Lidar validation of SAGE II aerosol measurements after the 1991 Mount Pinatubo eruption

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[1] After the Mount Pinatubo volcanic eruption on 15 June 1991 the Stratospheric Aerosol and Gas Experiment (SAGE) II instrument made extensive aerosol extinction retrievals using the limb-viewing technique. In regions of high-aerosol loading, SAGE II was not able to make measurements, resulting in large information gaps both in latitudinal and in longitudinal coverage as well as in the vertical. Here we examine the possibility of filling the vertical gaps using lidar data. We compare every coincident backscattering measurement (at a wavelength of 0.694 μm) from two lidars, at Mauna Loa, Hawaii (19.5°N, 155.6°W), and at Hampton Virginia (37.1°N, 76.3°W), for the 2-year period after the Pinatubo eruption with the SAGE II version 6.0 extinctions at 0.525 and 1.02 μm wavelengths. This is the most comprehensive comparison ever of lidar data with satellite data for the Pinatubo period. We convert backscattering to extinction at the above wavelengths. At altitudes and times with coincident coverage, the SAGE II extinction measurements agree well with the lidar data but less so during the first six months after the eruption, due to the heterogeneity of the aerosol cloud. This shows that lidar data can be combined with satellite data to give an improved stratospheric aerosol data set. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0370 Atmospheric Composition and Structure: Volcanic effects (8409); 0394 Atmospheric Composition and Structure: Instruments and techniques; 3360 Meteorology and Atmospheric Dynamics: Remote sensing; *KEYWORDS:* lidar, volcano, satellite, stratosphere, SAGE-II, aerosol

1. Introduction

[2] The aerosol loading of the stratosphere from the 15 June 1991 Mount Pinatubo volcanic eruption in the Philippines was the largest of the 20th century [*Bluth et al.*, 1992]. For several years after the eruption, the elevated stratospheric aerosol levels produced large perturbations to the climate system and to stratospheric ozone. The Pinatubo eruption provides a serendipitous opportunity to study the mechanisms driving these responses and to prepare more advanced models to accurately predict the climate effects of the next large volcanic eruption. In the course of our research [*Stenchikov et al.*, 1998; *Kirchner et al.*, 1999; *Ramachandran et al.*, 2000; *Robock*, 2000] however, it has become clear that even though the Pinatubo aerosol was better observed than any previously, there are still gaps in the coverage. The Stratospheric 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, 1993; *Trepte et al.*, 1993; *Yue et al.*, 1994; *Saxena et al.*, 1995; *Russell et al.*, 1996]. 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 from around 15°S to 20°N below 22 km, which was the result of the "saturation" of the satellite sensor by the dense aerosol cloud. Also, 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]. Therefore in this paper we investigate the idea of using vertical aerosol profiles from lidar observations to supplement the SAGE II data.

[3] The most extensive SAGE II validation program carried out so far included some lidars but was conducted for background aerosol conditions in the stratosphere [*Russell and McCormick*, 1989]. The European Correlative Experiment Program for SAGE II was conducted during five short periods of 3 to 4 days between November 1984 and September 1985 [*Lenoble*, 1989]. Four lidars participated in this campaign [*Ackerman et al.*, 1989]. Some

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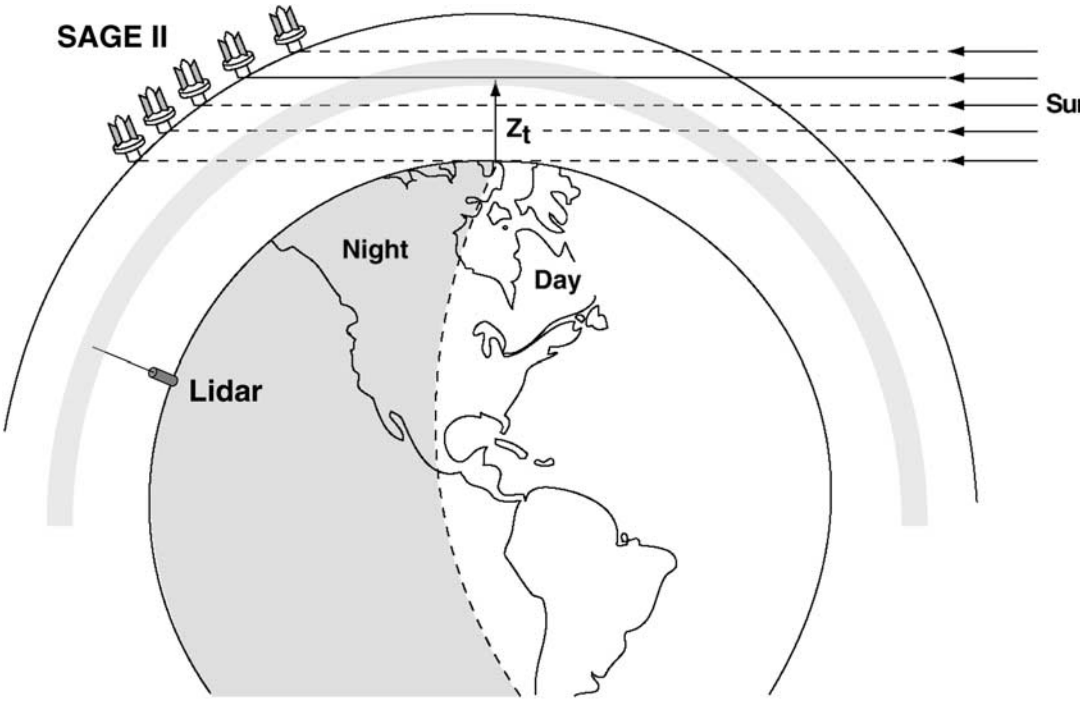

Figure 1. Schematic diagram of solar occultation technique used by SAGE II as compared to lidar backscattering. Z_t is the height of the tangent solar ray being observed by the satellite.

individual comparisons in the midlatitudes have also been done. In one comparison, an airborne lidar was used [*Osborn et al.*, 1989; *Oberbeck et al.*, 1989]. In the tropics, under aerosol background conditions, *Parameswaran et al.* [1991] conducted a comparison using data from Trivandrum, India (8.6°N, 77°E), for the period March–May 1987 of the average extinction profiles both from lidar and from SAGE II in a 3-month period and an individual comparison between two sets of SAGE II lidar profiles.

[4] Until now, however, a lidar-SAGE II stratospheric aerosol validation program has not taken place for the post-Pinatubo period. This has been the most complicated period for the species retrieval procedure, because of the presence of a large amount of aerosols. There are a few individual comparisons reported in the literature. One comparison uses the University of L'Aquila lidar station measurements, with six coincident lidar and SAGE II measurements from September 1991 to January 1992 [*Yue et al.*, 1995]. Another comparison, using lidar information from Garmish-Partenkirchen, compared four coincident lidar and SAGE II measurements for January 1993 and one for April 1993 [*Lu et al.*, 1997, 2000]. A qualitative comparison was made for one SAGE II measurement with three lidar measurements in April 1992 at Ahmedabad [*Jayaraman et al.*, 1995]. One SAGE II measurement on 25 October 1991 at 39.7°N and 67.6°W was compared with one aerosol-backscattering profile from Langley lidar (37.1°N, 76.3°W), at 2317 UT, 24 October 1991 [*Thomason and Osborn*, 1992].

[5] All the above comparisons have focused only on individual spatiotemporal coincident profiles. In the present study we make individual spatiotemporal comparisons using coincidence criteria we developed, but we also include a comparison between measurement time series from both instruments for the entire period from June 1991 to December 1993, whenever lidar measurements are available. This comparison will play an important role in the future improvements of the post-Pinatubo aerosol data set that we have recently developed [*Stenchikov et al.*, 1998], one of the goals of our ongoing research project.

[6] First, we describe the data sets we use. Then, we describe the coincidence criteria that we developed to decide how close, in time and space, a lidar and SAGE II observation need to be for us to compare them. Next, we present the comparisons.

2. Data Sets

[7] We used the version 6.0 SAGE II data set, provided by Langley Research Center [*Zawodny et al.*, 2000], which consists of vertical profiles of extinction every 0.5 km from the surface to 40 km at four wavelengths, 0.386, 0.452, 0.525, and 1.020 μm. The aerosol extinction values at 0.386 μm and 0.452 μm wavelengths were not used in the present study, because during the development of version 6.0, a systematic bias was noted at small optical depths [*Zawodny et al.*, 2000]. In addition, most of the available lidar data are at wavelengths of 0.532 and 0.694 μm, so adjustments to compare to the shorter wavelengths are not necessary. Most of the data below the tropopause are missing due to clouds, and here we use only the stratospheric data. This version of the data set includes an increase of vertical resolution from 1 km in all the former versions to 0.5 km and the implementation of an oblate Earth model in all geometrical calculations.

