

Spatial and temporal variability of the stratospheric aerosol cloud produced by the 1991 Mount Pinatubo eruption

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[1] As a critical quality control step toward producing a stratospheric data assimilation system for volcanic aerosols, we conducted a comparison between Stratosphere Aerosol and Gas Experiment (SAGE) II aerosol extinction profiles and aerosol backscatter measured by five lidars, both in the tropics and midlatitudes, for the two-year period following the 1991 Mt. Pinatubo eruption. The period we studied is the most challenging for the SAGE II retrieval because the aerosol cloud caused so much extinction of the solar signal that in the tropics few retrievals were possible in the core of the cloud. We compared extinction at two wavelengths at the same time that we tested two sets of conversions coefficients. We used both Thomason and Jäger's extinction-to-backscatter conversion coefficients for converting lidar backscatter profiles at 0.532 μm or 0.694 μm wavelengths to the SAGE II extinction wavelengths of 0.525 μm and 1.020 μm or the nearby ones of 0.532 μm and 1.064 μm respectively. The lidars were located at Mauna Loa, Hawaii (19.5°N, 155.6°W), Camagüey, Cuba (21.4°N, 77.9°W), Hefei, China (31.9°N, 117.2°W), Hampton Virginia (37.1°N, 76.3°W), and Haute Provence, France (43.9°N, 5.7°W). For the six months following the eruption the aerosol cloud was much more heterogeneous than later. Using two alternative approaches, we evaluated the aerosol extinction variability of the tropical core of the Pinatubo stratospheric aerosol cloud at the timescale of 1–2 days, and found it was quite large. Aerosol variability played the major role in producing the observed differences between SAGE II and the lidars. There was in general a good agreement between SAGE II extinction measurements and lidar derived extinction, and we conclude that all five lidar sets we compared can be used in a future data assimilation of stratospheric aerosols. This is the most comprehensive comparison yet of lidar data with satellite data for the Pinatubo period. *INDEX TERMS:*

0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0394 Atmospheric Composition and Structure: Instruments and techniques; 0370 Atmospheric Composition and Structure: Volcanic effects (8409); 3360 Meteorology and Atmospheric Dynamics: Remote sensing; *KEYWORDS:* volcano, lidar, satellite

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1. Introduction

[2] The June 15, 1991 Mount Pinatubo volcanic eruption in the Philippines (15.1°N, 120.4°E) placed a tremendous

aerosol load into the stratosphere and produced large perturbations to the climate system and to stratospheric ozone [Robock, 2000]. Even though the Pinatubo aerosols were better observed than any previously, there were still gaps in the coverage and discrepancies remain between measurements from several different instruments. The Stratosphere Aerosol and Gas Experiment (SAGE) II instrument [Russell and McCormick, 1989] on the Earth Radiation Budget Satellite (ERBS) produced limb-viewing vertical profiles of the aerosol cloud [Thomason, 1992; Thomason and Poole, 1993; Trepte et al., 1993; Yue et al., 1994]. However, coverage was limited by the ERBS orbital characteristics to sample any latitude only about once every 40 days, and in regions of high aerosol loading there are many gaps in the measurements. The SAGE II post-Pinatubo data set lacks aerosol measurements for the period June–August, 1991 in the region 15°S to 20°N below

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Table 1. Lidar Stations With Wavelength and Vertical Resolution of Lidars

Station	Latitude	Longitude	λ , μm	Resolution	Reference
Mauna Loa	19.5°N	155.6°E	0.694	300 m	<i>Barnes and Hofmann</i> [1997]
Camagüey	21.4°N	77.9°W	0.532	300 m	<i>Antuña</i> [1996]
Hefei	31.9°N	117.2°E	0.532	600 m	<i>Zhou et al.</i> [1993]
Hampton	37.1°N	76.3°W	0.694	150 m	<i>Osborn et al.</i> [1995]
Haute Provence	43.9°N	5.7°E	0.532	300 m	<i>Chazette et al.</i> [1995]

22 km, which was the result of the “saturation” of the satellite sensor by the dense aerosol cloud. The aerosol cloud caused so much extinction of the solar signal that no retrievals were possible [Stenchikov *et al.*, 1998]. In addition, SAGE II lacks information below the tropopause due to the presence of clouds, and at the poles due to the latitudinal coverage of the satellite [McCormick and Veiga, 1992]. In contrast to the almost global coverage provided by the SAGE II instrument, lidars provide vertical profiles of aerosol backscatter over their location with a greater vertical resolution than satellite limb measurements. Time series of lidar measurements are only constrained by weather conditions (cloud-free sky) and the measurement regime for each station. That regime conventionally is one or two measurements per week under the presence of stratospheric aerosols. Lidar stations were able to detect the presence of the Pinatubo aerosol cloud outside the tropical belt much earlier than satellite observations [Jäger *et al.*, 1995], because of their greater sensitivity.

[3] We have conducted an extensive comparison of SAGE II and lidar aerosol extinction profiles after Pinatubo. This comparison will play an important role in future improvements of the post Pinatubo aerosol data set we have recently developed [Stenchikov *et al.*, 1998], one of the goals of our ongoing research project.

[4] Recently we reported the first set of results of the comparison of SAGE II aerosol extinction profiles with aerosol derived extinction profiles from Mauna Loa and Hampton lidar station aerosol backscatter measurements [Antuña *et al.*, 2002]. We were unable to evaluate the magnitude of the aerosol variability at the temporal scale at which this comparison was conducted. Here we report the results from the same type of comparison but for the rest of the five stations. First, we make a brief review of the data sets and coincidence criteria. Next we describe the few previous lidar-SAGE II comparisons conducted in the tropics. Then, we evaluate aerosol extinction variability using SAGE II coincident sunset-sunrise extinction profiles, and consecutive one-day-and two-days-apart lidar backscatter profiles. Finally, we show and discuss the results of the comparisons between SAGE II extinction profiles and lidar derived extinction profiles at Camagüey, Hefei, and Observatoire de Haute Provence.

2. Data Sets and Coincidence Criteria

[5] We used aerosol extinction profiles at wavelengths of 0.525 μm and 1.020 μm from version 6.0 of the SAGE II data set, provided by the Langley Research Center [Zawodny *et al.*, 2000]. The current version 6.1 of the data set has virtually identical aerosol data; changes were made in other parameters. The lidar data set consists of the vertical profiles of lidar backscatter coefficients at 0.532 μm or 0.694 μm from five lidar stations (Table 1). The very few vertical gaps in the

backscatter vertical profiles were filled by interpolation and then the profiles were integrated to 0.5 km resolution, the same vertical resolution as the SAGE II data.

[6] SAGE II and lidar observations do not have an exact match between the regions they sample or the duration of each type of measurement. Our attempts to establish coincidence criteria between satellite and lidar measurements based on the variability of the Mt. Pinatubo aerosols extinction measured by SAGE II were unsuccessful [Antuña *et al.*, 2002]. When we did our previous comparison, we therefore selected criteria of $\pm 5^\circ$ in latitude, $\pm 25^\circ$ in longitude, and ± 24 hours in time based on the geometry of the SAGE II sampling. By applying these spatial-temporal criteria, we found 49 space-time coincident profiles for Mauna Loa, 20 for Camagüey, 55 for Hefei, 76 for Hampton and 178 for Haute Provence. Our coincidence criteria here, more relaxed than ones used previously by other authors [Antuña *et al.*, 2002], allow more pairs of lidar-SAGE II coincident profiles to be considered.

