Validation of two-channel VIRS retrievals of aerosol optical thickness over ocean and quantitative evaluation of the impact from potential subpixel cloud contamination and surface wind effect

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[1] TRMM/CERES-VIRS Single Satellite Footprint (SSF) data and AERONET Sun/sky radiometer observations from 1998 have been combined to validate SSF aerosol optical thickness (τ) retrievals over ocean along with a quantitative evaluation of the effects of potential subpixel cloud contamination and surface wind on the satellite τ retrievals. Potential subpixel cloud contamination is verified in Visible/Infrared Scanner (VIRS) SSF aerosol retrievals and constitutes a major source of systematic and random errors of the retrieval algorithm as determined from comparisons with AERONET observations. A positive correlation between the surface wind speed (which determines the roughness of the ocean surface) and the SSF τ has been observed for large surface wind speed. The validation results imply this correlation represents the real relationship between the surface wind and the wind-driven aerosols rather than the disturbing effect of the surface reflectance associated with the rough ocean surface. After the potential subpixel cloud contamination is minimized and the effects of large surface wind are 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 (0.63 μm) and 0.05 to 0.03 in channel 2 (1.61 μm). Random errors have also been reduced from 0.09 to 0.06 at 0.63 μm, and from 0.06 to 0.05 at 1.61 μm. The validation results support the application of the SSF aerosol data in radiation and climate studies as well as supply useful guidance for the adjustment and improvement of the aerosol retrieval algorithm.

INDEX TERMS: 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0345 Atmospheric Composition and Structure: Pollution—urban and regional (0305); 0360 Atmospheric Composition and Structure: Transmission and scattering of radiation; 0365 Atmospheric Composition and Structure: Troposphere—composition and chemistry; KEYWORDS: aerosol retrieval, validation, remote sensing, cloud contamination


1. Introduction

[2] New sets of Earth radiation balance data are now being provided to the science community by the National Aeronautics and Space Administration (NASA) Clouds and the Earth’s Radiant Energy System (CERES) experiment. One of these data sets, the Single Satellite Footprint (SSF) data set, is derived from measurements made by instruments aboard the Tropical Rainfall Measurement Mission (TRMM) satellite for eight months in 1998 [Wielicki et al., 2000]. The TRMM spacecraft was launched on November 1997 and was placed into a low-inclination 35°, 350km altitude orbit. Nominal scientific data collection operations commenced on January 1998. Five instruments, CERES, Lightning Sensor (LIS), Precipitation Radar (PR), TRMM Microwave Imager (TMI), and Visible/Infrared Scanner (VIRS) are aboard the TRMM satellite. The major objective of the TRMM mission is quantitative measurements of tropical rainfall on a continuing basis over the entire tropics.

[3] The TRMM/CERES instrument is designed to measure top-of-the-atmosphere (TOA) Earth radiation budget components in three broadband regions (0.3−5.0 μm, 0.3−100 μm, and 8−12 μm). This broadband instrument has a good calibration accuracy and stability due to onboard calibration sources [Priestley et al., 2000]. The coarse spatial resolution (~10km at nadir) is the main limitation of the instrument since it makes the detection of subfoot-
print-scale clouds difficult. The TRMM/VIRS instrument is a five-channel imaging spectroradiometer that measures radiation at 0.63, 1.61, 3.78, 10.8, and 12.0 μm. It is designed to measure cloud cover and cloud properties. The VIRS instrument is similar to the Advanced Very High Resolution Radiometer (AVHRR) but has a 2.11 km resolution at nadir compared to 1.1 km for AVHRR. Although VIRS was not designed to measure aerosol properties, to complement the radiation budget data, aerosol optical thickness retrieved from an AVHRR type retrieval algorithm using the two short wavelength channels (0.63 μm and 1.61 μm) of VIRS was added to the SSF data.

[4] The TRMM/CERES-VIRS Single Satellite Footprint (SSF) data set combines radiances from CERES, cloud and aerosol from VIRS, and assimilated meteorological fields in a single CERES footprint, and thus provides fairly complete and convenient data for radiation and climate studies. One of the major purposes of this merging is to improve the identification of cloud-free CERES fields of view using the higher resolution VIRS data. The improvement has been demonstrated by Loeb and Kato [2002] through a comparison of the aerosol direct radiative effect based on scene identification from the CERES SSF with that deduced from the CERES ERBE-like product. The SSF data, combined with the 16-year records of the Earth Radiation Budget Satellite (ERBS), are unique for the evaluation of radiative fluxes in tropical regions [see Wielicki et al., 2002].

[5] The SSF data are also useful 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 [Hansen and Lacis, 1990; Charlson et al., 1992]. Better information on the global distribution, chemical and microphysical properties of aerosols are needed to reduce these uncertainties.

[6] Satellite aerosol optical thickness (τ) retrieval supplies a unique tool to monitor the global distribution of aerosol particles. However, satellite aerosol retrieval requires a very careful separation of the weak aerosol signal from disturbing effects associated with radiometric and calibration errors of the sensor, inaccurate assumptions in the retrieval algorithm, atmospheric gas absorption, surface reflectance effect, and cloud contamination. The uncertainties associated with these elements are more notable in the τ1 and τ2 retrievals from the two VIRS channels (λ1 = 0.63 μm and λ2 = 1.61 μm) in the SSF data due to the following factors. First, there is a recognized sensor thermal leak defect in the VIRS 1.61 μm channel [Barnes et al., 2000] plus an unstable onboard calibration (R. A. Barnes, private communication, 2001). These radiometric defects will inevitably result in errors in the retrieval of τ (especially in channel 2) and the Ångström wavelength exponent (α) derived from τ1 and τ2 according to the formula, α = −ln(τ1/τ2)/ln(λ1/λ2). Second, a fixed aerosol model and constant surface wind speed were assumed in the retrieval algorithm due to the limitation of channels available for their retrieval. Moreover, the coarse resolution view makes the subpixel cloud contamination more likely since SSF τ is composed from the aerosol optical thickness retrieved from the subpixel radiance (with a resolution of about 2 × 2 km²) of VIRS in CERES footprints.

