CALIPSO Observations of Stratospheric Aerosols:

A Preliminary Assessment

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Abstract.

We have examined the 532-nm aerosol backscatter coefficient measurements by the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) for their use in the observation of stratospheric aerosol. CALIPSO makes observations that span from 82°S to 82°N each day and, for each profile, backscatter coefficient values reported up to ~40 km. The possibility of using CALIPSO for stratospheric aerosol observations is demonstrated by the clear observation of the 20 May 2006 eruption of Montserrat in the earliest CALIPSO data in early June as well as by observations showing the 7 October 2006 eruption of Tavurvur (Rabaul). However, the very low aerosol loading within the stratosphere makes routine observations of the stratospheric aerosol far more difficult than relatively dense volcanic plumes. Nonetheless, we found that averaging a complete days worth of nighttime only data into 5-deg latitude by 1-km vertical bins reveals a stratospheric aerosol data centered near an altitude of 20 km, the clean wintertime polar vortices, and a small maximum in the lower tropical stratosphere. However, the derived values are clearly too small and often negative in much of the stratosphere. The data can be significantly improved by increasing the measured backscatter (molecular and aerosol) by approximately 5% suggesting that the current method of calibrating to a pure molecular atmosphere at 30 km is most likely the source of the low values.

1. Introduction

Aerosol plays a significant role in the chemistry and dynamics of the lower stratosphere and upper troposphere including a critical role in the heterogeneous processes that lead to ozone destruction. Stratospheric aerosol is also highly variable due to episodic volcanic eruptions that inject aerosol and/or its gaseous precursors into the stratosphere. Over the last 25 years, the total aerosol loading has varied by more than a factor of one hundred and volcanic effects have dominated other natural and human-derived sources for stratospheric aerosol in all but the last few years when levels have apparently reached a stable background level (Thomason and Peter, 2006). In the absence of another volcanic eruption, aerosol levels may still under go significant changes over the next decade due to changes in the human-derived aerosol precursors. Global human-derived SO_2 has declined by nearly 20% since 1980 (Stern, 2003). On the other hand, emissions in the East Asia and China have increased dramatically over this period and are projected to continue to increase. It is believed that SO_2 or SO_2-derived aerosol makes it into the upper troposphere/lower stratosphere (UTLS) through entrainment by deep convection in the tropics and, since SO_2 has a short lifetime in the troposphere, emissions at low latitudes are far more likely to make it to the tropical tropopause than mid-latitude emissions (Notholt et al, 2006). As a result, it is possible that changes in human-derived SO_2 concentration in the lower stratosphere may produce either an increase or decrease in aerosol loading in the lower tropical stratosphere in the coming years. Changes in aerosol in the UTLS may affect the occurrence and properties of thin cirrus in this radiatively sensitive region (e.g., Kärcher, 2002).

As a result, measurements of stratospheric aerosol remain important, yet global measurements by space-borne instruments are at risk due to the end of the missions of several long-lived instruments (e.g., the Stratospheric Aerosol and Gas Experiment (SAGE II/III), The Halogen Occultation Experiment (HALOE), and the Polar Ozone and Aerosol Measurement (POAM III)) and instrument performance issues for on-going missions (the High Resolution Dynamics Limb Sounder or HIRDLS). Several instruments have the potential to produce stratospheric aerosol data products but have yet to produce them operationally (e.g., SCIAMACHY, ACE-FTS, and MAESTRO). In light of this, we examine the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations' (CALIPSO) Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) lidar backscatter coefficient profiles at 532 nm as a potential source of a scientifically useful stratospheric aerosol product. While we concede that this is challenging, our preliminary study (explained in detail below) suggests that a scientifically viable data product is possible even for the very low aerosol loading period currently observed.

