The SSF data, combined with 16-year record of the Earth Radiation Budget Satellite (ERBS), are unique for the evaluation of radiative fluxes in tropical regions (see Wielicki et al., 2002).

The SSF data are also used to address the effect of aerosols on radiative fluxes (referred generally as aerosol radiative forcing). The radiative forcing by aerosols is comparable to that by greenhouse gases but with larger uncertainties (IPCC, 2001). Better information on the distribution, chemical and microphysical properties of aerosols are needed to reduce these uncertainties. The current paper seeks to evaluate the error budget of aerosol retrievals over the ocean, made from the Visible/Infrared Scanner, in support of aerosol radiative forcing studies. At the same time, sub-pixel cloud contamination (CC) and surface wind effect (SWE), which are recognized as the two major error sources in the aerosol retrieval algorithm, will be addressed and their impact on aerosol optical thickness (τ) retrievals will be quantified through a validation against surface AErosol RObotic NETwork (AERONET) sun-photometer (SP) observations.

2. DATA AND APPROACH

The first data set used in our analysis is the Edition 2 data of SSF products. It consists of radiation, cloud, aerosol, and meteorological fields in the TRMM/CERES Single Satellite Footprint (SSF) (Geier et al., 2001). The SSF data used in this study covers the time period from January to August in 1998 before the failure of the CERES sensor aboard the TRMM satellite. Aerosol optical thickness (τ_1 and τ_2) in the SSF data are derived from averaging their pixel values according to the PSF of the CERES footprints.

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The AERONET aerosol optical thickness, τ_{sp}, observed from the automatic CIMEL Sun/sky radiometers (Holben et al., 1998) provide the ground truth used in the evaluation of the SSF aerosol optical thickness. Quality controlled Level 2 AERONET SP data (see Smirnov et al., 2000) from 1998 will be used in this study.

Our validation approach is to combine self-consistent check with ground truth validation. Probability distribution function, scatter plot, and histogram are used in the self-consistent check. For validation, we co-locate the aerosol optical thickness from the SSF satellite data (τ_{st}) with that from the AERONET SP observations (τ_{sp}) within an optimum time/space window (+/- 1 hour and a circle with 100km radius) at 8 selected AERONET marine stations (Andros Island, Bahrain, Bermuda, Cape Verde, Dry Tortugas, Kaashidhoo, Lanai, and Surinam). These stations cover the major regimes of global oceanic aerosol characteristics. Scatter diagrams of τ_{st} versus τ_{sp} are produced and statistics are calculated for the overpass match-up points. Linear regression analyses are performed, predicting the satellite retrieval values of τ_{st} as a function of τ_{sp} in the form of $\tau_{st} = A + B\tau_{sp}$. Retrieval algorithm performance can be evaluated from the resulting four statistical parameters of the linear regression: A (intercept), B (slope), σ (standard error), and R (correlation coefficient). A detailed description of the approach and the physical rationale behind it can be found in Zhao et al. (2002).

3. RESULTS

Results from the self-consistent checks and validation are presented below. Sub-pixel Cloud contamination and surface wind effect will be addressed and their impact on τ retrievals will be evaluated.

3.1 Self-Consistent Check

Figure 1 is an example of probability distribution functions (PDF) for aerosol optical thickness (τ_1 and τ_2) and Angstrom wavelength exponent (α) on May 1. The relationship between α (an aerosol size parameter) and τ is $\alpha=-\ln(\tau_1/\tau_2)/\ln(\lambda_1/\lambda_2)$. It is expected statistically that PDF of τ should be close to log-normal distribution while PDF of α should be more like a normal distribution. However, the PDFs of τ_1 and τ_2 in Figure 1 are not in ideal log-normal distribution. This defective feature is probably related to the radiometric noise and the unstable onboard calibration of the sensor or the sub-pixel cloud contamination. Correspondingly, the unexpected minor second peak in the PDF of α is noticed in Figure 1.

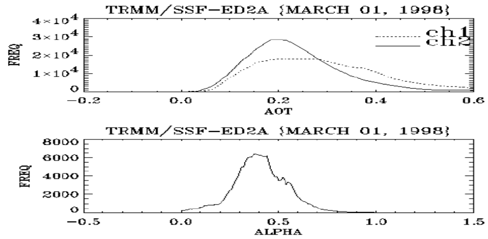

Fig.1. Probability distributions of τ (top panel) and α (bottom panel) for March 1, 1998.

