



Optical properties of stratospheric aerosols from wildfires and volcanic eruptions constrained by satellite and ground-based lidars – Part I: large scale evolution

5 Océane. Soares¹, Sergey. Khaykin², Sophie. Godin-Beekmann¹, Artem. Feofilov³, Tetsu. Sakai⁴, Yoshita. Jin⁵, Isamu. Morino⁵, Ben. Liley⁶, Richard. Querel⁶

¹LATMOS/IPSL, Sorbonne University, CNRS, Guyancourt, France

² LATMOS/IPSL, UVSQ, Sorbonne University, CNRS, Guyancourt, France

³ LMD/IPSL, Sorbonne University, CNRS/Ecole Polytechnique, Paris, France

10 ⁴ Meteorological Research Institute, Japan Meteorological Institute, Tsukuba, Japan

⁵ National Institute for Environment Studies (NIES), Tsukuba, Japan

⁶ New Zealand Institute for Earth Sciences, Lauder, New Zealand

15 *Correspondence to:* O. Soares (oceane.soares@latmos.ipsl.fr)

Abstract. Stratospheric aerosols exert a major influence on the Earth's radiative balance, atmospheric chemistry, and climate variability. Over the last two decades, the stratospheric aerosol layer has been repeatedly perturbed by explosive volcanic eruptions and, more recently, by extreme wildfire events capable of injecting large amounts of aerosols into the lower stratosphere. Characterizing the long-term evolution of these perturbations is therefore essential for improving our
20 understanding of stratospheric aerosol variability and its climatic impacts. This study is presented in two companion papers. Part I focuses on the large-scale evolution and persistence of major stratospheric aerosol perturbations over the CALIPSO observational period, while Part II investigates the optical properties and early evolution of individual volcanic and wildfire plumes.

25 In this study, we investigate the large-scale evolution of the stratospheric aerosol layer between 2006 and 2023 using a new dataset Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) Level 1 dataset (L1CC). The analysis combines stratospheric aerosol optical depth (SAOD), scattering ratio (SR), and bulk depolarization with the Global Space-based Stratospheric Aerosol Climatology (GloSSAC), Ozone Mapping and Profiler Suite Limb Profiler (OMPS-LP) observations, Atmospheric Lidar (ATLID) observations aboard EarthCARE, and independent Network for the Detection of Atmospheric
30 Composition Change (NDACC) lidar measurements at the Observatoire de Haute-Provence (44°N) and Lauder (45°S). The corrected dataset is validated against these independent observations, demonstrating its capability to reproduce the timing, magnitude and vertical evolution of the major stratospheric aerosol perturbations observed during the CALIPSO mission.



The observations reveal distinct long-term optical behaviours associated with volcanic eruptions and wildfire events, with volcanic plume properties depending on their ash and sulfate content, whereas wildfire plumes maintain persistently elevated depolarization associated with long-lived carbonaceous aerosols. The combined analysis of SAOD, scattering ratio and bulk depolarization further provides a consistent description of the temporal evolution of the stratospheric aerosol layer over nearly two decades.

Finally, a return-time analysis is introduced to quantify the persistence of individual perturbations. The results demonstrate that recovery of the stratospheric aerosol layer depends not only on the magnitude of the initial aerosol loading but also on injection altitude and subsequent atmospheric evolution. Together, these results provide a homogeneous lidar-based climatology of the large-scale evolution of the stratospheric aerosol layer over the complete CALIPSO mission, and enabling consistent comparisons of the long-term impacts of volcanic eruptions and extreme wildfire events.

1 Introduction

Stratospheric aerosols (SA) play a fundamental role in the Earth's climate system by altering both the radiative balance and atmospheric chemistry. They scatter incoming solar radiation, thereby cooling the Earth's surface, while simultaneously absorbing terrestrial infrared radiation and warming the lower stratosphere. These radiative perturbations influence atmospheric circulation, ozone chemistry, and climate variability on regional and global scales, making the stratospheric aerosol layer (SAL) an essential component of climate forcing assessments (SPARC, 2006; Robock, 2000; Kremser et al., 2016). Beyond their natural climatic influence, stratospheric aerosols have also become central to discussions of solar radiation management through Stratospheric Aerosol Injection (SAI), emphasizing the need for an accurate characterization of their optical and microphysical properties, and long-term evolution.

Under background conditions, the SAL is dominated by liquid sulfate droplets produced through the oxidation of sulfur-bearing gases such as carbonyl sulfide (OCS) and sulfur dioxide (SO₂), with additional contributions from meteoritic smoke particles and anthropogenic emissions (Kremser et al., 2016). Superimposed on this persistent background, explosive volcanic eruptions episodically inject volcanic ash, sulfur dioxide and other gases directly into the lower stratosphere. Subsequent oxidation of SO₂ produces sulfate aerosols that may remain for months to several years in the stratosphere depending on the eruption magnitude and injection altitude (Robock, 2000; Vernier et al., 2011; Ridley et al., 2014). During the last decade, another important source of stratospheric aerosols has emerged. Pyrocumulonimbus (pyroCb) events associated with extreme wildfires have demonstrated the ability to inject large amounts of carbonaceous smoke into the lower stratosphere, where absorbing particles may persist for many months owing to radiatively driven self-lofting and slow removal processes (Peterson et al., 2018; Yu et al., 2019; Khaykin et al., 2020).



65 Recent events, including the Pacific Northwest fires (2017) (Peterson et al., 2018; Yu et al., 2019), the Australian New Year
fires (2019–2020) (Khaykin et al., 2020), and the Panboreal Wildfire Outbreak (PWO) (2025) (Haarig et al., 2026), have shown
that wildfire smoke can perturb the global stratospheric aerosol layer on a scale comparable to moderate volcanic eruptions.
Although volcanic eruptions and extreme wildfires both perturb the SAL, they differ markedly in their temporal evolution,
geographical extent and atmospheric persistence. These differences are reflected in the evolution of aerosol optical properties,
70 including stratospheric aerosol optical depth (SAOD), scattering ratio (SR) and bulk depolarization, which together provide
valuable information on the long-term variability of the stratospheric aerosol layer. Continuous observations of these
parameters are therefore essential for understanding how successive perturbations influence the large-scale evolution of the
SAL over timescales ranging from months to years.

75 Long-term monitoring of stratospheric aerosols relies on complementary satellite and ground-based observing techniques, each
providing different information on the spatial distribution, vertical structure and optical properties of the aerosol layer. Solar
occultation instruments, such as the Stratospheric Aerosol and Gas Experiment (SAGE) series, provide accurate vertically
resolved aerosol extinction measurements and have played a central role in establishing long-term stratospheric aerosol records
(Thomason et al., 2018; Kovilakam et al., 2020). Limb-scattering instruments, including the Optical Spectrograph and InfraRed
80 Imaging System (OSIRIS) and the Ozone Mapping and Profiler Suite Limb Profiler (OMPS-LP), provide broader spatial
coverage and vertically resolved aerosol extinction profile measurements, enabling the evolution and transport of stratospheric
aerosol perturbations to be monitored on regional to global scales (Bourassa et al., 2012; Rieger et al., 2019; Taha et al., 2021).

Active lidar observations provide complementary information by resolving the vertical structure and optical properties of
85 aerosol layers. From space, the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) aboard the Cloud-Aerosol Lidar
and Infrared Pathfinder Satellite Observation (CALIPSO) mission provided global measurements of aerosol backscatter and
depolarization from 2006 to 2023 (Winker et al., 2009). More recently, the Atmospheric Lidar ATLID aboard EarthCARE
mission has extended spaceborne lidar observations using the high-spectral-resolution lidar technique at 355 nm, allowing
molecular and particulate backscatter contributions to be separated (Wehr et al., 2023). Ground-based lidars, particularly those
90 operated within the Network for the Detection of Atmospheric Composition Change (NDACC), complement satellite
observations through long-term measurements at fixed locations with high vertical resolution, providing independent
observations of the temporal and vertical evolution of stratospheric aerosol perturbations (Khaykin et al., 2017; De Mazière et
al., 2018).

The complementary nature of these observing techniques has enabled the construction of long-term multi-instrument datasets
95 such as the Global Space-based Stratospheric Aerosol Climatology (GloSSAC), which combines observations from several
satellite instruments to provide a consistent record of stratospheric aerosol extinction extending back to 1979 (Thomason et
al., 2018; Kovilakam et al., 2020). Combining these different observational approaches is particularly valuable because no
single instrument simultaneously provides long-term temporal coverage, global spatial sampling, high vertical resolution, and



multiple aerosol optical properties. Their combined use therefore provides a more complete characterization of the evolution
100 of the stratospheric aerosol layer.

Over the last decades, a number of studies have advanced our understanding of the long-term variability of the stratospheric
aerosol layer (Kremser et al., 2016; Khaykin et al., 2020, 2022). Most previous studies have focused on aerosol optical depth
or extinction, or have investigated individual volcanic and wildfire events separately. More recently, Martinsson et al. (2026)
provided a global assessment of stratospheric aerosol variability over the CALIOP period (2006–2023), using CALIOP Level
105 1B observations to derive stratospheric aerosol optical depth (SAOD) and scattering ratio profiles. Their retrieval relies on an
iterative approach to determine the lidar ratio and retrieve aerosol backscatter from the attenuated CALIOP measurements.
Their analysis highlighted the increasing contribution of wildfire smoke to the global stratospheric aerosol burden and
demonstrated its importance in the contemporary stratospheric aerosol climatology.

110 The present study provides a complementary assessment based on a different processing approach. The L1CC dataset uses the
GloSSAC climatology to correct the CALIOP Level 1 attenuated backscatter record and additionally combines SAOD and
scattering ratio with bulk depolarization, thereby providing information on both aerosol loading and particle non-sphericity.
The analysis is further constrained by independent ground-based lidar observations at OHP and Lauder and complemented by
GloSSAC, OMPS-LP, and ATLID observations, allowing the evolution of major stratospheric perturbations to be followed
115 beyond the CALIPSO observational period. Finally, the persistence of individual volcanic and wildfire perturbations is
quantified using a consistent return-time approach.

In this study, we investigate the large-scale evolution of the stratospheric aerosol layer over the 2006–2025 period using a new
Level 1 dataset (L1CC) based on the most recent Version 5.0 of the CALIOP Level 1B product, together with the GloSSAC
climatology, OMPS-LP and ATLID observations, as well as long-term NDACC lidar measurements at the Observatoire de
120 Haute-Provence and Lauder. We analyse the temporal evolution of stratospheric aerosol optical depth, scattering ratio and bulk
depolarization to characterize the large-scale variability associated with major volcanic eruptions and extreme wildfire events.
We further quantify the persistence of these perturbations through a return-time analysis and evaluate the consistency of the
L1CC dataset using independent ground-based lidar observations. This work provides a homogeneous lidar-based climatology
of the large-scale evolution of the stratospheric aerosol layer over the complete CALIPSO mission.

125 These objectives constitute Part I of the study. Part II complements this large-scale analysis by focusing on the early evolution
of individual volcanic and wildfire plumes using CALIOP Level 2 observations. It examines the temporal, statistical and
vertical evolution of scattering ratio, particulate linear depolarization ratio and color ratio during the first months following
injection, with additional ATLID observations used to investigate the PWO-2025 in Canada.