[7] We used two sets of extinction-to-backscatter conversion coefficients for converting lidar backscatter profiles at 0.532 or 0.694 μm wavelengths to SAGE II extinction profiles at 0.525 and 1.020 μm or the nearby ones at 0.532 μm and 1.064 μm respectively. Jäger and Deshler [2002] derived coefficients dependent on both time and altitude for the complete period after Pinatubo using the midlatitude particle size distribution measured at Laramie, Wyoming [Deshler *et al.*, 1993]. They converted aerosol backscatter at 0.532 μm to aerosol extinction at the same exact wavelength. Because of the very small difference between this wavelength and the 0.525 μm SAGE II channel and the magnitude of the error involved in the conversion they considered this difference insignificant; the same reasoning applies for the lidar-derived extinction at 1.064 μm and the SAGE II measured 1.02 μm . To convert aerosol extinction at 0.532 μm to aerosol extinction at 1.02 μm , we used two sets of Ångström coefficients provided by Jäger and Deshler [2002]. The first set of Ångström coefficients allows converting extinction from 0.532 μm to 0.694 μm and the second from 0.694 μm to 1.064 μm . Thomason and Osborn [1992] derived a set of conversion coefficients using a principal component analysis of the SAGE II extinction profiles kernels between 30° and 50°N for October 23–27, 1991. This set depends on the altitude, but it is constant in time. Thomason and Osborn converted aerosol backscatter at 0.532 μm to aerosol extinction at 0.525 and 1.020 μm .

3. Previous Stratosphere Aerosol and Gas Experiment (SAGE) II-Lidar Comparisons in the Tropics

[8] Comparing SAGE II stratospheric aerosol extinction measurements with tropical lidars is always a complicated

task, because of the different measurement principles and geometry as well as the few lidars available in the tropical region. However, if the period under comparison is the one following the 1991 Mount Pinatubo volcanic eruption the comparison is even more difficult because it is necessary to consider additional issues. These include gaps in the SAGE II data set during the period following the eruption because the densest part of the aerosol cloud attenuated the sunlight radiation to levels well below the detection limits of the SAGE II instrument [McCormick and Veiga, 1992]. In addition, the parameterizations included in the retrieval algorithm correspond to near background stratospheric aerosol conditions. Deriving aerosol extinction profiles under volcanic conditions represents a unique test for the robustness of the retrieval algorithm.

[9] Antuña *et al.* [2002] described previous lidar-SAGE II comparisons conducted in midlatitudes. Because two of the five lidar data sets we compare here are located in the tropics and one in the subtropics, we describe previous comparisons which have taken place in those latitude bands.

[10] Only a few comparisons of aerosol extinction profiles measured in the tropics by SAGE instruments and lidars have been reported. Under background conditions a comparison was conducted using SAGE I aerosol/molecular extinction ratio profiles at $1.0\ \mu\text{m}$ [McCormick *et al.*, 1979] and the aerosol scattering ratio at $0.694\ \mu\text{m}$ measured by the Mark II lidar system located at the University of West Indies (18°N , 76.8°W), Kingston, Jamaica [Kent *et al.*, 1971]. A set of six lidar aerosol scattering ratio profiles obtained on November 25–26, 1978 were compared qualitatively with a set of six SAGE I extinction ratio profiles measured on April 9, 1979. SAGE I profiles were selected within 5° of the lidar latitude. It was found that on average, lidar profiles had higher extinction values in the height range 20–25 km than in the height range 25–30 km in contrast with the SAGE I profile [Kent *et al.*, 1982], but the differences may have been due to the seasonal variability of background aerosol concentrations.

[11] Only two comparisons of stratospheric aerosol measurements from SAGE II with a lidar have been reported in the tropics, both qualitative. One of them was done under stratospheric aerosol background conditions using data from Trivandrum, India (8.6°N , 77°E) for the first months of 1987 [Parameswaran *et al.*, 1991]. The other comparison was conducted right after the Mount Pinatubo eruption at Ahmedabad (23°N , 72.5°E) in April 1992 [Jayaraman *et al.*, 1995].

[12] The first comparison was conducted in two steps. First, all the lidar aerosol backscatter profiles at $0.694\ \mu\text{m}$ for the three-month period were converted to extinction at the same wavelength using backscatter-to-extinction coefficients of 50 and 30 sr for all the altitudes. All the SAGE II extinction profiles at $0.525\ \mu\text{m}$, coincident in $\pm 5^\circ$ in latitude and $\pm 15^\circ$ in longitude with respect to the lidar site for the same three-month period were averaged as well as all the lidar derived extinction profiles. The averaged profiles were plotted together and qualitatively compared. In the second step lidar extinction profiles for two consecutive individual days, on January 14 and 15, 1987 were compared with three SAGE II extinction profiles at $0.525\ \mu\text{m}$ and $1.02\ \mu\text{m}$ that comply with their space coincident criteria. The comparison showed the consistency of the aerosol extinction measure-

ments from both instruments with a satisfactory agreement between them [Parameswaran *et al.*, 1991].

[13] In the second comparison three $0.532\ \mu\text{m}$ aerosol backscatter profiles for April 3, 6, and 14, 1992 were converted to extinction using a backscatter-to-extinction coefficient of 50 sr. Then they were compared with a SAGE II $0.525\ \mu\text{m}$ extinction profile taken on April 18, 1992 at 19°N and 71.3°E . A good agreement between the extinction profiles was found in the range of 22 to 29 km, differing above 29 km [Jayaraman *et al.*, 1995].

[14] All these comparisons conducted in the tropics and the ones conducted at midlatitudes have some common features. They characterized only a few pairs of lidar-SAGE II selected profiles. They were conducted only at one wavelength, mostly under stratospheric aerosol background conditions or only for a few lidar-backscatter profiles measured 1.5 yr after the Mt. Pinatubo eruption. Estimates of the magnitude of the relative percent differences were provided together with visual estimation of the magnitude of the extinction or backscatter differences derived from the plots of coincident profiles. However, they lack statistics on the magnitude of such differences. In general, all of them focused on instrument comparability.

[15] Here we go much farther than these previous studies, comparing all the lidar-SAGE II coincident extinction profiles from immediately after the Mt. Pinatubo eruption in June 1991 until December 1993, depending on the available coverage at each lidar site. We have conducted the test with two sets of conversion coefficients at two wavelengths. Also we calculated the mean magnitudes of the extinction relative differences as well as the average of the absolute percent differences for the two time periods we have defined, taking into account the changes of the magnitudes for each wavelength in time.

4. Aerosol Extinction Variability

[16] Antuña *et al.* [2002] were unable to evaluate the temporal and spatial scales of the aerosol variability using consecutive SAGE II profiles in time and space. The reasons were the structure of SAGE II sampling, together with the high variability of the cloud because of the transport processes taking place in the stratosphere, and the missing data values in the period after the Pinatubo eruption. Because of that, here we make use of two parallel approaches to obtain the magnitudes of the spatiotemporal variability of the aerosol cloud. First, we use coincident sunset and sunrise SAGE II extinction profiles. Later we use lidar-backscatter profiles measured on consecutive days as well as two days apart.

[17] Because of the structure of the SAGE II orbit, sunrise and sunset measurements coincide within $\pm 1^\circ$ in latitude and $\pm 5^\circ$ in longitude only a few times per year. Sunrise and sunset profiles show different behaviors for different species derived from the measurements of the solar radiation as it traverses the atmosphere. For NO_2 retrievals, only sunset measurements are used because of the solar heating transient of the instrument during sunrises [Cunnold *et al.*, 1991]. For ozone both types of measurements are expected to be mirror images up to approximately 55 km [Chu and Cunnold, 1994], but there are still differences [Wang *et al.*, 1996].