[8] *Maulding et al.* [1985] described the way that SAGE II observes the atmosphere. SAGE II uses solar occultation, as depicted in Figure 1, during each sunrise and sunset encountered by the spacecraft (about 30 per day) to measure line-of-sight transmission at seven wavelengths from the ultraviolet

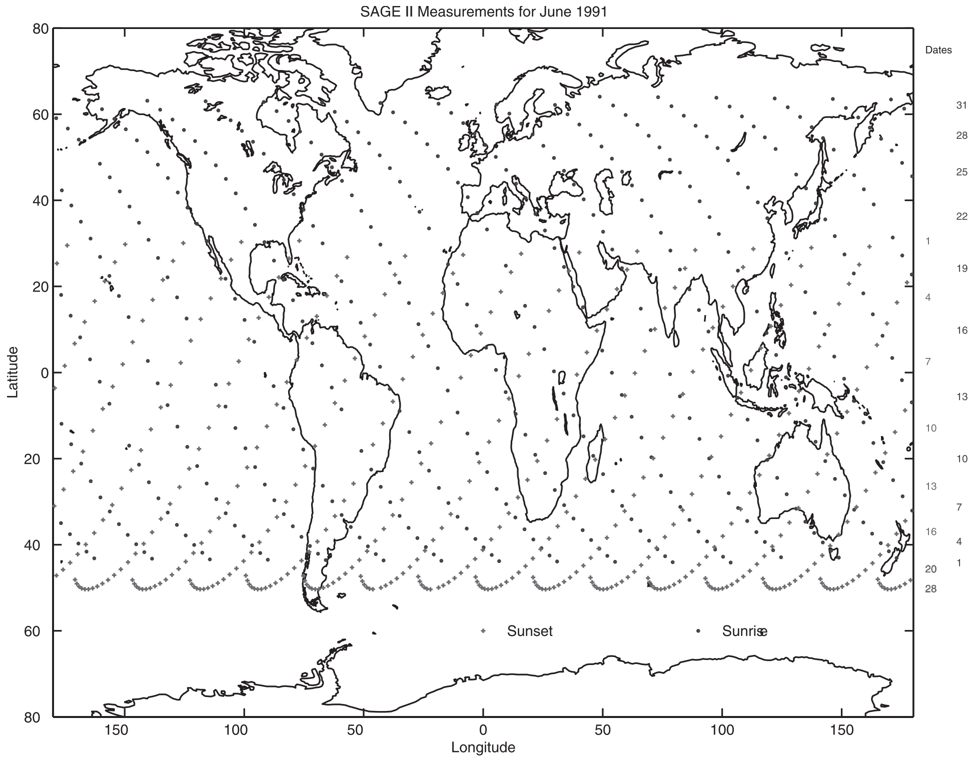

Figure 2. Location of all SAGE II observations for the month of June 1991, as an example of the spatial distribution of the sampling. Sunrise observations are indicated with a circle and sunset observations with a plus.

to the near infrared. Since SAGE II is in a 57° inclined orbit, measurement latitudes slowly vary from about 70°S to 70°N in 25 to 40 days, depending on the time of year. The longitude of the measurements also varies from day to day, advancing by about 5° per day, so even measurements on consecutive days are not closely colocated. Figure 2 shows the distribution of observations (sunrise and sunset) for June 1991.

[9] During an observation the instrument vertically scans across the disk of the Sun. Detection of the edges of the Sun is a key element of altitude registration of data and therefore in the quality of the data. The multiple measurements of atmospheric transmission around an altitude help to reduce the noise associated with the instrument electronics and with limitations in the algorithm. Since measurements at a given altitude do not follow the same ray through the atmosphere, geophysical variability may be mistaken for noise.

[10] From the measured transmission, vertical profiles of O_3, NO_2, water vapor, and aerosol extinction at four wavelengths (0.386, 0.452, 0.525, and 1.020 μm) are inferred. Despite the long path lengths inherent in this method, this geometry is favorable for stratospheric observations since the stratosphere is usually homogeneous on an appropriate scale and extinction at these wavelengths is low. However, in the aftermath of the Pinatubo eruption, aerosol extinction in the lower stratosphere frequently exceeded the dynamic range of the instrument and all species profiles terminated at abnormally high altitudes (the "saturation" effect).

[11] The lidar data sets consist of the vertical profiles of lidar-backscattering coefficients at 0.694 μm from two lidar stations. One is located at Hampton, Virginia, 37.1°N, 76.3°W [*Osborn et al.*, 1995] and the other at Mauna Loa, Hawaii, 19.5°N, 155.6°W [*DeFoor et al.*, 1992; *Barnes and Hofmann*, 1997]. The vertical resolution of the original data sets is 150 and 300 m, respectively. The very few gaps in the vertical profiles were filled by interpolation, and then the profiles were integrated to 0.5 km resolution. Mauna Loa measurements take place normally between 2000 and 2200 LT (0600–0800 UT) and the Hampton measurements are between 0000 and 0200 UT. We also used Sun photometer aerosol optical depth (AOD) data at 0.5 μm from Mauna Loa covering the period from 1991 to 1992 [*Dutton et al.*, 1994], and AOD values at 1.02 μm derived from the same data set [*Russell et al.*, 1996].

Table 1. Average Percent of Monthly Missing Data for Latitudinal Bands at Each Wavelength

	90°N–30°N		30°N–30°S		30°S–90°S		Global	
Wavelength	Non-Pinatubo	Pinatubo	Non-Pinatubo	Pinatubo	Non-Pinatubo	Pinatubo	Non-Pinatubo	Pinatubo
0.525 μm	9.8%	13.0%	1.7%	19.9%	11.3%	15.2%	7.6%	16.1%
1.020 μm	2.4%	6.7%	0.7%	14.8%	3.0%	8.4%	2.0%	10.0%

3. Coincidence Criteria

[12] Comparing satellite and ground-based measurements is a complex task, especially in the case of SAGE II and lidar observations. The two kinds of measurements operate on different principles and geometry (Figure 1). Consequently, they do not have an exact match between the regions they sample or the time each type of measurement lasts.

[13] To compare one individual lidar and one SAGE II measurement to see if measurements of a stratospheric aerosol cloud agree, ideally they should be sampling the same aerosol cloud. If the spatial and temporal scales of the aerosol cloud are larger than the difference in time and space between the two observations, then the comparison will be valid. If, however, the cloud changes between measurements or is inhomogeneous over the measurement time and space scales, then the differences in the cloud will overwhelm any instrumental differences. Unfortunately, until we can create a complete aerosol data set, we cannot properly measure the spatial and temporal scales. We made several attempts to establish coincidence criteria between satellite and lidar measurements on the basis of the variability of the Mount Pinatubo aerosols extinction measured by SAGE II, but they were unsuccessful. This was due to the structure of the SAGE II sampling, 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. Therefore we initially choose convergence criteria that take into account the spatial and temporal sampling patterns of the two instruments and then analyze the results to determine whether the measurements indeed are of the same cloud.

[14] SAGE II samples the Earth limb tangential to a point on the Earth's surface, with a tangential path length ranging from tens of kilometers at the top of the stratosphere down to about 1200 km near the Earth's surface. An "onion-peeling" inversion then assigns values to specific elevations. In the case of aerosol extinction the measurements cover from 40 km to the surface, lasting for approximately a minute. In contrast, lidar measures a single column of the atmosphere, but lidar soundings last from several minutes to approximately an hour depending on the pulse repetition frequency and the number of laser shots selected for the averaging process, which are parameters related to the technical characteristics of each particular instrument. Typically, many individual shots are averaged together. For Mauna Loa, 200 shots taken over 1 hour are averaged for the measurements we present, and for Hampton, 480 shots are taken over 1 hour and 15 min. With an average wind speed at the elevation of the aerosols of 50 km/h, for example, the lidar measurements would then be an average over a 50-km length.

[15] Different criteria for SAGE II comparisons are reported in the literature. Early comparisons of SAM II and SAGE II aerosol measurements used ±1° both in latitude and in longitude and ±3 hours [*Yue et al.*, 1989]. Polar Ozone and Aerosol Measurement (POAM) satellite measurements of ozone were validated using SAGE II ozone measurements using coincidence criteria of ±4° in latitude, ±12° in longitude, and ±2 hours in time [*Rusch et al.*, 1997]. Comparison with the lidar station at the University of L'Aquila used coincidence criteria of ±5° both in longitude and in latitude and within 1 day [*Yue et al.*, 1995]. One of the intercomparisons with the Garmisch lidar used 5° latitude, 8° longitude, and 24 hours [*Lu et al.*, 1997], and the most recent one used the same latitudinal and longitudinal window but reduced the time to 12 hours and included a Lagrangian approach [*Lu et al.*, 2000]. *Thomason and Osborn* [1992] compared one measurement from SAGE II at 1054 UT, 25 October 1991, at 39.7°N and 67.6°W with one aerosol backscattering profile from Langley lidar (37.1°N, 76.3°W), at 2317 UT, 24 October 1991. *Russell and Smit* [1998] used a convergence criterion between lidar and SAGE II O_3 observations of ±5° in latitude, ±12° in longitude, and ±24 hours or ±48 hours in time.