2 Data and Methods

2.1 CALIPSO - CALIOP

The Cloud–Aerosol Lidar with Orthogonal Polarization (CALIOP) served as the main lidar instrument aboard the Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite, launched on 28 April 2006. CALIOP acquired measurements until 30 June 2023, while the CALIPSO science mission officially ended on 1 August 2023, within NASA’s A-Train satellite formation. CALIOP was an elastic backscatter lidar that operated at two wavelengths—532 nm and 1064 nm—and included polarization measurements at 532 nm. Its mission was to deliver global, vertically resolved observations of clouds and aerosols (Winker et al., 2009). The system emitted linearly polarized laser pulses at a repetition rate of 20.16 Hz, with pulse energies of roughly 110 mJ at both 532 nm and 1064 nm. A 1-meter telescope collected the backscattered light, separated into three detection channels: the 532 nm parallel and perpendicular polarization channels, and the 1064 nm total backscatter channel (Winker et al., 2007).

CALIOP produced profiles of attenuated backscatter with an intrinsic vertical sampling of 30–60 m below 20 km altitude and 180 m above this level, alongside a horizontal resolution of 333 m (Hunt et al., 2009). The total backscatter coefficient $\beta(r)$, was retrieved from the representing the combined contributions from molecules and aerosols. Thanks to its measurement of both co-polarized and cross-polarized returns, CALIOP can also derive the volume depolarization ratio (VDR), an important parameter used to distinguish spherical particles such as sulfate droplets from non-spherical ones like volcanic ash or wildfire smoke (Omar et al., 2009).

2.2 Ground-based LiDAR observations

To complement satellite-based measurements from CALIOP, ground-based lidar observations were used to provide continuous, high-vertical-resolution monitoring of stratospheric aerosols. Two key stations from the NDACC (Network for the Detection of Atmospheric Composition Change) were considered: the LiO₃S lidar at the Observatoire de Haute-Provence (OHP, 44°N, 5.7°E) and the Lauder station in New Zealand (45°S, 170°E). These stations, located quasi-antipodally on the globe, represent respectively the northern and the southern mid-latitudes and their long-term observation records covering entirely the CALIOP time span, reflect the stratospheric aerosol perturbations in both hemispheres.

2.2.1 The OHP station

The LiO₃S (Lidar Ozone Stratospheric) is a differential absorption lidar (DIAL) system primarily designed to measure ozone vertical profiles. It has been continuously operated at OHP since the late 1980s as part of Network of the Detection of Atmospheric Composition Change (NDACC) (Godin-Beekmann et al., 2003). The system uses a Nd:YAG laser emitting at 355nm, corresponding to the ozone non-absorbing wavelength. In addition to ozone retrievals, the 355nm backscatter signal is used to derive aerosol backscatter and extinction coefficients, providing a long-term record of stratospheric aerosol



160 variability (Khaykin et al., 2017). Data processing follows the Sasano–Fernald inversion scheme, assuming molecular
reference conditions above 33 km (Fernald, 1984; Sasano and Browell, 1989). Profiles of aerosol backscatter and extinction
coefficients are derived at a vertical resolution of 150m and averaged over 2–4 hours during nighttime clear-sky or thin cloud
conditions. LiO_3S has been extensively used for validation of satellite instruments such as SAGE II, OSIRIS, CALIOP and
ATLID, and provides a benchmark for long-term trends in SAOD (Khaykin et al., 2017; Knepp et al., 2020; Khaykin et al.,
165 2026).

2.2.2 The Lauder station

The Lauder Atmospheric Research Station (45.0°S, 169.7°E), operated by the Earth Sciences New Zealand (Institute of Water
and Atmospheric Research, NIWA) in collaboration with the National Institute for Environmental Studies (NIES) in Japan, is
one of the principal NDACC lidar stations in the Southern Hemisphere. The station has routinely monitored stratospheric
170 aerosols with a Nd:YAG lidar operating at 532 nm since 1992. The system provides calibrated profiles of aerosol backscatter
and particle depolarization ratio (PDR), retrieved using the Fernald inversion method with molecular backscatter derived from
JRA-55 and JRA-3Q reanalysis (Kobayashi et al., 2015; Kosaka et al., 2014) and an aerosol lidar ratio constrained by long-
term optical particle counter observations over Lauder (Nagai et al., 2010; Sakai et al., 2016, 2025). The retrieved profiles are
reported at 150 m vertical resolution, and measurements were typically acquired one to two nights per week during the period
175 considered in this study.

2.3 GloSSAC dataset

The Global Space-based Stratospheric Aerosol Climatology (GloSSAC, version 2.23; Thomason et al., 2018; Kovilakam et
al., 2020) is a long-term, merged record of stratospheric aerosol optical properties derived from multiple satellite instruments.
In addition to this merged dataset, individual instrument records are also distributed separately. This is notably the case for
180 CALIOP, the backscatter coefficient time series is available as an individual record. GloSSAC combines extinction coefficient
measurements from the SAGE II, SAGE III, OSIRIS, and CALIOP missions, providing a consistent global dataset spanning
from 1979 to the present. The climatology is provided as monthly mean extinction coefficients at 525 nm on a 5° latitude by
1 km altitude grid, extending from the tropopause to approximately 40 km. The SAGE series provides high-accuracy solar
occultation measurements, which serve as the reference standard for the optical extinction scale. OSIRIS (Optical Spectrograph
and InfraRed Imager System) adds global coverage during the period between SAGE II and SAGE III missions, while CALIOP
185 ensures the continuity of the record in the post-2006 era through its active lidar observations at 532 nm.
In this study, GloSSAC serves as the reference dataset for the correction of the CALIOP Level 1C product.

2.4 OMPS-LP

The Ozone Mapping and Profiler Suite Limb Profiler (OMPS-LP), onboard the Suomi National Polar-orbiting Partnership
190 (Suomi-NPP) satellite that been in operation since April 2012 (Jaros et al., 2014), was used to extend the stratospheric aerosol



record beyond the CALIOP data time span. OMPS-LP is a passive limb-scattering spectrometer that measures solar radiation scattered along the atmospheric limb over the 280–1020 nm spectral range and retrieves vertical profiles of ozone density and aerosol extinction coefficients in the lower stratosphere to the upper stratosphere through radiative transfer inversion (Loughman et al., 2018). The sensor employs three vertical slits separated horizontally to provide near-global coverage in 3-4
 195 days and >7000 profiles a day. Here we use OMPS-LP V2.0 aerosol extinction data at 869nm (Taha et al., 2021)

2.5 CALIOP Level 1 Data Products

2.5.1 L1B Dataset

CALIOP raw photon counts are first processed into Level 1B data, which include time-tagged profiles of digitized backscatter signals along with instrument calibration data. Level 1B data consist of calibrated and geolocated single-shot lidar profiles, in
 200 which raw photon counts are radiometrically calibrated and converted into attenuated backscatter coefficients ($\text{km}^{-1} \cdot \text{sr}^{-1}$) at 532nm and 1064nm (Hostetler et al., 2006; Powell et al., 2009). Corrections are applied for background light, detector nonlinearity, and laser energy fluctuations.

2.5.1 L1C Dataset

The Level 1C (L1C) product used in this study is derived from the CALIOP Level 1B Version 5.00 observations
 205 (NASA/LARC/SD/ASDC, 2025). It consists of zonally averaged (1° latitude) and temporally averaged (3-day) 532 nm nighttime Level 1B attenuated backscatter coefficient profiles. In addition to this parameter, a spatially averaged volume depolarization ratio (hereafter referred to as the bulk VDR) is derived from the averaged parallel and perpendicular attenuated backscatter signals. Unlike the profile-by-profile depolarization products commonly used in previous studies (Prata et al., 2017), this bulk VDR represents the mean depolarization over the spatial and temporal averaging intervals of the
 210 L1C dataset, corresponding to 1° in latitude and 3 days, respectively. It is used here to monitor the long-term evolution of stratospheric aerosol plumes.

The VDR is calculated following this formulation of Vernier et al. (2016, Eq 1):

$$\delta = \frac{\beta_{\perp}}{\beta_{//}} = \frac{\beta_{\perp}}{(\beta_t - \beta_{\perp})} \quad (1)$$

215

Only nighttime measurements are used, which minimizes solar background contamination, while cloudy scenes are excluded by discarding the samples with VDR greater than 0.1. In addition, profiles located within the South Atlantic Anomaly (SAA) region ($60^\circ\text{S} - 0^\circ, 90^\circ\text{W} - 30^\circ\text{E}$) were excluded. The SAA is characterized by a local weakening of the Earth's magnetic field,



220 leading to enhanced fluxes of energetic charged particles at satellite altitude. These particles can increase detector noise and generate bad signals in CALIOP observations, potentially affecting aerosol retrievals (Noel et al., 2014).

The resulting dataset provides global coverage with high temporal resolution, making it particularly suitable for monitoring the evolution of stratospheric aerosol plumes. However, because the L1C product is derived directly from the attenuated L1B observations, neither the backscatter coefficient nor the depolarization measurements are corrected for signal attenuation
 225 within the atmosphere. This correction was implemented in the L1CC product as described in the following Sect. 2.6.

2.6 The L1CC: Dataset Correction

The CALIOP L1CC dataset was developed to combine high temporal resolution of the L1C product with the correction applied using GLOSSAC climatology. A monthly correction term was calculated as a function of latitude, altitude, and time from the difference between the backscatter derived from L1C and the corresponding GloSSAC backscatter coefficient. The same
 230 method was used for the extinction coefficient. This bias was subsequently removed from L1C data to produce the Level 1CC (corrected-version) of CALIOP L1C dataset. Corrected backscatter coefficients were then used to derive corrected scattering ratio and corrected extinction were used to derive corrected stratospheric aerosol optical depth. The depolarization is corrected using ground-based LiDAR (See Section 2.6.3).

2.6.1 Backscatter corection

235 The CALIOP in GloSSAC backscatter profiles, originally provided at 525 nm, were converted to 532 nm using a backscatter Ångström exponent (BAE) of 1.3 (Khakin et al., 2017) and regridded onto the L1C CALIOP spatial and temporal resolution 1° latitude and 3-day intervals. The resulting backscatter L1CC was defined as:

$$\beta_{L1CC(z, \varphi, t)} = \beta_{L1C(\varphi, z, t)} - \left(\beta_{L1C(\varphi, z, t)} - \beta_{CALIOP, GloSSAC(\varphi, z, t)} \right) \quad (2)$$

240

Where $\beta_{L1CC}(z, \varphi, t)$, is the corrected backscatter, $\beta_{L1C}(\varphi, z, t)$ is the backscatter coefficient from CALIOP L1C and $\beta_{CALIOP, GloSSAC}(\varphi, z, t)$ is the backscatter coefficient from CALIOP provided with GloSSAC.

The molecular (Rayleigh) backscatter coefficient was taken directly from the CALIOP product, where it is computed from atmospheric pressure and temperature fields from MERRA-2 reanalysis. The corrected backscatter profiles and the molecular
 245 backscatter were then used to derive the scattering ratio (SR). Aerosol extinction coefficients (α) were derived from the backscatter profiles using a constant lidar ratio (S) of 50 sr.



