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# Towards a combined SAGE II and SCIAMACHY aerosol dataset and implications for stratospheric aerosol trend analysis over East Asia

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## ABSTRACT

Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (SCIAMACHY) limb observation data are used to retrieve stratospheric aerosol extinction profiles. The retrieved aerosol profiles are compared with Stratospheric Aerosol and Gas Experiment (SAGE) II aerosol data records. The comparisons are made over the period 2003–2004. The results show that the SCIAMACHY aerosol profile retrievals exhibit general agreement with the coincident SAGE II data records. In the 15–35 km altitude range, the percentage differences between the SCIAMACHY-retrieved and SAGE II-measured zonal mean aerosol extinction profiles are less than 20% for the 20–30°N and 30–40°N latitude zones, and less than 25% for the 40–50°N zone. The stratospheric aerosol optical depths in this altitude range calculated from SCIAMACHY retrievals are in good agreement with SAGE II measurements, with present differences less than 6% for the three latitude zones. The aerosol retrievals from SCIAMACHY observations are combined with the SAGE II aerosol data records, form a long-term data-set for the period 2000–2010. Using the combined SAGE II and SCIAMACHY data-set, the variation trends of the stratospheric aerosol layer over East Asia (20–50°N, 70–150°E) are analyzed. The results indicate that the stratospheric aerosols have a significant trend of increase over East Asia during 2000–2010. The stratospheric aerosol optical depths increase by about 5% per year over the 11-yr period. The increase in stratospheric aerosols is found to be obviously related to moderate volcanic eruptions.

## 摘要

利用SCIAMACHY临边探测资料反演出平流层气溶胶消光系数廓线。将2003–2004年SCIAMACHY气溶胶反演结果同SAGE II探测结果进行对比,结果表明在15–35 km 高度范围,反演结果在20–30°N和30–40°N范围平均相对偏差小于20%,在40–50°N范围小于25%。计算出的平流层气溶胶光学厚度与SAGE II探测结果的相对偏差在3个纬度范围均小于6%。将SCIAMACHY反演结果与SAGE II探测资料相结合,构建平流层气溶胶长期探测资料。根据这些资料,分析东亚(20–50°N, 70–150°E)平流层气溶胶变化趋势。结果表明东亚平流层气溶胶在2000–2010年期间呈现显著增加趋势。平流层气溶胶光学厚度在这11年期间平均每年增加5%。中等强度火山爆发对平流层气溶胶增加有显著影响。

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## 关键词

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SCIAMACHY; SAGE II

## 1. Introduction

Long-term measurement of stratospheric aerosols is important and necessary for a correct understanding of the physical and chemical processes in the stratosphere. The longest record of satellite aerosol extinction profile measurements is provided by the Stratospheric Aerosol and Gas Experiment (SAGE) II, launched onboard the Earth Radiation Budget Satellite (ERBS) in October 1984 (McCormick 1987; Chu et al. 1989). SAGE II is a seven-channel sun photometer and employs the solar occultation technique to measure solar transmittance during each sunrise and sunset encountered by the ERBS spacecraft. SAGE II has a repeat cycle of slightly more than a month,

and provides the aerosol extinction profiles at four different wavelengths (386, 452, 525, and 1020 nm). The extensive validations of SAGE II aerosol extinction profiles have demonstrated that the SAGE II stratospheric aerosol data-set is one of the most accurate (e.g. Russell and McCormick 1989; Hervig and Deshler 2002; Reeves et al. 2008). The SAGE II instrument finally retired in August 2005.

In recent years, a series of new generation satellite instruments have been developed that measure solar irradiances scattered in Earth's atmosphere in limb geometry. The limb scatter measurement technique has a distinct advantage over solar occultation in terms of sampling. One of the instruments applying this technique

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is the Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (SCIAMACHY), onboard the European Space Agency's Environmental Satellite in March 2002 (Bovensmann et al. 1999). As a passive imaging spectrometer, SCIAMACHY comprises eight spectral channels and covers a wide spectral range from 240 to 2380 nm. SCIAMACHY performs observations in alternate nadir, limb, and solar/lunar occultation geometry, and provides daily near-global measurements of the spectral irradiance. In limb observation mode, SCIAMACHY measures the limb scattered spectra tangentially, starting at about 3 km below the horizon and extending to a tangent height of about 100 km, with a vertical resolution of about 3.3 km. The SCIAMACHY observations provide a valuable data-set of limb scattered spectra, and has already been applied to derive the vertical profiles of stratospheric aerosols (Ovigneur et al. 2011; Taha et al. 2011; Yang and Zong 2014, 2015; von Savigny et al. 2015).

