To be submitted to JGR #05.05.15

Inter-comparison of ILAS-II version 1.4 aerosol extinction coefficient at 780 nm with SAGE II, SAGE III, and POAM III aerosol data

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Short title: ILAS-II version 1.4 aerosol validation

Key Words:

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Abstract. The Improved Limb Atmospheric Spectrometer (ILAS) II on board the Advanced Earth Observing Satellite (ADEOS) II observed stratospheric aerosol in visible/near-infrared/infrared spectra over high latitudes in the Northern and Southern Hemispheres. Observations were taken intermittently from January to March, and continuously from April thorough October, 2003. We assessed the data quality of ILAS-II version 1.4 aerosol extinction coefficients at 780 nm from comparisons with the Stratospheric Aerosol and Gas Experiment (SAGE) II, SAGE III, and the Polar Ozone and Aerosol Measurement (POAM) III aerosol data. At heights below 20 km in the Northern Hemisphere, aerosol extinction coefficients from ILAS-II agreed with those from SAGE II and SAGE III within ±10%, and with those from POAM III within ±15%. From 20 to 26 km, ILAS-II aerosol extinction coefficients were smaller than extinction coefficients from the other sensors; differences between ILAS-II and SAGE II ranged from 10% at 20 km to 34% at 26 km. ILAS-II aerosol extinction coefficients from 20 to 25 km in February over the Southern Hemisphere had a negative bias (12-66%) relative to SAGE II aerosol data. The bias increased with increasing altitude. Comparisons between ILAS-II and POAM III aerosol extinction coefficients from January to May in the Southern Hemisphere (defined as the "non-Polar Stratospheric Cloud (PSC) season") yielded qualitatively similar results. From June to October (defined as the "PSC season"), aerosol extinction coefficients from ILAS-II were smaller than those from POAM III above 17 km, as in the case of the non-PSC season;

however, ILAS-II and POAM III aerosol data were within ±15% of each other from 12 to 17 km.

1. Introduction

Stratospheric aerosols greatly impact on stratospheric chemistry, including destruction of ozone. In polar regions, Polar Stratospheric Clouds (PSCs), which form under cold conditions in winter and early spring, lead to severe ozone depletion by providing the surface required for heterogeneous reactions that convert inactive chlorine into active chlorine [e.g., *Solomon*, 1999]. Moreover, PSCs irreversibly remove nitric acid from the gas phase through sedimentation (denitrification), and that removal could facilitate springtime ozone depletion [e.g., *Drdla and Schoeberl*, 2003]. Observation of stratospheric aerosols, particularly PSCs, is thus crucial for the understanding of ozone destruction processes. Many stratospheric aerosol measurements have been performed with lidar and Optical Particle Counter (OPC) [e.g., *Hofmann and Deshler*, 1991; *Adriani et al*., 1995]. Space-borne sensors that provide observations over a large area have also monitored stratospheric aerosols. The Stratospheric Aerosol Measurement (SAM) II is a solar occultation sensor on board a polar-orbiting satellite. It continuously observed stratospheric aerosols and PSCs over high latitudes for about 15 years starting in October 1978 [e.g., *McCormick et al*., 1982; *Poole and Pitts*, 1994]. Subsequently, several other solar occultation sensors, including the Polar Ozone and Aerosol Measurement (POAM) II (09/1993-11/1996) [*Randall et al*., 1996; *Randall et al*., 2000; *Fromm et al*., 1997; *Fromm et al*., 1999], the Improved Limb Atmospheric Spectrometer (ILAS) (11/1996-06/1997) [*Hayashida et al*., 2000; *Saitoh et al*., 2002], and POAM III (04/1998-present) [*Randall et al*., 2001; *Bevilacqua et al*., 2002] have obtained stratospheric aerosol and PSC data for latitudes similar to those covered by SAM II. In addition, the Stratospheric Aerosol and Gas Experiment (SAGE) II, a solar occultation sensor on board an inclined-orbiting satellite that can make more extensive observations from low/mid latitudes to high latitudes, began regular observations of stratospheric aerosols in October 1984 and is still in operation [e.g., *Hitchman et al*., 1994; *Thomason et al*., 1997]. SAGE III, which is the successor of SAGE II on board a polar-orbiting satellite, has measured stratospheric aerosols since February 2002 at high latitudes in the Northern Hemisphere and at mid latitudes in the Southern Hemisphere [*Thomason and Taha*, 2003].

ILAS-II is the successor to ILAS, and was launched on board the Advanced Earth Observing Satellite (ADEOS) II (polar-orbiting satellite) on 14 December 2002 [*Sasano et al*., 2001]. It made about 150 preoperational observations from January to March, and measured continuously for about 7 months from 2 April through 24 October 2003, at which time ADEOS-II satellite failed. ILAS-II is designed to observe profiles of stratospheric minor gases such as O_3, HNO_3, NO_2, N_2O, CH_4, and H_2O, as well as profiles of aerosol extinction coefficient (AEC) by stratospheric aerosols and PSCs at high latitudes of both hemispheres

(53.9-71.1º N and 63.6-88.0º S). ILAS-II carried three infrared spectrometers (ch.1: 6.21-11.76 μm, ch.2: 3.00-5.70 μm, ch.3: 12.78-12.85 μm), one visible spectrometer (ch.4: 753-784 nm), and a sun-edge sensor [*Nakajima et al*., 2005]. AEC is retrieved from eight window spectral data around 780 nm of the visible spectrometer and at 3.0, 3.8, 5.1, 7.1, 8.3, 10.6, and 11.8 μm of the infrared spectrometers. In this study, we assessed the data quality of ILAS-II AEC at 780 nm processed with the version 1.4 retrieval algorithm.