2.6.2 Extinction correction

Monthly GloSSAC extinction profiles were interpolated onto the CALIOP grid. The GloSSAC data, originally available at 525 nm, were converted to 532 nm using an Ångström exponent derived from GloSSAC extinction at 525 and 1020 nm wavelength pair and regridded onto the CALIOP L1C spatial and temporal grid (1° latitude, 3-day intervals). The resulting L1CC extinction was defined as:

$$\alpha_{L1CC}(z, \varphi, t) = \alpha_{L1C} - (\alpha_{L1C}(\varphi, z, t) - \alpha_{GloSSAC}(\varphi, z, t)) \quad (3)$$

Where $\alpha_{L1CC}(z, \varphi, t)$ is the corrected extinction. $\alpha_{L1C}(\varphi, z, t)$ is the extinction coefficient of CALIOP L1C and $\alpha_{GloSSAC}(\varphi, z, t)$ is the extinction coefficient of GloSSAC.

The corrected extinction profiles were then vertically integrated from the tropopause to 30 km to derive the SAOD. The tropopause altitude was obtained from the meteorological fields provided in the CALIOP Level 1B product. The resulting SAOD provides a quantitative measure of the stratospheric aerosol loading and its temporal variability.

2.6.3 Correction in depolarization

The CALIOP Level 1 volume depolarization ratio (VDR) used in this study is an experimental bulk product that has not yet been formally validated for long-term stratospheric aerosol monitoring. Therefore, an additional calibration procedure was required before using the dataset for quantitative analyses.

To assess the stability of the CALIOP VDR record, the background depolarization time series was compared with observations from the Lauder Atmospheric Research Station (45°S, New Zealand), a well-characterized NDACC reference lidar. As shown in Figure 1, the original CALIOP L1C VDR exhibits both a positive background bias and a small long-term drift relative to the Lauder measurements. A linear regression over the background period yielded a trend, while the mean background offset between the two datasets.

The bulk VDR values shown in Figure. 1 are vertically averaged between the tropopause and 30 km, with the tropopause altitude obtained from the meteorological fields provided in the CALIOP Level 1B product. The correction was performed in two steps. First, the long-term instrumental drift was removed by subtracting the fitted linear trend from the CALIOP background VDR time series. Second, a constant offset equal to the mean background difference between CALIOP and Lauder was removed to align the CALIOP baseline with the NDACC reference observations.

An additional correction was applied to the VDR record to account for the artefact observed between February 2008 and February 2009. This artefact stems from instrumental issues affecting CALIOP's 532 nm channel, including photomultiplier



transient recovery effects that can artificially enhance depolarization ratios (Hunt et al., 2009). The artefact was corrected by
 applying a constant offset calculated from the difference between the mean VDR during the affected period and the background
 level derived from the adjacent unaffected periods in 2007 and 2009. This correction removes the artificial discontinuity while
 preserving the temporal variability of the VDR signal.

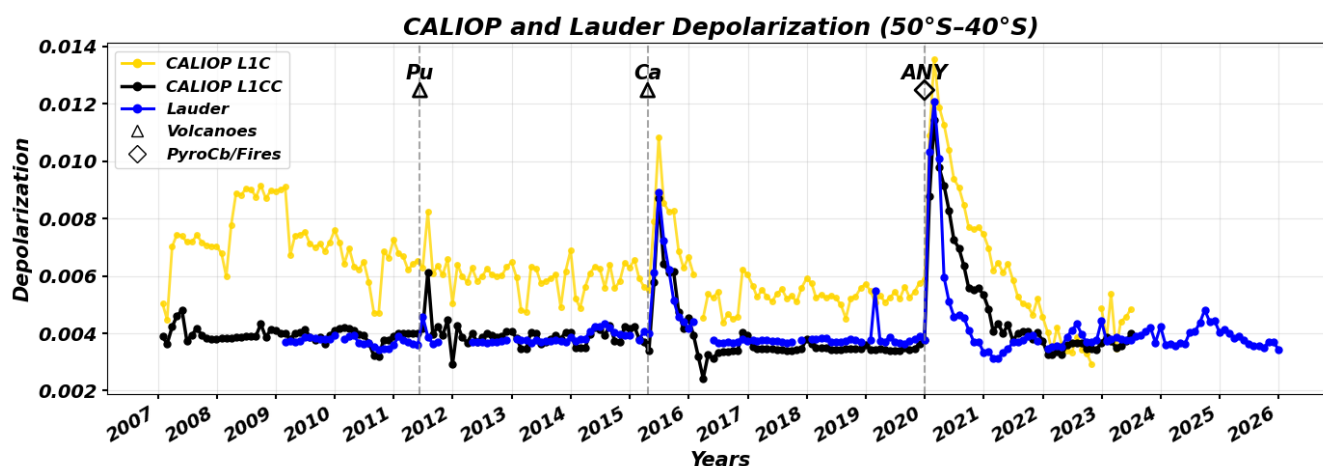


Figure 1: Comparison of the temporal evolution of the bulk depolarization ratio at 532 nm derived from the original CALIOP Level 1 dataset (L1C) and the bias-corrected Level 1 dataset (L1CC) with ground-based lidar observations at Lauder (45°S). The altitude layer considered is from the tropopause to 30km.

The resulting corrected VDR dataset exhibits a stable background consistent with the Lauder observations and provides a more reliable basis for the long-term analysis of volcanic and wildfire aerosol depolarization presented in this study.

2.7 EarthCare – ATLID

The Atmospheric Lidar (ATLID) aboard the EarthCARE satellite is a high-spectral-resolution lidar (HSRL) specifically designed to improve the characterization of aerosol–radiation interactions (Wehr et al.,2023). ATLID operates at 355 nm and exploits the spectral broadening difference between molecular (Rayleigh) and particulate (Mie) backscatter. A high-resolution Fabry–Pérot interferometer is used to spectrally discriminate between these contributions, enabling direct separation of molecular and particulate signals (Donovan et al.,2024).

In contrast to elastic backscatter lidars such as CALIOP, this HSRL technique allows the independent retrieval of aerosol backscatter and extinction without prescribing an extinction-to-backscatter ratio. This represents a major advantage for the observation of compositionally complex stratospheric plumes, where the assumption of a constant lidar ratio can introduce significant uncertainties, particularly in the presence of mixed sulfate, ash, and carbonaceous smoke particles.



ATLID data have already been used for stratospheric aerosol studies (Khaykin et al., 2026), and its performance in the stratosphere has been evaluated using SAGE III/ISS and ground-based lidar (Poncet et al., 2026). The latter study demonstrated the capability of ATLID to detect and characterize stratospheric aerosol layers under background, volcanic, and wildfire smoke conditions. Here we use SAOD data derived from ATLID Level-1 products (BA baseline) using the method described by Khaykin et al. (2026).

3 Results

3.1 Comparison of CALIOP and Ground-Based Lidars

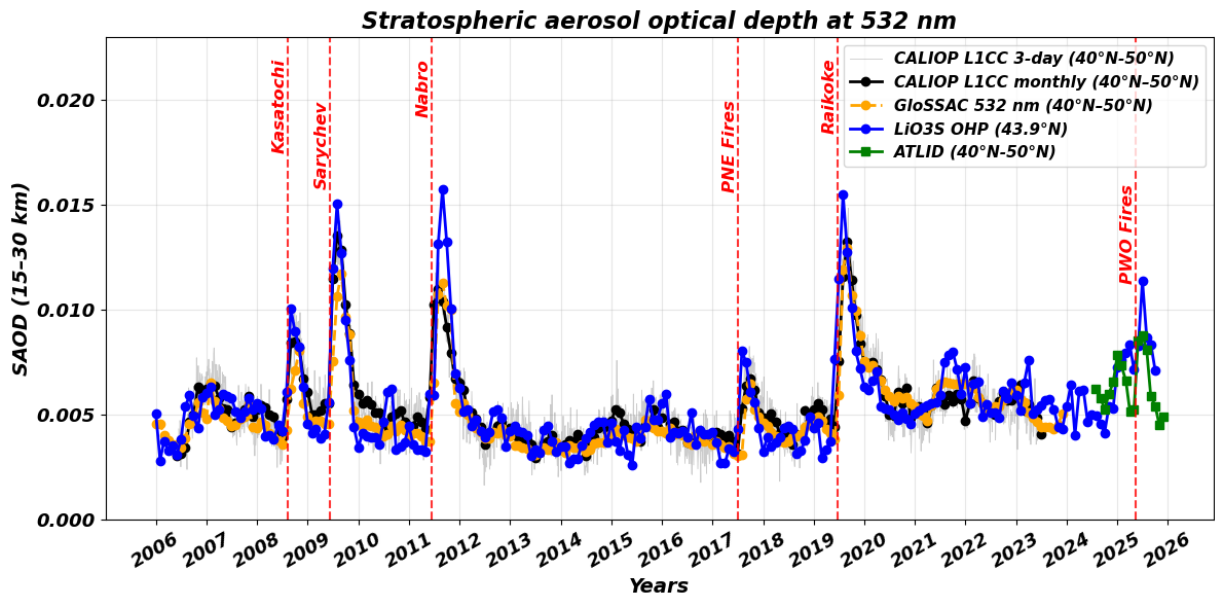
Before investigating the long-term evolution of stratospheric aerosol perturbations, the performance of the L1CC dataset is evaluated against independent reference observations. The comparison combines satellite-based datasets, providing a large-scale perspective, with ground-based lidar measurements at OHP and Lauder, which provide local observations with high vertical resolution. This complementary evaluation enables to assess the ability of L1CC to reproduce the temporal and vertical evolution of stratospheric aerosol perturbations to be assessed before its application to the long-term analysis.

To extend the satellite record beyond the end of the CALIPSO mission, ATLID observations are introduced from 2024 onward as a continuation of the CALIOP time series. To ensure consistency between the two satellite lidar records, ATLID SAOD and SR originally retrieved at 355 nm, were converted to 532 nm for comparison with CALIOP nm using an Ångström exponent derived from GloSSAC extinction at 525nm and 1020nm wavelength pair. In contrast, ATLID depolarization measurements were retained at their native wavelength of 355 nm. This combined CALIOP–ATLID record therefore extends the satellite-based monitoring of the stratospheric aerosol layer to the most recent perturbations observed in 2024–2025.