Table 2. Vertical Profiles of the Extinction Percentage Differences for Selected Coincident Sunrise and Sunset Measurements for the Period 1984–1985, Using the Stratosphere Aerosol and Gas Experiment (SAGE) II Original Data Set Version [Yue *et al.*, 1989] and Version 6.0^a

H[km]	Case 4a		Case 4b		Case 4c		Case 4f	
	$\lambda = 1.02 \mu\text{m}$		$\lambda = 1.02 \mu\text{m}$		$\lambda = 0.0525 \mu\text{m}$		$\lambda = 1.02 \mu\text{m}$	
	Yue	Ver. 6.0	Yue	Ver. 6.0	Yue	Ver. 6.0	Yue	Ver. 6.0
25.5	-15.2	-8.7	1.7	0.9	3.2	2.8	75.9	-8.6
24.5	-11.1	-18.7	-5.4	-11.1	-4.9	-4.0	76.5	32.5
23.5	1.7	-6.2	-6.6	-6.2	-6.7	0.2	74.1	14.9
22.5	2.1	3.0	3.3	-26.5	2.8	-20.0	70.5	-21.6
21.5	-0.2	-1.5	-2.2	10.2	-0.1	9.1	67.9	-7.4
20.5	-2.6	-2.0	-7.2	0.0	-5.6	3.5	61.8	12.7
19.5	-0.3	-4.1	-3.7	0.5	-8.7	0.7	51.8	4.8
18.5	-2.1	5.5	-16.2	-11.3	-22.3	-18.0	32	3.7
17.5	-30.3	5.9	-13.1	1.5	-3.7	-1.9	2.4	1.9
16.5	-50.4	-58.4	-4.1	-1.4	14.3	10.2	-10.5	21.3
15.5	-22.3	-32.4	-9.1	-17.1	1.8	2.7	-19.8	6.3

^aCases 4a, 4b, 4c, and 4f are from Yue *et al.* [1989]. Extinction percentage difference is defined as the ratio of the difference between extinction values at sunrise and sunset, to the mean of both values multiplied by 100.

[18] In the case of aerosol retrieval, coincident sunrise and sunset SAGE II measurements have been used in the past to test the consistency of aerosol extinction [Yue *et al.*, 1989]. This is the only SAGE II aerosol extinction sunrise-sunset comparison reported in the literature dating back to 1989, using both 0.525 μm and 1.02 μm wavelengths, and was part of the SAGE II aerosol data validation and initial data use effort [Russell and McCormick, 1989]. The coincidence criteria used for that comparison were $\pm 1^\circ$ in latitude and $\pm 5^\circ$ in longitude as the space coincidence criteria for sunrise and sunset measurements in a 12-hour window. From the time of that study to the present there have been several updated and upgraded data set versions released. Thus as a consistency test, we compare the extinction differences reported by Yue *et al.* [1989] for sunrise-sunset coincident measurements. We reproduced the sunrise-sunset comparison they reported, using the same set of measurements they reported in Table 6 of their paper, but using the updated SAGE II data set Version 6.0. There were small differences in time, latitude and longitude between the original and actual profiles due to improvements in the geometrical calculations in the updated data set version 6.0 [Zawodny *et al.*, 2000].

[19] For comparison purposes, cases 4a, 4b, 4c and 4f from Yue *et al.* [1989] were selected, because they were done with the same two wavelengths of our interest. Table 2 shows the percentage extinction differences between sunrise and sunset from [Yue *et al.*, 1989], taken from their Table 6 as well as our results. As our main interest is the lower stratosphere, levels begin at 15.5 km, and the table ends at 25.5 km, because that was the highest altitude reported by Yue *et al.* [1989]. Three of the cases are for the 1.02 μm wavelength (4a, 4b and 4f) and one for the 0.525 μm wavelength (4c).

[20] There is in general a good agreement between the same set of coincident sunrise-sunset profiles in both the original data set version and the data set version we used. In all such cases, the percentage differences remain in the same

range. However, in Case 4f in the new data set version the extinction percentage differences at all levels remain lower than $\pm 40\%$ in contrast with the original version showing highest values above 18 km, with values between 50 and 70%.

[21] We searched the period from January 1991 to December 1993 for SAGE II coincident sunset-sunrise measurements according to the aforementioned criteria, finding 20 cases (Table 3). The selected profiles have very few extinction data at 0.525 μm but at 1.02 μm , data are only missing below 19 km. Because 15 of the 20 coincident cases occurred in tropical latitudes around 17°N or 17°S , the whole set may be considered representative of the tropics. We calculated extinction differences between the pairs of coincident extinction profiles at 1.02 μm and then grouped the 20 cases into three sets. The first contains all seven pairs of profiles between January and March 1991 (before the Pinatubo eruption), the second all seven pairs of profiles between July 1991 and March 1992 (immediately after the eruption), and the third the six pairs of profiles between July 1992 and July 1993 (Figure 1). The average of the absolute percent extinction differences for the period from January to March 1991 is representative of the joint variability between sunrise and sunset measurements as well as the background natural aerosol extinction variability under background conditions. For two time series x_i and y_i ,

$$\text{Mean absolute percent difference} = 2 \sum_{i=1}^T \frac{|x_i - y_i|}{x_i + y_i}.$$

In the second period below 25 km, where the bulk of Pinatubo aerosols were located, there was a noticeable increase in variability from 15–25% for both January to March 1991 and July 1992 to July 1993 to 40–60% during the period July 1991 to March 1992. As result of this comparison, we estimate that the aerosol extinction

Table 3. Dates, Times, and Locations of the 20 Pairs of SAGE II Sunrise-Sunset Coincident Measurements for the Years 1991–1993

Date		Time, UTC		Latitude, deg		Longitude, deg	
Sunrise	Sunset	Sunrise	Sunset	Sunrise	Sunset	Sunrise	Sunset
910110	910110	2.25	13.09	18.33	17.42	62.94	67.53
910110	910110	4.02	14.45	18.02	17.74	38.65	43.24
910110	910110	5.38	16.22	17.72	18.07	14.36	18.96
910110	910110	7.15	17.59	17.41	18.39	-9.92	-5.33
910323	910324	15.59	4.31	47.87	47.22	-149.67	-154.45
910323	910324	17.36	6.07	47.44	47.79	-173.84	-178.56
910324	910323	6.29	18.51	43.70	43.68	-7.18	-9.76
910710	910710	11.35	22.19	-18.14	-17.35	-75.15	-70.52
910710	910710	13.12	23.55	-17.84	-17.67	-99.42	-94.80
910710	910711	14.48	1.32	-17.54	-17.98	-123.70	-119.07
920107	920108	15.12	1.55	17.40	17.63	-129.30	-124.43
920107	920108	16.48	3.31	17.09	17.95	-153.56	-148.69
920320	920319	9.10	21.31	41.33	40.53	-45.97	-50.83
920320	920319	10.46	23.08	40.84	41.11	-70.13	-74.95
920706	920706	11.31	22.14	-17.89	-16.92	-74.24	-69.39
920706	920706	13.08	23.50	-17.59	-17.24	-98.49	-93.64
920706	920707	16.21	3.03	-16.98	-17.87	-146.99	-142.15
930703	930703	3.06	13.48	-17.44	-16.87	51.92	56.83
930703	930703	4.42	15.25	-17.14	-17.18	27.67	32.58
930703	930703	6.19	17.01	-16.84	-17.49	3.42	8.34

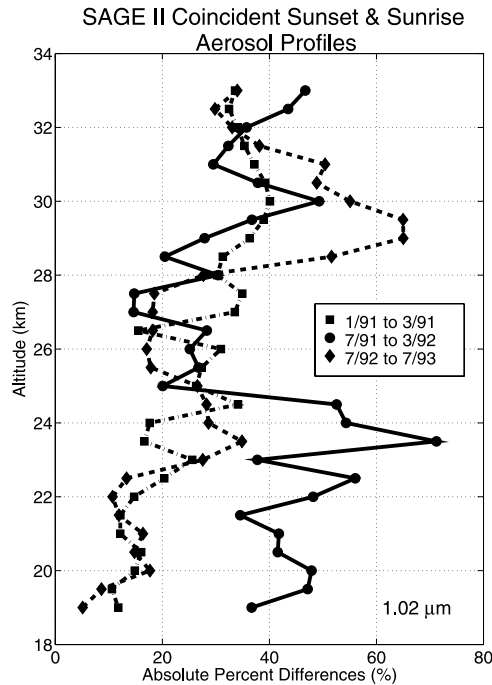


Figure 1. Mean absolute percent difference profiles of aerosol extinction for three sub-periods between January 1991 and December 1993 for the set of coincident sunset and sunrise Stratosphere Aerosol and Gas Experiment (SAGE) II measurements. See Table 3 for dates. See color version of this figure in the HTML.

variability in the core of the cloud in the tropical region for six months following the Mt. Pinatubo eruption ranged between 20 and 40% at the same point over the Earth's surface for a time lapse of 12 hours.