Recent observational studies on stratospheric aerosols show that, on the global scale, stratospheric aerosol loading has increased by 4%–10% per year since 2000 (Hofmann et al. 2009; Nagai et al. 2010; Vernier et al. 2011). These studies have shown that stratospheric aerosol loading is significantly influenced by atmospheric dynamics, human industrial emissions, and moderate volcanic eruptions. Several studies have proposed that the increase in anthropogenic sulfur emissions is the main source of the observed increasing trend in stratospheric aerosol loading (Hofmann et al. 2009); however, other studies have demonstrated that small and medium strength volcanic eruptions could be the primary source of the observed increases in stratospheric aerosol (Vernier et al. 2011; Neely III et al. 2013; Brühl et al. 2015). The main reasons behind the increase remain the subject of ongoing research.

In the present study, an improved method is used to retrieve the stratospheric aerosol extinction profiles from SCIAMACHY level 1 limb observations. To assess the quality of the retrieval, the retrieved aerosol profiles are compared with coincident SAGE II (version 6.2) aerosol data records. Applying the combined SAGE II and SCIAMACHY datasets, the variation trends of the stratospheric aerosol layer over East Asia (20–50°N, 70–150°E) during 2000–2010 are analyzed, and the main reason behind the increase in stratospheric aerosol loading is revealed.

## 2. Aerosol extinction profile retrieval

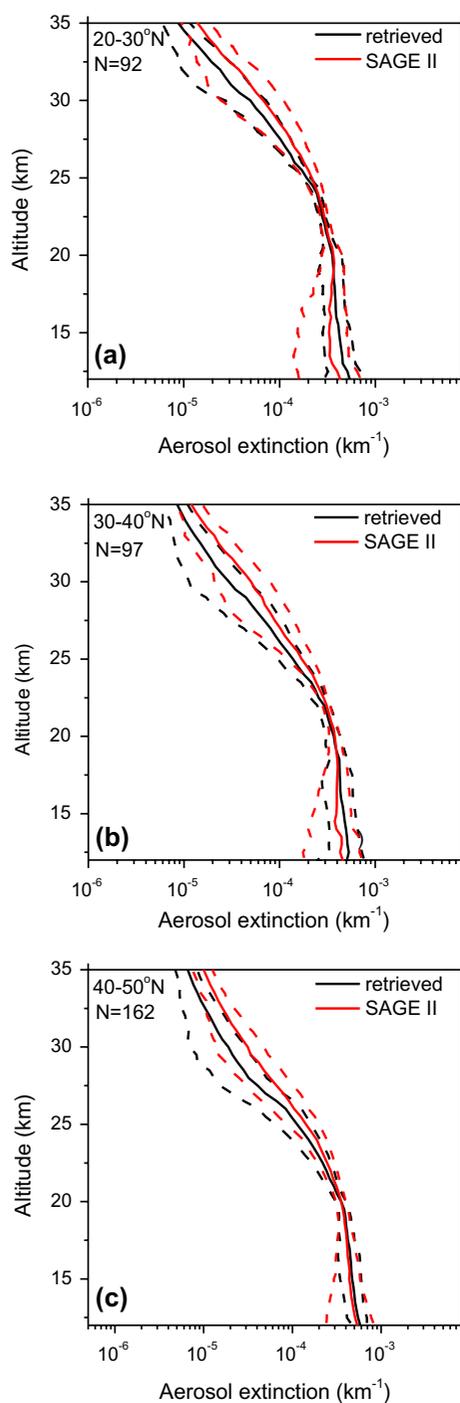
The method used to retrieve aerosol extinction profiles from SCIAMACHY limb spectra observations is described by Yang and Zong (2015). In this method, the measurement vector is taken as the normalized limb radiance at different tangent heights. The retrieval employs the SCIATRAN

software package (Rozanov et al. 2005) to compute the limb scatter radiance observed by SCIAMACHY, and uses a nonlinear optimal estimation algorithm to derive aerosol extinction profiles. During the retrieval calculation in this study, several improvements have been made in the process to compute the limb scatter radiance. The scattering phase functions used for the limb radiance computation are calculated using Mie scattering theory, and the values of surface albedo are determined according to the actual surface conditions. This is different from previous practice (Yang and Zong 2014, 2015), where the Henyey–Greenstein phase function parametrization was used, and the constant surface albedo value was assumed. By employing the improved retrieval algorithm, the aerosol extinction profiles are retrieved from SCIAMACHY limb spectra observations during the period 2003–2010 in the latitude range from 20 to 50°N.