[7] These uncertainties will be reduced in the aerosol retrieval from a more advanced imager sensor, such as MODIS, on the EOS satellite due to its high spectral and spatial resolutions and lower radiometric noise. In consideration of the above limitations, VIRS aerosol retrieval requirement is to make retrievals with an accuracy that is consistent with these limitations. The validation efforts presented in this paper are to verify the fulfillment of our objective as well as to supply a well documented error budget of aerosol retrievals over the ocean from the Visible/Infrared Scanner in support of aerosol radiative forcing studies. At the same time, the subpixel cloud contamination and surface wind effect (which are recognized as the two major error sources in the aerosol retrieval algorithm) will be addressed and their contribution to the error budget will be quantified through a validation against surface Aerosol Robotic Network (AERONET) observations.

2. Revised Aerosol Retrieval Algorithm

[8] A new version of the two-channel NOAA/NESDIS aerosol retrieval algorithm [see Ignatov and Stowe, 2000] is used to derive aerosol optical thickness (τ1 and τ2) in VIRS channels 1 (λ1 = 0.63 μm) and 2 (λ2 = 1.61 μm) on the pixel level (~2 × 2 km² resolution). The method determines τ1 and τ2 through a comparison of observed normalized radiances with precalculated ones that are stored in lookup tables (LUTs) for channels 1 and 2 at preselected τ values, view-Sun-azimuth angles, and fixed atmospheric parameters. Some modifications have been made in the current version of the retrieval algorithm compared to its early version used for AVHRR aerosol retrieval. For example, a more widely used bimodal (corresponding to small and large particles, respectively) lognormal aerosol size distribution replaced the mono-modal lognormal distribution even though the resulting changes in τ was not anticipated big [see also Geogdzhayev et al., 2002]. The more comprehensive and flexible 6S radiative transfer code [Vermote et al., 1997] has replaced the older Dave code [Dave, 1973] for the generation of the LUTs. In the 6S code, the surface reflectance is treated more realistically as a wavy Fresnel surface with wind-driven slopes (including foam and whitecap effects), whereas the Dave code assumed a Lambertian oceanic reflectance with a diffuse glint correction to the aerosol phase function. The independent-channel retrieval has also been replaced with combined usage of both independent- and dependent-channel approaches described below.

[9] Since only two radiances are available in the two-channel retrieval algorithm, deriving aerosol properties is a highly underdetermined process in which only two properties can be derived independently while holding other aerosol model parameters fixed. In the independent approach, τ1 and τ2 are retrieved independently for both channels. These τ1 and τ2 can be used further to derive the Ångström wavelength exponent α using the relationship α = −ln(τ1/τ2)/ln(λ1/λ2), which is thought to be indicative of aerosol particle size. In the dependent approach, the α parameter obtained from the independent retrieval is used as a first guess to determine a more realistic aerosol model to be used in the second iteration for the final τ1 and τ2 retrievals. In theory, the dependent retrieval is expected to better account for aerosol size than the independent retrieval. However, parameter α derived from actual satellite observations is noisier than the aerosol optical thickness
Existing two-channel aerosol retrieval algorithms [e.g., Stowe et al., 1997; Higurashi and Nakajima, 1999; Mishchenko et al., 1999; Ignatov and Stowe, 2000] used for AVHRR and VIRS type instruments are based on independent approaches with fixed aerosol model (or fixed $\alpha$) for the generation of LUTs. This may introduce errors in the retrieved $\tau$ values since various types of aerosols (with substantial spatial and temporal variations) coexist in the troposphere. To improve the representation of the various aerosol sizes, we use the dependent approach with three types of aerosol distribution, corresponding to large ($\alpha = 0.1$), medium ($\alpha = 0.9$), and small ($\alpha = 1.7$) particles, respectively. Even though the aerosols over the ocean are not completely confined in the regime of $0.1 \leq \alpha \leq 1.7$, we use it in the retrieval algorithm due to the following two considerations.

First, analyses on the AVHRR and VIRS aerosol retrieval [see Geogdzhayev et al., 2002; Ignatov and Nalli, 2002] revealed that the majority of aerosols over the ocean fall in this regime. Second, the retrieval of aerosols outside this regime is subject to more disturbance from radiometric noises, or surface reflectance, or cloud contamination. For example, an undetected cloud contamination may be wrongly interpreted by the retrieval algorithm as a signal of large aerosol particles (corresponding to smaller $\alpha$). On the other hand, small aerosol particles (corresponding to larger $\alpha$) are generally associated with weak aerosol signals (or low $\tau$ values) that are easily masked by radiometric noise.