[22] We then try an alternative method to evaluate aerosol extinction variability. We searched for consecutive days of lidar measurements at the same station, finding three at Mauna Loa on July 1, 2 and 3, 1991 and two at Camagüey on March 5 and 6, 1992 (Figure 2). Because the conversion from backscatter to extinction uses Thomason's conversion coefficients [Thomason and Osborn, 1992], which are constant at each level, for simplicity we employ lidar backscatter in the following calculations. Using zonal wind components from reanalysis [Kalnay et al., 1996] for those particular days at 100, 70, and 30 hPa we determined that at both sites the displacement of the cloud between the consecutive days ranged between 5 and 10° in longitude. Because that displacement is around half of the longitudinal step between two consecutive SAGE II measurements, the lidar's backscatter profile variability between consecutive observations provides a way of evaluating extinction spatial variability at a higher spatial resolution than that provided by consecutive SAGE II profiles. In Figure 2 we see that the absolute percent backscatter differences at each level for Mauna Loa ranged between 10 and 150% for the entire 15 to 33 km layer. The highest variability, as expected, was between 20 and 25 km, mainly in the range between 50 and 150%. Below that altitude, the absolute percent variability was around 70% and above it around 30%. For Camagüey the absolute percent variability was around 10% with maximums of 20% around 23 km, around 30% at 31 km

and around 50% immediately above 15 km. Further analysis of lidar backscatter profiles at both sites using measurements taken two days apart showed ranges of values similar to those taken on consecutive days. The individual percent difference values derived from consecutive days and two-days-apart lidar backscatter measurements are in good agreement with the average absolute percent extinction difference values obtained from coincident sunset and sunrise SAGE II extinction profiles, considering that the lidar profiles are separated by lapses of time of 24 or 48 hours.

5. SAGE II and Lidar Extinction Profiles Comparison

[23] Samples of individual extinction profiles from both SAGE II and lidars are shown in Figure 3 for Camagüey, at both wavelengths. The previously mentioned SAGE II truncated profiles are present at both wavelengths, in four of the five SAGE II profiles. In general, the gaps at the wavelength of 0.532 μm reach higher altitudes. Filling those gaps with lidar-derived extinction is one of our ultimate goals. There are not appreciable differences between the lidar extinction profiles derived using Thomason's extinction-to-backscatter conversion coefficients and the ones derived using Jäger's coefficients. This is true even though Jäger's extinction-to-backscatter coefficients were derived using particle size distributions measured at Laramie, Wyoming at 41°N [Deshler et al., 1993], a midlatitude location, while Camagüey is a tropical location. An explanation may be that Camagüey measurements were taken during the second period we analyzed, from February 1992 to November 1993. During that period, the cloud was homogeneous at different latitudes. In general, the figure shows a good agreement between the extinction profiles

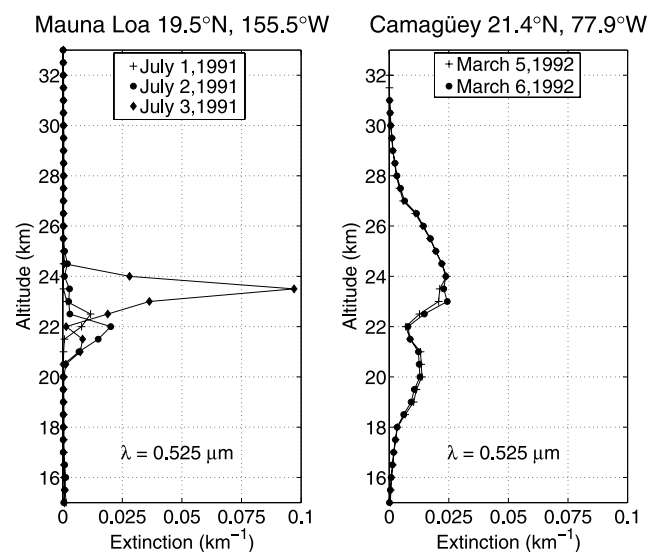


Figure 2. Lidar profiles for three consecutive nightly observations at Mauna Loa and two consecutive nightly observations at Camagüey. The variability was much higher at Mauna Loa, as the profiles were much sooner after the June 15, 1991 Pinatubo eruption. See color version of this figure in the HTML.

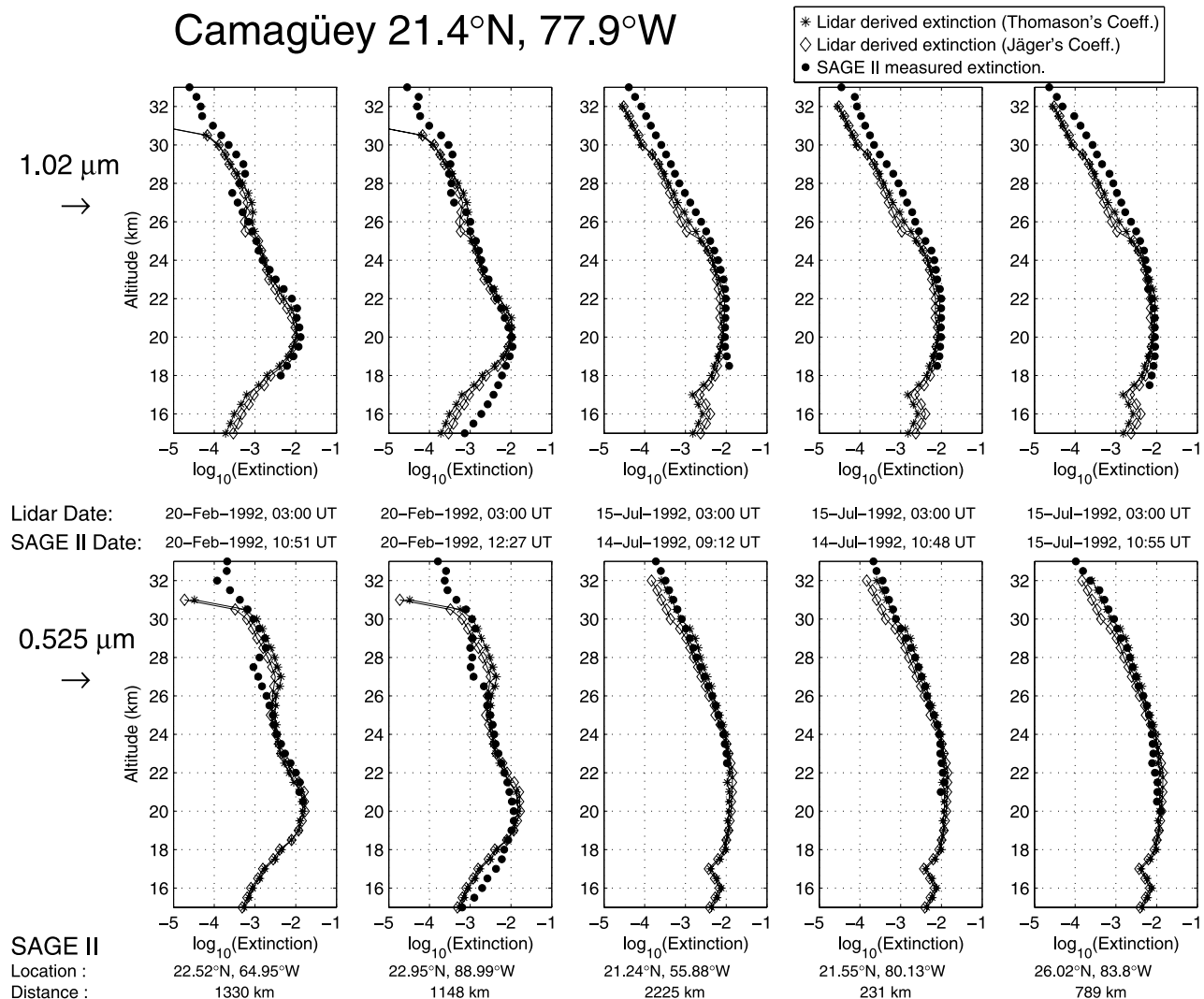


Figure 3. Examples of simultaneous lidar and SAGE II profiles for Camagüey during the period February 1992 to July 1992, with lidar-derived extinction at 0.525 μm and 1.02 μm wavelengths using Thomason's coefficients and lidar-derived extinction at 0.532 μm and 1.064 μm wavelengths using Jäger's coefficients. At the bottom of each profile are the latitude and longitude of the SAGE II profile and the distance between the lidar and SAGE II profiles. See color version of this figure in the HTML.

measured by the SAGE II instrument and the ones derived from lidar using both sets of conversion coefficients.

