INCREASING TREND OF ANGSTROM EXPONENT OVER EAST ASIAN WATERS OBSERVED IN 1998-2005 SEAWIFS DATA SET

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ABSTRACT: Monthly mean data of Ångström exponent and Aerosol optical thickness (AOT) from Sea-viewing Wide Field-of-view Sensor (SeaWiFS) measurements over the East Asian waters were analyzed. Increasing trend of the satellite-derived Ångström exponent from 1998 to 2004 was found while AOT mean was observed stable during the same period. The trend of Ångström exponent is then interpreted as increase in fraction of small aerosol particles to give quantitative estimates on the variability of aerosols. The mean increase is evaluated to be 4~5% over the 7-year period in terms of the contribution of small particles to the total AOT, or sub-micron fraction (SMF). Possibilities of the observed trend arising from the sensor calibration or algorithm performance are carefully checked, which confirm our belief that this observed trend is rather a real fact than an artifact due to data processing. Another time series of SMF data (2000-2005) estimated from the fine-mode fraction (FMF) of Moderate Resolution Imaging Spectroradiometer (MODIS) supports this observation yet with different calibration system and retrieval algorithms.

KEY WORDS: Ångström coefficient, Temporal variability of aerosol, Anthropogenic effect, MODIS

1. INTRODUCTION

Aerosols, with great spatial and temporal variability in species and concentrations, play an important role in Earth's radiation budget. Aerosols would influence radiative forcing directly through scattering and absorbing effects in the, and also indirectly by modifying cloud albedo, lifetime, precipitation and extent. Knowledge of aerosol property would effectively help to improve the accuracy of radiative forcing.

East Asian area is supposed to be one of the strongest source regions of anthropogenic aerosols due to the rapid growing economy. In addition, natural aerosols (such as Asian dust or non-farming biomass burning products), are also affected by the human activities, which further enhance the complexity of aerosols in this region. Temporal and spatial variability of aerosol loadings in East Asia are still poorly understood, especially the area over the ocean, where field measurements are hard to perform routinely, although various campaigns such as ACE-Asia have been carried out recently in this area.

SeaWiFS-derived aerosol data were used in this paper to study the temporal variability of aerosols above ocean in East Asia. Seven year time series of monthly mean AOT and Ångström exponent for 6 sub-areas were analyzed. A slightly increasing trend of Ångström exponent was observed and the trend was then evaluated in terms of sub-micron fraction of AOT. The increasing trend of Ångström exponent is most possibly related to the increase in fraction of small aerosol particles, in view of the high reliability of the SeaWiFS sensor calibration. MODIS retrieved fine-mode fraction data were compared with the result of SeaWiFS data and similar trend was observed.

2. DATA AND PROCESSING METHOD

SeaWiFS, launched in 1997, has generated more than 8-year global aerosol (over the ocean) and ocean color data simultaneously. SeaWiFS was primarily designed for global ocean color measurement and thus has very high signal-to-noise characteristics. It has 8 bands, centered at 412, 443, 490, 510, 555, 670, 765 and 865nm, with bandwidth of 20nm for the first six and 40nm for the last two NIR bands.

SeaWiFS Global Area Coverage (GAC) data with spatial resolution of 4km were used in this study and were processed with SeaWiFS Data Analysis System (SeaDAS 4.8) [Baith et al, 2001], a comprehensive image analysis package that employs Gordon and Wang's [1994] method for atmospheric correction to estimate and correct the aerosol effect. Local variance method was applied to mask the cloud pixels, with the threshold of 0.02 for the 3*3 local variance of AOT at 490nm. This method is less strict compared to the SeaWiFS standard cloud mask algorithm, leaving enough data even under higher aerosol loadings.

For the standard atmospheric correction and the aerosol retrieval implemented by SeaDAS, a set of 12 non-absorptive or weakly absorptive aerosol models, including oceanic, maritime, coastal and tropospheric models with different relative humidity (RH), is adopted in the calculation of aerosol lookup tables [Wang, 2000].