## 3. Comparisons

To assess the quality of the SCIAMACHY aerosol retrievals, the SCIAMACHY limb aerosol profiles are compared with coincident SAGE II aerosol data records. The comparisons are made within 10°-wide latitude zones from 20 to 50°N in the Northern Hemisphere over the period 2003–2004, when both SCIAMACHY and SAGE II were in operation. The coincident criteria employed to select data pairs from the two instruments are  $\pm 6$  h,  $\pm 4^\circ$  latitude, and  $\pm 8^\circ$  longitude. Within this limits, the nearest match between the SCIAMACHY and SAGE II profile is selected. These criteria provide 92, 97, and 162 coincident pairs in the three latitude zones of 20–30°N, 30–40°N, and 40–50°N, respectively. From these coincident pairs, the zonal mean SCIAMACHY and SAGE II aerosol extinction profiles are calculated separately for each latitude zone.

Comparisons between the zonal mean SCIAMACHY-retrieved and SAGE II-measured aerosol extinction profiles from 15 to 35 km in the three latitude zones are shown in Figure 1. It is found that, for each latitude zone, the SCIAMACHY aerosol extinction values are smaller than the SAGE II-measured values at altitude levels above approximately 25 km; whereas, in the lower stratosphere below 17 km, the SCIAMACHY aerosol extinctions are larger than the SAGE II measurements. Although there are some deviations, the retrieved SCIAMACHY aerosol profiles exhibit general agreement with the SAGE II profiles. The percentage differences between the SCIAMACHY aerosol extinctions and SAGE II data records are less than 20% in the latitude zones 20–30°N and 30–40°N, and less than 25% in 40–50°N. For further assessment, the zonal mean stratospheric aerosol optical depths (between 15 and 35 km in altitude) calculated from the SCIAMACHY



**Figure 1.** Comparison of zonal mean aerosol extinction profiles (at 525 nm) from SCIAMACHY retrievals and coincident SAGE II data records.

Notes: The correlated standard deviations (dashed lines in corresponding colors) for each profile are also provided. The measurements were performed during 2003–2004. The number ( $N$ ) in the top-left corner for each plot shows the number of coincident data records.

retrievals and SAGE II data records are compared. Table 1 presents the calculated aerosol optical depth values and the standard deviations from SCIAMACHY retrievals and SAGE II measurements for the three latitude zones. The SCIAMACHY aerosol optical depths are found to be in good

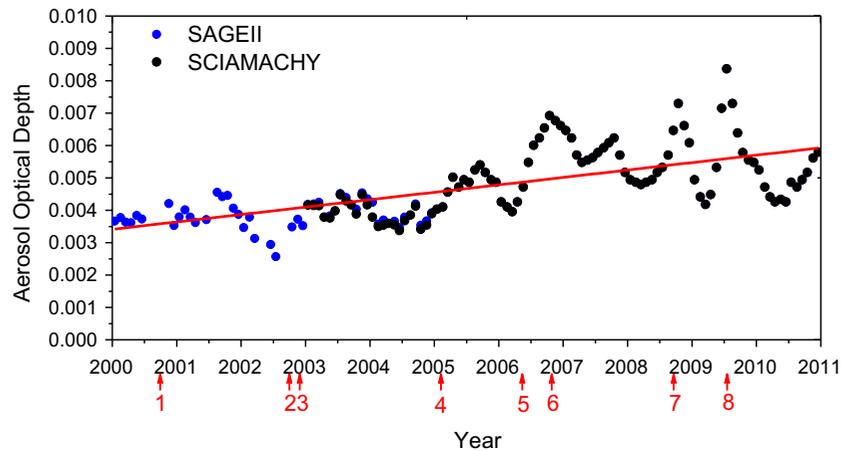
**Table 1.** Zonal mean stratospheric aerosol optical depth (AOD) and standard deviation ( $\sigma$ ) from SCIAMACHY retrievals and SAGE II measurements for three latitude zones during 2003–2004.

	SCIAMACHY		SAGE II	
	AOD ( $\times 10^{-3}$ )	$\sigma$ ( $\times 10^{-3}$ )	AOD ( $\times 10^{-3}$ )	$\sigma$ ( $\times 10^{-3}$ )
20–30°N	4.03	0.51	4.12	0.58
30–40°N	3.89	0.47	4.01	0.52
40–50°N	3.51	0.32	3.73	0.36

quantitative agreement with the SAGE II measurements, with the percentage differences less than 6%. The comparison results indicate that the SCIAMACHY limb aerosol retrievals provide an independent aerosol data record for stratospheric aerosol trend studies.