Data quality was assessed over the Northern Hemisphere by comparing ILAS-II AEC data with SAGE II, SAGE III, and POAM III data. Over the Southern Hemisphere, ILAS-II data were examined in two separate groups. One group included data from June through October, when PSCs are frequently observed (hereafter referred as the "PSC season"). The second group included data from January through May, when PSCs do not occur ("non-PSC season"). ILAS-II AEC data from the non-PSC season were compared to SAGE II and POAM III AEC data. In addition, an OPC and a Laser Particle Counter (LPC) observed aerosol data over Syowa Station on 22 February 2003. These data were converted into AEC at 780 nm and compared to nearby and same-day ILAS-II AEC data. During the PSC season, it is difficult to assess aerosol data quality from comparisons with other nearby measurements because of the inhomogeneity of PSCs. Nevertheless, we made statistical comparisons between ILAS-II and POAM III PSC data because many ILAS-II and POAM III PSC measurements were made in very close vicinity.

Section 2 in this paper describes ILAS-II measurements and AEC retrieval at 780 nm. Section 3 characterizes the dataset used in the comparisons. Comparison results are presented in Section 4 and summarized in Section 5.

2. ILAS-II aerosol extinction retrieval and characteristics

ILAS-II measures solar radiance in the exosphere (direct sunlight) and radiance attenuated as sunlight travels through the atmosphere as a function of tangent height. Sunlight incident from the entrance slit of the visible spectrometer is dispersed by the spectrometer grating, and then observed with a 1024-element metal-oxide-semiconductor (MOS) photodiode array with spectral resolution of ~0.06 nm. The entrance slit size corresponds to an instantaneous field of view (IFOV) of 1-km in the vertical and 2-km in the horizontal at the tangent point. *Nakajima et al*. [2005] detailed the ILAS-II hardware characteristics.

The visible spectrometer of ILAS-II measures temperature and pressure by obtaining the absorption spectrum by oxygen molecules (O_2 A-band). Simultaneously, AEC is retrieved for wavelengths around 780 nm, outside the O_2 A-band. The ILAS-II algorithm to retrieve AEC from the spectral data obtained with the visible spectrometer is similar to the algorithm used for ILAS data that was described by *Hayashida et al*. [2000] and *Yokota et al*. [2002]. ILAS-II can also measure solar luminosity of the whole solar disk in the exosphere (solar scan data acquisition) [*Nakajima et al*., 2005]. Thus, sunspot and limb darkening effects on the

AEC data can be estimated from the measured solar luminosity in the ILAS-II retrieval, while a theoretical luminosity is used in the ILAS retrieval. *Yokota et al.* [2005] discussed the improvements of ILAS-II AEC retrieval over ILAS retrieval.

ILAS AEC data include "internal error" that comprises random noise in the observed solar signals, error in the estimate of direct sunlight during atmospheric transmission (100% level), and error in the estimate of ozone absorption in the Wulf band [*Hayashida et al.*, 2000; *Yokota et al.*, 2002]. On the other hand, internal error defined and provided in the ILAS-II version 1.4 product is estimated on the basis of measurement repeatability. In addition, error in the estimate of Rayleigh scattering by atmospheric molecules is estimated from uncertainties in UKMO temperature data that we assume. This error is provided as "external error" in the ILAS-II product, as in the case of the ILAS product. Root-Sum-Square (RSS) of the internal and external errors is defined as the "total error".

Measurement repeatability is defined as the "closeness of the agreement between the results of successive measurements of the same measurand" [*BIPM et al.*, 1993]. Measurement repeatability was calculated empirically in the ILAS-II version 1.4 retrieval as follows. Mean ($\overline{x}_{rep}$) and 1σ standard deviation (σ_{rep}) of ILAS-II AEC data were calculated for every 100 occultation events (OE) at each altitude level in each hemisphere. The smallest relative standard deviations, defined as $\varepsilon_{rep}=\sigma_{rep}/\overline{x}_{rep}$, was selected for each altitude level and defined as the measurement repeatability of the altitude level. In this way, the ε_{rep} value calculated for the period when variability in AEC was smallest during ILAS-II operations is selected as the measurement repeatability; therefore, measurement repeatability can be regarded as the precision of ILAS-II AEC measurements. Precision was 5-15% at 12-26 km in the Northern Hemisphere and 6-20 % at 12-23 km in the Southern Hemisphere [Figure xx, *Yokota et al.*, 2005]; precision was smaller than 10% between 15-25 km in the Northern Hemisphere and between 15-21 km in the Southern Hemisphere.

At almost all altitudes, the magnitude of the measurement repeatability over the Southern Hemisphere was larger than the magnitude over the Northern Hemisphere (e.g., five times larger at 25 km). ILAS-II made observations for less than an entire year, only for seven months from April to October. The values of measurement repeatability over the Southern Hemisphere were estimated from data obtained in April or in October when the atmosphere is sometimes perturbed. In contrast, the values of measurement repeatability over the Northern Hemisphere were estimated from data acquired primarily in the summer (July- October), a more quiescent time of year. The values of measurement repeatability over the Southern Hemisphere reflect larger variability in atmospheric aerosol compared to the Northern Hemisphere because of the seasons sampled.

Uncertainty attributable to sunspots is not included in either internal or external errors of the ILAS-II version 1.4 product. Sunspot effects on the AEC data can be estimated from the measured solar luminosity in the ILAS-II retrievals [*Yokota et al.*, 2005], but the effects cannot always be corrected in the current version due to a hardware problem on ILAS-II [*Nakajima et al.*, 2005]. Sunspots affect at least about one-sixth of all the ILAS-II AEC data judging from the observed solar luminosity data. In the current version, most of those AEC data still include sunspot effects above ~30 km in the Northern Hemisphere and above ~25 km in the Southern Hemisphere. Therefore, this study focused on AEC data below 30 km in the Northern Hemisphere and below 25 km in the Southern Hemisphere.