1. CALIPSO Stratospheric Aerosol Measurements

Description of CALIPSO

The primary objective of CALIPSO is to provide measurements that will significantly improve our understanding of the effects of aerosols and clouds on the climate system. As part of the Aqua satellite constellation that includes the Aqua, CloudSat, Aura, and PARASOL satellites, CALIPSO is in a 98^o inclination orbit with an altitude of 705 km that provides daily global maps of the distribution of aerosol and clouds. The CALIPSO payload consists of three instruments: the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP), an Imaging Infrared Radiometer (IIR), and a moderate spatial resolution Wide Field-of-view Camera (WFC). CALIOP provides profiles of backscatter at 532 and 1064 nm, as well as two orthogonal (parallel and perpendicular) polarization components at 532 nm. CALIOP instrument characteristic are shown in Table 1 and the vertical and horizontal resolution of the data products is shown in Table 2. A detailed discussion of CALIOP data products can be found in Vaughan et al. (2004). In the routine processing, the parallel component of the 532-nm backscatter is calibrated to the expected molecular volume backscatter coefficient between 30 and 34 km altitude where the molecular density is derived from the GEOS-4 atmospheric analyses provided by the Global Modeling and Assimilation Office. Independent calibrations occur every 55 km of the dark side of each orbit and is smoothed using a 27-point mean (1485 km) (Hostettler et al., 2006) and interpolated onto the sunlit side. The perpendicular component is transferred from the parallel term using an on-board optical system. The calculation of a stratospheric aerosol product is highly sensitive to the quality of this normalization and any deficiency in the calibration represents the greatest obstacle to the successful production of a scientifically useable stratospheric aerosol product.

Initial assessment

With its first observations in mid-June 2006, CALIPSO provided detail of condensed material within the stratosphere. These observations included polar stratospheric clouds (Poole et al., 2006; Pitts et al., 2007) as shown in Figure 1a and a distinct aerosol plume associated with the May 20, 2006 eruption of Montserrat (e.g., Carn et al., 2007). Figure 1b is an example of the observations of a second volcanic event that appeared in the lower tropical stratosphere following the 7 October 2006 eruption of Tavurvur. This plume remained clearly observable in the tropics to at least the end of November 2006. However, apart from these kinds of events, CALIOP backscatter data does not readily show the presence of the stratospheric aerosol layer that has been regularly measured in the past by instruments such as SAGE II and HALOE (see, for example, the browse images at http://www-calipso.larc.nasa.gov/products/lidar/index.php).

Currently, the stratospheric aerosol integrated backscatter lies between 2 and 7. 10^{-5} str^{-1} at 532 nm with a peak scattering ratio between 1.03 and 1.06 and most of this aerosol lies within 5 to 6 km of the tropopause (Vaughan and Wareing, 2004). The integrated column back scatter is about a factor of 100 less than that following the 1991 Pinatubo eruption and also much less than what can be observed in the boundary layer. With such low values, it is not surprising that stratospheric aerosol was not a science target of the CALIPSO mission. To establish the feasibility of producing a stratospheric 532-nm aerosol backscatter product from CALIPSO, we made use of the CALIOP data simulator developed by the CALIPSO data processing team (Powell et al., 2002). This simulator includes all known sources of measurement error including shot noise and electronic performance. As input we used a column total of 6. 10^{-5} str^{-1} at 532 nm that corresponds to ground-based lidar measurements and is also consistent with the stratospheric aerosol optical depth at 525 nm reported by SAGE II (~0.003). The aerosol is dispersed in a 'top hat' profile over a 6 km layer between 16 and 22 km. We then produced a 20000-km track using the CALIPSO lidar data simulator. The output was produced at the nominal resolution reported by CALIPSO of 1 km along track and 60 m vertical resolution below 20 km and 5/3 km along track and 180 m vertical resolution above 20 km. We simulated only nighttime measurements in light of the low backscatter levels and noting that nighttime measurements are a much higher signal-to-noise ratio than daytime measurements.

Figure 2a shows 100 individual profiles of this data between 14 and 30 km. Other than the change in resolution (see Table 2) at 20 km, there are no obvious features in this figure and the aerosol layer is invisible. Fortunately, there is no overriding reason to produce stratospheric aerosol data at anywhere close to this resolution. The most prominent existing stratospheric aerosol measurements, SAGE II and HALOE, are made by solar occultation and provide a total of only 30 profiles a day and have a horizontal extent of hundreds of kilometers (Thomason et al., 2003). As a result, we feel that substantial averaging to produce a stratospheric product is justifiable. At the same time, given the lack of operational global stratospheric aerosol measurements, averaging above and beyond that representative of current measurements could be justified as a mechanism to preserve stratospheric record. Figure 2b shows the result of reducing the resolution to 1.5 km vertically and averaging along 15 tracks through a 5-deg latitude band (a total ground track of 7500 km) or essentially, a 1-day zonal average. At this resolution, the aerosol layer is clearly visible and the uncertainty in the mean profile is only about 1%. Realistically, while the simulator is as realistic as possible, it no doubt is missing some components of the measurement noise that will be observed in the real data. As a result, we recognize that it is necessary to explore various techniques to produce robust stratospheric aerosol profiles including along track averaging, vertical averaging, and zonal averaging.