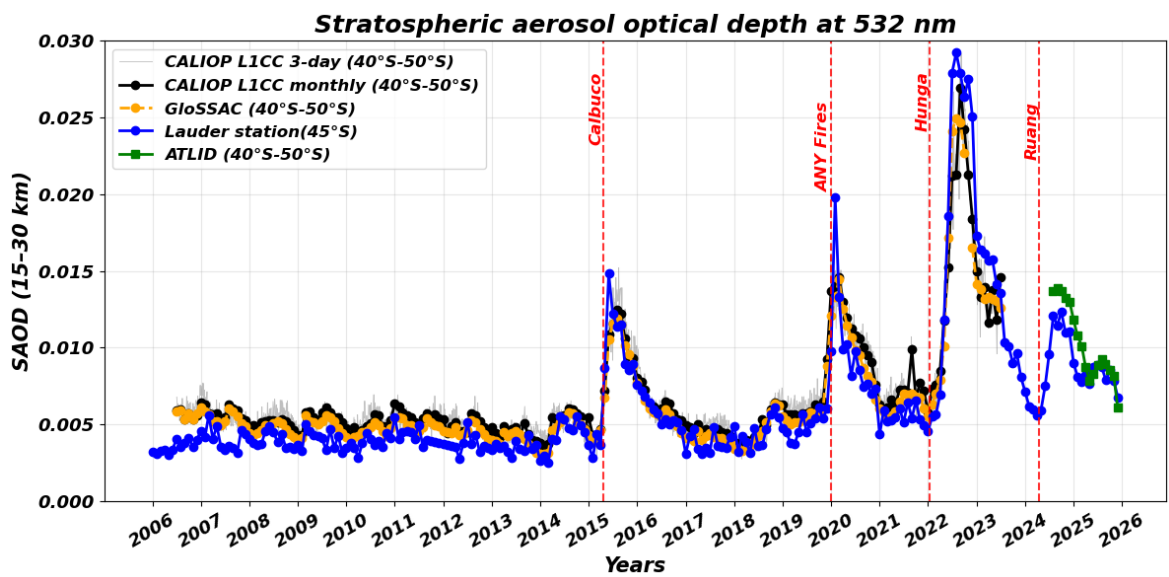
Figure 2 compares the new CALIOP L1CC dataset with independent NDACC lidar observations from the Observatoire de Haute-Provence, OHP (44°N; Fig. 2a) and Lauder (45°S; Fig. 2b), as well as with the GloSSAC climatology. In both hemispheres, the L1CC dataset successfully reproduces the timing, relative magnitude and return time of the major stratospheric aerosol perturbations, demonstrating the consistency of the corrected satellite observations with independent ground-based measurements. Both OHP and Lauder series occasionally exhibit stronger SAOD peaks than the CALIOP zonal means because ground-based lidars sample localized aerosol structures that are smoothed by the satellite spatial averaging, as discussed in Sect. 4.1. Despite these differences, the overall temporal evolution remains highly consistent, confirming the suitability of the L1CC dataset for monitoring the long-term evolution of volcanic and wildfire-driven perturbations on hemispheric scales.



a)



b)



345 **Figure 2: Comparison and evolution of stratospheric aerosol optical depth (SAOD) and scattering ratio derived from different observation datasets.**

(a) SAOD time series for the Northern Hemisphere, comparing CALIOP L1CC with the GloSSAC climatology and ground-based LiO3S lidar observations at the Observatoire de Haute-Provence (OHP; 44°N). (b) Corresponding comparison for the Southern Hemisphere using CALIOP L1CC, GloSSAC and ground-based lidar observations at Lauder (45°S). ATLID observations extend the lidar-based record beyond the CALIOP observational period for the most recent perturbations. Red dashed vertical lines indicate the dates of the major volcanic eruptions and wildfire outbreaks discussed in this study, with the corresponding event names indicated above each line.

350

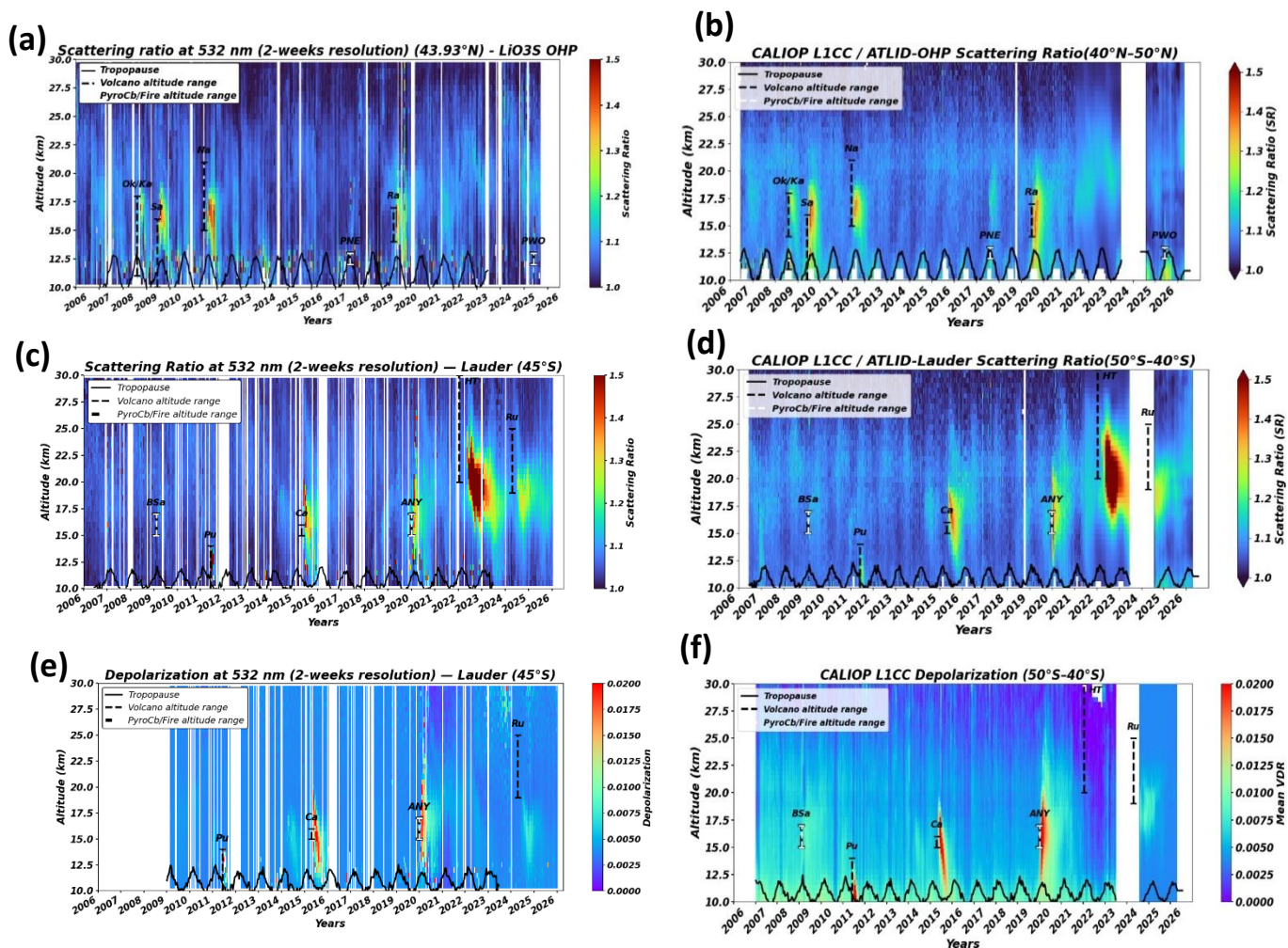


Figure 3: Latitude-dependent evolution of stratospheric aerosol properties observed by ground-based LiDAR, CALIOP and ATLID between 2006 and 2025.

(a, b) Scattering ratio and depolarization ratio at 532 nm between 10 and 30 km altitude for the northern mid-latitudes using OHP station and CALIOP L1CC. (40°N–50°N); (c, d) same for the southern mid-latitudes using Lauder station and CALIOP L1CC (50°S–40°S). (e, f) Depolarization for the southern mid-latitudes using Lauder station and CALIOP L1CC (50°S–40°S). Volcanic eruptions and wildfire outbreaks are indicated by their event abbreviations, as defined in Table 1. Volcanic eruptions and wildfire events are indicated by vertical dashed bars representing their reported stratospheric injection altitude ranges. Volcanic events are shown in black, while wildfire events are shown in white with a black outline for visibility. The tropopause altitude is shown by the black curve. For the CALIOP period, the tropopause is derived from MERRA-2 meteorological reanalysis, whereas for the EarthCARE/ATLID period, it is derived from ECMWF meteorological data.

The corresponding time–altitude observations in Fig. 3 further support this validation. The scattering-ratio measurements at OHP (Fig. 3a) and the corresponding CALIOP L1CC zonal means between 40 and 50°N (Fig. 3b) show consistent



enhancements associated with the main Northern Hemisphere perturbations. Both datasets reproduce the occurrence and vertical extent of the enhanced aerosol layers, including the pronounced perturbations following Sarychev, Nabro, PNE fires, Raikoke and PWO fires. The ground-based measurements resolve relatively thin and localized layers, whereas the CALIOP zonal means generally exhibit smoother and more spatially extended structures.

A similar agreement is observed in the Southern Hemisphere. The Lauder scattering-ratio measurements (Fig. 3c) and CALIOP L1CC observations averaged between 50 and 40°S (Fig. 3d) reproduce the major perturbations and their vertical evolution, including Puyehue-Cordón Caulle, Calbuco, the 2019–2020 Australian New Year wildfire event and Hunga. Particularly persistent aerosol layers are observed following the ANY fires and Hunga, with elevated scattering ratios extending over prolonged periods and broad altitude ranges.

The depolarization measurements at Lauder (Fig. 3e) and the corresponding CALIOP L1CC zonal means (Fig. 3f) also show consistent temporal variations associated with the major Southern Hemisphere perturbations. Enhanced depolarization is observed during several volcanic and wildfire events, although the magnitude and vertical structure can differ between the local and zonally averaged observations. This behaviour is particularly evident during the 2019–2020 ANY wildfire event, when the Lauder lidar sampled a mature smoke-charged vortex (SCV), producing pronounced local depolarization maxima that are largely smoothed in the CALIOP zonal averages because of their broader spatial sampling.

Overall, despite the limited spatial coverage of the individual ground-based stations, the comparison shows that LiO3S and Lauder reproduce the main aerosol layers and their vertical evolution observed by CALIOP. Local measurements provide a more detailed representation of individual plume structures, whereas the CALIOP zonal averages capture the broader evolution of the stratospheric aerosol layer. During the most recent period covered by ATLID, the Ruang eruption in April 2024 produced a pronounced stratospheric aerosol perturbation. ATLID observations show an enhanced aerosol layer extending through the tropical and Southern Hemisphere stratosphere, which is also detected by the Lauder lidar as the plume reaches southern mid-latitudes. The consistency between ATLID and Lauder therefore extends the satellite–ground-based comparison beyond the end of the CALIOP record and confirms that the Ruang aerosol perturbation can be followed across the transition from CALIOP to ATLID observations.

3.2 Global evolution of stratospheric aerosol loading and bulk depolarization

Figure 4 presents the time-latitude evolution of SAOD at 532 nm computed between the tropopause and 30 km, together with the mean depolarization ratio computed between the tropopause and 22 km, derived from the CALIOP L1CC dataset over the period 2006–2023, extended with recent ATLID data.