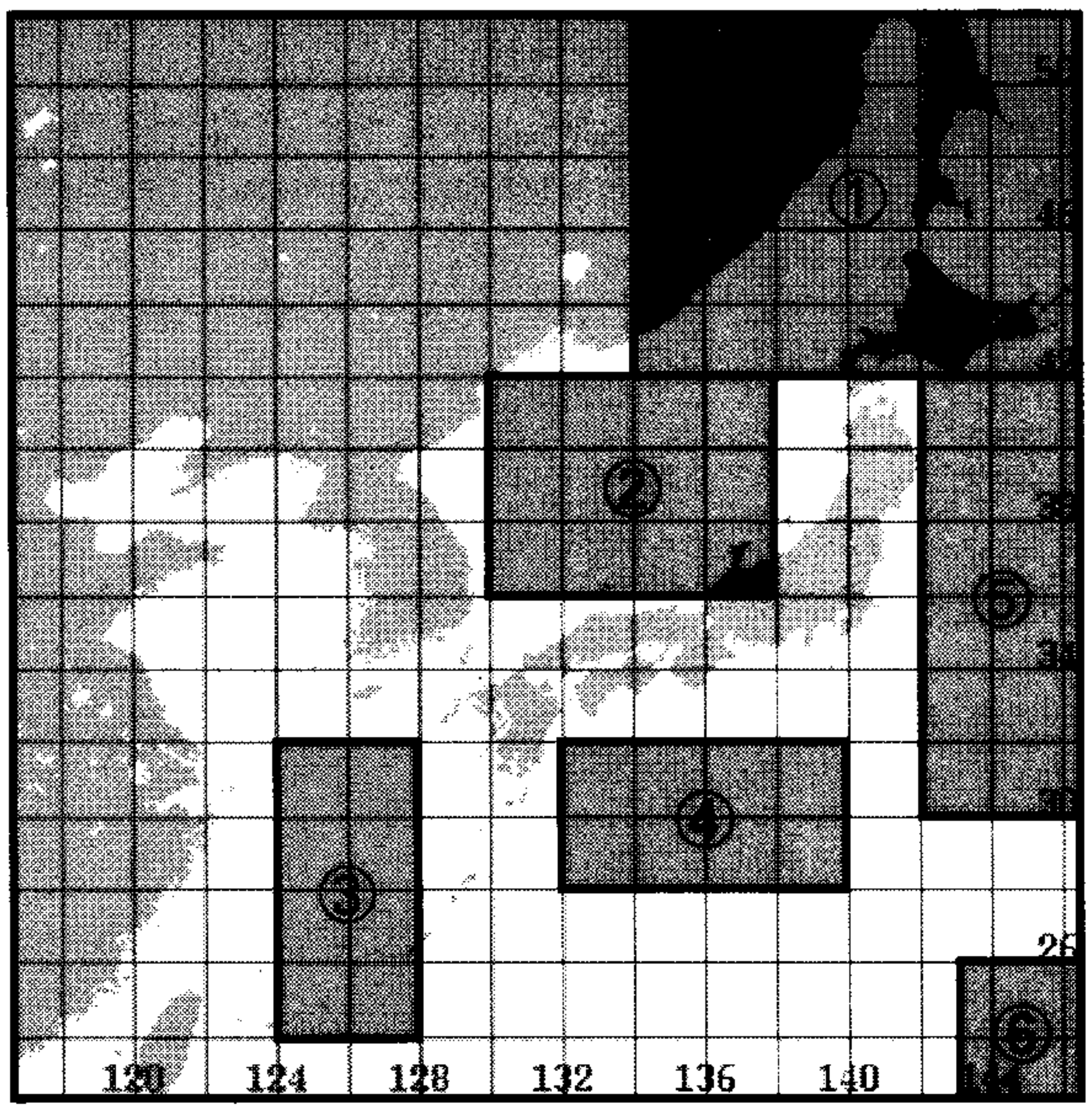

Figure 1. The geographic location of the selected sub-areas in this study. 1) Okhotsk-North Japan, 2) Sea of Japan, 3) East China Sea, 4) South of Japan, 5) East of Japan, 6) East of Iwo Island.

Most of these aerosol models are from Shettle and Fenn [1979], representing aerosols usually present in the ocean environment. Two-band approach (765 and 865nm) is used in SeaWiFS atmospheric correction method. By using the candidate aerosol models, the spectral variation of aerosol reflectance at the SeaWiFS two NIR bands can be evaluated. Two most adjacent aerosol models with their interpolating weights are determined by comparing the model reflectance to the observed NIR reflectance. The AOT and Ångström exponent are then retrieved based on the two aerosol models, their weights and the SeaWiFS measurement [Gordon and Wang, 1994].

The target region of the present analysis is focused on the East Asian Pacific, which is supposed to be under the significant influence of natural and anthropogenic aerosols from Asian continent. We selected 5 sub-areas in this region as examples to study the temporal variability of aerosols. They were 1.Okhotsk-North Japan, 2.Sea of Japan, 3.East China Sea, 4.South of Japan and 5.East of Japan, as shown in Figure 1. We also processed data of sub-area 6, the East of Iwo Island, which is located far away from the mainland of Asia, as a reference and supplement.