As the initial stratospheric aerosol grid, we chose a meridianal analyses of all 14 nighttime orbit segments averaged in 5 degree latitude between 80ºS and 80ºN and 1-km altitude bins covering from 10 to 40 km. This resolution is much less fine than that reported in the standard data product files and spans several changes in horizontal and vertical resolutions in these files (see Table 2). The total number of profiles going into the analysis is on the order of 8×10^{5} though replication of data points to account for changes in resolution reduces the effective number of independent measures. Nonetheless, the volume of data is significantly greater than has been previously available. For instance, the daily number of profiles is almost twice as many profiles as SAGE II produced during its 21-year lifetime. The molecular backscatter term is removed using the embedded molecular density originating from GEOS-4. While no effort has been made to eliminate cirrus clouds, we have crudely accounted for the presence of PSCs by eliminating all observations where the temperature was less than 195 K and aerosol backscatter is greater than 4 10^{-3} km^{-1} str^{-1}at latitudes higher than 60º in the winter hemisphere. An additional fact to note is that the Level 1backscatter data product (v1.10) is the attenuated backscatter that has not been corrected for attenuation by molecules, ozone, and aerosol for the two way trip between the measurement altitude and the spacecraft. As a result, the reported attenuated backscatter values will underestimate true values. However, this effect is a very small in the stratosphere where the backscatter values particularly above the main aerosol layer are exceedingly small. As a result, we believe that the use of attenuated backscatter is unlikely to have a significant effect on the analysis.

Figure 3a and 3b show the aerosol backscatter meridianal cross sections for 2 July 2006 and 7 January 2007. At first glance, the quality of these depictions of stratospheric aerosol is not encouraging. While there is no evidence of the analyses being pathologically noisy, both analyses exhibit substantial areas where the meridianal average is less than zero and the regions that are positive are at best only somewhat consistent with expectations of how the stratospheric aerosol layer should appear. For comparison purposes, we offer a mean meridianal SAGE II aerosol extinction analysis from July 2004 as shown in Figure 4. This is a fair comparison because SAGE II is a well-known and well-validated stratospheric aerosol data set and stratospheric aerosol has been relatively constant since 2000 (e.g., Deshler et al., 2006) apart from minor effects by volcanic eruptions such as those by Montserrat and Tavurvur.

In the CALIPSO analysis, we found a consistent region in southern mid-latitudes above 25 km that is consistently enhanced relative to other latitudes. This is most likely not a physical feature and is more likely due to CALIOP instrument related effects associated with the South Atlantic

Anomaly. On a more positive note, in both Figures 3a and particularly 3b, there are substantial regions that are at least reminiscent of the aerosol layer shown in Figure 4. For a 1020-nm extinction to 532-nm backscatter ratio of 10 to 20 str (Jager and Deshler, 2002) the backscatter values range between 10^{-6} and 10^{-5} km^{-1} str^{-1} and thus are somewhat lower than would be expect based on the SAGE II analysis. The most robust feature in these analyses, including other days not shown, is a maximum in backscatter coefficient between 18 and 22 km in the tropics. This is at least in part the remnant of the Montserrat and Tavurvur eruptions but may also reflect the tropical stratospheric aerosol cycle reported by SAGE II (Thomason et al., 2007).

Clearly, the current state of the CALIOP data makes it unusable for stratospheric aerosol analyses at current aerosol levels. The question remains, however, whether improvements to the data processing and particularly the calibration process could improve the data to a more useful state. Currently, the CALIOP is calibrated between 30 and 34 km assuming that the atmosphere is strictly molecular including absorption by ozone or that the backscatter ratio (total to molecular backscatter coefficient) is 1.0 at these altitudes. This decision was based on the fact that there is no routinely produced global stratospheric aerosol product available at this time as well as the desire to keep the initial processing algorithm simple as possible. Nonetheless, based on 2004 SAGE II data, our best guess is that the backscatter ratio at these altitudes is actually at least 1.03 and possibly as large as 1.10 in the tropics (CALIOP ATDB, 2006). This discrepancy of 3 to 10% in backscatter ratio translates into a similar magnitude over-estimate of the calibration coefficient for the entire depth of the profile and roughly into an underestimate of the total backscatter coefficient of the same magnitude. Since even in the main stratospheric aerosol layer, the backscatter ratio remains relatively small, the impact of the calibration overestimation may have a disproportionate effect on the measured aerosol backscatter coefficient profile.