[16] To evaluate the availability of SAGE II measurements after Pinatubo, compared to the rest of the period covered by the data set, we calculated the monthly percent of missing profiles, available in the monthly SAGE II version 6.0 data files. We choose two periods, one covering June 1991 to June 1994 (Pinatubo period) and the other covering the rest of the available data (non-Pinatubo), and we averaged the monthly values over each one of the selected periods. The average percent of monthly missing profiles in the Pinatubo period was much larger than during the non-Pinatubo period (Table 1).

[17] On the basis of the geometry of the SAGE II sampling (Figure 2) we selected criteria of ±5° in latitude, ±25° in longitude, and ±24 hours in time. As a result of applying the spatial criteria, we found 126 coincident profiles for Mauna Loa and 227 for Hampton during the period June 1991 to December 1993. Adding the criterion of ±24 hours in time, there were 49 space-time coincident profiles for Mauna Loa and 76 for Hampton. Because of the properties of the SAGE II orbit, at Mauna Loa latitudes, daily longitudinal scans are separated by 5° in latitude, but at Hampton, the latitude separation is reduced to 3° (Figure 2). This explains why the number of coincident measurements at Hampton is larger than at Mauna Loa. The criteria we selected allow a maximum distance between the lidar sites and the SAGE II measurements of 2300 km for Hampton and 2600 km for Mauna Loa.

4. Extinction to Backscattering Coefficients

[18] Because the lidars and SAGE II measure the Pinatubo aerosol cloud at different wavelengths, we must use theory to convert one or the other to the same wavelength. We chose to convert the lidar observations both to 0.525 and to 1.020 μm. Converting backscattering to extinction is theoretically a well-established procedure, making use of the well-known Mie computations [*Wiscombe*, 1980], but it requires knowledge of the particle size distribution and the refractive index. In particular, those parameters become critical when the lidar measurements are done with a high concentration of sulfuric acid aerosols from volcanic eruptions [*Jäger and Hofmann*, 1991, 1995]. The lack of information about the particle size distribution during the period following the Mount Pinatubo eruption makes it difficult to obtain such coefficients. Only midlatitude extinction-to-backscattering conversion coeffi-

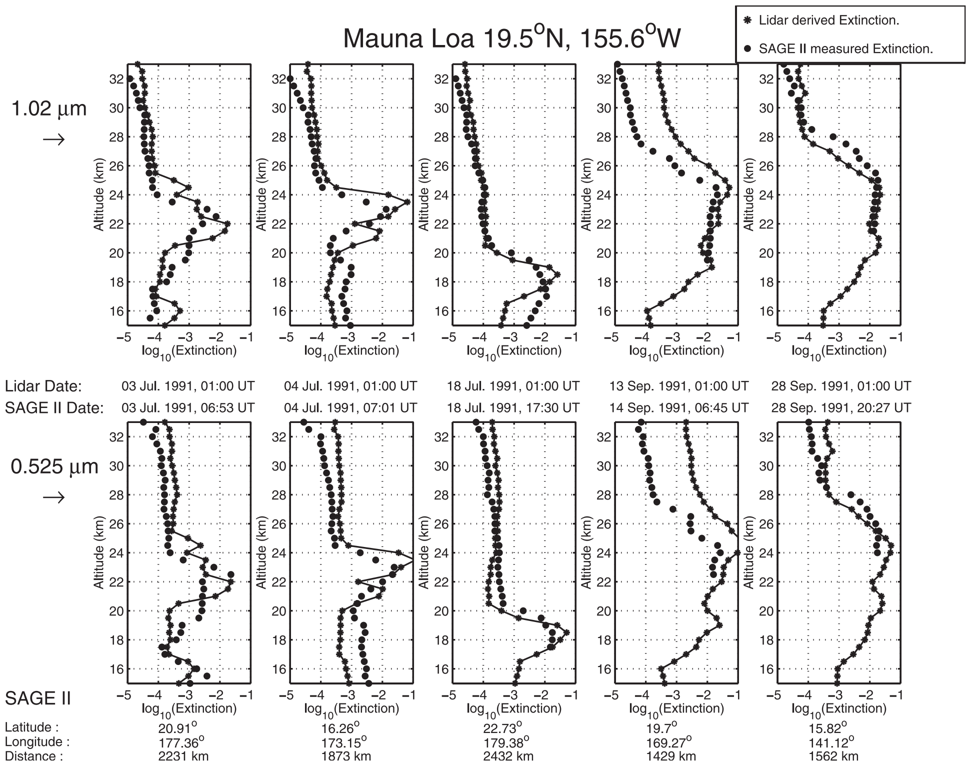

Figure 3. Examples of simultaneous lidar and SAGE II profiles for Mauna Loa during the period immediately following the 15 June 1991 Pinatubo eruption for wavelengths of 0.525 μm and 1.02 μm. At the bottom of each profile are the latitude and longitude of the SAGE II profile and the distance between the lidar and the SAGE II profiles.

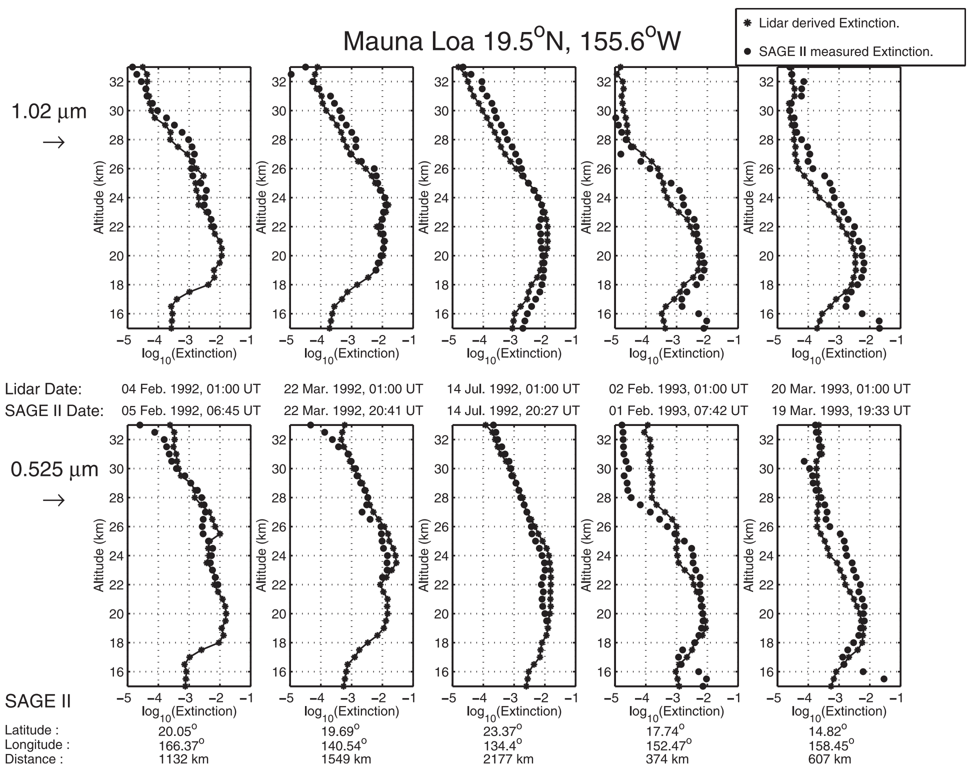

Figure 4. As in Figure 3 but for the later period.