As a measure of aerosol abundance, values of AOT at visible and near-infrared wavelength were determined first based on the observations of SeaWiFS at the two near infrared bands. Ångström exponent is then calculated based on the definition

$$\alpha(490,865) = \ln(\tau_a 490 / \tau_a 865) / \ln(865/490), \quad (1)$$

AOT at 490nm was used in data analysis in this paper since 500nm is often regarded as a reference wavelength for visible band.

3. RESULT

Figure 2 provides the time series of monthly mean AOT and Ångström exponent for each sub-area. It is interesting to observe a slightly increasing trend of Ångström exponent in the monthly average time series, with a mean slope of 0.0146 per year and standard deviation of 0.002 for the first 5 sub-areas. The uptrend is consistent with the result of Sobajima et al. [2004] who used the AVHRR data from NOAA-11 and NOAA-14, while they found a rapid increase in Ångström exponent during 1998-2000, which is different from the steady and gradual increase we observed from the SeaWiFS data. The mean increasing slopes (per year) of Ångström exponent for each sub-area were 0.0147, 0.0144, 0.0165, 0.0114, 0.0161 and 0.0092 respectively, where sub-areas 1, 2, 3 and 5 have higher increasing rates, while East of Iwo Island showed a relatively weak trend. We also notice in Figure 2 that no apparent trend in AOT was observed over this period. This differs from the result of Sobajima et al., where they reported a rapid increase in annual mean AOT at 500nm in Eastern East China Sea, Sea of Japan, south coast of Japan, and the area far east of Japan, with AOT increase of 0.16, 0.08, 0.06, 0.03 respectively, over 1989-1990 to 1999-2000.

Since Ångström exponent is an indicator of aerosol size distribution, this uptrend derived from satellite data can be interpreted as increasing in fraction of small aerosol particles in this area. An empirical relationship was chosen to estimate the sub-micron fraction (SMF) of AOT at 550nm from α (450,700),

$$SMF = -0.0512\alpha^2 + 0.5089\alpha + 0.02, \quad (2)$$

which was originally obtained from C-130 measurements conducted throughout the ACE-Asia campaign [Anderson et al., 2005]. Here SMF represents the fraction of AOT caused by actual aerosol that exists at low-RH aerodynamic diameters smaller than 1 μm, compared to the term "Fine-mode fraction (FMF)" adopted by the MODIS project referring to the contribution of fine-mode particle to the AOT. Although the wavelength used to derive Ångström exponent in Eq. 2 is a little different from the one we used in this study, it would not influence the result much larger if the absorption of aerosols is not very strong. The retrieved monthly mean SMF time series is plotted in Figure 3 for each sub-area. Annual mean SMF slopes for each sub-area are 0.0065, 0.0065, 0.0077, 0.0053, 0.0074 and 0.0045, which result in a total mean value of 0.0067 for the first 5 sub-areas. Thus an estimate of about 4~5% increase of sub-micron particle fraction above the ocean in East Asia over 7 year would be given based on equation 2, although we notice that a decrease in Ångström exponent and AOT appeared after year 2004, with the reason remaining unclear.