3. Data for comparison

Figure 1 shows latitudinal coverage of ILAS-II (black dots), POAM III (light gray circles), SAGE II (thick gray line), and SAGE III (solar occultation measurements only; thin gray line) during ILAS-II operations from January to October 2003. POAM III observations occurred at similar latitudes and times as ILAS-II in both hemispheres. Coincident pairs of ILAS-II and POAM III observations were chosen when the distance between the two measurement locations was less than 150 km and the time difference was less than 1 hour in the Northern Hemisphere or for the non-PSC season in the Southern Hemisphere. A more stringent criterion for coincident PSC pairs was applied during the PSC season in the Southern Hemisphere because of the spatial inhomogeneity of PSCs. Here, a maximum distance of 50 km and a maximum time difference of 1 hour were applied for the selection. Comparisons in the Northern Hemisphere only used AEC data after 25 April, because the polar vortex as defined by *Nash et al*. [1996] persisted at ILAS-II measurement latitudes before 25 April. Large gradients in stratospheric aerosol concentration exist at the boundary of the polar vortex [*Thomason and Poole*, 1993]. There were 245 coincident pairs after 25 April in the Northern Hemisphere and 198 coincident pairs in the non-PSC season in the Southern Hemisphere. During the PSC-season in the Southern Hemisphere, 163 coincident PSC profiles were identified.

SAGE II and SAGE III made observations at greater distances from ILAS-II measurements than POAM III did. Thus, the distance constraint between the two measurement locations was 300 km, although the same 1-hour maximum time difference was used. These criteria yielded sufficient numbers of coincident pairs in the Northern Hemisphere. For the Southern Hemisphere, however, the criteria yielded only a few coincident pairs. Thus, looser criteria were applied. Coincident pairs in the Southern Hemisphere were required to be within 500 km of each other, with a time difference of at most 12 hours. These looser criteria allowed multiple SAGE II observations to match a single ILAS-II data point. In that case, all observations were accepted as individual pairs. Consequently, 8, 8, and 18 coincident profiles were selected between SAGE II and ILAS-II in April, July, and September, respectively, over the Northern Hemisphere. Eight profiles were selected in February over the Southern Hemisphere. The number of coincident profiles between SAGE III and ILAS-II were 5, 46, and 36 in April, August, and September, respectively, in the Northern Hemisphere. Table 1 summarizes all comparison criteria.

SAGE II does not observe AEC at 780 nm, so that those data could not be directly compared to ILAS-II AEC data. SAGE II AEC data at 525 nm and 1019 nm were interpolated to AEC at 780 nm by assuming that the logarithm of AEC is roughly proportional to the logarithm of wavelength in the lower stratosphere, as in *Burton et al*. [1999]. This study uses SAGE II version 6.2 AEC data, although the version 6.2 AEC data have not yet been validated. It has been already established that the previous versions of 5.93 [e.g., *Osborn et al*., 1989; *Ackerman et al*., 1989; *Russell and McCormick*, 1989] and 6.0 [*Hervig and Deshler*, 2002] AEC data have no clear bias at the two relevant wavelengths. Here, the version 6.2 data were compared to the validated version 5.93 data. They agreed to within the RSS of both reported errors. The difference was within ~10% from 18 to 30 km, although the version 6.2 AEC data were on average smaller than the version 5.93 data below 18 km. Better agreement was also seen in comparisons between the version 6.2 and 6.0 AEC data. SAGE II version 6.2 AEC data interpolated to 780 nm should have no systematic bias.

SAGE III AEC data at 756 nm and 869 nm were interpolated to AEC at 780 nm using methods similar to those applied to SAGE II AEC data. SAGE III version 3.0 data were used in this study, and AEC data in that version, which are nearly identical to the version 2.0 data, have a positive bias at all altitudes at 756 nm and a negative bias above 24 km at 869 nm [*Thomason and Taha*, 2003]. Here, the bias in SAGE III AEC data interpolated to 780 nm was estimated by comparing the interpolated values to SAGE II AEC data interpolated to 780 nm. April and September SAGE II and SAGE III measurements yielded 32 coincident pairs in the Northern Hemisphere when a distance maximum of 300 km and a time difference maximum of 1 hour were applied as criteria for the data from April to October 2003. The relative difference, $D_{SAGE3\text{-}SAGE2}$ (%), is:

$$D_{SAGE3\text{-}SAGE2}(\%) \equiv \frac{100 \times (\text{SAGE III} - \text{SAGE II})}{\text{SAGE II}}.$$

$D_{SAGE3\text{-}SAGE2}$ was calculated for all 32 coincident pairs. Figure 2a shows profiles of the mean ($\overline{D}_{SAGE3\text{-}SAGE2}$, black line) and 1σ standard deviation (gray line). Figure 2a shows close agreement between SAGE III and SAGE II AEC data during ILAS-II operations, although SAGE III AEC was slightly larger at almost all altitude levels.

POAM III measures AEC at 780 nm, so that a direct comparison can be made with ILAS-II AEC data. POAM III AEC data (version 4.0) at 780 nm used in this study have not been validated through inter-comparisons with other measurements. Here, POAM III AEC data at 780 nm were also compared with SAGE II AEC data interpolated to 780 nm. Comparison criteria in the Northern Hemisphere were a distance maximum of 300 km and a time difference maximum of 1 hour, yielding 21 total coincident pairs in April, July, and September 2003. Comparison criteria in the Southern Hemisphere were a distance maximum of 500 km and a time difference maximum of 12 hours, which yielded 34 coincident pairs in February. The relative difference between SAGE II and POAM III, $D_{POAM3\text{-}SAGE2}$ (%), was calculated for all coincident pairs as:

$$D_{POAM3\text{-}SAGE2}(\%) \equiv \frac{100 \times (\text{POAM III} - \text{SAGE II})}{\text{SAGE II}}.$$

Figure 2b shows the mean and 1σ standard deviation of $D_{POAM3\text{-}SAGE2}$ for the Northern Hemisphere; Figure 2c the same for the Southern Hemisphere. POAM III AEC data agreed with SAGE II AEC data in the Northern Hemisphere to within 1σ standard deviation, although POAM III AEC was 14-22% larger on an average than SAGE II AEC from 22 to 24 km. In contrast, differences between POAM III and SAGE II AEC data from 13 to 23 km in the Southern Hemisphere deviated from the 0% line even considering 1σ standard deviation; POAM III AEC clearly showed a 13-30% systematic positive bias relative to SAGE II AEC.