[24] To obtain a quantitative measure of the differences we calculated “extinction differences,” the differences between each pair of coincident SAGE II measured and lidar-derived values at each level and “percent differences,” the differences at each level divided by the mean of the two extinction values. Figure 4 shows the averages of these differences for all 20 SAGE II-lidar coincident cases at Camagüey. In the lower part of the aerosol cloud at 1.02 μm , the SAGE II measured extinction is larger on average than the extinction derived from lidar, and the opposite happens for 0.525 μm . Average differences in the layer 15 to 25 km are on the order of 10^{-3} km^{-1} for 1.02 μm wavelength and 10^{-4} km^{-1} at 0.525 μm . Above 25 km, the average differences are on the order of 10^{-5} km^{-1} at both wavelengths, which is the accepted limit for SAGE II extinction detection. The percent differences are also lower at 0.525 μm

than at 1.02 μm . The percent differences are the smallest (20–30%) at an altitude of 20 km, the location of the maximum extinction, indicating that the volcanic aerosols are well-observed by both the lidar and SAGE II.

[25] The Haute Provence Observatory lidar data set is the largest we used for the comparison, and consequently, it also provides the largest number of coincident profiles with 178. Figure 5 shows samples of the individual profile comparisons. SAGE II profiles are truncated also at this latitude, mainly at 0.525 μm . One feature common to almost all the derived lidar profiles is that the lidar-derived extinction values are higher than the coincident ones from SAGE II above around 24 km. This happens for those derived using Thomason's extinction-to-backscatter conversion coefficients at both wavelengths as well as for those derived using Jäger's extinction-to-backscatter conversion coefficients. In general, there is a better agreement for the profiles derived using Jäger's coefficients (Figure 6). At

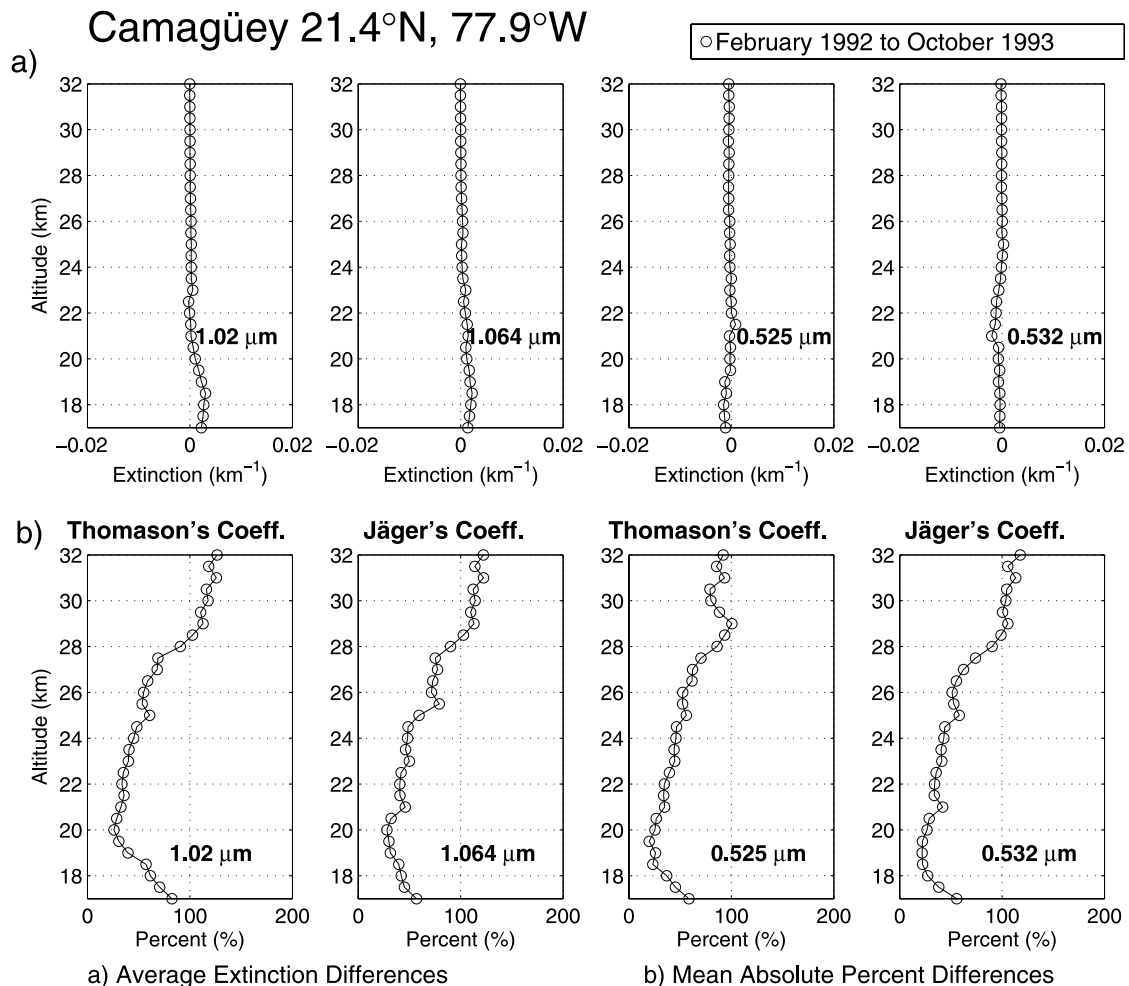


Figure 4. Average differences between extinctions in all 20 coincident lidar and SAGE II coincident profiles for Camagüey. a) Average extinction differences. b) Mean absolute percent differences. See color version of this figure in the HTML.

both wavelengths, there is a systematic difference between both instruments for lower extinction values, which increases with altitude. As we have found for Mauna Loa and Hampton comparisons both the average extinction differences and the mean absolute percent differences are higher in general for the period July 1991 to January 1992 than for February 1992 to December 1993. Despite the trend of increasing mean absolute percent differences with altitude, the average extinction differences at the core of the Mt. Pinatubo aerosol cloud remain around the same range of variability than the results we have obtained so far for Hampton [Antuña *et al.*, 2002]. In fact, a comparison between SAGE II aerosol extinction profiles at 0.525 μm and lidar-derived extinction at the same wavelength from the lidar located at Garmisch-Partenkirchen, Germany (47.5°N, 11.1°E) for January and April 1993 showed percent differences in general less than 50%, but at certain altitudes around 25 km percent differences reached 100% [Lu *et al.*, 1997]. An important feature of that comparison is that it was restricted to extinction values larger than 10^{-4} km^{-1} .

[26] The systematic differences between Haute Provence and SAGE II retrievals is probably due to the technique used there to choose a reference altitude to begin the lidar

retrievals. At Haute Provence, this was done by choosing a layer above the aerosol cloud that was presumably aerosol free, but still had a lidar signal [Chazette *et al.*, 1995]. However, the aerosol cloud extended so high that it was somewhat extinguished by the cloud, thus making determination of the reference altitude very difficult. A secondary effect may be the choice of extinction to backscattering coefficient, but this effect was probably smaller. The reference altitude error increases with height, while the coefficient error decreases with height. This discrepancy merits further investigation, and points to the value of intercomparison of multiple data sets. The discrepancies between SAGE and lidar profiles could be related to several causes, including differences in the acquisition methodology, inversion procedures, differences in vertical resolution, differences in geographical sampling, and differences in seasonal sampling. All these points would have to be taken into account and identified for each coincidence event, and it is beyond the scope of this paper to do that. Our results point to the need for standardized processing algorithms for lidar, including using the same molecular profile for the coincident lidar and SAGE II profiles.