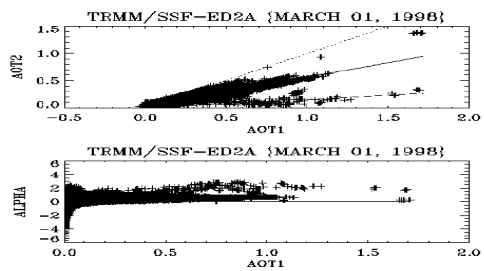

Fig.2. Scatter plots of τ_1 vs. τ_2 (top panel) and τ_1 vs. α (bottom panel) for March 1, 1998. In the top panel, The dotted line is α=0, the dashed line is α=2, and the general line is the linear regression line. In the bottom panel, the general line is α=0.

Corresponding scatter plots for both τ_1 verse τ_2 and τ_1 verse α is given in Figure 2. We can see almost all the points are in the right regime (0<α<2). There are two clusters have been observed. The majority of the points fall in the first cluster with $\alpha \approx 0.4$ (the common value for the marine type aerosol) while few points fall in the second cluster with $\alpha \approx 2$ (the value for very small particles). We believe the second cluster is the artificial feature that probably related to the radiometric noise or the sub-pixel cloud contamination.

Histograms of τ_1 and τ_2 versus clear strong index (CSI) and the surface wind speed (SWS) are given respectively in Figures 3 and 4 for March 1. We can see (in Figure 3) τ increases for the SSF with CSI less than 5%. We also find (without shown here) the population of SSF with CSI < 5% is very large. These two factors indicate a potential sub-pixel cloud contamination on the τ retrievals of SSF. The indication of the potential influence of ocean surface roughness associated with SWS in Figure 4 becomes noticeable only at high wind speeds (> 12 m/s).

3.2 Validation

Figs. 5a and b show the scatter plots of τ_1 and τ_2 respectively for 94 SSF-AERONET match-up points, which correspond to the 94 overpasses found in the 1998 SSF data for the eight AERONET sites. The corresponding linear regression formula is also given in the plots. We can see the match-up points are dispersed due to the existence of some outliers. Corresponding systematic and random errors are summarized on the first row in Table 1. The systematic and random errors are mainly due to radiometric noise, calibration errors, cloud contamination, surface reflection variability, and errors in the assumption of aerosol optical properties in the retrieval algorithm. The random error is ±0.09 for channel 1 and ±0.06 for channel 2. Small positive systematic bias exists in both channels for small and mean aerosol loading conditions. This bias becomes large as well as changes sign in both channels for large aerosol loading condition, which indicates the error sources of the retrieval are different for small and large aerosol loading conditions.

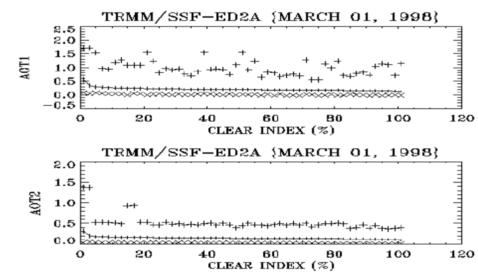

Fig. 3. Histograms of τ_1 (top panel) and τ_2 (bottom panel) versus clear strong index (CSI) for March 1, 1998. The line with the vertical bars is mean, plus signs are maximum, and cross signs are minimum. The vertical bars are one standard deviation long.

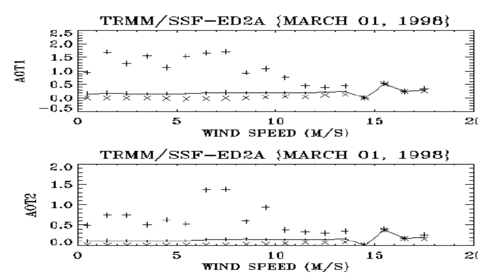

Fig. 4. Similar to Fig. 3 but for τ_1 (top panel) and τ_2 (bottom panel) versus surface wind speed (SWS).