Measurements of balloon-borne OPC and LPC were taken at Syowa Station (69º S, 40º E, star in Figure 1) by the 43rd and 44th Japan Antarctic Research Expedition (JARE) on 22 February in 2003 during the ILAS-II preoperational period. AEC values estimated from the size distribution measurements were compared to nearby ILAS-II AEC data. Syowa Station is about 599 km from the nearest ILAS-II measurement location (74.0º S, 36.6º E) on the same day. Comparisons to data from in situ measurements like OPC and LPC are meaningful even for just one comparison, because the measurement principle differs from that of satellite sensors. A particle counter counts the number of particles and measures their sizes by detecting light scattered by particles that are exposed to incident light. The OPC and LPC use a halogen lamp and a He-Ne laser, respectively, as a light source. The OPC (LPC) measures particles with radii from 0.15 to 3.5 μm (from 0.056 to 0.25 μm). By assuming refractive indices for sulfate aerosols, a bimodal lognormal distribution function was fit to the measured cumulative number concentrations for each particle size range, and AEC at 780 nm was then derived from the particle size distribution by performing Mie scattering calculations. Here, the refractive indices (1.439-1.452) were estimated following *Steele and Hamill* [1981]. Simultaneously observed temperature and pressure data were used, and a mixing ratio of water vapor of 4 ppmv and a sulfate content of an aerosol droplet of 1.0×10^{-15} g were assumed. Error in the OPC/LPC data was defined as the RSS of the systematic measurement error and statistical random error of the counting. The systematic measurement error, which includes uncertainty in the flow rate, was around ±5% for all altitude levels. Uncertainty in a count C is $\pm\sqrt{C}$ [e.g., *Willeke and Li*u, 1976]. The relative counting error ($1/\sqrt{C}$) in this study was calculated for each particle size range and each level. RSS of the calculated counting errors was then defined as the statistical counting error and ranged from 0.4% to 44%.

4. Results

4.1. Northern Hemisphere

Figure 3 compares ILAS-II AEC data to SAGE II AEC data. The left panel shows mean profiles of 34 pairs of coincident ILAS-II (thick black line) and SAGE II (thick gray line) AEC data. Black (gray) dashed lines show 1σ standard deviation profiles for ILAS-II (SAGE II). Triangles illustrate the difference between the mean profiles of ILAS-II and SAGE II. Black (gray) triangles correspond to negative (positive) values of ILAS-II minus SAGE II AEC. The right panel shows profiles of the mean relative percent difference (thick black line) and 1σ standard deviation (thin black lines). Here, the relative percent difference, D (%), is:

$$D \equiv \frac{100 \times (\text{ILAS-II} - \text{other sensors})}{\frac{1}{2} \times (\text{ILAS-II} + \text{other sensors})}.$$

RSS of the total error of individual ILAS-II AEC data and the reported error of the coincident SAGE II AEC data (defined as “combined error”) was divided by the mean of both AEC data (equal to the denominator of the above D expression) to define a relative error. Gray dashed lines in the right panel indicate the mean of the relative errors. At altitude levels between 12 and 19 km, ILAS-II AEC was within around ±10% of SAGE II AEC; the difference was within the range of the combined error. In contrast, $\overline{D}$ (mean of D) values of ILAS-II and SAGE II from 20 to 26 km ranged from -10 to -34%, which were far from the 0% line even when 1σ standard deviation (6-29%) was considered. Furthermore, the values exceeded the range of the combined error (7-18%). The magnitude of the $\overline{D}$ values at these altitude levels arose from absolute AEC differences as small as 0.7-1.8×10^{-5} km^{-1} (triangles in the left panel of Figure 3).

ILAS-II and SAGE III AEC data are compared in Figure 4. As above, D was calculated for each of the ILAS-II and SAGE III coincident pairs. Comparisons between ILAS-II and SAGE III are similar to comparisons between ILAS-II and SAGE II shown in Figure 3. Below 20 km, ILAS-II and SAGE III AEC data were also within around ±10% of each other, and that difference was within the range of the combined error. From 20 to 26 km, ILAS-II AEC values were smaller than SAGE III AEC values; $\overline{D}$ and 1σ standard deviation ranged from -12±8 to -45±26%, exceeding the combined errors (7-21%). However, the magnitude of the absolute AEC difference was as small as 1.1-2.2×10^{-5} km^{-1}.

Figure 5 compares ILAS-II and POAM III AEC data. From 11 to 19 km, ILAS-II and POAM III AEC differences were within around ±15%. The difference was almost within the range of the combined error. ILAS-II AEC data from 20 to 24 km were small compared to POAM III AEC data. $\overline{D}$ and 1σ standard deviation ranged from -17±12 to -37±25%, exceeding the combined errors (8-16%). At these altitudes, the magnitude of the $\overline{D}$ and the absolute AEC difference (1.9-3.5×10^{-5} km^{-1}) between ILAS-II and POAM III were slightly larger than those between ILAS-II and SAGE II and those between ILAS-II and SAGE III at the same altitudes.