In the current version of the VIRS retrieval, three LUTs for both VIRS visible (0.63 $\mu$m) and near-IR (1.61 $\mu$m) channels have been calculated in advance. For each channel, they correspond to three combinations of large and small size modes in the bimodal lognormal size distribution (corresponding to three values of $\alpha$: 0.1, 0.9, and 1.7). The two LUTs with $\alpha = 0.9$ are the standard tables for the independent retrieval from channels 1 and 2. The final retrieval for each of the two channels is performed through the interpolation between the two tables selected (out of three) based on the value of the first guess $\alpha$ from the independent retrieval. If the dependent retrieval fails (e.g., first guess $\alpha$ is not in the range of 0.1 $\alpha$ 1.7), the independent retrieval is applied instead using the LUTs with $\alpha = 0.9$. Thus, the retrievals are confined to within $0.1 \leq \alpha \leq 1.7$, which is similar to the “constrained” version of the two-channel AVHRR aerosol retrieval algorithm developed by Geogdzhayev et al. [2002].

The readers may refer to Ignatov and Stowe [2002a, 2002b] for a more detailed description on both dependent and independent approaches. Retrieved VIRS pixel level $\tau$ were averaged according to a point spread function (PSF) over the larger CERES Single Satellite Footprint (with a resolution from about 10 $\times$ 10 to 50 $\times$ 50 $\text{km}^2$) to form the SSF product.

3. Data Sets

The first data set used in our analysis is the Edition 2A 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 combine one hour of instantaneous CERES radiation data with scene information from the higher-resolution Visible/Infrared Scanner on TRMM along with some ancillary meteorological fields. Scene identification, cloud, and aerosol properties are defined at the higher imager resolution (~2km $\times$ 2km), so they are averaged according to a point spread function (PSF) over the larger CERES footprint (about 10km $\times$ 10m at nadir). There are 131 product parameters in the SSF data. A detailed description of the SSF data can be found in the SSF Collection Guide (http://asd-www.larc.nasa.gov). 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 ($\tau$$_g$, and $\tau$$_c$) in the SSF data are derived from averaging their pixel values according to the PSF of the CERES footprints.

The AERONET observations from the automatic CIMEL Sun/sky radiometers [Holben et al., 1998, 2001] provide the ground truth used in the evaluation of the SSF aerosol optical thickness. The AERONET was initiated [Holben et al., 1998] by the NASA Earth Observing System and expanded recently through federation with many non-NASA institutions [Holben et al., 2001; Fargion et al., 2001]. The AERONET aerosol optical thickness, $\tau$_sp, is derived from the Sun photometer measurement of spectral attenuation of the direct solar beam (while the size distribution is derived from the Sun and sky radiance data measured from sky radiometer). Thus, the accuracy of AERONET $\tau$ observation is much higher than that derived from backward scattering radiance measured from satellite, which is “contaminated” by varying surface (land, ocean, cloud) properties. The AERONET $\tau$$_sp$, has served as the ground-truth for the validation of the aerosol retrieval from AVHRR [Higurashi et al., 2000; Zhao et al., 2002], MODIS [Remer et al., 2002; Chu et al., 2002], and SeaWiFS [Ainsworth et al., 2001; Liberti et al., 2001].

In our validation, $\tau$_sp were interpolated or extrapolated to the wavelengths of the two VIRS channels since none of the AERONET spectral channels match exactly the two VIRS channels. An optimal interpolation/extrapolation scheme designed to minimize the errors associated with the interpolation/extrapolation was applied. The scheme was constructed based on sensitivity studies; a detailed description of the technique is provided in Section 2 (pages 298–301) of Zhao et al. [2002]. For convenience, we subsequently refer to these AERONET solar extinction measurements as Sun photometer (SP) data. Quality controlled Level 2 AERONET SP data [see Smirnov et al., 2000] from 1998 have been used in this study, which is available through the AERONET web site (http://aeronet.gsfc.nasa.gov).

4. Methodology

In general, the quality of satellite $\tau$ retrievals depends on the accuracy of the instrument (e.g., errors in calibration and radiometric digitization) and the uncertainties of the retrieval algorithm (e.g., aerosol model assumption, cloud contamination, and treatment of surface reflection). This can be more clearly illustrated by using the following linearized single scattering approximation of
the radiative transfer equation in a clear-sky condition [see Stowe et al., 1997]:

$$\tau_{ST} = 4\mu_a \mu_v \frac{\rho - \rho^a - \rho^d}{\omega P^d}, \tag{1}$$

where $\rho$, $\rho^a$, and $\rho^d$ are satellite measured apparent reflectance, Rayleigh scattering contribution, and diffuse surface reflectance, respectively; $P^d$ and $\omega$ are the aerosol phase function and single scattering albedo; $\mu_a$ and $\mu_v$ are the cosines of solar and view zenith angles. The errors in the aerosol optical thickness $\tau_{ST}$ come mainly from uncertainty in $\rho$ due to radiometric and calibration errors, and cloud contamination, $\rho^a$ (due to foam, whitecap, and bidirectional reflection), $P^d$ and $\omega$ (due to errors in the assumption of aerosol optical properties) since all other terms are reasonably well known. We note that equation (1) is used here only for illustration. The LUTs employed in the actual aerosol retrieval are based on calculations from the 6S code that accounts for the aerosol multiple scattering effects of the radiative transfer.

[18] The unique TRMM/CERES-VIRS SSF data allow new insight into the effect of clouds and surface wind on aerosol retrievals. Simultaneous VIRS observations of aerosol and cloud cover along with the assimilated ocean surface wind speed (SWS) allow the $\tau$ retrievals to be classified for variable sky and surface conditions. At the same time, the AERONET observations supply the “ground truth” for aerosol optical thickness, which conveniently allows the impact of the two elements on the $\tau$ retrievals to be evaluated and quantified.