First-order 'simple' calibration fix and results

To evaluate the effect of the calibration issue on the stratospheric aerosol backscatter, we performed an experiment by taking the ratio of a mid-latitude northern hemisphere CALIOP medianally-averaged 532-nm backscatter profile from July 2006 and a similar SAGE II 1020-nm extinction profile from 2004. We are relying on the belief that stratospheric aerosol loading has not changed significantly over the past two years. Based on data independent of either instrument, the expected 1020-nm extinction to 532-nm backscatter ratio should lie between 10 and 20 str (Jäger and Deshler, 2002). Figure 5a shows that the ratio profile is extremely noisy with values running between -60 and 60 str between 15 and 35 km. As a first-order calibration correction, we multiply the total CALIOP 532-nm backscatter coefficient profile by 1.025, 1.050, and 1.075, remove the computed molecular backscatter, and take the ratio with the SAGE II extinction profile. These profiles demonstrate substantially better behavior than the non-corrected data sets particularly below 23 km. The 1.025-corrected profile is still generally too large and varies between 15 and 45 str. On the other hand, the 1.050 and 1.075 profiles are nearly constant around values of 8 and 15 str. The values for the 1.050-corrected profile are well within the expected range of extinction-to-backscatter values. The behavior above 23 km for all three profiles is quite similar, the extinction-to-backscatter profiles converge to values between 2 and 4, or significantly smaller than the nominal values. To some degree, the smaller values at higher altitudes are non unexpected as the size of aerosol generally decreases with altitude due to sedimentation and evaporation of aerosol. However, it appears that a 5% correction to the total backscatter profiles that looks promising in the 15 to 23 km range leaves backscatter too large at altitudes above 23 km.

Since a 5% correction seems generally promising, we looked at monthly cross sections of 532-nm aerosol backscatter coefficient for July 2006 through February 2007 as shown in Figure 6a-h. Here we see very regular behavior in each frame that shows a stratospheric aerosol layer that stretches from about 15 km to around 22 km. There is a persistent maximum magnitude in the lower tropical stratosphere that generally decreases in magnitude with time. At this point, it is not clear what the primary source of this feature is, however, it is likely that it is related either to the May 2006 Monserrat eruption or a lower tropical aerosol annual cycle that peaks in the second half of the calendar year and that has been reported previously by Thomason et al. (2006). The polar vortex measurements remain negative in this analysis. This is partly due to the very low level of aerosol associated with both the northern and southern vortices and due to a known deficiency in the GEOS-4 data in which temperatures within the polar vortex are often biased cold by as much as 10 K (REF). This problem is expected to greatly diminish in GEOS-5 data that will be used in future releases of CALIOP aerosol products. The increase of backscatter coefficient in the lower stratosphere in late 2006 in the southern hemisphere is due to aerosol originating with the October 2006 Tavurvur eruption that appears to have been transported preferentially to southern latitudes in late 2006 in fashion similar to the 1990 eruption of Kelut (Thomason et al. 1997). The aerosol anomaly above 25 km in southern mid-latitudes is not affected by the correction. Immediately above the main aerosol layer, the backscatter coefficient does not decrease away from the poles as would be suggested by the SAGE II analysis shown in Figure 4. It is fairly independent of latitude and, as previously noted, also appears to decrease too slowly with increasing altitude. It is possible that a simple constant correction is not adequate. This would not be surprising since the expected backscatter ratio between 30 and 34 km (and its concomitant effect on the calibration coefficient) is a fairly strong function of latitude.

Conclusions

The development of a CALIPSO stratospheric aerosol product may provide a bridge between current stratospheric aerosol-measuring instruments like SAGE II and HALOE and future instruments like NPOES. Linking these aerosol data sets is important to maintain trends but far from trivial since none of these instruments measure the same subset of aerosol optical properties and the conversion between measurement types is difficult (e.g., Thomason and Peter, 2006). On the basis of this analysis, we believe that CALIPSO lidar measurements hold some promise for stratospheric applications. While it is obvious that the current version does not produce stratospheric aerosol backscatter that is ready for scientific applications at current stratospheric aerosol levels, there is a clear pathway to substantial improvement. The CALIOP calibration process needs a more realistic model for the aerosol content of the stratosphere above 30 km as a function of latitude or the derivation of aerosol at these altitudes must become part of the calibration process. It is possible that instruments currently in orbit may provide the needed information or a climatology based on SAGE II and/or other instruments may be adequate in the absence of significant perturbations by volcanoes. The use of GEOS-5 may improve the quality of the aerosol data within the polar vortex (note that these concerns do not apply to observations of polar stratospheric clouds). Efforts to account for calibration difficulties associated with the South Atlantic Anomaly by the CALIPSO team are already underway and should be part of the next release of the data. It is clear that the examination of the CALIOP stratospheric aerosol data will be useful in evaluating on-going efforts to improve operational data processing.