4.2. Southern Hemisphere

4.2.1. Non-PSC season

Figure 6 compares between ILAS-II and SAGE II AEC data in February. ILAS-II AEC was larger than SAGE II AEC from 10 to 16 km. Four of the eight coincident cases showed good agreement at these altitudes. However, the ILAS-II data in the other four cases were truncated at higher altitudes, around 12-13 km, and the AEC data were unusually large, resulting in poor agreement with SAGE II data. These two features in the comparison yielded large standard deviations from 10 to 16 km, as shown in Figure 6. The difference was therefore not significant. From 17 to 19 km, ILAS-II and SAGE II were within ±10% of each other. From 20 to 25 km, ILAS-II AEC was smaller than SAGE II AEC. $\overline{D}$ and 1σ standard deviation ranged from -12±12 to -66±23%, exceeding the combined errors (9-24%). These results are similar to those in the Northern Hemisphere. The $\overline{D}$ values from 20 to 25 km matched the absolute AEC difference of 1.4-2.2×10^{-5} km^{-1}, which was slightly larger than the absolute difference in the Northern Hemisphere (0.7-1.8×10^{-5} km^{-1}).

Figure 7 shows comparisons between ILAS-II and POAM III AEC in the non-PSC season (January-May). They agreed to within ±5% from 11 to 14 km, but ILAS-II AEC was smaller than POAM III AEC at and above 15 km. $\overline{D}$ and 1σ standard deviation between 15 and 24 km ranged from -13±9 to -94±51%. These values exceeded the combined errors (7-41%) and corresponded to the absolute AEC difference of 2.5-5.5×10^{-5} km^{-1} that was larger than the absolute difference between ILAS-II and SAGE II in the non-PSC season.

Figure 8 shows comparison between ILAS-II and OPC/LPC data. The left panel shows profiles of ILAS-II AEC and total error as indicated by thick and thin black lines, and profiles of AEC and error both calculated from the OPC/LPC data indicated by thick and thin gray lines. Relative percent differences (D) between the ILAS-II AEC and the OPC/LPC AEC and the relative value of RSS of both errors are shown in the right panel. Good agreement within the error bars occurred between the two profiles at most altitude levels. The differences were within ±15% between 13 and 18 km, although the ILAS-II AEC was smaller than the OPC/LPC AEC at all levels above 15 km.

4.2.2. PSC-season

Figure 9 shows comparisons between ILAS-II and POAM III AEC data during the PSC season (June-October). The left panel shows that both AEC data in the PSC season were one-half to one order of magnitude larger than those during the non-PSC season. In addition, both 1σ standard deviations during the PSC season were also larger than those in the non-PSC season, because the height at which PSCs occurred from June to October varied depending on temperature profiles coupled with the movement of cold region. As shown in the right panel, ILAS-II AEC data were smaller than POAM III AEC data from 18 to 24 km; $\overline{D}$ ranged from -16 to -112%, exceeding the range of the combined error (10~57%). This characteristic is similar to the results for the non-PSC season in both hemispheres. However, ILAS-II and POAM III AEC data were within ±15% of each other from 12 to 17 km in the PSC season even when PSCs were present.

5. Discussion and Summary

We assessed the data quality of ILAS-II AEC at 780 nm processed with the version 1.4 retrieval algorithm. The focus of this study was AEC data below 30 km in the Northern Hemisphere and below 25 km in the Southern Hemisphere. Above those altitude levels, at least about one-sixth of all ILAS-II AEC data are affected by sunspots, and most of those data still include sunspot effects because of shortcomings in the sunspot correction in the current version. Care should therefore be taken when using the version 1.4 AEC data above these altitudes. The precision of ILAS-II AEC data as estimated from measurement repeatability was 5-15% at 12-26 km in the Northern Hemisphere and 6-20 % at 12-23 km in the Southern Hemisphere.

Comparisons of ILAS-II AEC data at 780 nm in the Northern Hemisphere were made with SAGE II and SAGE III AEC data, both of which were interpolated to 780 nm, and with POAM III AEC data at 780 nm. ILAS-II AEC data above 19 km were systematically smaller than AEC data of the other three sensors. Comparisons with SAGE II AEC data, which have no clear bias [e.g., *Russell and McCormick*, 1989; *Hervig and Deshler*, 2002], revealed the mean relative percent difference ($\overline{D}$) of -10 to -34% between 20 and 26 km (Figure 3). Magnitudes of $\overline{D}$ between ILAS-II and SAGE III AEC data ranged from -12% at 20 km to -45% at 26 km (Figure 4), and magnitudes between ILAS-II and POAM III AEC data ranged from -17% at 20 km to -37% at 24 km (Figure 5). These values were slightly larger than those between ILAS-II and SAGE II AEC data, because SAGE III and POAM III AEC data were slightly larger on average than SAGE II AEC data (Figure 2a and 2b). Below 20 km, ILAS-II AEC agreed well with AEC from all three sensors. The differences between ILAS-II AEC data and SAGE II and SAGE III AEC data were within around ±10%. The difference between ILAS-II AEC and POAM III AEC data was within around ±15%.

ILAS-II and SAGE II AEC data comparisons for February in the Southern Hemisphere suggest that ILAS-II has a negative bias ranging from -12 to -66% as altitude increases from 20 to 25 km. Their agreement was closer, within ±10%, from 17 to 19 km. During the non-PSC season in the Southern Hemisphere (January-May), ILAS-II AEC was systematically smaller than POAM III AEC at all levels above 15 km. The difference ranged from -13 to -94%, which was larger than the difference between ILAS-II and SAGE II. However, in contrast to the Northern Hemisphere, POAM III AEC data have a distinct positive bias (13-30%) relative to SAGE II AEC data in the Southern Hemisphere (Figure 2c).

The bias can explain why ILAS-II AEC data have a larger negative bias against POAM III AEC data during the non-PSC season in the Southern Hemisphere (Figure 7).

Aerosol data obtained with an OPC and LPC over Syowa Station on 22 February were compared to nearby ILAS-II AEC data. Error of the OPC/LPC data was estimated to be 5-44%; however, this is probably an underestimate, because the systematic error of the measurement and the statistical error of the counting were used as an alternative to the error of the OPC/LPC AEC data. A more proper error estimate would use a Monte Carlo simulation to infer the impact of the measurement uncertainties on the lognormal parameters and the derived parameters such as aerosol extinction coefficient, as done by *Deshler et al*. [1993]. The ILAS-II and the OPC/LPC data do agree to within their error bars if the insufficient error estimate is considered. The difference was within ±15% from 13 to 18 km, although ILAS-II AEC was smaller than the OPC/LPC AEC at all levels above 15 km.