[19] We will focus our analyses on the accuracy of the retrieval algorithm (especially the errors associated with the subpixel cloud contamination and the surface roughness) rather than on that associated with the instrument for two reasons. First, accurate onboard calibration of the VIRS instrument is not an easy task, especially due to the sensor defect (thermal leak) on its channel 2 (see Barnes et al. [2000] and later discussions). Efforts are still ongoing to improve the calibration [see Lyu et al., 2000], especially for the channel 2. Its impact on the aerosol retrieval will be evaluated separately after the VIRS calibrations have been finalized. The second reason is that subpixel cloud contamination and surface roughness (associated with foam, whitecap, and bidirectional reflection) have been recognized as the two major error sources of many retrieval algorithms [Tanre et al., 1996; Wagener et al., 1997; Mishchenko et al., 1999; Higurashi and Nakajima, 1999]. Previous attempts to assess their effects on $\tau$ retrievals were limited to theoretical (or sensitivity) studies and self-consistency checks [e.g., Tanre et al., 1997; Mishchenko et al., 1999; Geogdzhayev et al., 2002; Ignatov and Nalli, 2002]. Thus, quantifying the impact of these two elements on the $\tau$ retrievals is highly relevant.

[20] It has been mentioned above that subpixel cloud contamination and inappropriate treatment of the rough ocean surface can lead to a false aerosol signal. On the other hand, the increase of the radiance due to the presence of a cloud near the clear-sky pixel used for aerosol retrieval, or due to an increased wind speed may not all be false. For example, the meteorological conditions (such as humidity) around cloud edges are different from those far away from the cloud. Thus, aerosol optical properties may be different, just as the aerosol optical thickness may actually be enhanced [Nemesure et al., 1995]. Increasing wind speed can also produce more aerosols associated with enhanced breaking waves [e.g., Blanchard and Woodcock, 1980]. A simple correlation of satellite-retrieved aerosol optical thickness with cloud cover and wind speed (used in sensitivity studies and self-consistency checks) can only detect mixed (real and false) aerosol signals without separating these two components. In contrary, the false signals are absent or much reduced in aerosol optical thickness retrievals performed on the ground, such as the AERONET observations. Therefore, we use the AERONET data to represent the true aerosol signal, and interpret any deviation from the AERONET data as a false signal indicative of cloud contamination and wind speed effect.

[21] Our approach is to combine correlation analysis with surface validation. Histograms of $\tau$ versus an index that can represent clear-sky conditions (such as cloud fraction) or surface roughness (such as surface wind speed) will be used to identify the potential correlation between $\tau$ and the index. However, as pointed out above, the identified potential correlation may include both real and false (contaminated) aerosol signals. Validation with the “ground truth” (which is less contaminated) is added to further isolate possible contamination.

[22] In the validation, the aerosol optical thickness from the SSF satellite data ($\tau_{sp}$) are colocated with that from the AERONET SP observations ($\tau_{sp}$) 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 [see Husar et al., 1997; Dubovik et al., 2002; Smirnov et al., 2002]. A circular area with a 25km radius around each AERONET station is eliminated from the match-up window to reduce the effect of land surface reflectance. Scatter diagrams of $\tau_{st}$ versus $\tau_{sp}$ are produced and statistics are calculated for the overlap match-up points. Linear regression analyses are performed, predicting the satellite retrieval values of $\tau_{sp}$ as a function of $\tau_{sp}$ in the form of $\tau_{sp} = A + B\tau_{sp}$. Retrieval algorithm performance can be evaluated from the resulting four statistical parameters of the linear regression: A (intercept), B (slope), $\sigma$ (standard error), and $R$ (correlation coefficient). For example, a nonzero intercept tells us the retrieval algorithm is biased at low $\tau$ values, which may result from the additive errors (refer to equation (1)) associated with calibration, ocean surface reflectance, and subpixel cloud contamination. A slope that is different from unity (proportional error) is mainly associated with incorrect assumptions in the aerosol model of the retrieval algorithm. The latter becomes dominant when $\tau$ is large (especially for a retrieval algorithm with a fixed global aerosol model). The standard error ($\sigma$) represents the magnitude of random error, which is proportional to radiometric measurement noise, ocean surface reflectance variability, and subpixel cloud contamination. A detailed description of the approach and the physical rationale behind it is given by Zhao et al. [2002].

[23] Since the number of the match-ups obtained for individual AERONET stations is not sufficient for statisti-
cally conclusive regional (or called second order) validation, all match-ups obtained over the eight AERONET stations are lumped together to form a “global” (or called first order) validation. The rational behind this is the expectation that, as a minimum, any satellite aerosol retrieval algorithm should perform reasonably well at least in the “global” sense. The concepts of the global and the regional validations have been described in detail by Zhao et al. [2002].

It is also worth clarifying that the oceanic aerosols mentioned in this paper refer to aerosols over the ocean rather than just those originating from oceanic sources. Actually, the aerosols originating from land are over wide regions of the ocean for a considerable period of time in a year due to atmospheric global transport. The various types of aerosols over the ocean are subjected to the same disturbing noises, except the relative importance of these disturbing factors may be different for the different aerosol types. For example, the aerosol signals from small aerosol particles are easily masked by false signals related to radiometric and digitization instability, cloud contamination, and surface reflectance variability. However, the error due to the improper assumption of aerosol absorption becomes the major disturbing factor for the retrieval of large particles.