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Table 1. CALIOP instrument characteristics

laser:	Nd: YAG, diode-pumped, Q-switched, frequency doubled
wavelengths:	532 nm, 1064 nm
pulse energy:	110 mJoule/channel
repetition rate:	20.25 Hz
receiver telescope:	1.0 m diameter
polarization:	532 nm
footprint/FOV:	100 m/ 130 μrad
vertical resolution:	30-60 m
horizontal resolution:	333 m
linear dynamic range:	22 bits
data rate:	316 kbps

Table 2. CALIOP spatial resolution of downlinked data

Altitude Range (km)	Horizontal Resolution (km)	Vertical Resolution (m)
30.1- 40.0	5.0	300
20.2-30.1	1.67	180
8.2-20.2	1.	60
-0.5-8.2	0.33	30
-2.0--0.5	0.33	300

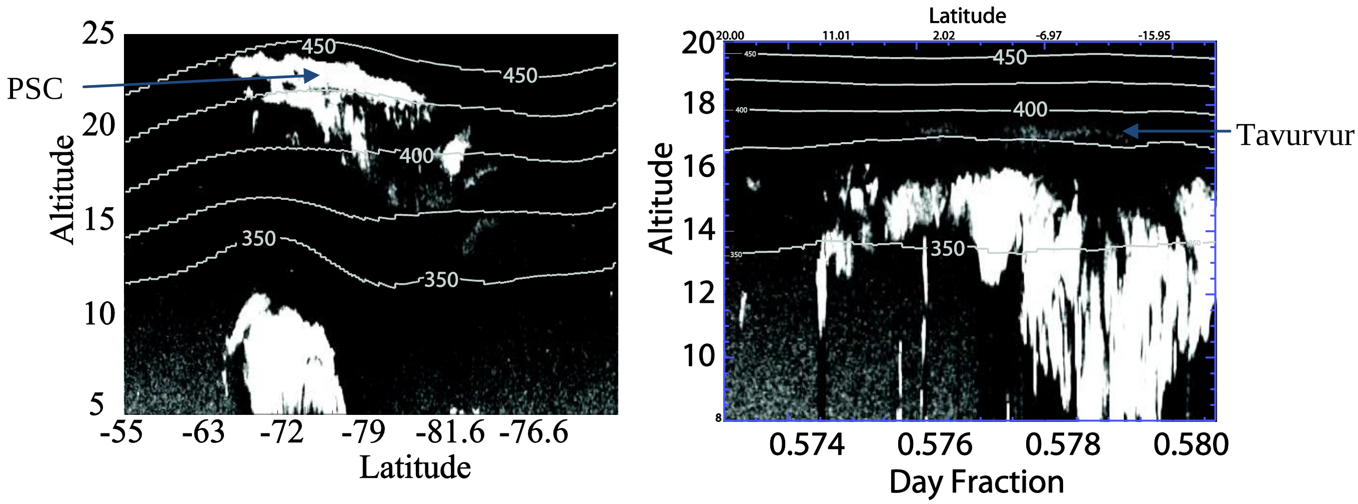


Figure 1. CALIOP observations of (a) a PSC observed on 24 July 2006 and (b) a qualitative depiction of the volcanic plume from the 7 October 2006 Tavurvur eruption as measured on 15 October 2007. In both frames, the solid grey lines denote potential temperature.