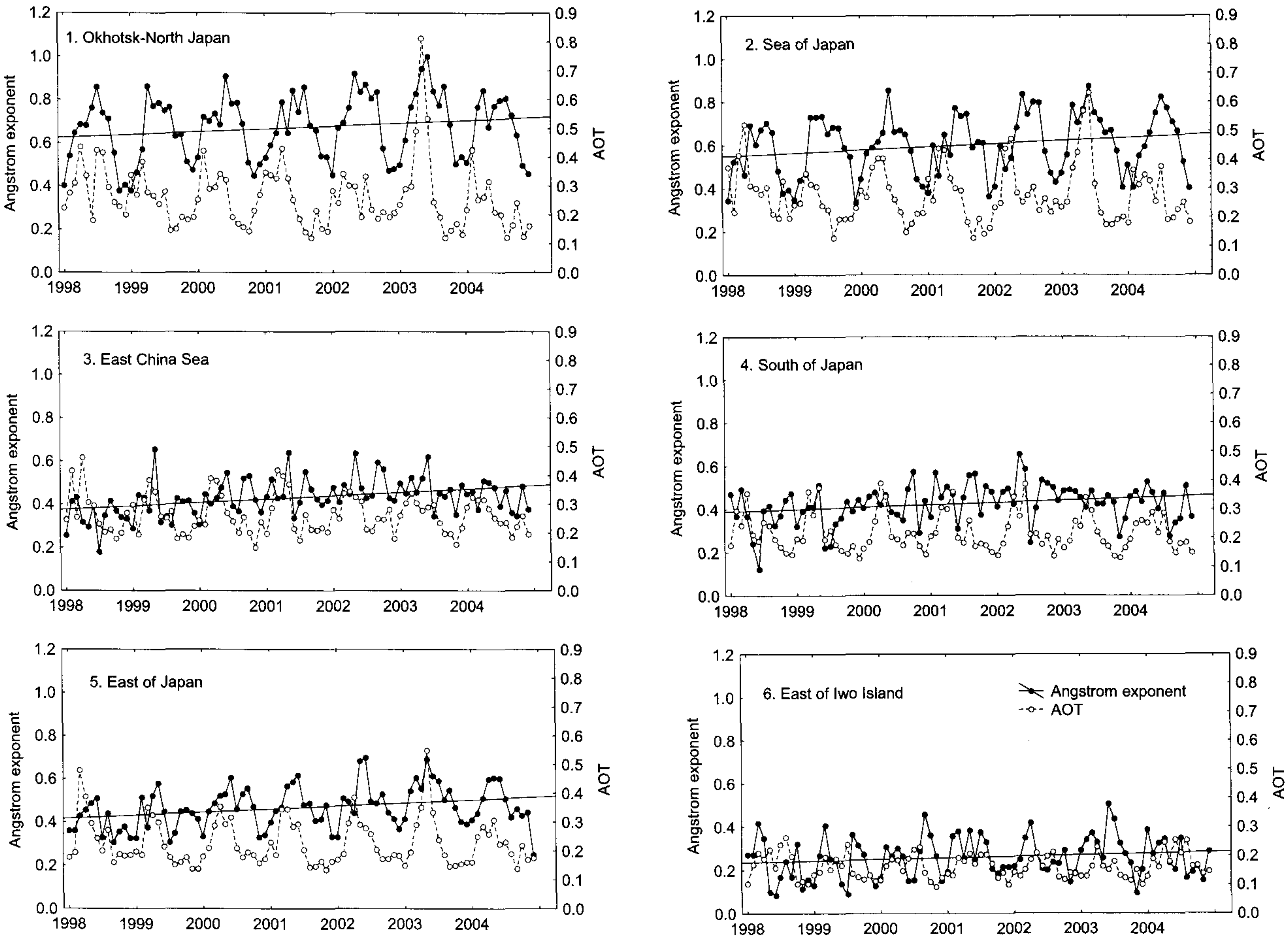

Figure 2. Time series of monthly mean AOT and Ångström exponent derived from SeaWiFS for sub-areas shown in Figure 1. Straight line which shows the uptrend in each sub-plot is the linear fit line of Ångström exponent.

4. DISCUSSION

4.1 Calibration Issue

Is this uptrend of Ångström exponent we observed here a real fact of nature or an illusion caused by the temporal degradation of the sensor? This is a crucial issue we have to face first. SeaWiFS project has taken comprehensive approaches, includes the pre-launch calibration, the Transfer-to-Orbit, and the post-launch calibrations, so as to provide reliable satellite measurements. The monthly lunar calibrations, which was used to monitor the on-orbit radiometric stability of SeaWiFS over the course of mission, has been applied to the 5th reprocessing and provide the top-of-atmosphere radiances as stable to better than 0.07% over 2500-day course of the mission [Eplee et al., 2004]. In addition, other SeaWiFS products, e.g., water-leaving radiance, were observed without any statistically significant trend and remained stable during the mission. These facts confirm that the trend of Ångström exponent observed here would not be due to potential effects of SeaWiFS calibration, according to the current understanding.

Besides that, the Ångström exponent is known to depend on the ratio of band 765nm and 865nm and thus sensitive to the change of relative calibration between the two bands. The most recent result of the refined lunar