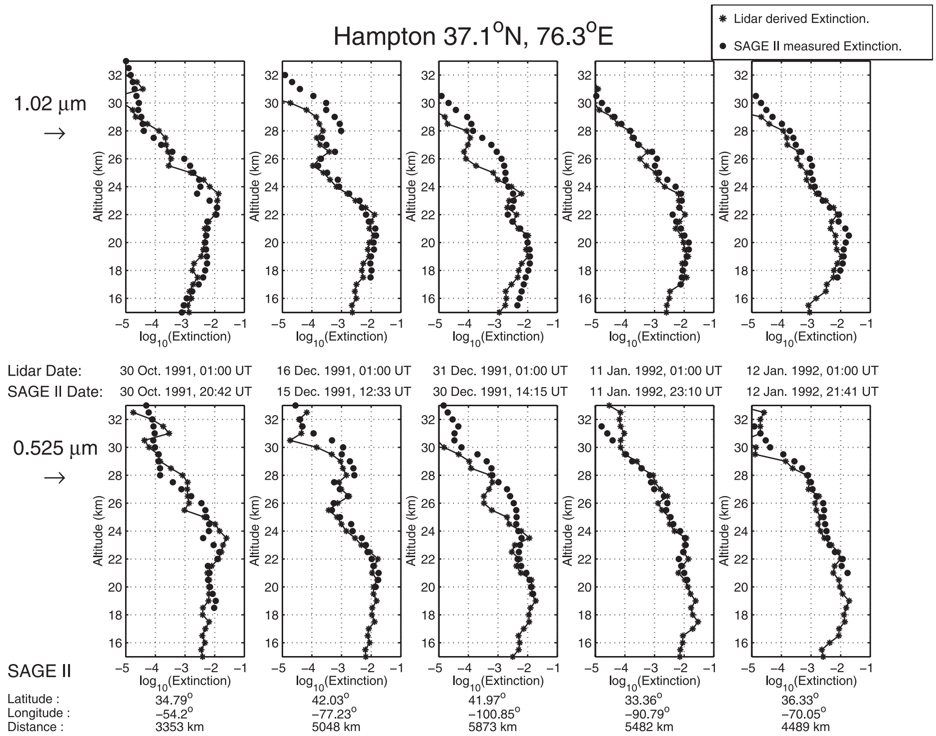

Figure 5. As in Figure 3 but for Hampton.

cients are available for the complete period after Pinatubo [*Jäger et al.*, 1995]. Some spotty conversion coefficient values are available for low altitudes [*Russell et al.*, 1993; *Pueschel et al.*, 1994]. Here we make use of the extinction-to-backscattering coefficients derived by *Thomason and Osborn*[1992] to convert lidar backscattering at 0.694 μm to extinction at 0.525 and 1.020 μm using a principal component analysis of the SAGE II kernels. These factors

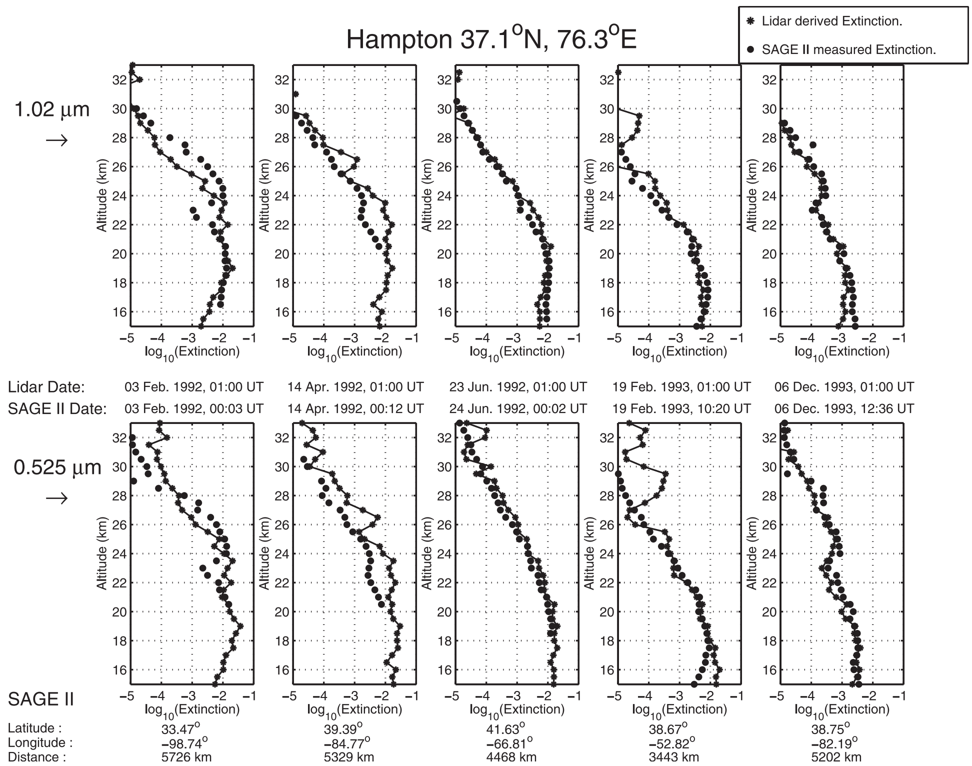

Figure 6. As in Figure 5 but for the later period.

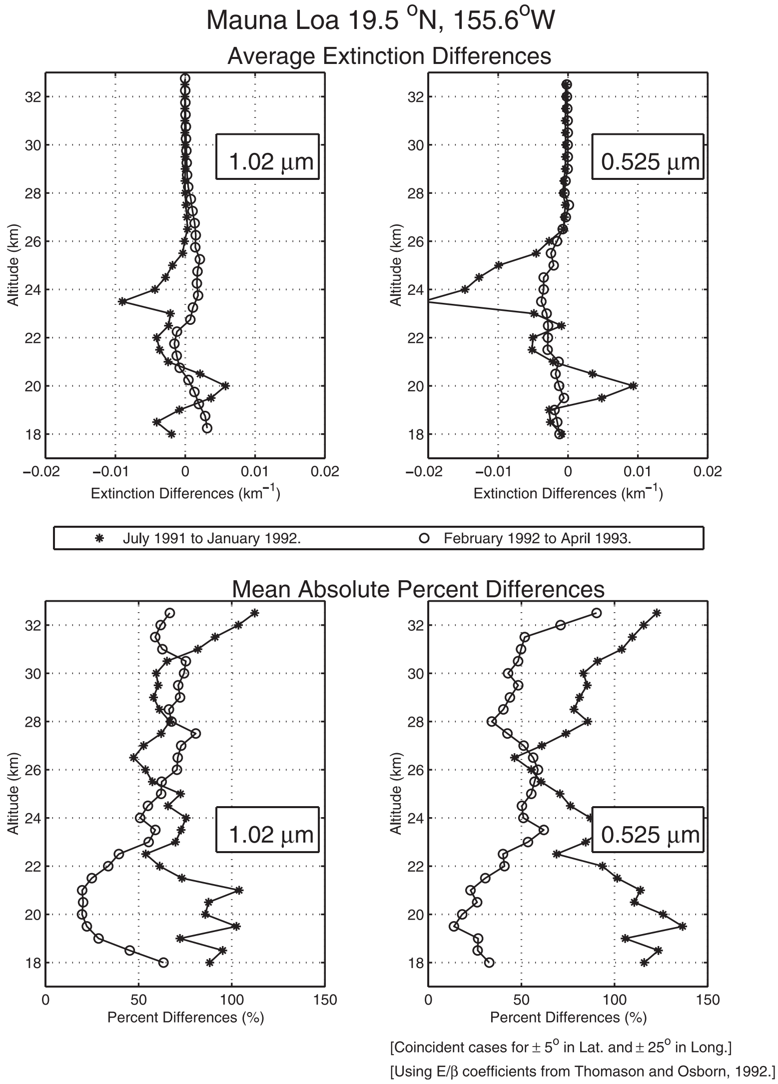

Figure 7. Average differences between extinctions in all 49 coincident lidar and SAGE II coincident profiles for Mauna Loa.

are variable in altitude and were obtained for all SAGE II extinction profiles between 30° and 50°N for 23–27 October 1991.

5. Sources of Error

[19] In addition to the sampling error sources discussed above, each of the instruments we use introduces possible errors. The procedure to convert from lidar backscatter to extinction also can introduce errors, and these are discussed here.

[20] The SAGE II data set includes error estimates for each measurement. These errors have four possible sources: measurement (instrumental) error, error associated with determination of the Rayleigh scattering, altitude determination error, and error from a contribution from the other species inversion [*Chu et al.*, 1989]. Version 6.0 has lower error estimates than the previous versions, showing that altitude registration errors play the main role in the total estimated error [*Zawodny et al.*, 2000].

[21] Lidar errors also have four sources: signal measurement error, two-way transmission correction errors, Rayleigh error, and error in the determination of the minimum backscattering ratio used for normalizing the profiles [*Russell et al.*, 1979]. An important feature related to lidar measurements is that the increase of the signal-to-noise ratio for measurements of dense volcanic aerosol clouds produces a notable decrease of the relative error [*Russell et al.*, 1979].

[22] The backscattering-to-extinction conversion procedure is an additional source of error, because of the assumptions necessary due to the lack of detailed information about particle size distributions and refractive index. The conversion coefficients we used show a relative error ranging from 5 to 50% [*Thomason and Osborn*, 1992].