Events	Code	Coordinates	Date	Altitude (km)	VEI	E-folding time (days)	Return time (days)	SO ₂ /Smoke mass (Tg)	References mass
Soufrière Hills	So	17°N / 62°W	20-05-2006	17-21	3			0.1-0.2	Carn & Prata (2010)
Tarvurur	Ta	4°S / 152°E	07-10-2006	16-18	3	18 ± 2	111 ± 16	0.3-0.5	Prata & al. (2007)
Okmok/Kasatochi	Ok/Ka	52°N / 176°W	07-08-2008	11-12/14-18	4	77 ± 6	204 ± 25	0.1-0.2/1.0-1.7	Heue et al. (2010) Karagulian et al. (2010)
Black Saturday fires (Australia)	BSa	34°S / 141°E	07-02-2009	15-17		25 ± 3	120 ± 11	0.6-1	Siddaway & Petelina (2011)
Sarytchev	Sa	48°N / 153°E	11-06-2009	10-16	4	85 ± 5	234 ± 32	0.8-1.2	Jégou et al. (2013)
Merapi	Me	8°S / 110°E	05-11-2010	12-17	4	46 ± 4	196 ± 26	0.3-0.5	Jousset et al. (2012)
Puyehue–Cordón Caulle	Pu	41°S / 72°W	04-06-2011	9-14	5	15 ± 2	148 ± 31	0.2-0.4	Nakamae et al. (2014)
Nabro	Na	13°N / 42°E	03-06-2011	15-21	4	97 ± 7	354 ± 47	1.3-2	Clarisse et al. (2014)
Kelud	Ke	8°S / 112°E	03-02-2014	19-21	4	143 ± 10	220 ± 32	0.2-0.3	Vernier et al. (2016)
Calbuco	Ca	41°S / 73°W	22-04-2015	15-16	4	139 ± 13	407 ± 31	0.3-0.5	Pardini et al. (2018)
PNE fires (Canada)	PNE	54°N / 127°W	12-08-2017	12-13		243 ± 30	330 ± 34	0.1-0.3	Peterson et al. (2018)
Ambae	Am	15°S / 168°E	27-07-2018	16-18	4	117 ± 10	270 ± 14	0.3-0.6	Carn et al. (2018)
Raikoke	Ra	48°N / 153°E	22-06-2019	14-17	4	220 ± 22	410 ± 54	1.4-2.1	Wu et al. (2022)
Ulawun	Ul	5°S/151°E	26-06-2019	14-17	4	190 ± 25	300 ± 22	0.14-0.2	Kloss et al. (2019)
ANY fires (Australia)	ANY	33°S / 151°E	31-12-2019	15-17		180 ± 20	381 ± 24	0.3-1.1	Khaykin et al. (2020)
Soufrière St-Vincent	Sv	17°N / 62°W	20-04-2021	16-20	4	156 ± 14	203 ± 29	0.3-0.6	Taylor et al. (2023)
Hunga	HT	20°S / 175°W	15-01-2022	20-30	5	379 ± 20	913 ± 28	0.4-0.5	Khaykin et al. (2022)
Ruang	Ru	2°N/ 125°E	18-04-2024	19-25	4	290 ± 19	738 ± 21	0.3-0.4	Khaykin et al. (2026)
Panboreal fires (Canada)	PWO	60°N/ 110°E	29-05-2025	12-13		25 ± 5	109 ± 15	0.05-0.2	Vieille et al. (2026)

Table 1: Major volcanic eruptions and wildfire events with an identified stratospheric aerosol impact during the 2006–2025 period considered in this study. For each event, the table reports the event abbreviation used throughout the manuscript, geographical coordinates, event date, reported stratospheric injection altitude range, Volcanic Explosivity Index (VEI) for volcanic eruptions, SAOD e-folding time, SAOD return time, and reported SO₂ or smoke mass. VEI denotes the Volcanic Explosivity Index and is therefore not applicable to wildfire events. Injection altitudes and emitted SO₂ or smoke masses are taken from the literature sources listed in the last column. Return and e-folding times were derived from the aerosol time series using the methodology described in Sect. 3.4; uncertainties represent the sensitivity of these estimates to the pre-event background variability. Values are not reported for Soufrière Hills (2006) because this event occurred before the beginning of the analysis period required to derive the corresponding persistence metrics.



410 The SAOD field (Fig. 4a) reveals a sequence of significant stratospheric perturbations associated with volcanic eruptions and intense wildfire events. In the Northern Hemisphere, pronounced enhancements are observed following the Kasatochi (2008) and Sarychev (2009) eruptions, as well as Nabro (2011) and Raikoke (2019). In the Southern Hemisphere, distinct enhancements follow the Puyehue (2011) and Calbuco (2015) eruptions, while the 2019–2020 Australian New Year (ANY) wildfire event produces a broad and persistent enhancement maximizing in the southern mid-latitudes. The most important
 415 perturbation occurs in 2022 following Hunga, whose impact rapidly extends across hemispheres and produces the largest SAOD anomaly of the CALIOP era. The ATLID observations extend this record beyond the end of the CALIPSO mission and reveal the subsequent perturbations associated with the Ruang eruption in 2024 and the PWO wildfire event in 2025. Ruang produces a marked tropical SAOD enhancement, whereas the PWO event is characterized by an enhancement concentrated primarily at Northern Hemisphere mid-latitudes. Table 1 summarizes the stratospheric perturbation events identified in our
 420 analysis.

The bulk depolarization ratio (Fig. 4b) provides complementary information on particle morphology and phase. Elevated depolarization values are observed during the early stages of ash-rich volcanic eruptions and wildfire outbreaks, in particular after Black Saturday fires, Pyehue-Cordon-Caulle, Kelud, Calbuco, PNE fires, Soufriere St-Vincent and ANY fires, reflecting
 425 the injection of irregularly-shaped smoke or ash particles into the lower stratosphere. These signals generally decrease over time, consistent with sedimentation and progressive coating of ash particles by sulphuric acid (e.g Vernier et al.,2016). The Hunga eruption shows comparatively weak depolarization despite its large SAOD signal, consistent with rapid dominance of spherical sulfate droplets following the initial injection phase.

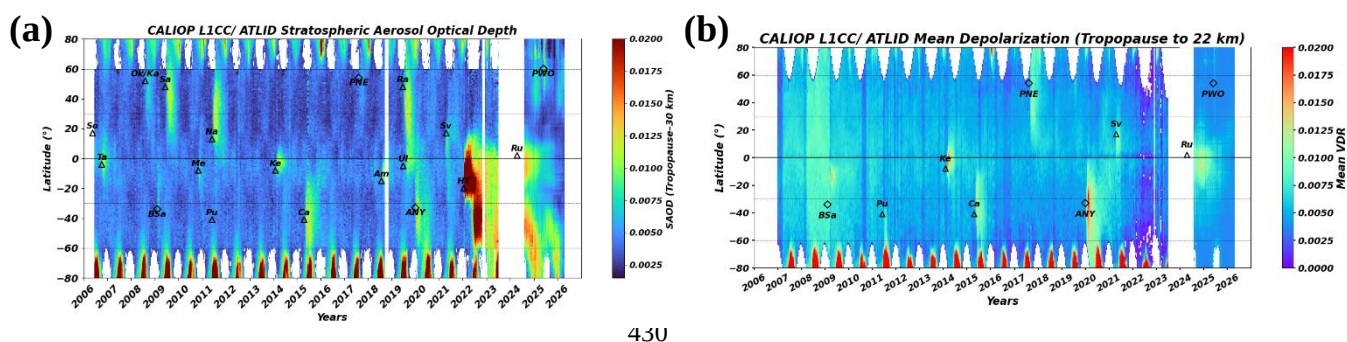


**Figure 4: Temporal evolution of bulk stratospheric aerosol properties observed by CALIOP and ATLID at 532 nm between 2007 and 2025, as a function of latitude. (a) Stratospheric aerosol optical depth (SAOD) at 532 nm, computed between tropopause and 30 km and derived from CALIOP L1CC and ATLID data, highlighting episodic increases associated with explosive volcanic eruptions (marked by triangles) and wildfire outbreaks (rombus). (b) Mean depolarization ratio from
 435 CALIOP L1CC and ATLID data at 532 nm, between the tropopause and 22 km, illustrating variations in particle shape and phase in response to volcanic and wildfire perturbations.**



The recurring enhancements in SAOD at high latitudes during winter are likely associated with Polar Stratospheric Clouds (PSCs), which can occur in both the Antarctic and Arctic polar vortices. In the Antarctic stratosphere, these enhancements are particularly frequent and intense because of the colder and more stable winter vortex. They may include liquid supercooled ternary solution particles (STS, Type 1b) as well as ice PSCs (Type 2) (Pitts et al., 2018). Because liquid STS particles exhibit low depolarization, they may bypass the cloud screening based on a depolarization ratio threshold of 0.1.

Overall, the combined SAOD and depolarization fields reveal distinct optical signatures associated with volcanic and wildfire perturbations. While SAOD highlights the temporal and meridional extent of enhanced aerosol loading, the bulk depolarization field reveals distinct depolarizing signatures for several major events, providing complementary information on the presence of non-spherical particles.

3.3 Evolution of vertical distribution of stratospheric aerosol scattering and depolarization in broad latitude bands

While the previous section characterized the temporal evolution and persistence of the main stratospheric aerosol perturbations, the altitude-resolved lidar observations provide additional information on their vertical structure and evolution. Figure 4 presents the time–altitude evolution of the scattering ratio and depolarization ratio within midlatitude and tropical bands. This vertical perspective allows the altitude and vertical extent of individual aerosol layers to be identified and reveals whether changes in aerosol loading and particle depolarization occur uniformly throughout the plume or are confined to specific altitude ranges.

In the Northern midlatitudes (30°N–60°N; Fig. 5a), the dominant signal comes from mid-latitude eruptions like Kasatochi (2008), Sarychev (2009), Nabro (2011), and Raikoke (2019). Among these, Raikoke (2019) and the PNE fires (2017) produce the most prominent depolarization enhancements, with values clearly elevated above the background for several months (Fig. 4b). The high depolarization ratios observed immediately after these events reflect the presence of non-spherical particles, including volcanic ash following eruptions and absorbing carbonaceous aggregates following wildfire events. The ATLID observations extend the record beyond the CALIOP period and capture the 2025 PWO wildfire perturbation, characterized by an enhanced aerosol layer in the Northern mid-latitudes.