Regional validation will be made from this simulated SSF data and the results will be reported in a future paper.

5. Primary Validation Results

Figures 1a and 1b show the scatterplots of $\tau_1$ and $\tau_2$, 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 is also given in the plots. We can see the match-up points are dispersed due to the existence of some outliers. The nonunity slope (B ≠ 1) comes from incorrect assumptions in the aerosol model. The random error is ±0.09 for channel 1 and ±0.06 for channel 2. A 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 conditions, which indicates the error sources of the retrieval are different for small and large aerosol loading conditions (see later discussions).

[27] We will check below to see whether the outliers observed in Figure 1 are due to the contamination by subpixel cloud and the surface roughness. If this is the case, we also would like to demonstrate that the validation results (systematic and random errors) can be improved after removing individual match-up SSF records (averaged to derive the SSF τ values for the overpass match-up points) that may have been influenced by the two contamination elements.

6. Subpixel Cloud Contamination

[28] Since our retrieval applies only to cloud-free pixels over oceans (represented by spatially uniform low surface albedo), the retrieved aerosol optical thickness will be biased high in the presence of even slight cloud amounts. Any residual cloud or its edge effect left in a clear subpixel from a cloud screening (or mask) scheme will result in the overestimation of aerosol optical thickness due to the retrieval algorithm incorrectly interpreting the enhanced reflectance from the brighter cloud surface as a higher aerosol signal.

[29] The CERES cloud mask scheme is based on a successive application of space-and-time-contrast and uniformity tests as well as temperature and radiance thresholds on the five VIRS channels (0.63, 1.61, 3.7, 10.8, and 12.00 μm). The scheme has incorporated many aspects of the three well-known cloud mask schemes developed for the International Satellite Cloud Climatology Project (ISCCP), Cloud from AVHRR (CLAVR), and Support of Environmental Requirements for Cloud Analysis and Archive (SERCAA). Detailed description of the scheme can be found in the algorithm theoretical basis document (ATBD) of CERES Imager Clear-Sky Determination and Cloud Detection (http://earth-www.larc.nasa.gov/~cwg/cloudmask/cloudmask.html) or in the works of Baum et al. [2001] and Minnis et al. [2001]. Each VIRS pixel is classified as clear, cloudy, bad data, or no retrieval. Each clear pixel is categorized as “weak” or “strong” to indicate the degree of confidence in the selection.

[30] A Clear Strong Index (CSI) is calculated as the PSF-weighted percent (from 0 to 100) of clear-strong pixels in the CERES field of view (FOV). If there are no clear-strong pixels in the FOV, then the coverage is set to zero (CSI = 0). If there are clear-strong pixels in the FOV, the coverage is set to 1% or greater (CSI ≥ 1). In addition to CSI, a Clear Area Percent Coverage (CAPC) is also reported in the SSF data. The CAPC is based on the subpixel resolution cloud fraction and is also PSF-weighted. It will be set to 0 when the percent coverage is less than 0.5%. A Cloud Fraction (CF) is derived by subtracting from 100 the SSF Clear Area Percent Coverage. More details on these parameters can be found in the SSF Collection Document [Geier et al., 2001]. This detailed classification of clear and cloudy conditions facilitates our analyses on subpixel cloud contamination. The two parameters, CSI and CF, provide two unique auxiliary indices that are used in the present study to identify and quantify subpixel cloud contamination in the aerosol optical thickness data. In general, the lower (higher) the CF (CSI) value, the less possibility for contamination from subpixel cloud. Therefore, we interpret an increase of τ with increasing cloud cover (and decreasing CSI) as a sign of potential subpixel cloud contamination.

[31] To identify the possible subpixel cloud contamination in the SSF match-up points displayed in Figure 1, we first checked to see if there is any correlation between retrieved τ and CSI (or CF). The approach is to average satellite τ1 and τ2 in selected bins of the ssf CSI for all 12950 match-up ssf records contained in the 94 match-up overpasses (or points). The result is plotted in Figure 2a. The corresponding number of records (or frequency) used in averaging for each bin is given in Figure 2b. Similar results but specified for derived CF are plotted in Figures 2c and 2d, respectively. One can see that τ1 and τ2 increase when CF increases (CSI decreases). This trend, as pointed out above, could be a sign of potential subpixel cloud contamination or the real aerosol signal, or a mixing of them.

[32] An attempt has been made to minimize the effect of possible subpixel cloud contamination as much as possible in the match-up records. The method is to pick out all the match-up records with CSI larger than 90% to form 74 new match-up points. It is expected that these new match-up points are less likely affected by subpixel cloud contamination. To prove this argument, the validation is applied to the new match-up points, and the results are given in Figure 3, and the systematic and random errors are presented in the second row of Table 1. It is obvious that some outliers observed in Figure 1 disappear in Figure 3. As a result, the mean SSF aerosol optical thickness in the two channels have also been reduced from $\bar{\tau}_1$(ST) = 0.214 and $\bar{\tau}_2$(ST) = 0.109 in Figure 1 to $\bar{\tau}_1$(ST) = 0.164 and $\bar{\tau}_2$(ST) = 0.083 in Figure 3. The corresponding AERONET aerosol optical thickness are