6. Individual Extinction Profiles Comparison

[23] Samples of individual profile comparisons are shown in Figures 3–6. For both 0.525 and 1.020 μm extinction

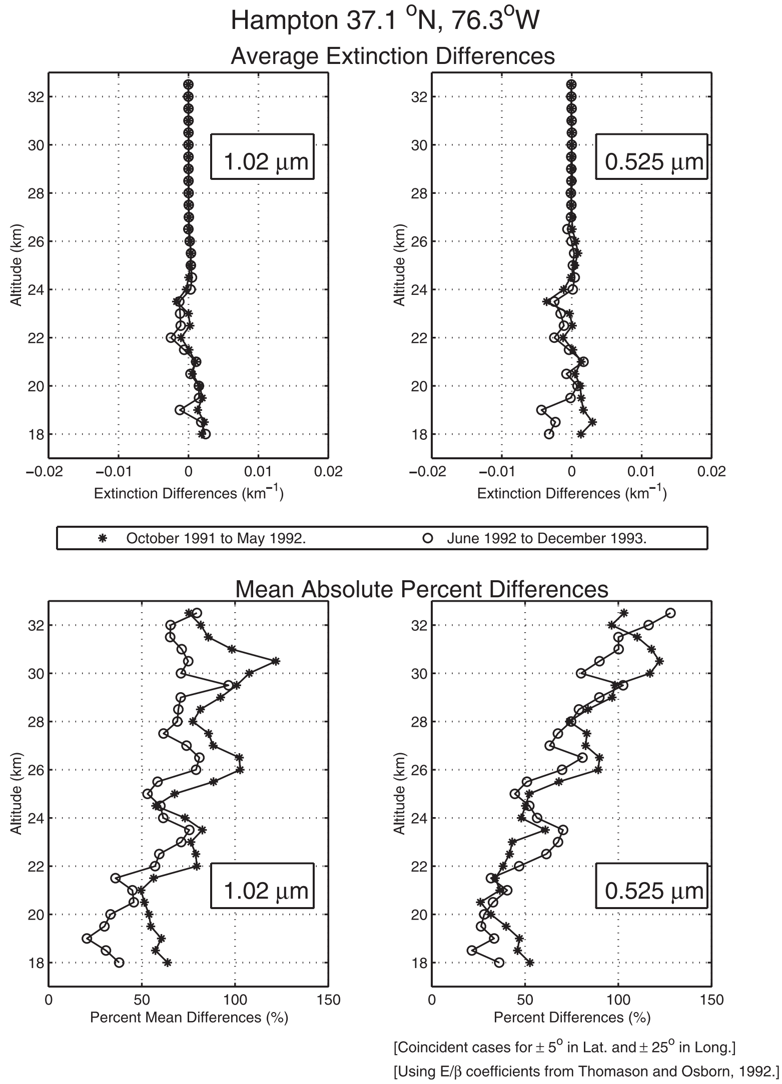

Figure 8. Average differences between extinctions in all 76 coincident lidar and SAGE II coincident profiles for Hampton.

profiles, we calculated the differences between each pair of coincident SAGE-II-measured and lidar-derived values, called "extinction differences." We also divided the differences at each level by the mean of the two extinction values, called "percent differences." The means for each station (Figures 7 and 8) show that the largest differences are located below 26 to 28 km, where the aerosols are located. We show the differences for two separate periods for each station, an initial period with large differences, and a later period with smaller differences.

[24] The differences are larger at Mauna Loa than at Hampton, because of the higher variability of the stratospheric cloud during its initial stage in low latitudes. The lidar-derived extinction is higher, in general, than that measured by SAGE II, except around 20 km. The maximum positive and negative differences are located around 20 and 23 km, respectively. Such differences can be illustrated by the profiles shown in Figure 3. From 24 km to around 33 km and between 21 and 22 km the extinction derived from lidar is higher, but the situation is the opposite below 21 km. There are two possible reasons for such differences: the high inhomogeneity of the cloud (mainly meridionally), sampled at different latitudes, and the known vertical displacement errors in the SAGE II retrieval [*Chu and McCormick*, 1979]. The displacement error is the uncertainty in assigning the real geometric altitude at which the measurement took place. It can amount to a few hundred meters and is calculated determining the standard deviation of the data from the continuous median profile in each 0.5 km vertical bin [*Zawodny et al.*, 2000]. At both wavelengths the maximum mean percentage differences take place in the first period around 20 km (the lower part of the cloud during that period) and at high altitudes, as can be seen in Table 2. In general, there is a decrease in the mean percentage differences from the first period to the second, which could be caused by longitudinal mixing, which smoothes the cloud.

[25] For Hampton, as in the Mauna Loa case, the first period is characterized by larger mean percent differences, but they are lower in magnitude than the ones at Mauna Loa, because the cloud did not arrive at Hampton until 3 August 1991 [*Osborn et al.*, 1995]. By that time, the initially highly nonhomogeneous cloud had become more

Table 2. Vertically Averaged Mean Absolute Extinction Differences Between Lidar and SAGE II for Two Periods Selected at Each Lidar Station

	Mauna Loa		Hampton	
Wavelength	Period I[a]	Period II[b]	Period I[c]	Period II[d]
0.525 μm	90%	40%	70%	57%
1.020 μm	72%	50%	68%	51%

[a]October 1991 to May 1992.
[b]June 1992 to December 1993.
[c]July 1991 to January 1992.
[d]February 1992 to April 1993.

homogeneous after the settling of the volcanic ash and the mixing effect produced by the wind transport. The mean percentage extinction differences do not show a peak in the lower part of the profiles. The vertically averaged mean percentage differences show a decrease of around 15% in the whole column from the first to the second period (Table 2). The second period coincides with significantly smaller peak scattering ratios, with smoother and fewer layered profiles [*Osborn et al.*, 1995].

[26] The values of the mean percentage extinction differences for Hampton for the second period are in good agreement with the ones obtained at another midlatitude lidar station. Comparison between eight coincident SAGE II and lidar aerosol profiles at Garmisch-Partenkirchen, Germany (47.5°N, 11.1°E), for the period January to April 1993, reports percentage extinction differences ranging, in general, between 30 and 50%, with values >50% for the poor agreement cases [*Lu et al.*, 2000].

[27] For both places we found almost no difference between the coincident measurements located less than 1200 km from the lidar stations and the ones between 1200 and 2000 km for the two periods selected. This means that there is not a significant variability on such a spatial scale and, consequently, there is not a strong sensitivity to the convergence criteria selected.

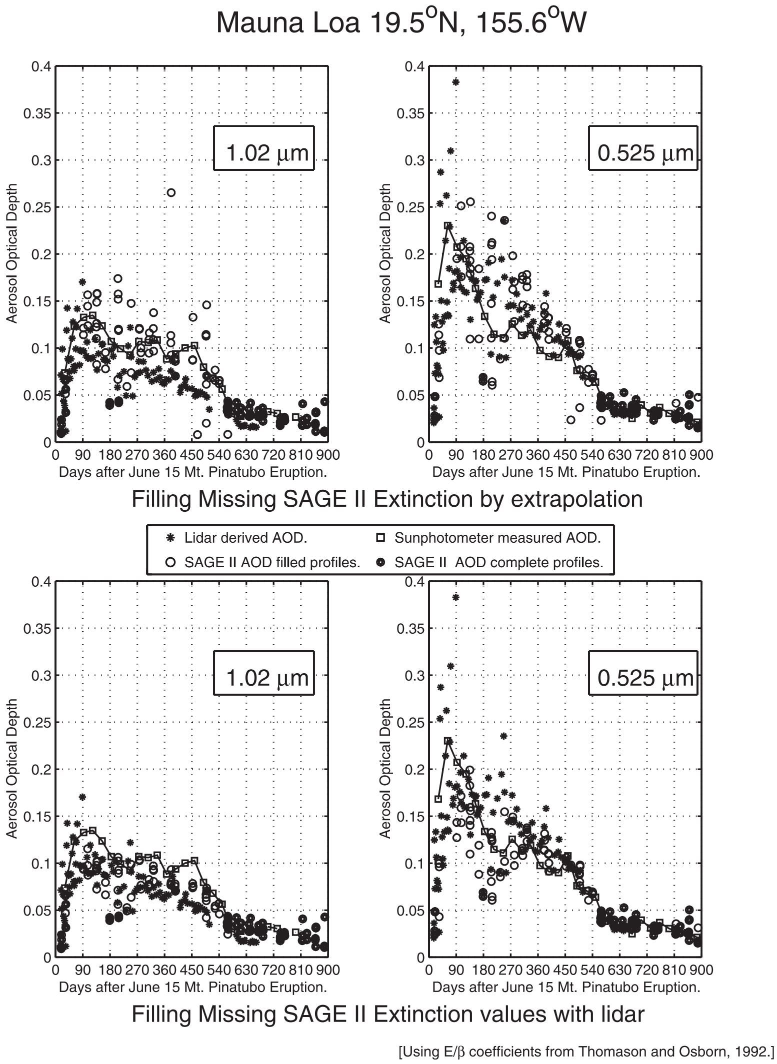

Figure 9. Aerosol optical depths for all coincident profiles, illustrating the effects of missing SAGE II extinctions for Mauna Loa. (top) Comparison of lidar-derived and Sun photometer aerosol optical depth (AOD) with SAGE II complete profiles and those filled by extrapolation. (bottom) Comparison with those filled by nearest lidars. See color version of this figure at back of this issue.