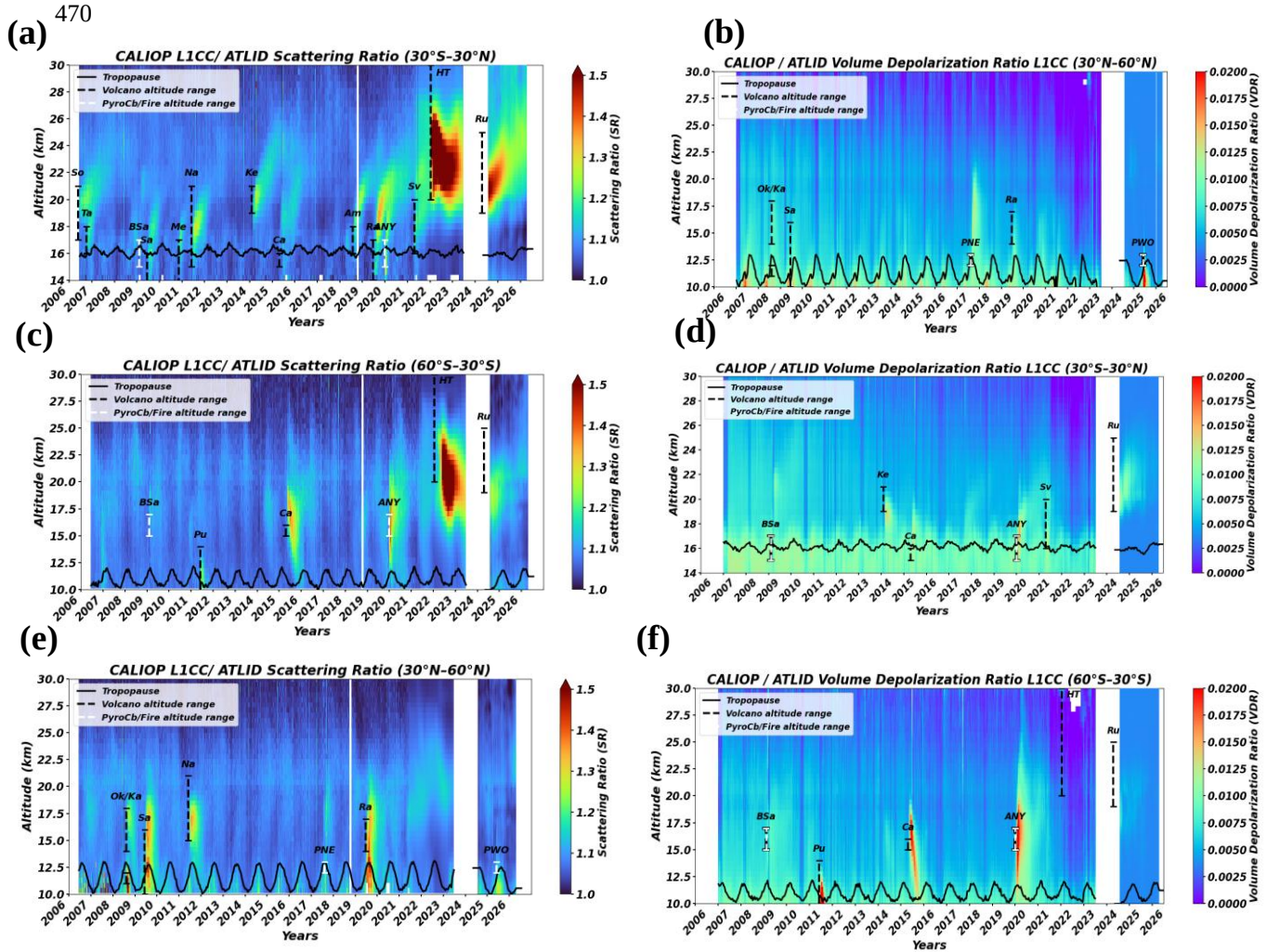


Figure 5: Time–altitude evolution of stratospheric aerosol properties observed by CALIOP and ATLID between 2006 and 2025. (a, b) Scattering ratio (SR) and volume depolarization ratio (VDR), respectively, for the northern mid-latitudes (30°N–60°N); (c, d) same for the tropics (30°S–30°N); and (e, f) same for the southern mid-latitudes (60°S–30°S). Event labels correspond to the abbreviations defined in Table 1. Volcanic eruptions and wildfire events are indicated by vertical dashed bars representing their reported stratospheric injection altitude ranges. Volcanic events are shown in black, while wildfire events are shown in white with a black outline for visibility. The tropopause altitude is shown by the black curve. For the CALIOP period, the tropopause is derived from MERRA-2 meteorological reanalysis, whereas for the EarthCARE/ATLID period, it is derived from ECMWF meteorological data. Scattering ratio is shown at 532 nm, with ATLID SR converted from 355 to 532 nm using backscatter Angstrom exponent of 1.6, whereas ATLID depolarization is shown at 355 nm.



In the tropical band (30°S–30°N; Fig. 5c–d), the influence of strong eruptions is evident through vertically extended aerosol layers that persist over longer timescales. The strongest perturbation is associated with the Hunga eruption in January 2022. In addition to tropical eruptions, the tropical stratosphere is also affected by aerosol transported from several extratropical events in NH, including Sarychev (2009), PNE (2017), Raikoke (2019), and SH BSa (2009), as well as in Southern hemisphere: Puyehue (2011), Calbuco (2015) and ANY (2019–2020). During the ATLID period, the Ruang eruption in 2024 also produces a pronounced tropical aerosol enhancement, visible in both scattering ratio and depolarization. This prolonged residence is largely controlled by the ascending branch of the Brewer-Dobson Circulation (BDC), whose tropical upwelling slowly lofts freshly injected aerosols higher into the stratosphere, extending their residence time in the tropical stratosphere before their transport toward mid and high latitudes. The tropical reservoir thus acts as a conduit for interhemispheric transport, allowing plumes from tropical eruption to spread poleward and affect both hemispheres, although the timing and efficiency of this transport can be modulated by the phase of the quasi-biennial oscillation (QBO) as was pointed out by Aquila et al., (2012).

In the Southern midlatitudes (60°S–30°S; Fig. 5e–f), the most prominent perturbations are associated with Calbuco (2015), the Australian New Year wildfire outbreak (ANY, 2019–2020), and Hunga (2022), while Puyehue (2011) and the Black Saturday wildfire outbreak (BSa, 2009) appear as weaker but still detectable signals. Puyehue and Calbuco stand out for their exceptionally high depolarization ratios, reflecting the ash-rich nature of their plumes; both eruptions were characterized by violent explosive phases that injected large quantities of non-spherical ash particles into the lower stratosphere (Vernier et al., 2013; Prata et al., 2017; Lopes et al., 2019). Their time–altitude evolution shows a downward progression of the depolarizing aerosol layers, consistent with gravitational sedimentation of the largest particles and large-scale stratospheric subsidence. The ANY wildfire plume exhibits persistent elevated depolarization together with a progressive ascent of the aerosol layer. This ascent is linked with radiatively driven self-lofting of absorbing carbonaceous aerosols, whereby solar absorption induces diabatic heating and sustains the vertical transport of the smoke layer, thereby extending its stratospheric residence time (Yu et al., 2019; Khaykin et al., 2020).

Overall, the CALIOP observations reveal that stratospheric aerosol perturbations exhibit distinct hemispheric pathways and dynamical evolution depending not only on their origin, but also on the latitude and latitude of injection, as a well as on the variability of the Brewer-Dobson circulation.

3.4 Persistence of stratospheric injections

To complement the analysis of the large-scale evolution of stratospheric aerosol perturbations, we quantify their persistence using a return-time approach. This analysis provides a common metric to compare the duration of individual volcanic and wildfire perturbations and to assess the timescale required for the stratospheric aerosol layer to return to pre-event level conditions.



515 The return time in Figure 6a was calculated from the SAOD time series using latitude bands selected to isolate the aerosol
perturbation associated with each event. For all extratropical events, the corresponding hemispheric extratropical band was
used (30–60°N in the Northern Hemisphere and 60–30°S in the Southern Hemisphere). For Hunga, a broader latitude range
extending from 20°N to 60°S was selected to account for the tropical origin, rapid meridional spreading, and cross-hemispheric
520 unrelated extratropical aerosol perturbations. The same latitude bands were used for both the SAOD in depolarization analyses.
The return time was defined as the time between the date of the eruption or wildfire injection and the date at which the SAOD
returned to its pre-event background level. The pre-event level SAOD was calculated as the mean value over the week
preceding the event. Following the identification of the maximum SAOD associated with the vent, the time series was
examined until the first date for which the SAOD became equal to or lower than the pre-event level. The return time was then
525 computed as the difference between this return date and the event date.

The uncertainty of the return time was estimated from the variability of the pre-event background. The standard deviation of
the SAOD values during the week preceding the event was used as an estimate of the background uncertainty. Two additional
background levels were therefore considered, corresponding to the background maximum and minimum standard deviation.
530 The return date was recalculated for each of these thresholds, yielding a minimum and maximum return time. The uncertainty
on the return time was then defined as half difference between these two external values.

For events occurring during the CALIPSO observational period, return times were derived from CALIOP observations. For
the more recent events occurring after the end of the CALIPSO mission, complementary datasets were used to extend the
535 analysis. For the 2024 Ruang eruption, the SAOD return time was estimated from OMPS-LP observations. For the 2025 PWO
wildfire event and Ruang volcano, the return time was estimated from ATLID observations. In each case, the same return-time
criterion was applied, based on the recovery of the observed parameter toward its pre-event background level.

Return times differed substantially among the events and can be separated into several characteristic timescales (Fig. 6). The
540 shortest-lived perturbations, including PWO, Tarvurur, Black Saturday and Puyehue Cordon-Caulle, returned toward
background conditions within approximately 6 months. A second group, comprising several moderate volcanic eruptions
including Merapi, Soufriere St Vincent, Okmok/Kasatochi, Kelud, Sarychev and Ambae, exhibited return times ranging from
approximately 6 months to 1 year. Longer persistence, on timescales of approximately 1–2 years, was observed for Nabro,
Calbuco and Raikoke, and for the PNE and ANY wildfire events. Finally, Ruang and Hunga stand out as the most persistent
545 perturbations, with SAOD return times exceeding 2 years, due to the high altitude of injection (Table 1). Hunga exhibited the
longest SAOD return time of the record, reaching 913 ± 28 days.