To minimize the effect of sub-pixel cloud contamination and surface wind effects, we picked out sequently all the match-up records with CSI larger than 90 percent and SWS less than 1 m/s (which is the value adopted in the retrieval algorithm) to form two sets of 74 new match-up points. The systematic and random errors of the validation statistics for the two sets of new match-up points are given respectively on the second and third row in Table 1. The scatter plots of τ_1 and τ_2 for the match-ups, in which both sub-pixel cloud contamination and surface wind effect have been minimized, are given in Figure 6. It is obvious that some outliers observed in Fig. 5 disappear in Fig. 6. As a result, the positive biases in the SSF τ (compared to AERONET τ) for the mean SSF aerosol optical thickness in the two channels have been reduced from 0.05 to 0.02 in VIRS channel 1 (0.63µm) and 0.05 to 0.03 in channel 2 (1.61µm). Random errors have also been reduced from 0.09 to 0.06 at 0.63µm, 0.06 to 0.05 at 1.61µm.

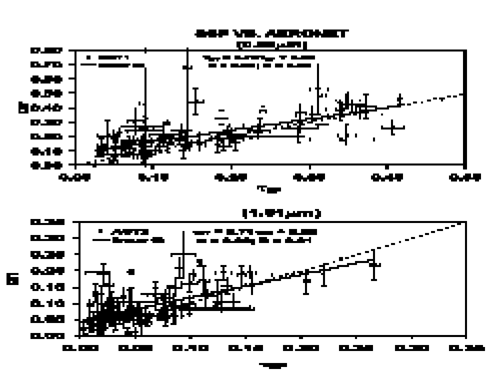

Fig. 5. Scatter plots of (a) τ_1 and (b) τ_2, and linear regression lines from the validation of 1998 SSF-AERONET match-up data. Horizontal and vertical error bars are +/- one standard deviation. Dash line is 1:1 relationship.

Table 1. Systematic errors of three aerosol loading scenarios: minimum (MIN), τ=0.0; mean, $\tau = \bar{t}$; and maximum (MAX), τ=1.0, along with the random (RND) errors for 1998 SSF τ data before and after the sub-pixel cloud contamination (CC) and surface wind effect (SWE) have been minimized sequentially in the match-up (MP) data.

		|---------- SYSTEMATIC ----------		|	RND
MP DATA	λ(µm)	MIN	MEAN	MAX	+/-
Raw	0.63	+0.09	+0.05	-0.13	0.09
Match-up	1.61	+0.05	+0.05	-0.25	0.06
SPCC	0.63	+0.07	+0.03	-0.25	0.06
Minimized	1.61	+0.03	+0.03	-0.26	0.05
CC & SWE	0.63	+0.07	+0.02	-0.25	0.06
Minimized	1.61	+0.03	+0.03	-0.27	0.05

4. SUMMARY AND DISCUSSIONS

We used TRMM/CERES-VIRS SSF data and AERONET SP observations from 1998 to investigate the effects of sub-pixel cloud contamination and surface wind on the satellite aerosol optical thickness retrieval over ocean through validation and self-consistent check. The validation was first performed for the original (or raw) match-up points found in 1998 with sub-pixel cloud contamination and varying surface wind speeds. The validation was next performed for a subset of match-up points with the sub-pixel cloud contamination minimized (or removed). Finally, the surface wind effect was also removed from the remaining match-up points for a third validation against the AERONET observation. The standard error of the linear regression for the match-up samples with these three levels of contamination provided estimates of the random errors. The slopes and intercepts of the linear regression were used to estimate the systematic errors of the aerosol retrieval over the range of observed τ, namely low, average, and high aerosol loadings. The systematic errors of the retrieval algorithm for the three aerosol loading scenarios and the three contamination levels in the match-up data along with the random errors are summarized in Table 1.

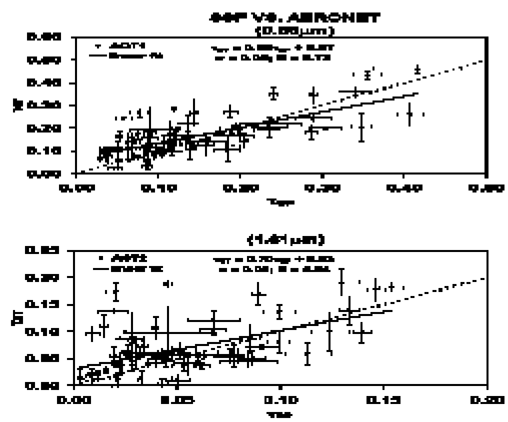

Fig.6. Similar to Fig. 5 but for the match-up data in which both the sub-pixel cloud contamination (CC) and surface wind effect (SWE) have been minimized.