7. Aerosol Optical Depth Comparison

[28] Considering the relatively good agreement in the extinction profiles derived from both instruments, we decided to compare the behavior of the AOD during the complete period using all the coincident profiles. We used two methods to fill in the missing data. The first one assumes that the truncated profiles have a constant extinction value down to 15 km, which is equal to the extinction value at the truncation altitude [*McCormick and Veiga*, 1992]. In addition, we filled the few gaps above the truncation level by linear interpolation. The second method fills the missing extinction values at each level with the ones at the same level from the lidar profile closest in time.

[29] Figure 9 shows the results for both wavelengths. With no filling, there are very few SAGE II profiles available at all. The results using the lidar-filling method show better agreement with the available lidar profiles (and with the Sun photometer data at Mauna Loa), than the ones filled with downward extrapolation, and produce AOD time series that are less variable in time.

8. Discussion

[30] These results show that both lidar and SAGE II observations of the stratospheric aerosols from the 1991 Pinatubo eruption provide important information. Both types of data provide vertical profiles of stratospheric aerosols, but neither can provide comprehensive global coverage because of sampling issues. There are no lidars currently making stratospheric observations in the latitude band between 23°S and 19°N, with the exception of the one in Bandung, Indonesia, and its observations are severely hampered by its wet climate. Therefore for future measurement of aerosols from tropical volcanic eruptions, a new lidar station should be installed in a dry tropical location, such as Quito, Ecuador, on the equator.

[31] These results also point to the utility of a stratospheric aerosol data assimilation project, where satellite and lidar data would be blended within the constraints of an atmospheric general circulation model, including the effects of the aerosols on the radiative forcing. Such an approach would produce a global aerosol data set maximizing the information currently available from sensors with incomplete coverage.

[32] Filling the gaps in SAGE II extinction values with derived lidar extinction at the same levels shows encouraging results. However, aerosol optical depth time series still show differences, mainly at 0.532 μm. Extinction-to-backscattering coefficients after volcanic eruptions, in lower latitudes, remain as an unsolved issue. A global SAGE II-lidar intercomparison will require a global set of such coefficients. We are presently working in that direction.

[33] **Acknowledgments.** We thank the NASA Langley Research Center and the NASA Langley Aerosol Research Branch for providing the SAGE II and Hampton lidar data sets and Ellsworth Dutton for the Mauna Loa Sun photometer data. This work has been supported by NASA grant NAG 1-2154.

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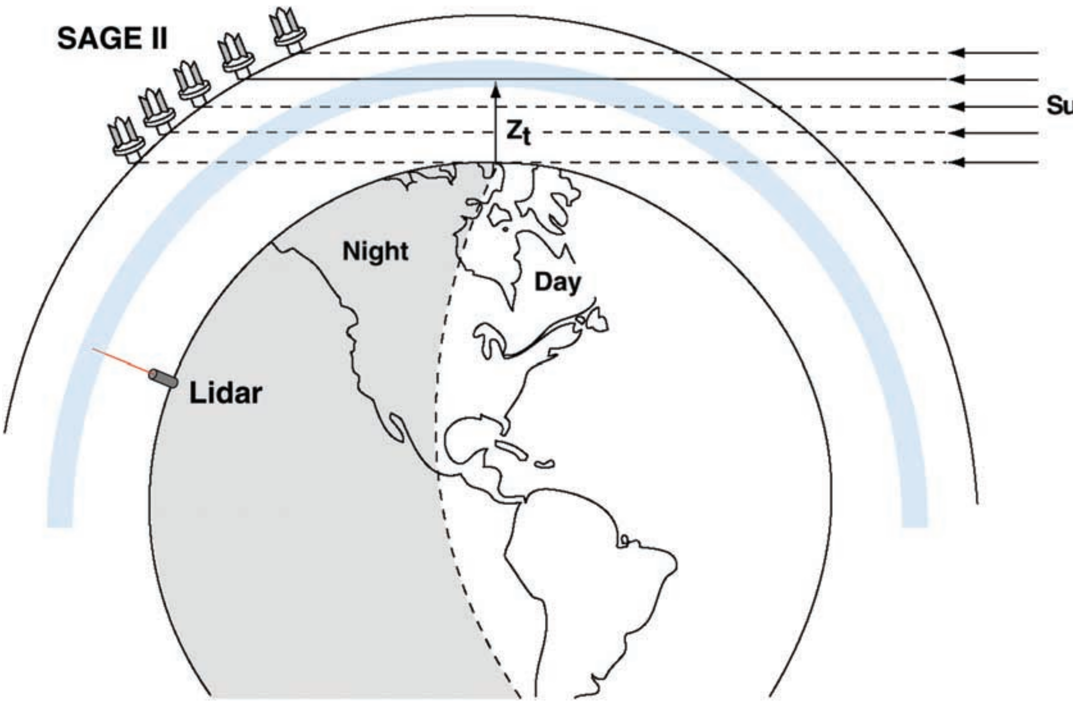

Figure 1. Schematic diagram of solar occultation technique used by SAGE II as compared to lidar backscattering. Z_t is the height of the tangent solar ray being observed by the satellite.

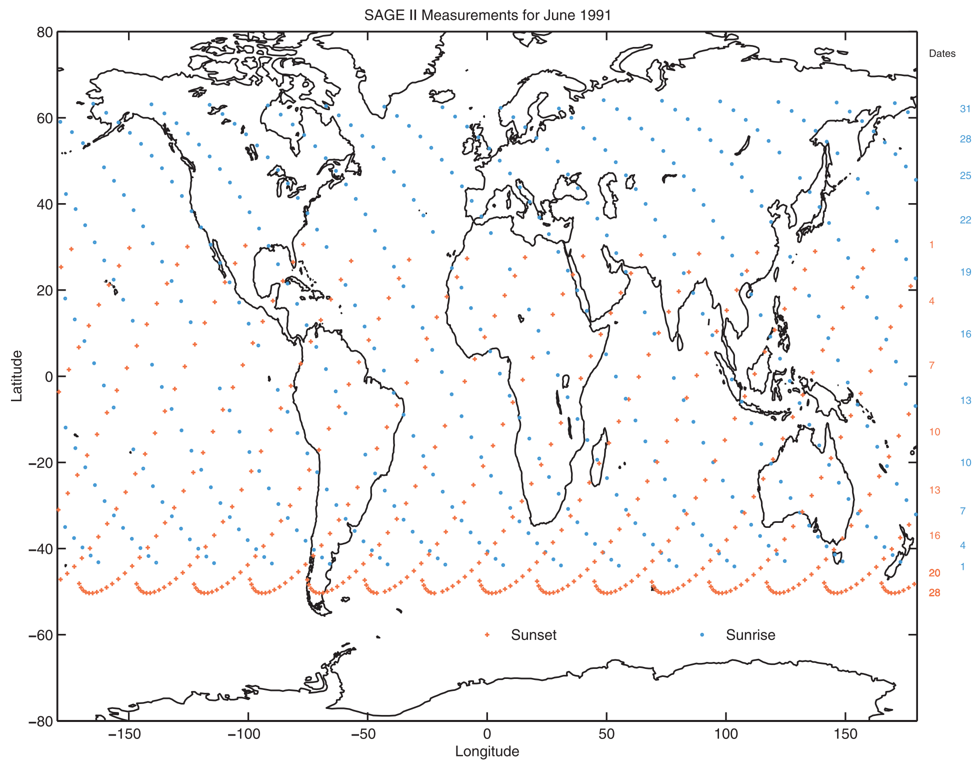

Figure 2. Location of all SAGE II observations for the month of June 1991, as an example of the spatial distribution of the sampling. Sunrise observations are indicated by the blue circle (○) and sunset observations by the red plus (+).