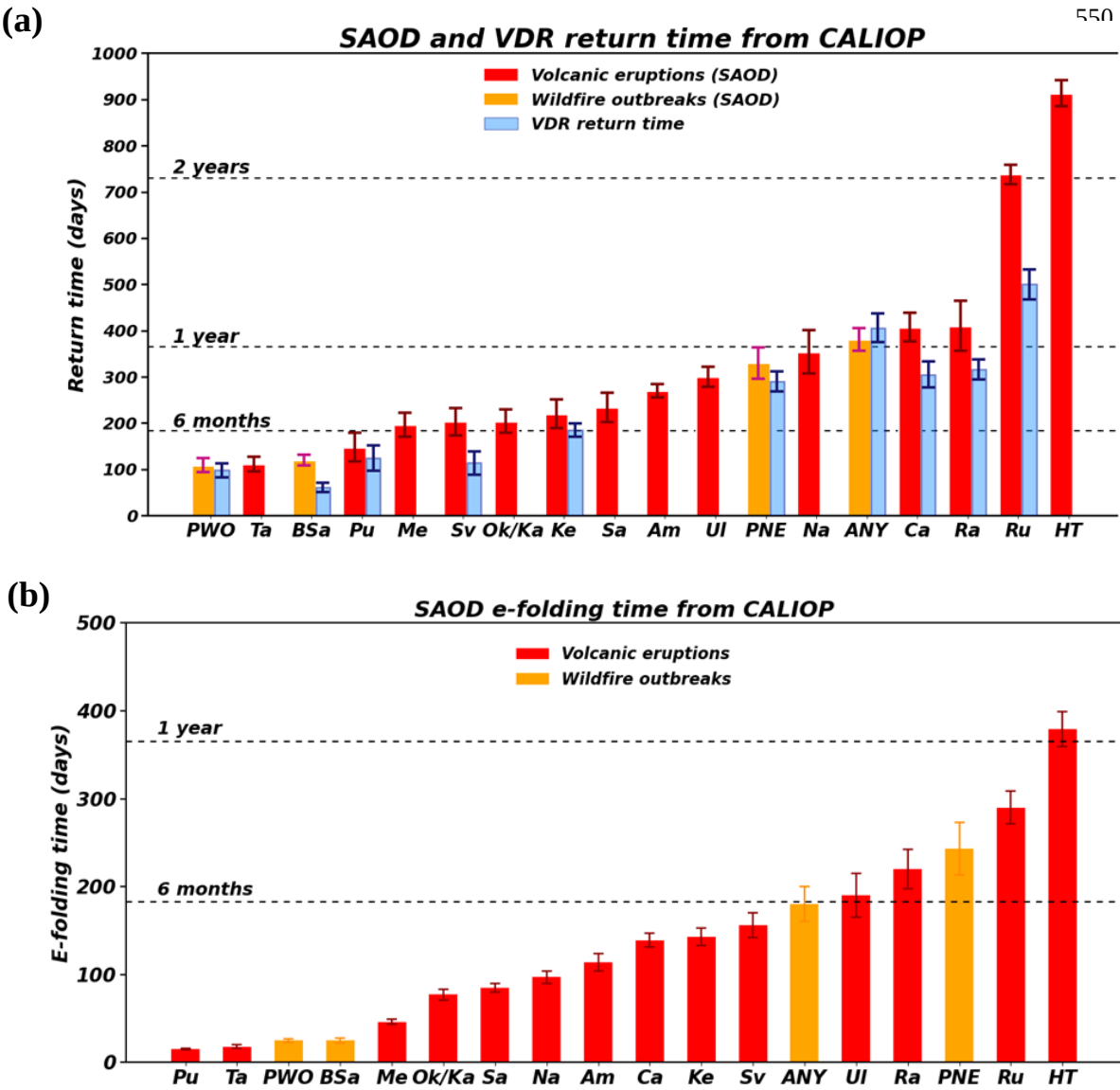


Figure 6: Return times and e-folding times of major stratospheric aerosol perturbations associated with volcanic eruptions and wildfire events between 2006 and 2025. (a) Return times of SAOD and VDR for major perturbations between 2006 and 2025. **(b)** E-folding times of SAOD for major perturbations between 2006 and 2025. Red bars represent SAOD return times for volcanic eruptions, while pink bars represent SAOD return times for wildfire events. Blue bars represent the corresponding bulk depolarization return times for volcanic and wildfire events. Error bars indicate the estimated uncertainty in the return time.



Differences are also observed between the SAOD and bulk depolarization return times. For all volcanic eruptions for which both quantities could be determined, the VDR returned to background levels earlier than the SAOD perturbation, suggesting that changes in particle shape and composition generally occurred on shorter timescales than the decay of the overall aerosol loading. This faster recovery of VDR may partly result from the preferential sedimentation of larger ash particles, which contribute strongly to the depolarization signal, while smaller sulfate particles remain suspended in the stratosphere for longer periods. In contrast, wildfire events exhibited a different behaviour. For PNE, the SAOD and VDR return times were relatively similar, whereas for ANY, the depolarization perturbation persisted substantially longer than the SAOD perturbation, with return times of 486 ± 29 and 381 ± 24 days, respectively. This indicates that the depolarizing properties of the ANY smoke particles persisted even after the aerosol loading had returned close to its pre-event level. The longest depolarization persistence was observed following the Ruang eruption in 2024, with a VDR return time of 500 ± 32 days. This prolonged perturbation is consistent with the exceptional persistence of Ruang aerosols independently reported from satellite and ground-based observations, with SAOD remaining above pre-eruption levels for at least 16 months (Khaykin et al., 2026).

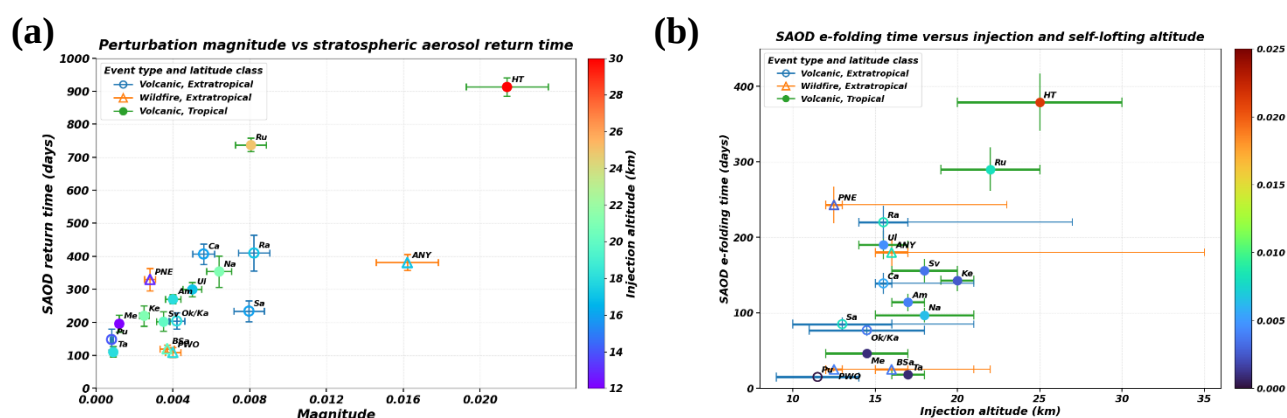
The e-folding time provides (Fig. 6b) a complementary measure of aerosol persistence by characterizing the characteristic decay timescale of the SAOD perturbation. It was defined as the time required for the SAOD anomaly above the pre-event background to decrease to $1/e$ of its maximum value. As for the return time, the uncertainty was estimated from the variability of the pre-event background. The calculation was repeated using background levels corresponding to the mean value plus and minus one standard deviation, and the resulting spread in e-folding times was used to estimate the uncertainty. While the return time describes the total duration required for the aerosol layer to recover toward background conditions, the e-folding time is more representative of the characteristic decay rate of the perturbation. The two metrics therefore provide complementary information on aerosol persistence.

The e-folding times also exhibit substantial variability among events (Fig. 6b), ranging from 15 days for Puyehue to 379 days for Hunga. The shortest e-folding times are observed for Puyehue (15 ± 1 days), PWO (25 ± 2 days) and Black Saturday (25 ± 3 days). Most volcanic perturbations exhibit intermediate e-folding times between approximately 45 and 160 days, whereas longer decay timescales are observed for PNE (243 ± 30 days), Ruang (290 ± 19 days) and Hunga (379 ± 20 days). ANY also exhibits a relatively long e-folding time of 180 ± 20 days. Overall, the ordering of events according to e-folding time differs from that obtained using the return time. Nevertheless, the two metrics are strongly correlated (Pearson's $r = 0.90$), although the deviation from a perfect correlation indicates that the characteristic decay timescale and the total duration of a perturbation represent distinct aspects of aerosol persistence, likely reflecting differences in the relative efficiency of aerosol removal pathways among events.

To further characterize the intensity of each perturbation, the maximum SAOD anomaly was quantified relative to the long-term stratospheric aerosol background. The background was defined as the mean GloSSAC SAOD over the 1995–2003 period



for the latitude band corresponding to each event. The perturbation magnitude was expressed as the increase of the maximum
 605 SAOD above the pre-event background. Separate background values were used for the Northern and Southern extratropical
 bands and for the broader latitude range considered for Hunga. The uncertainty was estimated from the standard deviation of
 the GloSSAC SAOD over the same 1995–2003 period.



610 **Figure 7: Relationship between stratospheric aerosol perturbation magnitude, decay timescales, and injection altitude. (a)** SAOD
 return time as a function of the maximum SAOD anomaly relative to the GloSSAC background. **(b)** SAOD e-folding time as a function of
 the reported injection altitude. Colors indicate the upper boundary of the initial injection altitude range, while symbols distinguish wildfire
 and volcanic events. Error bars indicate the estimated uncertainties in the SAOD return and e-folding times.

615 The relationship between the maximum relative SAOD perturbation and return time shows an overall tendency toward longer
 persistence with increasing perturbation magnitude (Fig. 7a). The weakest relative perturbations, including Puyehue and Black
 Saturday, are associated with relatively short return times, whereas several of the largest perturbations are found among the
 more persistent events. Hunga represents the most extreme case, combining the largest relative SAOD perturbation with the
 longest return time (913 ± 28 days). However, substantial dispersion is observed around this general tendency. Events
 620 characterized by comparable relative perturbation magnitudes can exhibit markedly different return times. For example,
 Sarychev and Raikoke show similar relative perturbations but substantially different return times, of 234 ± 32 and 410 ± 54
 days, respectively. Similarly, Ruang and Calbuco exhibit comparable relative perturbation magnitudes but markedly different
 return times, with Ruang persisting for 738 ± 21 days compared with 407 ± 31 days for Calbuco. ANY also stands out from
 the general distribution, exhibiting a comparatively large relative perturbation for a return time of 381 ± 24 days. Thus,
 625 although perturbation magnitude and return time broadly increase together, a large spread in persistence is observed among
 perturbations of comparable relative magnitude.



The relationship between injection altitude and e-folding time also shows an overall increase in decay timescale with increasing altitude (Fig. 7b). Hunga, reaching approximately 30 km, exhibits the longest e-folding time (379 ± 20 days), while Ruang, reaching approximately 25 km, shows the second longest value (290 ± 19 days). However, considerable dispersion is observed among perturbations reaching comparable altitudes. Raikoke, for example, exhibits an e-folding time of 220 ± 22 days despite reaching lower initial altitudes than Ruang and Hunga, while other perturbations reaching broadly similar altitude ranges decay substantially faster. More generally, events reaching approximately 16–21 km span a wide range of e-folding times, from a few tens of days to more than 200 days. The reported vertical ranges also highlight that several perturbations subsequently reached altitudes above their initial injection range, particularly wildfire events affected by self-lofting. However, this additional vertical ascent is not systematically associated with longer e-folding times. Volcanic and wildfire events occupy overlapping ranges of both injection altitude and e-folding time, with no clear separation between the two source types.

4 Discussion and summary

4.1 New CALIOP L1CC product

The consistency of the L1CC dataset with the OHP and Lauder lidar observations supports its use for investigating the large-scale variability of the stratospheric aerosol layer over the CALIPSO record. Despite the different spatial and temporal sampling of satellite and ground-based observations, the main temporal and vertical characteristics of the aerosol perturbations are consistently reproduced. Ground-based lidars resolve localized plume structures and may therefore capture stronger aerosol enhancements, whereas the CALIOP zonal averages smooth these local features and provide a broader representation of the large-scale zonal-mean aerosol field. The agreement between satellite and ground-based observations indicates that the spatial averaging applied to L1CC preserves the main characteristics of the long-term evolution of stratospheric aerosol perturbations.

A major strength of the L1CC dataset is the combined availability of stratospheric aerosol optical depth, scattering ratio and bulk depolarization within a common processing framework. An additional advantage is its good coverage of the lowermost stratosphere, where the use of depolarization measurements enables an efficient filtering of cloud-contaminated observations near the tropopause. This is particularly valuable in comparison with limb-scattering observations such as OMPS-LP and SAGE, for which the discrimination between thin clouds and aerosol layers can be challenging. While SAOD quantifies the temporal evolution and persistence of stratospheric aerosol, the scattering ratio provides vertically resolved information on the distribution and vertical transport of enhanced aerosol layers. Bulk depolarization provides complementary information on the presence and persistence of non-spherical particles, allowing differences in aerosol optical characteristics to be followed over time. The simultaneous analysis of these parameters therefore enables major stratospheric aerosol perturbations to be characterized beyond changes in aerosol loading alone and allows events of different origins, magnitudes and compositions to be compared consistently over the CALIPSO record.