<table>
<thead>
<tr>
<th>Level of Data Quality</th>
<th>Channel Wavelength, μm</th>
<th>Minimum Δτ(τsp = 0) (or A)</th>
<th>Mean Δτ(τsp = τ) (or A + B $\bar{\tau}$ − $\bar{\tau}$)</th>
<th>Maximum Δτ(τsp = 1) (or A + B − 1)</th>
<th>Random Error (or $\sigma$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw match-up</td>
<td>0.63</td>
<td>+0.09</td>
<td>−0.05</td>
<td>−0.13</td>
<td>(±)0.09</td>
</tr>
<tr>
<td>data</td>
<td>1.61</td>
<td>+0.05</td>
<td>−0.05</td>
<td>−0.25</td>
<td>(±)0.06</td>
</tr>
<tr>
<td>Cloud effect minimized</td>
<td>1.61</td>
<td>+0.03</td>
<td>+0.03</td>
<td>+0.26</td>
<td>(±)0.05</td>
</tr>
<tr>
<td>Cloud and wind</td>
<td>0.63</td>
<td>+0.07</td>
<td>+0.02</td>
<td>−0.25</td>
<td>(±)0.06</td>
</tr>
<tr>
<td>effects minimized</td>
<td>1.61</td>
<td>+0.03</td>
<td>−0.03</td>
<td>−0.27</td>
<td>(±)0.05</td>
</tr>
</tbody>
</table>

$^a$ Systematic error is defined as $\Delta\tau = \tau_{SF} - \tau_{SP}$ (or $\Delta\tau = A + B\tau_{SP} - \tau_{SP}$), and random error is defined as $\sigma$. Parameters A, B, and $\sigma$ are intercept, slope, and standard deviation, respectively, of the linear regression line.
...and $t_2$ at 0.139 and $t_2$ at 0.062 in Figure 1, and $t_1$ at 0.139 and $t_2$ at 0.050 in Figure 3.

One can also see (in Table 1) the random errors in $t_1$ and $t_2$ have been reduced along with the reductions of systematic errors at the low and mean $t$ values. However, the systematic errors increase at large aerosol optical thickness. As pointed out in our earlier validation on AVHRR aerosol retrieval (Zhao et al., 2002), the systematic error at large $t$ is mainly due to the improper assumptions in the aerosol optical properties (such as refractive index). The larger systematic error observed at large $t$ (after the subpixel cloud contamination is minimized) implies the systematic errors caused by the subpixel cloud contamination and by the improper assumption of aerosol optical properties are in opposite sign. As a result, the systematic error due to the subpixel cloud contamination offsets part of the systematic error due to the improper assumption of aerosol optical properties.

**Figure 2.** SSF $\tau_1$ and $\tau_2$ values averaged for all the match-up records according to selected bins of (a) the SSF Clear Strong Index and (c) the SSF Cloud Fraction. The corresponding number (frequency) of the match-up records used in averaging for each bin is given in (b) and (d), respectively.

**Figure 3.** The same as Figure 1, but for the match-up data in which the subpixel cloud contamination has been minimized by selecting only the match-up records with Clear Strong Index larger than 90% from all the records contained in every individual match-up point.
error caused by the improper assumption of aerosol optical properties in the case before the subpixel cloud contamination is reduced.

[34] The reduction of the random errors and the increase of systematic errors at large $\tau$ in the channel 1 aerosol optical thickness by minimizing the subpixel cloud contamination is greater than that in channel 2. One would expect a similar improvement on the retrieved optical thickness in both channels after removing the subpixel cloud contamination since the wavelength dependence of cloud optical thickness in the wavelength range of channels 1 and 2 is weaker than that of aerosol optical thickness. The cause of this inconsistent improvement of the optical thickness in the two channels is still not clear. It is probably related to the radiometric noise and the unstable onboard calibration of the channel 2 sensor. The thermal leak of VIRS channel 2 filter at 5.2 μm is now a widely recognized radiometric defect of the VIRS sensor [Barnes et al., 2000]. Ignatov and Stowe [2000] estimated that this thermal leak may lead to errors in $\tau_2$ of 100% or more considering the aerosol retrieval is performed on weak signals (over dark and uniform ocean surface). A thermal leak correction for the VIRS $\tau_2$ retrieval was thus developed based on an empirical function of radiances in VIRS channels 4 (10.8 μm) and 5 (12 μm) and view angle [Ignatov and Stowe, 2000]. Since it is derived from data limited to a 1-day (May 1, 1998) period as well as without considering the variations in the surface emissivity, its performance under varying surface and seasonal conditions still need to be verified.

[35] Inconsistencies in cloud droplet size retrieved from channels 2 (1.61 μm) and 3 (3.7 μm) radiances have also been observed [Young et al., 1999]. The particle sizes derived at 1.61 μm are much larger than their 3.7 μm counterparts using the normal VIRS calibration but were in excellent agreement using the ERS-2 Along Track Scanning Radiometer (ATSR-2) gains. Thus, it was concluded that additional correction must be applied to the 1.61 μm radiance and an empirical value of $r_2 = 1.17/r_2$ has been adopted [see Minnis et al., 1999a, 1999b]. This empirical correction factor may also cause errors in $\tau_2$ retrieval since it is based on the radiance from a bright cloud surface so that a small error (negligible for the cloud retrieval) can be significant for the aerosol retrievals relying on a weak signal from the dark ocean surface. This is especially true for small $\tau$.