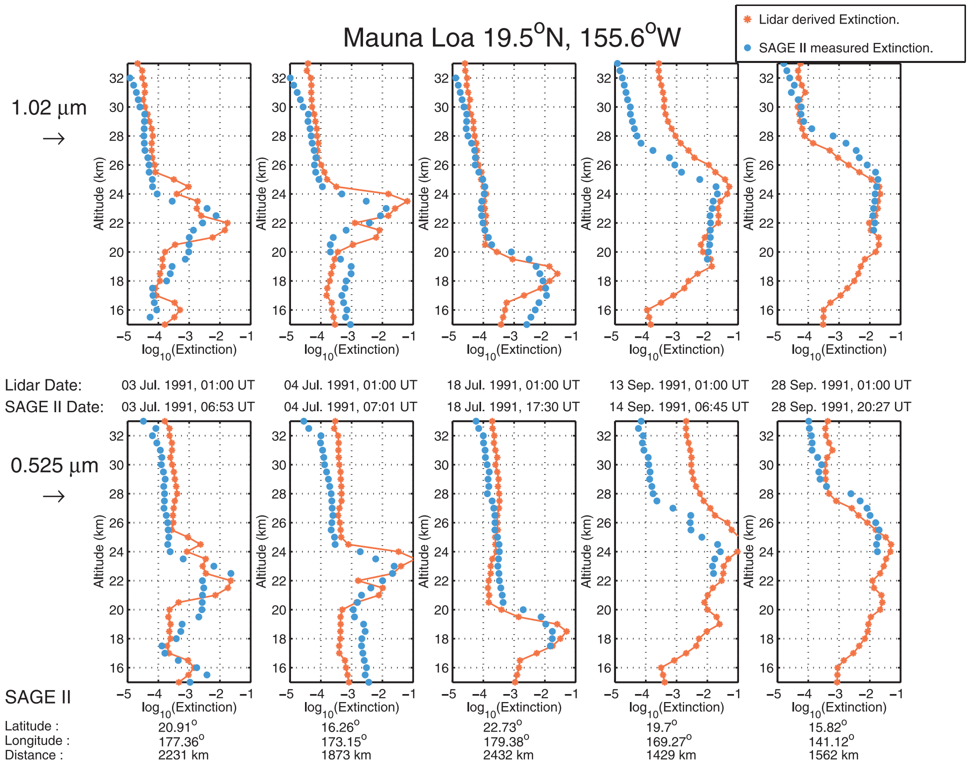

Figure 3. Examples of simultaneous lidar and SAGE II profiles for Mauna Loa during the period immediately following the 15 June 1991 Pinatubo eruption for wavelengths of 0.525 μm and 1.02 μm. At the bottom of each profile are the latitude and longitude of the SAGE II profile and the distance between the lidar and the SAGE II profiles.

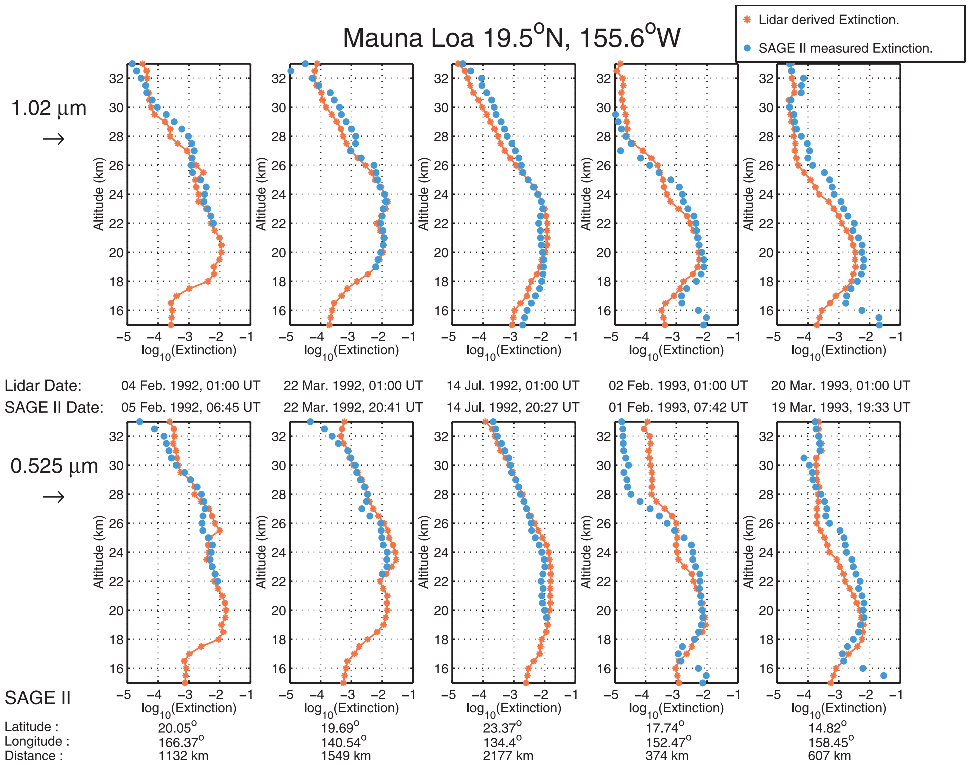

Figure 4. As in Figure 3 but for the later period.

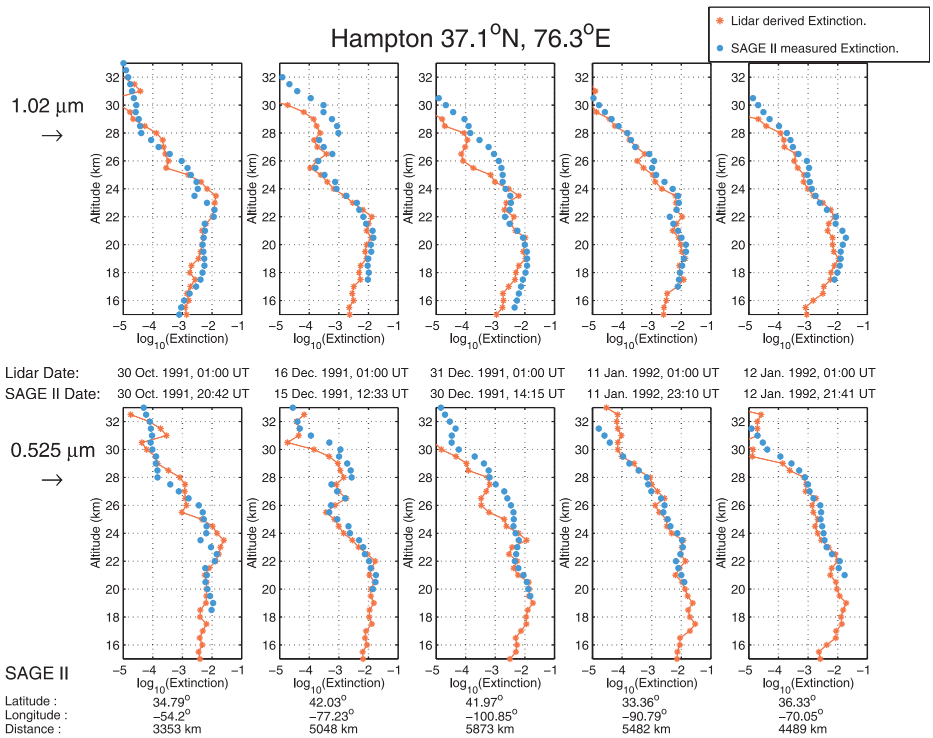

Figure 5. As in Figure 3 but for Hampton.

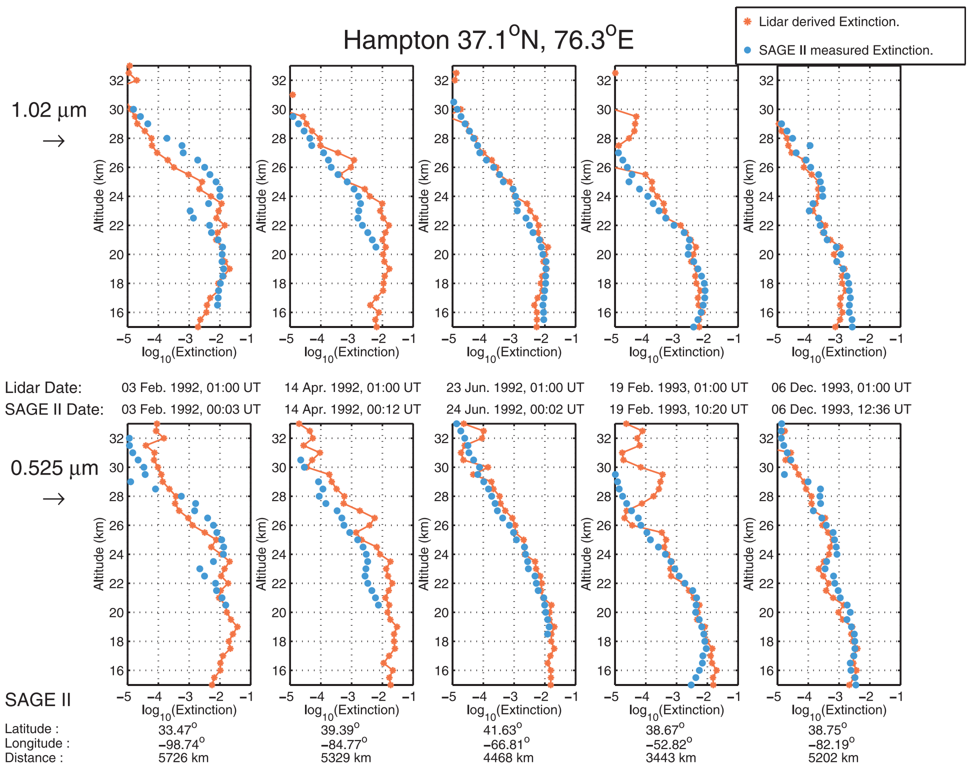

Figure 6. As in Figure 5 but for the later period.