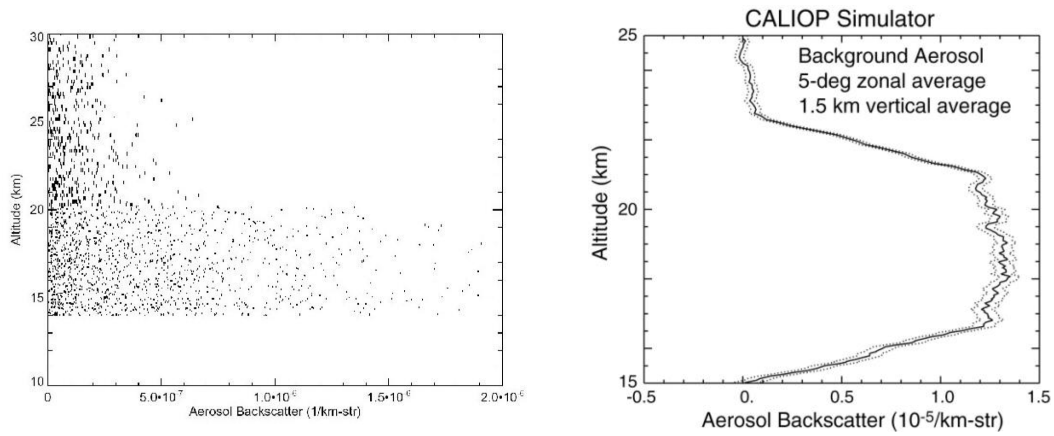


Figure 2. (a)A depiction of 100 individual simulated CALIPSO 532-nm backscatter profiles for a ‘top hat’ stratospheric layer between 16 and 22 km. The abrupt change in noise at 20 km is due to a change in on-board smoothing and not due to any atmospheric signal. (b) Simulated retrieval of a stratospheric aerosol layer using CALIPSO backscatter data. This profile is a 1-day, 5-deg latitudinal average for background conditions.

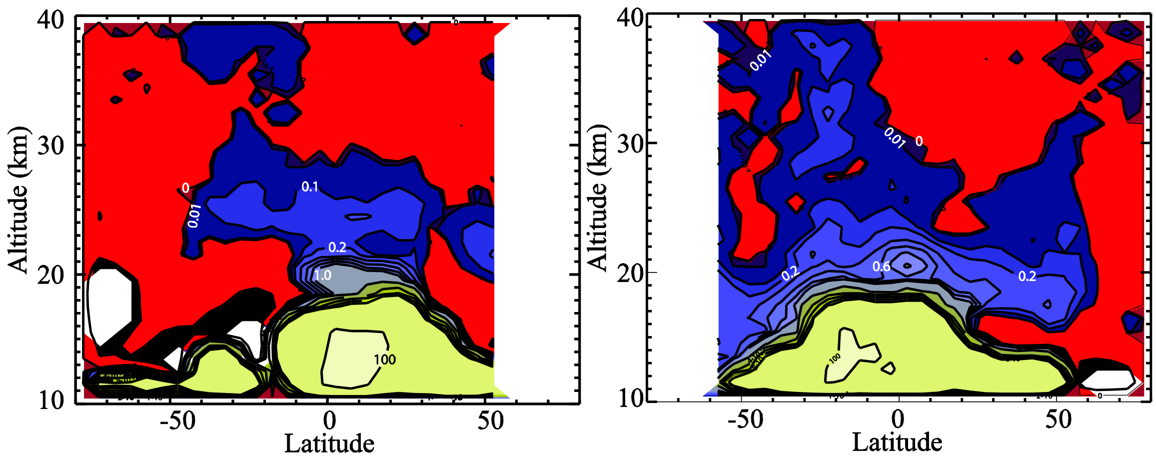


Figure 3. CALIPSO stratospheric 532-nm aerosol backscatter profiles for (a) 2 July 2006 and (b) 7 January 2007. Red regions have aerosol backscatter less than zero, while white areas showing missing values. The contour values are 0, 0.001, 0.01, 0.1, 0.2, 0.4, 0.6, 0.8, 1, 2, 4, 6, 8, 10, and 100 for aerosol backscatter coefficient in km^{-1} str^{-1} times 10^5. Areas in the troposphere with extinction coefficient values greater than 10^{-4} km^{-1} str^{-1} are strongly influenced by the presence of cloud.