[27] Hefei is an important geographical point, because of its location near the transition region from the tropics to

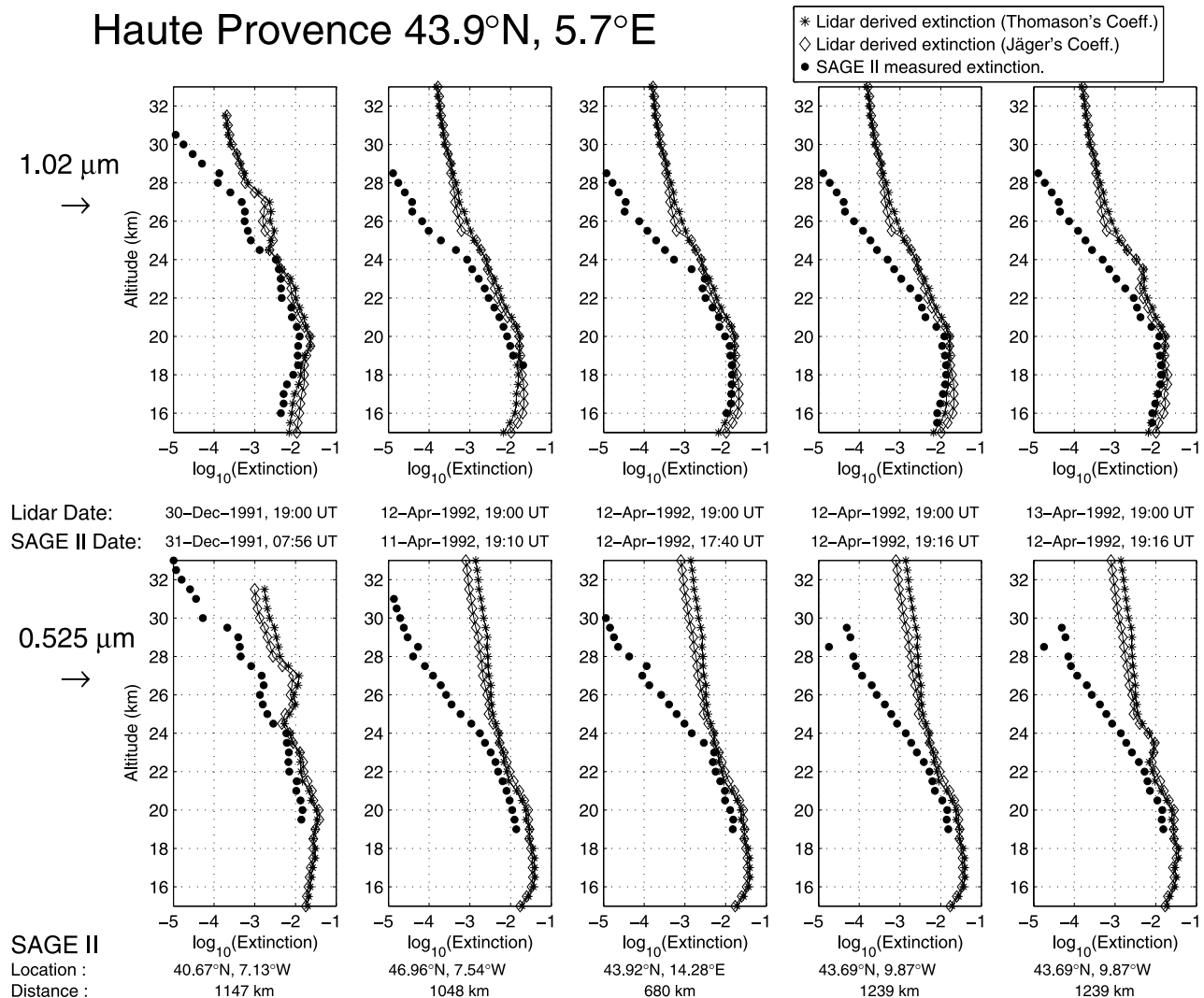


Figure 5. Examples of simultaneous lidar and SAGE II profiles for Haute Provence during the period December 1991 to April 1992, as in Figure 3. See color version of this figure in the HTML.

subtropics at latitude 31.9°N. For this location, lidar profiles are available from June 1991 to June 1992. Of a total of 55 space-coincident lidar SAGE II profiles for Hefei 40 are from the first period (July 1991 to January 1992) and only 15 from the second one. In addition to the low number of coincident profiles for the second period, the coincident SAGE II extinction profiles completely lack data below 18 km at 0.532 μm and there were only four complete profiles at 1.02 μm . Coincident profiles (Figure 7) illustrate both the lack of data at lower levels as well as the higher differences above around 24 km. In Figure 8, we can see that the average extinction differences show higher values in the core of the aerosol cloud for the period July 1991 to January 1992 than for February 1992 to May 1993, as we found for Mauna Loa [Antuña *et al.*, 2002]. Above this layer the mean absolute percent differences show an increase with altitude, similar to the one we found in Haute Provence. In the same figure the lack of data below 18 km is shown at the shortest wavelength. The unusual large values below 20 km at those same wavelengths are the results of very few coincident data (2 to 4 profiles) at those levels with

high extinction difference values, making a bias in the results. Because of that, we do not consider such values in our analysis and show them here only to illustrate some of the difficulties we have to deal with.

[28] The increase of the mean absolute percent differences with altitude seen at Hefei and Haute Provence is not present at Hampton, Mauna Loa or Camagüey. It should be the subject of future research. However, because the mean absolute percent differences remain $\leq 100\%$ for the altitudes where the main part of the aerosol cloud was located, we consider that both lidar-derived extinction data sets could be included in future aerosol data assimilation after the Mt. Pinatubo eruption. Together with Mauna Loa, Hampton and Camagüey data sets, the five will provide an important amount of information for such a task.

[29] At Hefei, during the first of the two periods after the eruption, the extinction-to-backscatter conversion coefficients derived by Jäger show better results in the comparison in the core of the aerosol cloud for 1.064 μm than the ones derived by Thomason and Osborn at 1.02 μm . This happens both for the average extinction differences and for