Sub-pixel loud contamination was found to be a major source of systematic and random error for the VIRS aerosol retrieval algorithm used in the SSF data. The random errors in τ_1 and τ_2 were improved along with the reductions of systematic errors at low to mean τ values after sub-pixel cloud contaminated records were removed from the match-up samples.

The effect of ocean surface condition and roughness associated with the surface wind on the retrieval was identified especially at very large wind speed (SWS > 12 m/s). The minor difference of the statistic error budgets between the row 2 and 3 in Table 1 suggests the correlation between surface wind speed and retrieved τ represents a real aerosol signal from the wind driven aerosol particles rather than the disturbing effect from the false surface reflectance that was claimed in the self-consistent check studies performed by, for example, Ignatov and Nalli (2002) for AVHRR aerosol retrieval.

After the sub-pixel cloud contamination and surface wind effects are minimized (or removed) in the τ match-ups, the positive biases in the SSF τ (compared to AERONET τ) for mean conditions have been reduced from 0.05 to 0.02 in VIRS channel 1 (0.63μm) and 0.05 to 0.03 in channel 2 (1.61μm). Random errors have also been reduced from 0.09 to 0.06 at 0.63μm, and 0.06 to 0.05 at 1.61μm. The remaining proportional systematic error (see Table 1), especially at large optical thickness, was mainly the result of improper assumptions on the aerosol parameters in the retrieval algorithm. For example, we have proved in our early validation work (Zhao et al., 2002) that the proportional systematic error at large τ can be reduced by increasing aerosol absorption (the imaginary part of the refractive index). This is understood on the physical grounds that larger optical thickness is always associated with larger particles where absorption becomes more important than in small particles. The remaining small systematic error at low τ and the random error were mainly due to calibration error, radiometric noise, and measurement instability, which was not the focus of this paper.

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REFERENCE

Geier, E. B., R. N. Green, D. P. Kratz, P. Minnis, W. F. Miller, S. K. Nolan, and C. B. Franklin, 2001: CERES Data Management System: Single Satellite Footprint TOA/Surface Fluxes and Clouds (SSF) Collection Document, Release 1, Version 6, 194pp, Radiation and aerosols branch, Atmospheric sciences research, NASA Langley Research Center, Hampton, Virginia.

Holben, B. N.,F. Eck, I. Slutsker, D. Tanre, J. P. Buis, A. Setzer, E. Vermote, J. A. Reagan, Y. J. Kaufman, T. Nakajima, F. Lavenu, I. Jankowiak, and A. Smirnov, 1998: AERONET-A federated instrument network and data archive for aerosol characterization, *Remote Sens. Environ.*, **66**, 1-16.

Ignatov, A. M., and N. R. Nalli, 2002: Aerosol retrievals from multi-year multi-satellite AVHRR pathfinder atmosphere (PATMOS) dataset for correcting remotely sensed sea surface temperatures, manuscript submitted to *J. Atmos. Ocean. Tech.*

IPCC, 2001: *Climate Change 2001: The Scientific Basis*, Cambridge University Press, 881pp.

Smirnov, A., B. N. Holben, T. F. Eck, O. Dubovik, and I. Slutsker, Cloud screening and quality control algorithms for the AERONET data base, *Remote Sens. Environ.*, **73**, 337-349, 2000.

Wielicki, B. A., B. R. Barkstrom, E. F. Harrison, R. B. Lee III, G. L. Smith, and J. E. Cooper, 1996: Clouds and the Earth's Radiant energy System (CERES): An earth observing system experiment, *Bull. Amer. Meteor. Soc.*, **77**, 853-868.

Wielicki, B. A., T. Wong, R. P. Allan, A. Slingo, J. T. Kiehl, B. J. Soden, C. T. Gordon, A. J. Miller, S-K. Yang, D. A. Randall, F. Robertson, J. Susskind, and H. Jacobowitz, 2002: Evidence for large decadal variability in the tropical mean radiative energy budget, *Science*, **295**, 841-844.

Zhao, T. X.-P., L. L. Stowe, A. B. Smirnov, D. Crosby, J. Sapper, and C. R. McClain, 2002: Development of a global validation package for satellite oceanic aerosol retrieval based on AERONET Sun/sky radiometer observations and Its application to NOAA/NESDIS operational aerosol retrievals, *J. Atmos. Sci.*, **59**, 294-312.