[36] In consideration of the above uncertainties in the channel 2 radiance, the validation of the retrievals from this channel could not be considered conclusive. Subsequent results and discussions will focus on the retrieval from channel 1, while those from channel 2 will be mentioned just for completeness. In conclusion, subpixel cloud contamination is identified in the VIRS aerosol retrieval in the SSF data. The validation results are improved after the subpixel cloud contamination removed or minimized in the match-up points.

7. Surface Wind Effect

[37] Even though we have removed a circular area (with a radius of 25 km) around the eight AERONET stations from our match-up window to reduce the coast effect, the surface roughness effect still need to be consider in the retrieval. It is worth examining the importance of this effect on the VIRS aerosol retrieval in the SSF data. As pointed out before, the absolute magnitude of this disturbing effect is the same for all the aerosols over the ocean (originating from both ocean and land) but the relative importance can be different. Moreover, for the marine type aerosols, more particles may actually be generated due to the enhanced wave breaks on a more wavy coastal ocean surface. It would be desirable to separate this real aerosol signal from the disturbing noise for different aerosol types through the regional validation. Unfortunately, the match-ups obtained so far are not sufficient for this purpose. Thus, the following analyses of the surface roughness effect on the retrieval of aerosols are only performed on the ensemble of all aerosols included in the match-ups. However, one can still see below that separation of real correlation between the surface wind and retrieved $\tau$ from the disturbing effect of a rough ocean surface is still possible in the qualitative sense, through a logical deduction from the global validation results.

[38] Since sea surface conditions, such as roughness, foam, and whitecaps, are strongly related with the surface wind speed [Koepke, 1984; Morel, 1988; Frouin et al., 1996; Wagener et al., 1997], the SSF Surface Wind Speed (SWS) parameter is a good indicator of the variability of the surface condition and roughness. We derived SWS from the U and V vectors of the observed surface wind. These two SSF parameters are taken from the DAO and ECMWF assimilation wind fields and merged to CERES FOV through interpolation [Geier et al., 2001].

[39] Similar to the analyses on the relationship between retrieved $\tau$ and CSI (or CF) presented in Figure 2, the relationship between retrieved $\tau$ and SWS has also been examined, and the results are displayed in Figure 4. One can see that, similar to Figure 2, a trend is also observed in Figure 4. The aerosol retrieval becomes very sensitive to SWS when the surface wind is very strong (SWS > 12 m/s), and the $\tau_1$ can increase by as much as 0.6 over those associated with low wind speeds. In situ measurements on both an island station [Platt and Patterson, 1986] and ship decks over the open ocean [Smirnov et al., 1995] indicated more aerosols are generated from the ocean surface when the surface wind becomes strong. A satellite retrieval algorithm may or may not be able to capture this real physical process. This is because strong winds can sharply intensify the formation of bright foam (white caps) and the roughness of the ocean surface (which may enhance the bidirectional reflection by increasing the mean square slope) [e.g., Wagener et al., 1997; Nalli et al., 2001]. The retrieval algorithm may incorrectly interpret this enhanced reflectance as a higher aerosol signal and mask the real signal from the wind-driven aerosol since a constant wind speed (1 m/s) is assumed in our retrieval algorithm. Thus, the trend displayed in Figure 4 is expected to contain a mixture of real and false aerosol signals. Interestingly, Ignatov and Nalli [2002] have also observed similar wind speed dependence on the PATMOS aerosol data for both AVHRR channels 1 (0.63 μm) and 2 (0.83 μm) using an independent-channel algorithm similar to the one used here. This wind speed dependence can further propagate into the aerosol direct radiative effect noticed by Loeb and Kato [2002] in their analysis with TRMM/CERES-VIRS SSF data.
The inconsistent wind speed dependence between VIRS channels 1 and 2 ($\tau_2$ decreases) at large wind speed in Figure 4 is not an expected result. The cause is not yet clear, although it may very well be associated with the channel 2 defect mentioned above. The empirical thermal leak correction may overcorrect the thermal leak errors of VIRS channel 2 since it was derived from only a single day of dark albedo data but applied to all the observation time as mentioned above. The relative large spectral difference of whitecap reflectance at large wind speed between VIRS two channels [see Moore et al., 2000] may also explain some of the difference. However, more investigation is necessary for the final confirmation of the assumptions.

To minimize the disturbing effect due to the wind-driven variability of ocean surface reflectance, the match-up SSF records with surface wind speed less than or equal to 1 m/s (which is also the value adopted in the aerosol retrieval algorithm) were further selected from the above individual match-up points, in which subpixel cloud contamination had already been removed. These filtered records were used to form a total of 70 overpass match-up points, in which both subpixel cloud contamination and surface wind effect had been removed or at least been minimized. The validation of the new match-up data is for the conditions without strong surface wind.

The validation result after the subpixel cloud contamination and surface wind effects have been minimized is given in Figure 5. The mean aerosol optical thickness is $\bar{\tau}_1$(ST) = 0.165 and $\bar{\tau}_2$(ST) = 0.081 for SSF data, and $\bar{\tau}_1$(SP) = 0.144 and $\bar{\tau}_2$(SP) = 0.051 for AERONET SP data. It is interesting to note that the results displayed in Figure 5 is very close to that in Figure 3 (actually no visual difference). The improvement in the error budgets (refer to the last two rows in Table 1) is also minor (only significant at the third decimal place). Let us first assume the false aerosol signal resulted from the improper representation of the variable surface reflectance at the wind speed larger than that used in the retrieval algorithm (1m/s) is dominant for the trend observed in Figure 4. Discarding the satellite records with surface wind speed > 1 m/s in the match-up points removes both the false (assuming dominant) and the real aerosol signals related to large surface wind. The resultant new match-up points (used in Figure 5) are subject to much less influence from the variable surface reflectance. Thus, we should see the improvement on the validation results in Figure 5.