Haute Provence 43.9°N, 5.7°E

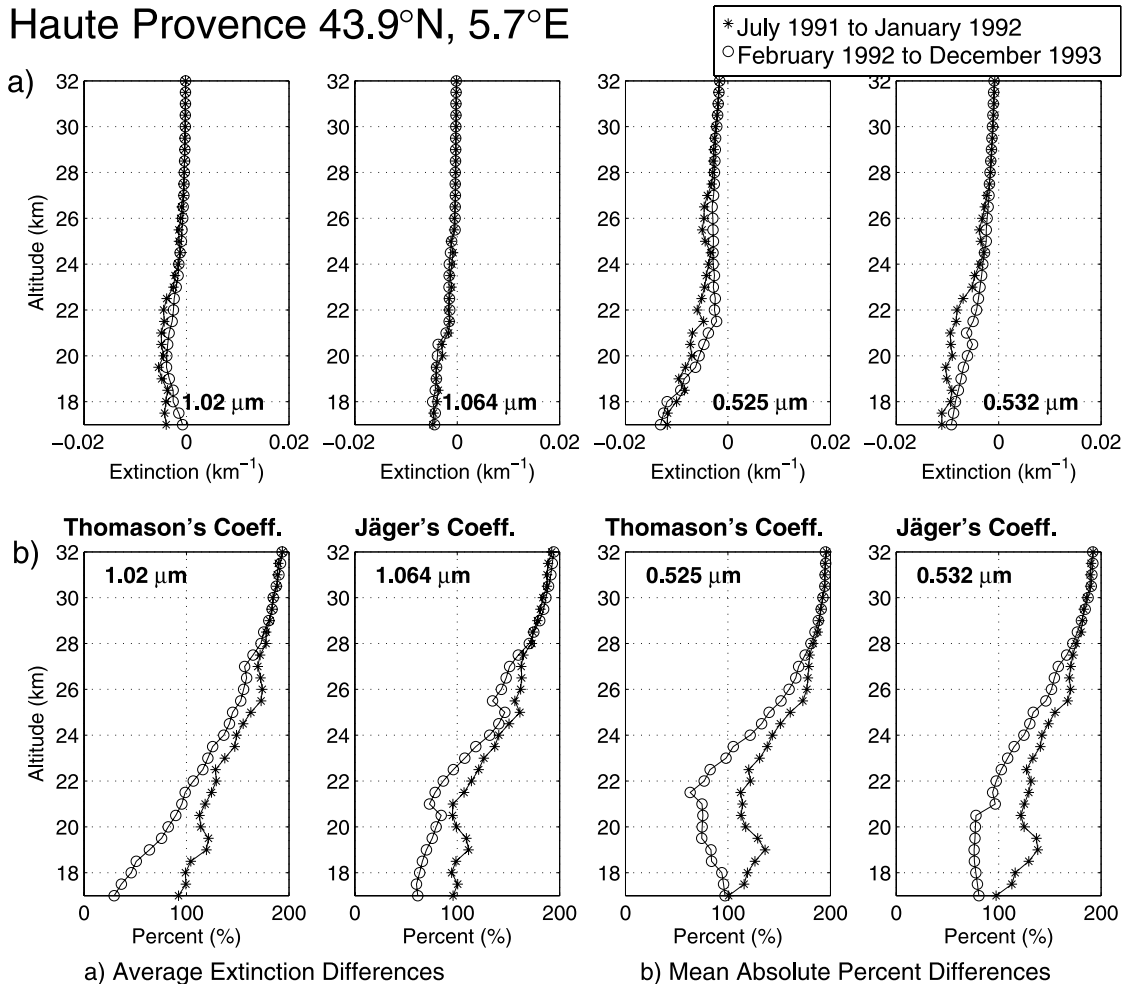


Figure 6. Average differences between extinctions in all 178 coincident lidar and SAGE II coincident profiles for Haute-Provence. (a) Average extinction differences. (b) Mean absolute percent differences. See color version of this figure in the HTML.

the mean absolute percent differences. For the same period for the shorter wavelengths, however, Thomason's coefficients provide better results.

[30] In general, considering the magnitude of the aerosol extinction variability we have determined for both periods, as well as the other sources of uncertainties discussed above, there are not noticeable differences between the lidar extinction profiles at Camagüey, Haute Provence and Hefei derived using Thomason's and Jäger's extinction-to-backscatter conversion coefficients.

6. Discussion and Conclusions

[31] We have conducted an extensive SAGE II-lidar aerosol extinction comparison for the period following the Mt. Pinatubo eruption. With the exception of Hefei, in general there were not noticeable differences between the extinction to backscatter sets of coefficients derived by Thomason and by Jäger.

[32] There were two well-defined periods (June 1991 to January 1992 and February 1992 on) related to the homogeneity of the aerosol cloud, as the initial heterogeneous latitudinal and longitudinal distribution became much more homogeneous about six months after the eruption. *Trepte et*

al. [1993], emphasizing a difference in the transport regime, and *Chazette et al.* [1995], looking at a difference in the residence time and sedimentation speed, previously identified similar periods.

[33] Magnitudes for the aerosol extinction time-variability of the Mt. Pinatubo aerosol cloud were obtained from consecutive days and two-days-apart lidar backscatter profiles as well as coincident SAGE II sunset-sunrise extinction profiles. That variability reached values between 50 and 150% absolute differences at the core of the cloud for the initial, heterogeneous period, for time lapses of 12 to 48 hours.

[34] The analysis provides a glimpse of the extinction aerosol variability in the tropical core of the Mt. Pinatubo stratospheric aerosol cloud for the period of around six months following the eruption. The estimated variability in the range of 20 to 40% for 12 hours, and 50 to 150% for time lapses of 24 and 48 hours will play an important role in the analysis of the comparison between aerosol extinction profiles measured by SAGE II and coincident lidar derived extinction profiles.

[35] The lidar-collected data set represents a unique set of information about the stratospheric aerosol from the 1991 Mount Pinatubo eruption. For the regions surrounding the lidar locations, it provides better vertical resolution than the

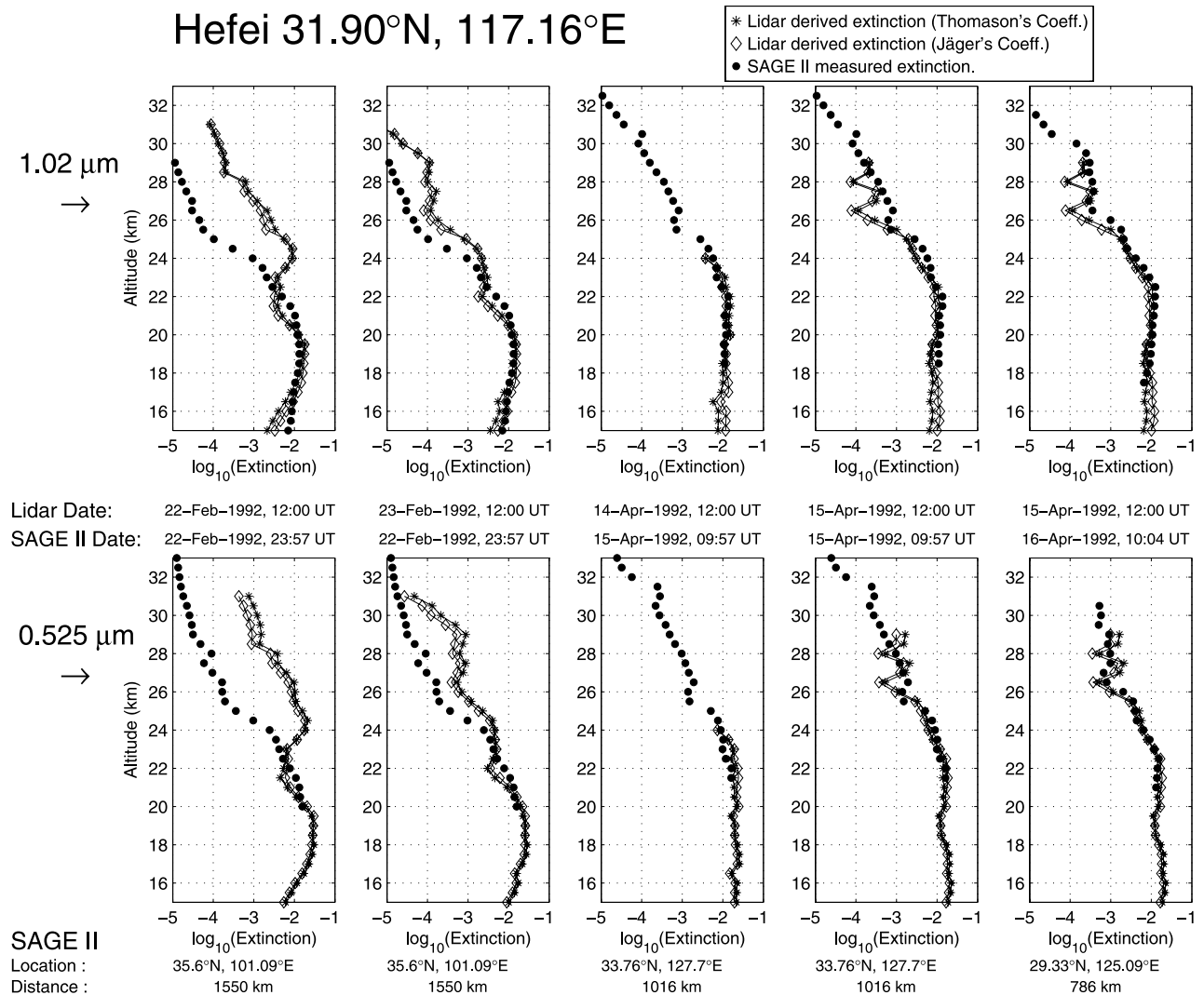


Figure 7. Examples of simultaneous lidar and SAGE II profiles for Hefei during the period February 1992 to April 1992, as in Figure 3. See color version of this figure in the HTML.