#### 4. Stratospheric aerosol trend analysis over East Asia

The retrieved SCIAMACHY aerosol data are combined with the SAGE II aerosol data records, form a long-term time series for the period 2000–2010. By employing this combined SAGE II and SCIAMACHY data-set, the variation trends of the stratospheric aerosol layer over East Asia (20–50°N, 70–150°E) are analyzed. Figure 2 shows the temporal evolution of monthly mean stratospheric aerosol optical depths at 525 nm over East Asia. The temporal locations of moderate volcanic events (Volcanic Explosivity Index = 4) are also denoted in Figure 2. Figure 2 shows that, in addition to periodic variations, which are influenced by atmospheric dynamic processes, the stratospheric aerosols show a rising trend over East Asia between 2000 and 2010. The stratospheric aerosol optical depths increase by about 5% per year over the 11-yr period. The values of aerosol optical depths in the stratosphere are 0.0026–0.0047 from 2000 to 2004, and increase to 0.0035–0.0084 from 2005 to 2010. The temporal evolution exhibits a sequence of enhancements associated with volcanic eruptions. For instance, the optical depth increases to 0.0084 in July 2009 after the Sarychev eruptions. These variations are in good general agreement with the results presented by Neely III et al. (2013). Neely III et al. (2013, their Figure 1) presented time series of monthly averaged stratospheric aerosol optical depths (15–30 km) at 525 nm, based on SAGE II, Global Ozone Monitoring by Occultation of Stars, and Cloud Aerosol Lidar with Orthogonal Polarization satellite data records. They showed aerosol optical depths of about 0.003–0.0045 within the 30–50°N latitude range during 2000–2004, and of about 0.0035–0.010 during 2005–2009. Of note is that their results show a maximum optical depth of about 0.01 after the eruption of Sarychev, which is larger than the value of 0.0084 found in the present study. The difference could primarily be due to the difference in latitude range. Figure 2 suggests that the



**Figure 2.** Temporal evolution of monthly mean stratospheric aerosol optical depth (15–35 km) at 525 nm over East Asia (20–50°N, 70–150°E).

Notes: The linear fit is plotted in red. The temporal locations of volcanic events are denoted as follows: 1, Ulawun (5°S, 29 September 2000); 2, Ruang (2°N, 25 September 2002); 3, Reventador (0°N, 3 November 2002); 4, Manam (4°S, 27 January 2005); 5, Soufriere Hills (16°N, 20 May 2006); 6, Tauruvur (4°S, 7 October 2006); 7, Kasatochi (55°N, 7 August 2008); 8, Sarychev (48°N, 12 June 2009).

rising trend of the stratospheric aerosol record is related to moderate volcanic eruptions, both in the tropics and in the mid latitude regions. Moderate volcanic eruptions inject sulfur-containing gases such as sulfur dioxide into the troposphere. These gases are transported into the stratosphere by dynamical processes and can react to form aerosol particles, enhancing the aerosol burden in the stratosphere.

## 5. Summary and conclusions

The present study uses SCIAMACHY limb observation data to retrieve stratospheric aerosol extinction profiles. The SCIAMACHY limb aerosol retrievals are then compared with the coincident SAGE II aerosol data records within 10°-wide latitude zones from 20 to 50°N over the period 2003–2004. The comparison results indicate that the SCIAMACHY aerosol profiles exhibit general agreement with the SAGE II profiles, albeit with deviations. The aerosol optical depths calculated from SCIAMACHY retrievals show good agreement with the coincident SAGE II measurements, with the percentage differences less than 6% for three latitude zones of 20–30°N, 30–40°N, and 40–50°N. The comparisons demonstrate that the SCIAMACHY aerosol retrievals provide an accurate aerosol data-set for stratospheric aerosol trend analysis.

Using the combined SAGE II and SCIAMACHY aerosol data, the variation trends of the stratospheric aerosol layer over East Asia are analyzed. The results indicate a clear rising trend for stratospheric aerosols over East Asia during the period 2000–2010. The stratospheric aerosol optical depth values increase by about 5% per year over this 11-yr period. The increase in stratospheric aerosol

loading is mainly related to volcanic events in the tropical and mid latitude regions in the Northern Hemisphere. This study provides evidence that moderate volcanic eruptions contribute substantially to the budget of stratospheric aerosols.

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## Disclosure statement

No potential conflict of interest was reported by the author.

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