The only logical explanation for this observed minor difference in the validation results before and after the SSF records associated with surface wind speed > 1m/s being removed is the assumption that false aerosol signal is dominant for the trend observed in Figure 4 is incorrect. Instead, the trend observed in Figure 4 must represent the real signal of the wind-driven aerosols, or, at least, the wind-driven aerosol signal is dominant compared to the disturbing effect from the rough ocean surface. This conclusion is consistent with that from the analyses of the in situ measurements over the ocean [e.g., Platt and Patterson, 1986; Smirnov et al., 1995]. We have noticed (in Figure 4a) this wind-driven aerosol signal becomes identifiable only when surface wind speed is large (>12 m/s). For general surface wind condition (~3–8 m/s), it is difficult to identify the wind-driven aerosol signal due to the disturbing noise associated with different aerosol types. Thus, detailed regional validation is necessary in the future to single out the maritime optical situation for the general surface wind condition.

8. Summary and Discussions

We used the TRMM/CERES-VIRS SSF data and AERONET SP observations from 1998 to investigate the
The effects of subpixel cloud contamination and surface wind on the satellite aerosol optical thickness retrieval over ocean through validation. The purpose of the work is to document the error budget of the VIRS aerosol retrievals in the SSF data and to identify the major potential error sources associated with the retrieval algorithm. The results have implications for aerosol radiative forcing studies that use the SSF aerosol data and for the improvement of the aerosol retrieval algorithm.

The validation was first performed for the original (or raw) match-up points found in 1998 with subpixel cloud contamination and varying surface wind speeds. The validation was next performed for a subset of match-up points with the subpixel cloud contamination minimized. Finally, the surface wind effect was also minimized 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 \( \tau \), 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. Due to the sensor defect and the calibration uncertainties in VIRS channel 2, the validation results for this channel could not be considered conclusive. Subsequent conclusions and discussions are mainly based on the results from the channel 1.

Subpixel cloud contamination was found to be a major source of systematic (additive and multiplicative) and random error for the VIRS aerosol retrieval algorithm used in the SSF data. The random errors in \( \tau_1 \) and \( \tau_2 \) were improved along with the reductions of systematic errors at low to mean \( \tau \) values after subpixel cloud contaminated records were reduced from the match-up samples.

A positive correlation between surface wind speed and retrieved SSF aerosol optical thickness was identified in the correlation analysis. The validation result further indicated this correlation (especially for large surface wind condition) represented mainly a real aerosol signal from the wind-driven aerosols rather than the disturbing effect from the surface reflectance.

After the subpixel cloud contamination and surface wind effects are minimized in the match-ups, the positive biases in the SSF \( \tau \) (compared to AERONET \( \tau \)) for mean conditions have been reduced from 0.05 to 0.02 in VIRS channel 1 (0.63 \( \mu \)m) and 0.05 to 0.03 in channel 2 (1.61 \( \mu \)m). Random errors have also been reduced from 0.09 to 0.06 at 0.63 \( \mu \)m, and from 0.06 to 0.05 at 1.61 \( \mu \)m. These values supply a useful guidance for the adjustment and the improvement of the retrieval algorithm in the study. For example, if the aerosol retrieval is performed on more stringent clear-sky condition (such as Clear Strong Index is larger than 20%), retrieved \( \tau \) will less affected by subpixel cloud contamination.

The remaining small systematic error at low \( \tau \) and the random error were mainly due to calibration error, radiometric noise, and measurement instability, which was not the focus of this paper. These sensor related error sources are anticipated to have less effect on the aerosol retrieval from more advanced image instruments, such as multispectral imaging spectrometers like MODIS, and multiangular viewing radiometers like MISR aboard the EOS satellite. Currently, the MODIS measurements on the TERRA satellite are used for the aerosol retrieval in the TERRA/CERES-MODIS SSF data. Inter-comparison of the TERRA/CERES-MODIS SSF aerosol data and the TRMM/CERES-VIRS SSF aerosol data will supply us a unique opportunity for analyzing the effect of these sensor related errors in the near future.

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

![Figure 5](https://example.com/figure5.png)
in a previous validation work [Zhao et al., 2002] that the proportional systematic error at large $\tau$ 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.

[51] Due to the limitation of the match-up points for selected individual validation sites, only the global ensemble validation was performed and all the aerosols over the ocean are treated together regardless of their type. Thus, the conclusions drawn in the paper are in the sense of a global (or the first order) validation. Validation of the performance of the retrieval algorithm for different aerosol types over the ocean and evaluation of the relative importance of the disturbing effects on each individual type are necessary. This will be the target of our regional validation effort in the future. Fortunately, the generation of CERES SSF data from VIRS retrievals in the CERES project at NASA Langley is now being extended beyond August 1998 (the month of CERES instrument on TRMM failed). Aerosol products are generated for simulated CERES footprints from the retrieval on the subpixel radiance of VIRS. The new data (called simulated SSF data) will cover multiple years (from September 1998 to about July 2001). Therefore, more match-ups will be searched when the simulated SSF data are available for our analysis, and the regional validation will be performed to evaluate the performance of the retrieval algorithm for different aerosol types.

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