SAGE II data. In addition, it provides more regular time information. It will be valuable for a set of future studies like comparisons with other satellite measurements, stratospheric aerosol data assimilation, transport studies, and simulations of volcanic impacts on climate and O_3 . However, the major contribution, in our opinion, will be for future stratospheric aerosol data assimilation.

[36] The analysis of the geographical distribution of the collected lidar data sets showed one more time the lack of information near the equator and the scarcity in the tropics and subtropics. Because we have been aware of this situation, several of the authors are participating together with other scientists in the region in an ongoing effort to create an American Lidar Network (ALINE) in Latin America and to establish new lidar stations in the region, particularly in the tropical region [Robock and Antuña, 2001a, 2001b].

[37] The coincidence criteria we developed take into account the SAGE II sampling structure. It is a new approach, in which the number of coincident profiles is maximized. It has proven to be useful.

[38] The extinction-to-backscatter conversion coefficients comparison showed that both sets of conversion coefficients are useful for the period under study. In the core of the cloud, below about 25 km, the extinction differences at $1.064 \mu\text{m}$ obtained using Jäger's conversion coefficients show lower values than at $1.02 \mu\text{m}$ obtained using Thomason's conversion coefficients for Hefei and Mauna Loa. However for Mauna Loa and Hefei the extinction differences between those at $0.525 \mu\text{m}$ (using Thomason's conversion coefficients) and those at $0.532 \mu\text{m}$ (obtained using Jäger's conversion coefficients) are smaller. From Camagüey extinction differences plots it is much more difficult to see differences, because of the lack of data during the first period, but a detailed analysis of the profiles shows the same behavior as at Mauna Loa and Hefei.

[39] In the case of the midlatitude stations, there is not a definite pattern. At Hampton, both sets of coefficients produce extinction differences of the same magnitude at wavelengths both near 0.5 and $1.0 \mu\text{m}$. On the other hand, at Haute Provence, Jäger's conversion coefficients produce

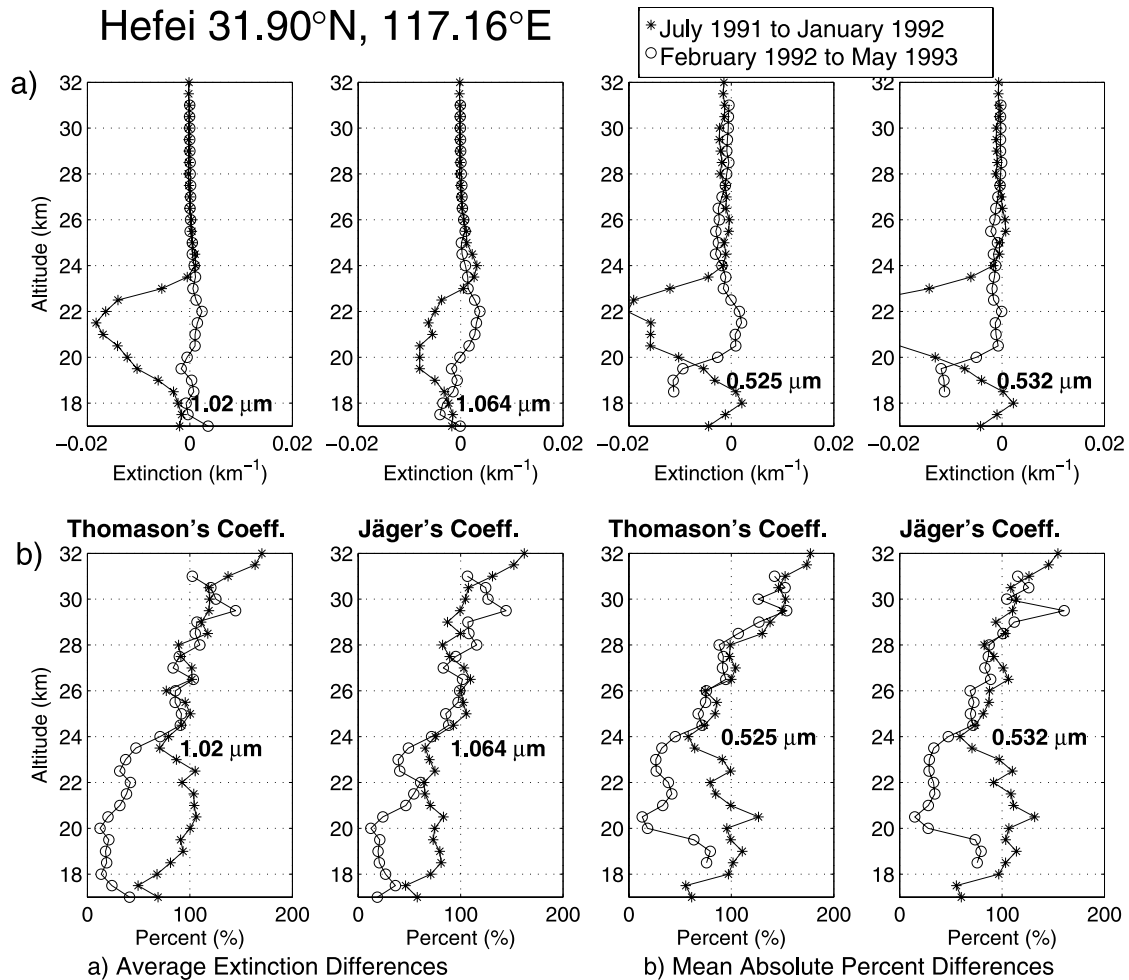


Figure 8. Average differences between extinctions in all 55 coincident lidar and SAGE II coincident profiles for Hefei. (a) Average extinction differences. (b) Mean absolute percent differences. See color version of this figure in the HTML.

better results at 1.064 μm , except for the second period below 19 km. At 0.5 μm for the first period, Thomason's coefficients provide lower differences than Jäger's. In addition, for the second period the same thing happens but from the top of cloud core to around 19 km. Below that altitude, Jäger's produce lower differences.

[40] All the results discussed above show that both sets of backscatter to extinction coefficients are useful for converting lidar backscatter to extinction for the period we are analyzing. The possible differences between them have a lower magnitude, or at least the same, as the aerosol extinction variability which we discuss below.

[41] The procedure we have conducted for comparing lidar and SAGE II aerosol extinction could be potentially used for quality control purposes in future stratospheric aerosol data assimilation. In fact, the quantitative magnitudes like the average extinction differences and the mean absolute percent differences will be useful to establish acceptance criteria for the individual profiles.

[42] Antuña *et al.* [2002] classified the temporal evolution of the Mount Pinatubo stratospheric cloud into two periods based on qualitative features. Here we have provided a quantitative measure of the aerosol variability, allowing a more precise timing of both periods.

[43] We reported the unsuccessful attempt to establish coincidence criteria between lidar and SAGE II, based on the aerosol cloud variability derived from consecutive SAGE II extinction profiles. However, we were able to quantify the magnitude of the aerosol variability using coincident sunset and sunrise SAGE II extinction profiles combined with lidar backscatter measurements on consecutive days and two days apart. This is the first time that the stratospheric aerosol extinction variability has been quantified at a daily timescale after the Mount Pinatubo eruption. This is important because the coincidence criteria we have developed consider ± 24 hours in time as the temporal window inside which the comparison is conducted.

[44] All the lidar derived extinction data sets we have compared are suitable to be used in future aerosol data assimilation. They will contribute to fill existing gaps from satellite sensor with incomplete coverage. Their importance is critical in the tropics, because of the gaps on SAGE II measurements at that latitude after the Mount Pinatubo. At the same time these results remind us that there is only one lidar currently making stratospheric measurements in the latitude band from 23°S to 19°N, located in Bandung, Indonesia (6.9°S, 107.6°E), and it is severely hampered

by its wet climate. There is a strong need for more tropical stratospheric aerosol lidar observations.

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