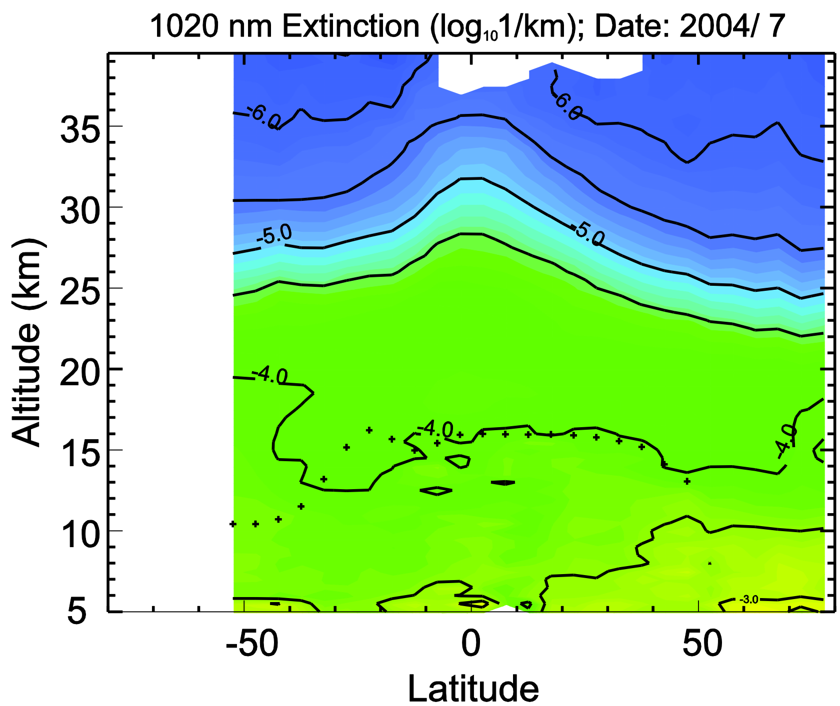
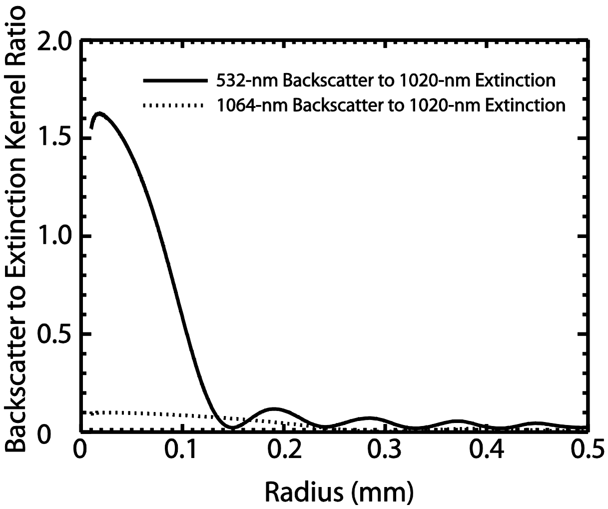
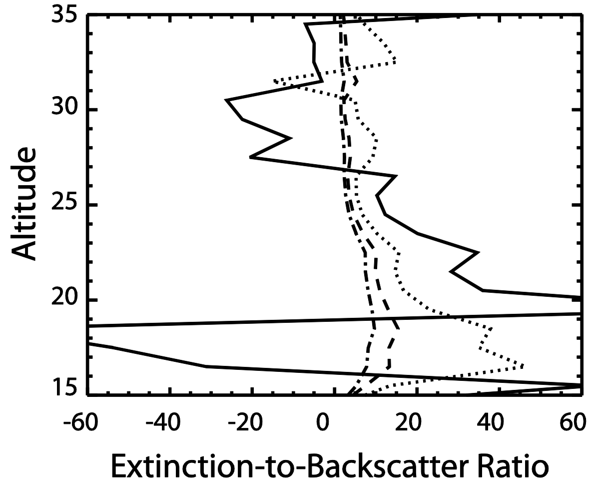


Figure 4. Cross section of 1020-nm aerosol extinction for July 2007 as measured by the solar occultation instrument SAGE II (in km^{-1} in log_{10}). The '+' signs denote the mean tropopause height. This analysis has been had events influenced by cloud removed using the method developed by Kent et al. (199x).



Backscatter to Extinction Kernel Ratio
2.0
1.5
1.0
0.5
0
0.1
0.2
0.3
0.4
0.5
Radius (mm)
532-nm Backscatter to 1020-nm Extinction
1064-nm Backscatter to 1020-nm Extinction



Altitude
35
30
25
20
15
-60
-40
-20
0
20
40
60
Extinction-to-Backscatter Ratio

Figure 5. (a) (b)