During the PSC season in the Southern Hemisphere (June-October), ILAS-II and POAM III made many close simultaneous PSC measurements. The two sensors often obtained PSC profiles with similar vertically-layered structures. Comparisons in the PSC season showed that ILAS-II AEC data agreed with POAM III AEC data to within ±15% from 12 to 17 km despite the high frequency of PSC, although ILAS-II AEC was smaller than POAM III AEC at and above 18 km, which is similar to the results in the non-PSC season.

Tangent height registration errors can induce errors in retrieved AEC data. Uncertainties in tangent height registration were less than 100 m for SAGE II version 6.2 retrieval, around 100 m for SAGE III version 3.0 retrieval [*Wang et al*., 2002; *J. Zawadny*, personal communication, 2005], and 250 m for POAM III version 4.0 retrieval [*Lumpe et al*., 2002; *J. Lumpe*, personal communication, 2005]. Uncertainty in the tangent height registration for ILAS-II version 1.4 retrieval was a systematic error of ±180 m and random error of ±30 m [*Tanaka et al*., 2005]. A sensitivity study using ILAS-II data suggested that height assignments 100 m higher than in the current retrieval caused a ~5-25% increase in AEC below 25 km, and vice versa. Uncertainties in tangent height registration as noted here are one possible cause for AEC differences between ILAS-II and the other three satellite sensors.

Table 2 and 3 summarize the comparisons of AEC data between ILAS-II and other satellite sensors over the Northern Hemisphere and the Southern Hemisphere, respectively. Over the Northern Hemisphere, the magnitudes of relative differences in AEC between ILAS-II and the other three sensors, SAGE II, SAGE III, and POAM III, were similar. The difference characteristics in the vertical were also similar. Below 20 km, ILAS-II AEC data have the same reliability as the other three sensors. Above 20 km, ILAS-II AEC data are valid for scientific studies if the negative bias relative to the other three sensors presented in Table 2 is considered. Over the Southern Hemisphere, characteristics of ILAS-II AEC data as summarized in Table 3 should be considered in the scientific use of ILAS-II AEC data coupled with SAGE II and/or POAM III AEC data for both the non-PSC season and the PSC season.

Acknowledgements. We thank all members of the ILAS-II science team and the validation team and their associates. We are also grateful to the United Kingdom Meteorological Office (UKMO) for supplying the UKMO assimilation data. OPC/LPC measurements at Syowa Station for ILAS-II validation were carried out by the 43rd and 44th Japanese Antarctic Research Expedition (JARE) in cooperation with the National Institute of Polar Research (NIPR) and the ILAS-II project of the National Institute for Environmental Studies (NIES) with help of Japan Meteorological Agency (JMA). The ILAS-II data retrieval processing was carried out at the ILAS Data Handling Facility (DHF) at NIES. The ILAS-II project has been funded by the Ministry of the Environment of Japan (MOE).

References.

Ackerman, M., C. Brogniez, B.S. Diallo, G. Fiocco, P. Gobbi, M. Herman, M. Jager, J. Lenoble, C. Lippens, G. Megie, J. Pelon, R. Reiter, and R. Santer, European validation of SAGE II aerosol profiles, *J. Geophys. Res.*, *94*, 8399-8411, 1989.

Adriani, A., T. Deshler, G.D. Donfrancesco, and G.P. Gobbi, Polar stratospheric clouds and volcanic aerosol during spring 1992 over McMurdo Station, Antarctica: Lidar and particle counter comparisons, *J. Geophys. Res.*, *100*, 25,877-25,897, 1995.

BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, and OIML, *Guide to the Expression of Uncertainty in Measurement*, 100 pp., ISO/TAG4/WG3 Technical Advisory Group on Meteorology, 1993.

Deshler, T., B.J. Johnson, and W.R. Rozier, Balloonborne measurements of Pinatubo aerosol during 1991 and 1992 at 41 N: Vertical profiles, size distribution, and volatility, *Geophys. Res. Lett.*, *20*, 1435-1438, 1993.

Bevilacqua, R.M., M.D. Fromm, J.M. Alfred, J.S. Hornstein, G.E. Nedoluha, K.W. Hoppel, J.D. Lumpe, C.E. Randall, E.P. Shettle, E.V. Browell, C. Butler, A. Dornbrack, and A.W. Strawa, Observations and analysis of polar stratospheric clouds detected by POAM III during the 1999/2000 Northern Hemisphere winter, *J. Geophys. Res.*, *107*, 10.1029/2001JD000477, 2002.

Burton, S.P., L.W. Thomason, Y. Sasano, and S. Hayashida, Comparison of aerosol extinction measurements by ILAS and SAGE II, *Geophys. Res. Lett.*, *26*, 1719-1722, 1999.

Drdla, K., and M.R. Schoeberl, Microphysical modeling of the 1999-2000 Arctic winter 2. Chlorine acrivation and ozone depletion, *J. Geophys. Res.*, *108*, 10.1029/2001JD001159, 2003.

Fromm, M.D., R.M. Bevilacqua, J. Hornstein, E. Shettle, K. Hoppel, and J.D. Lumpe, An analysis of Polar Ozone and Aerosol Measurement (POAM) II Arctic polar stratospheric cloud observations, 1993-1996, *J. Geophys. Res.*, *104*, 24,341-24,357, 1999.

Fromm, M.D., J.D. Lumpe, R.M. Bevilacqua, E.P. Shettle, J. Hornstein, S.T. Massie, and K.H. Fricke, Observations of Antarctic polar stratospheric clouds by POAM II: 1994-1996, *J. Geophys. Res.*, *102*, 23,659-23,672, 1997.