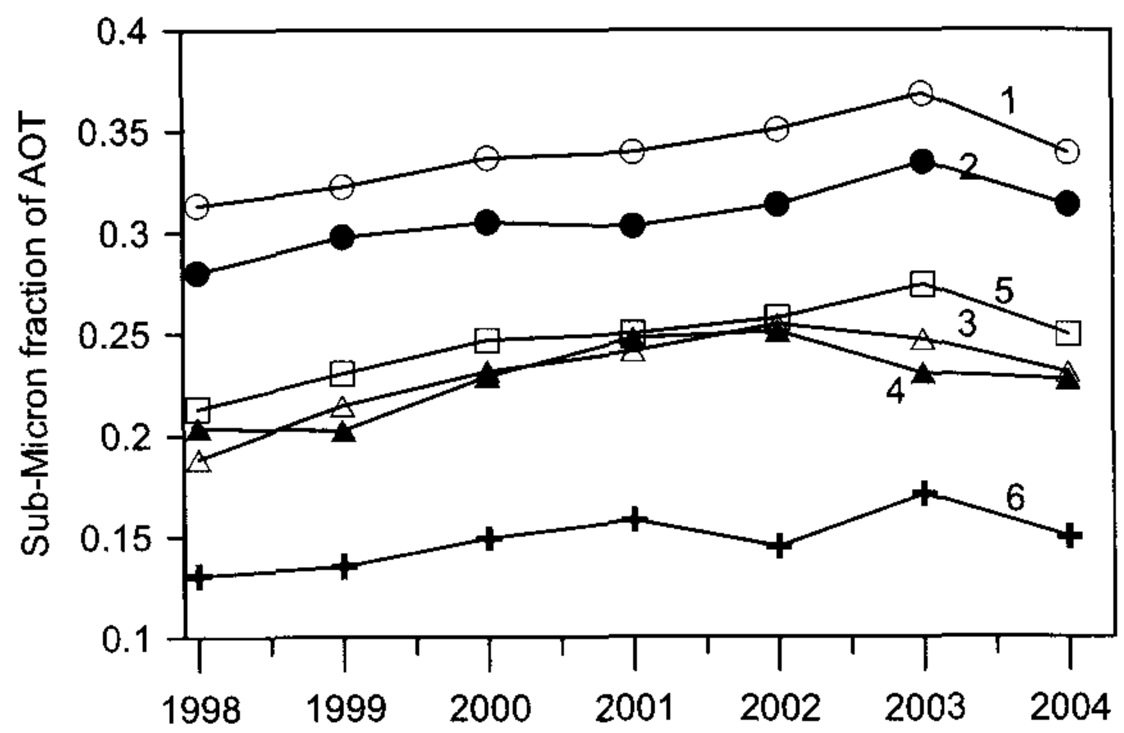

Figure 3. Annual mean sub-micron fraction (SMF) of AOT at 550nm over East Asian waters. Marked numbers represent different sub-areas shown in Figure 1.

calibration shows that residual drift of this band ratio over 2500-day course of SeaWiFS is -0.17% [Eplee, personal comm.]. This difference, since with the minus sign, would even enhance the uptrend we observed.

4.2 Uncertainties of Ångström exponent

We noticed that the mean Ångström exponent of SeaWiFS is systematically lower than the seasonal mean data gathered with sunphotometer in Japan [Aoki and Fujiyoshi, 2003]. Our emphasis here, however, is focused on the relative variability of Ångström exponent with time, not the absolute value itself. Influence on Ångström exponent from the algorithm performance or other factors may be complicated but should be statistically the same for each year, and would not induce such an increasing trend as we observed.

4.3 Comparison with other sensors

For further comparison, we also analyzed the monthly mean data collected by Terra/MODIS, a different sensor whose observation period overlaps with that of SeaWiFS. MODIS Level-3 monthly mean values (1x1 degree grid) of FMF and AOT were used, which are publicly available from NASA via MODIS Online Visualization and Analysis System (MOVAS). An increasing trend which is similar to the SeaWiFS measurements was observed in the MODIS aerosol FMF (not shown), although the uptrend of MODIS starts after year 2002 and continuously increases after 2004, which is different from the SeaWiFS result.

To compare MODIS-derived FMF more quantitatively with the SeaWiFS-derived SMF data, we converted FMF to SMF using

$$SMF = -0.1009FMF^2 + 0.5224FMF - 0.0011. \qquad (3)$$

This equation was derived from the SMF-Ångström relationship of Equation 2, and an FMF-Ångström relationship derived from our radiative transfer simulation for aerosols externally mixed with different mixture ratio of soot, tropospheric and sea-spray particle. The converted MODIS SMF shows an increase slope of 0.0072 during the period of 2002-2005, which is very close to the SeaWiFS derived 0.0067 per year. The difference between SeaWiFS and MODIS is acceptable because the calibration method and retrieval algorithm of MODIS are different from that of SeaWiFS.

From the above we conclude that the trend of Ångström exponent is most likely due to the increase in fraction of small aerosol particles in the atmosphere, rather than being caused artificially by the SeaWiFS sensor.

5. CONCLUSION

In this paper we reported the observed fact related to the temporal variability of aerosol, that is, the fraction of small aerosol particles in the atmosphere is slightly increasing over the ocean in recent years. Interpretations of this increase require further investigation, but the industrial, energy-related and land-use human activities may act as one of the factors.

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