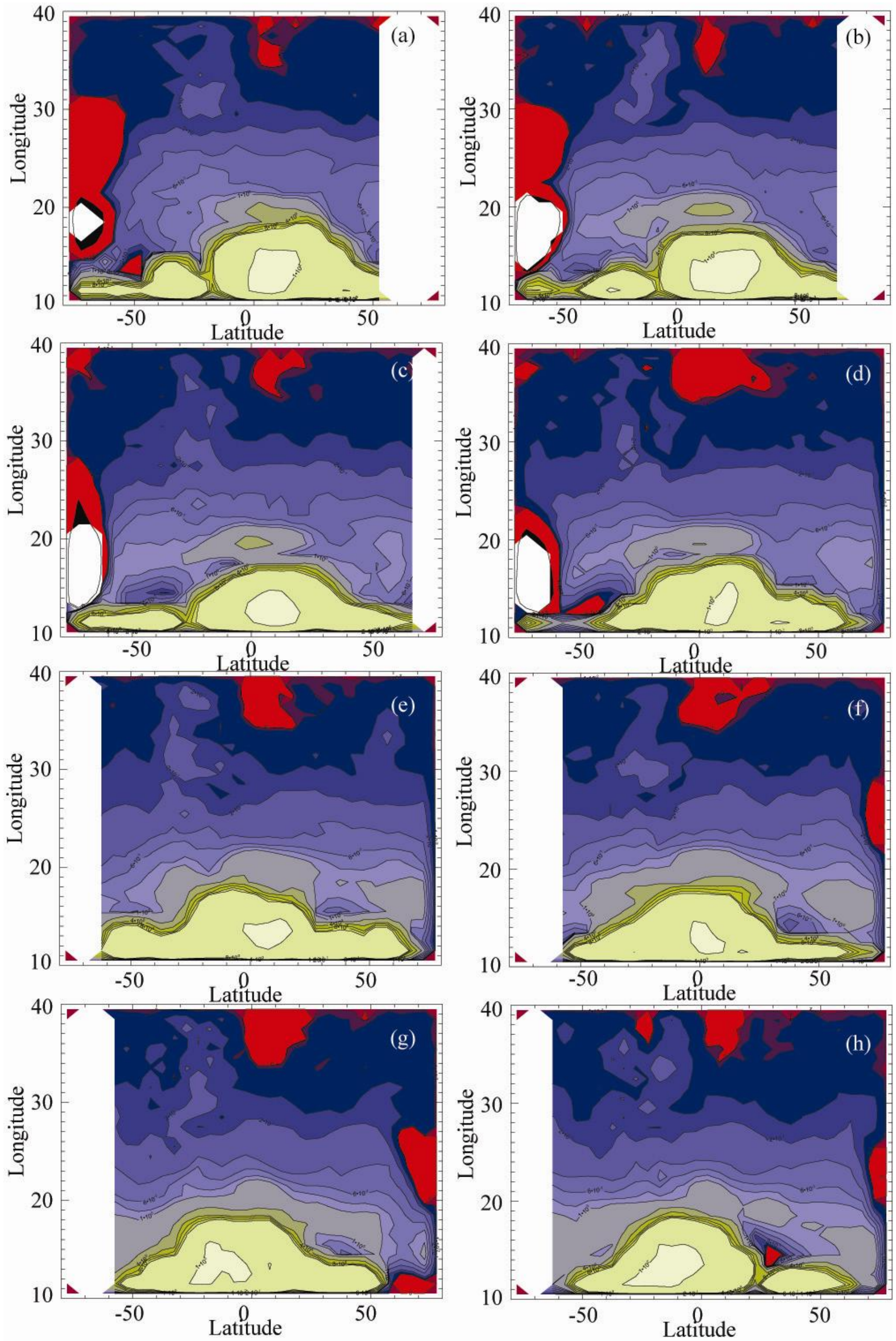


Figure 6. Cross sections of CALIOP aerosol attenuated backscatter at 532 nm where the total backscatter has been adjusted by +5% for (a) 2 July 2006, (b) 6 August 2006, (c) 3 September 2006, (d) 1 October 2006, (e) 5 November 2006, (f) 3 December 2006, (g) 7 January 2007, and (h) 4 February 2007. Red regions have aerosol backscatter less than zero, while white areas showing missing values. The contour values are 0, 0.001, 0.01, 0.1, 0.2, 0.4, 0.6, 0.8, 1, 2, 4, 6, 8, 10, and 100 for aerosol backscatter coefficient in km^{-1} str^{-1} times 10^5. Areas in the troposphere with extinction coefficient values greater than 10^{-4} km^{-1} str^{-1} are strongly influenced by the presence of cloud. Areas within either winter time polar vortex, known to have very low aerosol content, are found to have backscatter coefficient values less than 0.