Hayashida, S., N. Saitoh, A. Kagawa, T. Yokota, M. Suzuki, H. Nakajima, and Y. Sasano, Arctic polar stratospheric clouds observed with the Improved Limb Atmospheric Spectrometer during winter 1996/1997, *J. Geophys. Res.*, *105*, 24,715-24,730, 2000.

Hervig, M., and T. Deshler, Evaluation of aerosol measurements from SAGE II, HALOE, and balloonborne optical particle counters, *J. Geophys. Res.*, *107*, 10.1029/2001JD000703, 2002.

Hitchman, M., M. McKay, and C. Trepte, A climatology of stratospheric aerosol, *J. Geophys. Res.*, *99*, 20,689-20,700, 1994.

Hofmann, D.J., and T. Deshler, Stratospheric cloud observations during formation of the Antarctic ozone hole in 1989, *J. Geophys. Res.*, *96*, 2897-2912, 1991.

Lumpe, J.D., R.M. Bevilacqua, K.W. Hoppel, and C.E. Randall, POAM III retrieval algorithm and error analysis, *J. Geophys. Res.*, *107*, 10.1029/2002JD002137, 2002.

McCormick, M.P., H.M. Steele, P. Hamill, W.P. Chu, and T.J. Swissler, Polar stratospheric cloud sightings by SAM II, *J. Atmos. Sci.*, *39*, 1387-1397, 1982.

Nakajima, H., T. Sugita, T. Yokota, H. Kobayashi, Y. Sasano, T. Ishigaki, Y. Mogi, N. Araki, K. Waragai, N. Kimura, T. Iwasawa, A. Kuze, J. Tanii, T. Togami, H. Kawasaki, M. Horikawa, and N. Uemura, Characteristics and performance of the Improved Limb Atmospheric Spectrometer-II (ILAS-II) onboard the ADEOS-II satellite, *J. Geophys. Res.*, this issue.

Nash, E.R., P.A. Newman, J.E. Rosenfield, and M.R. Schoeberl, An objective determination of the polar vortex using Ertel' s potential vorticity, *J. Geophys. Res.*, *101*, 9471-9478, 1996.

Osborn, M.T., J.M. Rosen, M.P. McCormick, P.-H. Wang, J.M. Livingston, and T.J. Swissler, SAGE II aerosol correlative observations: Profile measurements, *J. Geophys. Res.*, *94*, 8353-8366, 1989.

Poole, L.R., and M.C. Pitts, Polar stratospheric cloud climatology based on Stratospheric Aerosol Measurement II observations from 1978 to 1989, *J. Geophys. Res.*, *99*, 13,083-13,089, 1994.

Randall, C.E., R.M. Bevilacqua, J.D. Lumpe, and K.W. Hoppel, Validation of POAM III aerosol: Comparison to SAGE II and HALOE, *J. Geophys. Res.*, *106*, 27,525-27,536, 2001.

Randall, C.E., R.M. Bevilacqua, J.D. Lumpe, K.W. Hoppel, D.W. Rusch, and E.P. Shettle, Comparison of Polar Ozone and Aerosol Measurement (POAM) II and Stratospheric

Aerosol and Gas Experiment (SAGE) II aerosol measurements from 1994 to 1996, *J. Geophys. Res.*, *105*, 3929-3942, 2000.

Randall, C.E., D.W. Rusch, J.J. Olivero, R.M. Bevilacqua, L.R. Poole, J.D. Lumpe, M.D. Fromm, K.W. Hoppel, J.S. Hornstein, and E.P. Shettle, An overview of POAM II aerosol measurements at 1.06 um, *Geophys. Res. Lett.*, *23*, 3195-3198, 1996.

Russell, P.B., and M.P. McCormick, SAGE II aerosol data validation and initial data use: An introduction and overview, *J. Geophys. Res.*, *94*, 8335-8338, 1989.

Saitoh, N., S. Hayashida, Y. Sasano, and L.L. Pan, Characteristics of Arctic polar stratospheric clouds in the winter of 1996/1997 inferred from ILAS measurements, *J. Geophys. Res.*, *107*, 10.1029/2001JD000595, 2002.

Sasano, Y., T. Yokota, H. Nakajima, T. Sugita, and H. Kanzawa, ILAS-II instrument and data processing system for stratospheric ozone layer monitoring, in *Soc. Photo Opt. Instrum. Eng.*, pp. 106-114, Sendai, Japan, 2000.

Solomon, S., Stratospheric ozone depletion: A review of concepts and history, *Rev. Geophys.*, *37*, 275-316, 1999.

Thomason, L.W., and L.R. Poole, Use of stratospheric aerosol properties as diagnostics of Antarctic vortex processes, *J. Geophys. Res.*, *98*, 23,003-23,012, 1993.

Thomason, L.W., L.R. Poole, and T. Deshler, A global climatology of stratospheric aerosol surface area density deduced from Stratospheric Aerosol and Gas Experiment II measurements: 1984-1994, *J. Geophys. Res.*, *102*, 8967-8976, 1997.

Thomason, L.W., and G. Taha, SAGE III Aerosol Extinction Measurements: Initial Results, *Geophys. Res. Lett.*, *30*, 10.1029/2003GL017317, 2003.

Wang, H.J., D.M. Cunnold, L.W. Thomason, J.M. Zawadny, and G.E. Bodeker, Assessment of SAGE version 6.1 ozone data quality, *J. Geophys. Res.*, *107*, 10.1029/2002JD002418, 2002.

Yokota, T., H. Nakajima, T. Sugita, H. Tsubaki, Y. Itou, M. Kaji, M. Suzuki, H. Kanzawa, J.H. Park, and Y. Sasano, Improved Limb Atmospheric Spectrometer (ILAS) data retrieval algorithm for Version 5.20 gas profile products, *J. Geophys. Res.*, *107*, 10.1029/2001JD000628, 2002.