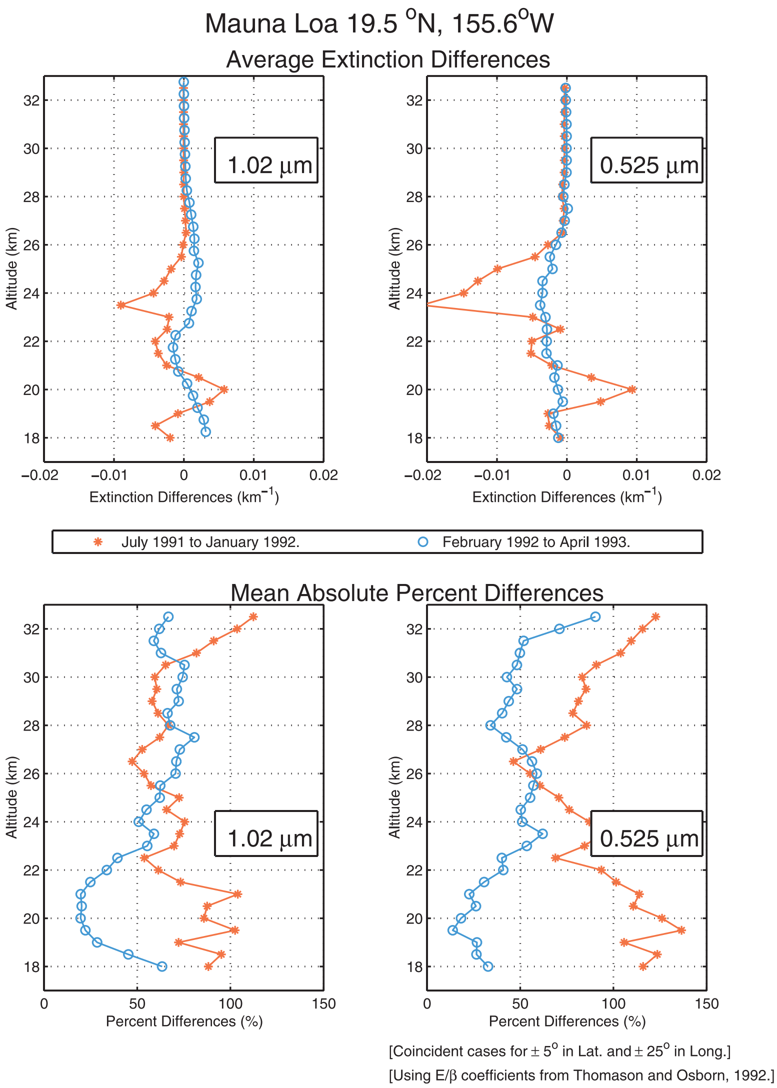

Figure 7. Average differences between extinctions in all 49 coincident lidar and SAGE II coincident profiles for Mauna Loa.

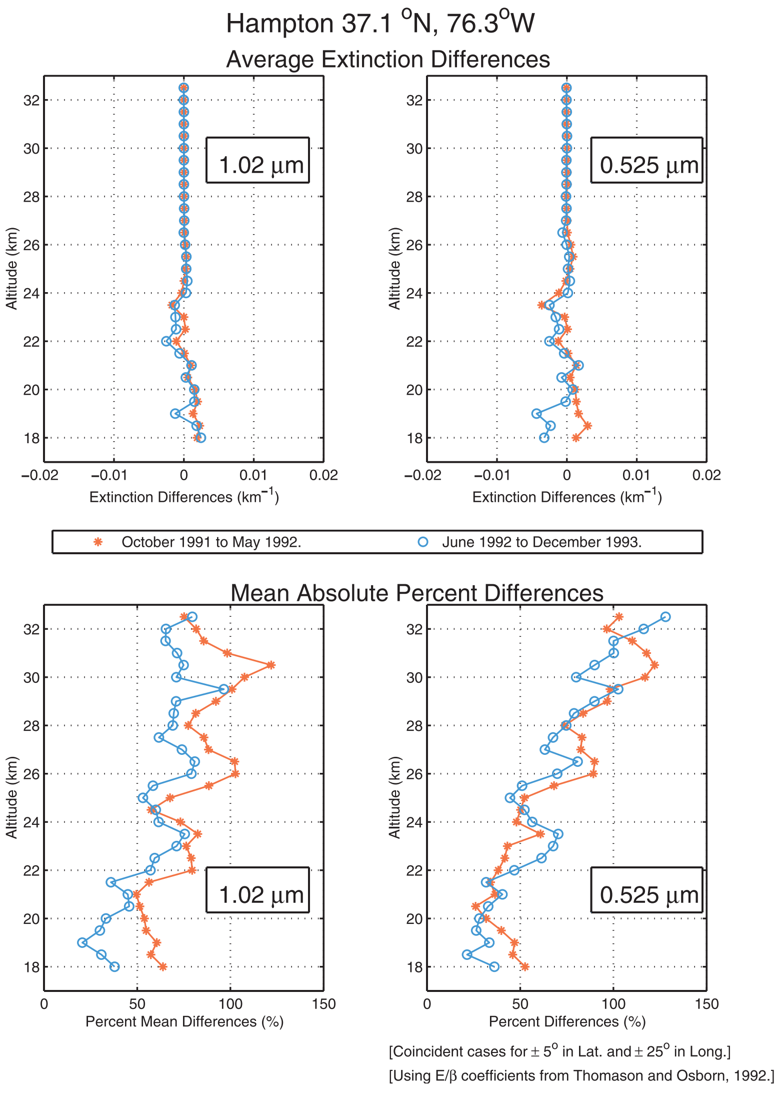

Figure 8. Average differences between extinctions in all 76 coincident lidar and SAGE II coincident profiles for Hampton.

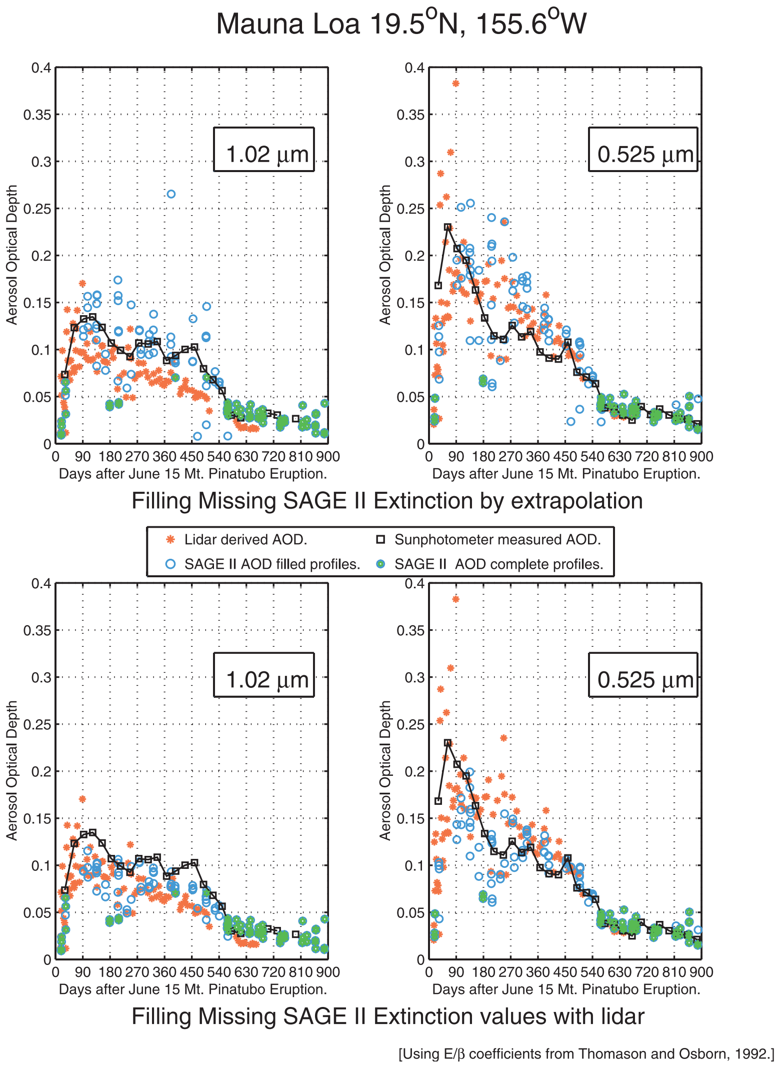

Figure 9. Aerosol optical depths for all coincident profiles, illustrating the effects of missing SAGE II extinctions for Mauna Loa. (top) Comparison of lidar-derived and Sun photometer aerosol optical depth (AOD) with SAGE II complete profiles and those filled by extrapolation. (bottom) Comparison with those filled by nearest lidars.