Yokota, T., Improved Limb Atmospheric Spectrometer-II (ILAS-II) data retrieval algorithm for version 1.4 level 2 products, *J. Geophys. Res.*, this issue.

Tables.

	NH	non-PSC season in SH	PSC season in SH
POAM III	150 km, 1 hour (245)	150 km, 1 hour (198)	50 km, 1 hour (163)
SAGE II	300 km, 1 hour (34)	500 km, 12 hour (8*)	–
SAGE III	300 km, 1 hour (87)	–	–

Table 1. Distance and time difference criteria for selecting coincident pairs in the comparisons of ILAS-II to SAGE II, SAGE III, and POAM III. The numbers of selected pairs

are also shown in parentheses. *More than one coincident profile is accepted for one ILAS-II profile as the individual pairs. NH, Northern Hemisphere; SH, Southern Hemisphere.

Alt.	SAGE II	SAGE III	POAM III
11-19 km	±10%	±10%	±15%
20-26 km	-10%/-34%	-12%/-45%	-17%/-37%*

Table 2. The mean percent difference ($\overline{D}$) between ILAS-II and SAGE II, SAGE III, or POAM III in the Northern Hemisphere.

SAGE II	±10%	-10%/-40%
	17-19 km	20-23 km
POAM III (non-PSC)	±5%	-10%/-40%
	11-14 km	15-20 km
POAM III (PSC)	±15%	-15%/-60%
	12-17 km	18-20 km

Table 3. The mean percent difference ($\overline{D}$) between ILAS-II and SAGE II or POAM III in the Southern Hemisphere.

Figure Captions.

Figure 1. Time series of the latitudinal coverage of ILAS-II (black dots), POAM III (light gray circles), SAGE II (thick gray line), and SAGE III (solar occultation mode only; thin gray line) during ILAS-II operations from January to October in 2003. The star denotes the position of Syowa Station (69º S, 40º E), where the OPC/LPC measurement was conducted on

22 February.

Figure 2. (a) Profiles of the mean difference (black line) between SAGE II (version 6.2) and SAGE III (version 3.0) AEC data ($\overline{D}_{SAGE3-SAGE2}$) in the Northern Hemisphere both interpolated to 780 nm and 1σ standard deviation (gray lines). Here, the logarithms of SAGE II AEC at 525 nm and 1019 nm and SAGE III AEC at 756 nm and 869 nm are linearly interpolated with the logarithms of the wavelengths, yielding the AEC at 780 nm. (b) Profiles of the mean difference between SAGE II and POAM III (version 4.0) AEC data at 780 nm ($\overline{D}_{POAM3-SAGE2}$) in the Northern Hemisphere and 1σ standard deviation. (c) Profiles of the mean difference between SAGE II and POAM III AEC data at 780 nm ($\overline{D}_{POAM3-SAGE2}$) in the Southern Hemisphere and 1σ standard deviation. Criteria for coincident pairs are a distance from a SAGE II measurement location of no more than 300 km and a measurement time difference of no more than 1 hour for the Northern Hemisphere, and a distance of no more than 500 km and a time difference of no more than 12 hours for the Southern Hemisphere.

Figure 3. Comparison between ILAS-II AEC and SAGE II AEC (interpolated to 780 nm) in the Northern Hemisphere. A maximum distance of 300 km and a time difference of no more than 1 hour yielded 34 coincident pairs after 25 April.

Left Panel. Profiles of the mean of ILAS-II (black line) and SAGE II (gray line) AEC used in the comparison. Dashed lines are the 1σ standard deviation profiles. Triangles show the difference between ILAS-II and SAGE II AEC mean values. Black (gray) triangles correspond to negative (positive) values of ILAS-II minus SAGE II AEC.

Right Panel. The mean of relative percent difference (D) computed for all coincident ILAS-II and SAGE II AEC data (thick black line) and 1σ standard deviation (thin black lines). See text for the definition of D. Gray dashed lines indicate the relative error defined as the RSS of both reported errors of ILAS-II and SAGE II divided by the mean of ILAS-II and SAGE II AEC (equal to the denominator of the D expression).

Figure 4. As in Figure 3, but for 87 coincident ILAS-II and SAGE III (interpolated to 780 nm) pairs in the Northern Hemisphere. The criteria for coincident pairs between ILAS-II and SAGE III are the same as the case between ILAS-II and SAGE II.

Figure 5. As in Figure 3, but for 245 coincident ILAS-II and POAM III pairs in the Northern Hemisphere. Coincident pairs were selected when a distance of no more than 150 km and a time difference of no more than 1 hour were applied for AEC data after 25 April.

Figure 6. As in Figure 3, but for comparison of eight coincident pairs in the Southern Hemisphere. Coincident pairs were selected by applying a distance criterion of no more than 500 km and a time difference of within 12 hours.

Figure 7. As in Figure 3, but for 198 coincident ILAS-II and POAM III pairs in the non-PSC

season in the Southern Hemisphere. Coincident pairs were selected when a distance criterion of within 150 km and a time difference within 1 hour were applied for AEC data from January to May.

Figure 8. Comparison between the ILAS-II (74.0º S, 36.6º E) and the OPC/LPC (74.0º S, 36.6º E) on 22 February. The distance between the measurement locations was 599 km. See text for the detail of estimate of error in the OPC/LPC AEC data.

Left Panel. ILAS-II AEC profile (thick black line) and the total error profile (thin black line). Thick gray and thin gray lines also indicate AEC profile calculated from the OPC/LPC data and the error profile.

Right Panel. Relative percent difference (D) between the ILAS-II and the OPC/LPC AEC data and the relative error defined as RSS of the both errors divided by the mean are indicated by black and gray dashed lines, respectively.

Figure 9. As in Figure 3, but for 163 coincident ILAS-II and POAM III pairs in the PSC season in the Southern Hemisphere. Coincident pairs were selected when a maximum distance of 50 km and a maximum time difference of 1 hour were applied to AEC data from June to October.