The consistency between L1CC, GloSSAC and the NDACC lidar observations concurs with previous assessments demonstrating the capability of CALIOP observations to reproduce the variability of the stratospheric aerosol layer (Thomason et al., 2018; Kovilakam et al., 2020). This study represents the first application of the recently released CALIOP Level 1 Version 5.00 product to the long-term monitoring of stratospheric aerosols. The present approach extends these long-term analyses by retaining the vertically resolved scattering and bulk depolarization information provided by CALIOP Level 1 measurements and applying a consistent analysis throughout the CALIPSO mission. This combination makes it possible to investigate simultaneously the aerosol loading, vertical distribution and persistence of depolarizing aerosol layers over nearly two decades, providing additional constraints on the large-scale evolution of the stratospheric aerosol layer following both volcanic eruptions and extreme wildfire events.

Some limitations should nevertheless be considered when interpreting the L1CC observations. The use of zonal averaging inevitably smooths localized aerosol structures and can reduce the apparent magnitude of spatially confined perturbations compared with ground-based lidar measurements. This effect is particularly relevant during the early stages of a perturbation or when coherent aerosol structures pass over the individual lidar stations. Conversely, the broader spatial sampling of CALIOP reduces the influence of individual plume encounters and is therefore better suited to characterizing the large-scale evolution of the aerosol layer. L1CC should consequently be considered primarily as a dataset for investigating the long-term and large-scale evolution of stratospheric aerosol perturbations rather than the detailed properties of individual aerosol layers.

These characteristics make the L1CC dataset particularly suitable for the consistent comparison of the large-scale and long-term evolution of volcanic and wildfire perturbations, which is discussed in the following sections.

4.2 Volcanic and wildfires aerosol regimes

During the CALIOP observational period, the stratospheric aerosol layer was repeatedly perturbed by volcanic eruptions and major wildfire events. The present analysis includes 15 volcanic eruptions and three major wildfire events observed during the CALIOP era, complemented by the 2024 Ruang eruption and the 2025 PWO wildfire event observed by ATLID and ground-based lidars. These recent events extend the analysis beyond the end of the CALIPSO mission and provide a first assessment of whether the optical regimes identified from the long-term CALIOP record are also observed with ATLID.

Taken together, these observations demonstrate that lidar-derived optical properties provide an effective framework for identifying the different aerosol regimes governing the long-term evolution of major stratospheric perturbations. Volcanic eruptions exhibit different optical behaviours depending on their ash and sulfate content, while major wildfire events are characterized by persistent bulk depolarization signatures and long-lived aerosol layers. The persistence of these optical signatures at large spatial scales over nearly two decades highlights the capability of the L1CC dataset to investigate the diversity and long-term evolution of stratospheric aerosol perturbations within a homogeneous observational framework.



The long-term CALIOP observations reveal that volcanic eruptions are not followed by a uniform optical evolution but can instead be grouped into several characteristic aerosol regimes according to the relative contributions of volcanic ash and sulfate aerosols. Although all eruptions initially perturb the stratospheric aerosol layer, their subsequent optical evolution strongly depends on the eruptive plume composition, sulfur emissions and injection conditions.

This large-scale classification complements previous climatological studies (e.g., Kremser et al., 2016; Martinson et al., 2026), which primarily described the temporal variability of the stratospheric aerosol layer. Here, the combination of SAOD, scattering ratio and bulk depolarization further demonstrates that volcanic eruptions follow distinct long-term optical evolution depending on their relative ash and sulfate contributions.

Ash-rich eruptions, such as Puyehue (Nakame et al., 2014; Vernier et al., 2017), Calbuco (Bignami et al., 2015; Lopes et al., 2019) and Raikoke (Vaughan et al., 2021; Osborne et al., 2022), are initially characterized by elevated depolarization values reflecting the abundance of coarse, non-spherical ash particles injected into the lower stratosphere. As the plume evolves, depolarization gradually decreases owing to the preferential sedimentation of the largest ash particles together with the progressive formation of sulfate aerosols through SO₂ oxidation. This transition from ash-dominated to sulfate-dominated aerosol populations has previously been reported for the Sarychev eruption (Jégou et al., 2013; Prata et al., 2017) and for the Kasatochi eruption (Karagulian et al., 2010; Hoffmann et al., 2010), and is consistently reproduced by the long-term L1CC observations. The pronounced and persistent depolarization enhancement observed following the 2024 Ruang eruption reveals the remarkable persistence of non-spherical volcanic aerosols in the stratosphere. Importantly, this feature is independently observed by both ATLID and the ground-based lidar at Lauder, providing consistent satellite and ground-based evidence of the long-lasting non-spherical character of the Ruang aerosol plume. The detailed analysis of the early evolution and optical properties of young volcanic plumes is presented in Part II, completing the long-term analysis presented here to the early stages following injection.

In contrast, sulfur-rich eruptions with relatively limited ash content can rapidly evolve toward sulfate-dominated aerosol populations characterized by weak depolarization. The Hunga eruption represents the clearest example of this behaviour in the L1CC record. Despite producing a major stratospheric aerosol perturbation, its optical signature was characterized by low depolarization values, consistent with a predominantly sulfate aerosol population. This behaviour is consistent with observations of the Hunga plume reported by Legras et al. (2022), which showed a rapid evolution toward sulfate-rich aerosols.

These observations show that volcanic plumes follow different long-term evolutionary pathways depending on their ash and sulfate content. The relative importance of each regime is primarily controlled by eruption intensity, sulfur emissions, ash



content and injection altitude, which together determine the subsequent evolution of the stratospheric aerosol layer (Cashman
et al., 2013).

Wildfire plumes exhibit distinct long-term optical and dynamical signatures. The ANY and PNE wildfire events are characterized by persistent bulk depolarization enhancements, indicating the prolonged presence of non-spherical carbonaceous particles in the stratosphere. Their long-term evolution is also strongly influenced by radiatively driven self-lofting, whereby absorption of solar radiation induces diabatic heating and sustained ascent of the smoke layer (Khaykin et al., 2020; Ohneiser et al., 2023). This mechanism contributes to the prolonged stratospheric residence of wildfire aerosols and is consistent with the ascent of the aerosol layers observed in the L1CC record. The 2025 PWO event, observed by ATLID after the end of the CALIOP record, similarly exhibits a detectable stratospheric aerosol perturbation, although its magnitude and persistence are substantially lower than those of PNE and ANY. This contrast further illustrates the large event-to-event variability among stratospheric wildfire perturbations.

Taken together, these results demonstrate that major volcanic and wildfire perturbations follow distinct long-term optical and dynamical regimes. Volcanic eruptions exhibit different evolutionary pathways depending on their relative ash and sulfate contributions: ash-rich eruptions such as Puyehue, Calbuco, and Raikoke are characterized by pronounced bulk depolarization signatures that progressively decrease as non-spherical ash is removed and the relative contribution of sulfate aerosol increases, whereas sulfate-dominated events such as Hunga exhibit much weaker depolarization. In contrast, major wildfire perturbations such as PNE and ANY maintain persistent depolarization signatures associated with long-lived carbonaceous aerosols, together with sustained self-lofting driven by radiative heating. The ATLID observations of Ruang and PWO extend these analyses beyond the CALIOP period and demonstrate the continuity of satellite-lidar monitoring of recent volcanic and wildfire perturbations. The combined analysis of SAOD, SR, and bulk depolarization therefore enables these contrasting aerosol regimes and vertical transport pathways to be identified consistently over the CALIPSO record. The early-stage evolution of these volcanic and wildfire aerosol populations is further investigated in Part II, complementing the present long-term analysis by focusing on the properties and evolution of young stratospheric plumes.

4.3 Factors controlling long-term aerosol persistence

The return-time analysis provides a complementary perspective to conventional aerosol optical depth diagnostics by quantifying the duration required for the stratospheric aerosol layer to recover its background state following a significant perturbation. Whereas peak SAOD primarily reflects the intensity of an event, the return time integrates the complete evolution of the aerosol layer and therefore represents the combined effects of transport, dilution and removal processes acting over timescales of months to years (Kremser et al., 2016; Andersson et al., 2015). The e-folding time provides a complementary measure by characterizing the decay timescale of the aerosol perturbation following its maximum. The differences observed



755 between the two metrics indicate that the characteristic decay of aerosol loading and the total duration of a perturbation represent distinct aspects of aerosol persistence.

The results demonstrate that aerosol persistence varies considerably between events. Hunga is characterized by both an exceptionally long return time and the longest e-folding time, consistent with the highly explosive nature of this VEI 6 eruption and its tropical location (Khaykin et al., 2022; Legras et al., 2022; Sellitto et al., 2022). In contrast, several moderate volcanic eruptions exhibit considerably shorter decay and return times. Although the return and e-folding times are strongly correlated (Pearson's $r = 0.90$), the correlation is not perfect and the relative ordering of the events differs between the two metrics. This indicates that a rapid characteristic decay does not necessarily imply a rapid return to background conditions and suggests that differences in aerosol removal pathways and their efficiency contribute to the event-to-event variability in persistence.

765 The comparison with perturbation magnitude reveals a general tendency toward longer return times with increasing relative SAOD perturbation. Most events broadly follow this relationship, suggesting that the initial aerosol loading contributes to determining the subsequent persistence of the perturbation. However, events with comparable relative SAOD anomalies can exhibit substantially different return times, demonstrating that magnitude alone is insufficient to explain aerosol persistence. Hunga represents the most extreme case, combining the largest relative SAOD anomaly with the longest persistence, whereas other relatively strong perturbations recover substantially faster. ANY is also shifted toward a comparatively high relative perturbation magnitude for its return time.

775 Injection altitude provides another important, but non-unique, control on aerosol persistence. Higher-reaching perturbations tend overall to exhibit longer e-folding times, consistent with a longer residence of aerosols injected farther into the stratosphere. Ruang provides a notable example, combining a high-altitude stratospheric injection with a particularly long e-folding time (290 ± 19 days), among the longest observed in this study. Nevertheless, injection altitude alone cannot explain the full event-to-event variability. Nevertheless, events reaching comparable initial altitudes exhibit markedly different decay timescales, indicating that injection altitude alone cannot account for the observed variability. Self-lofting can further modify the vertical evolution after injection, particularly for wildfire smoke, meaning that the altitude subsequently reached by the aerosol layer may differ substantially from its initial injection altitude. The overlap between volcanic and wildfire events also indicates that source type alone cannot explain the observed differences in persistence. Overall, the large event-to-event variability suggests that aerosol persistence results from a combination of initial loading, injection altitude and latitude, and subsequent microphysical and dynamical evolution, rather than from any single parameter.

785 Wildfire events illustrate particularly well the importance of this subsequent dynamical evolution. The ANY fires remained detectable for considerably longer than the 2025 PWO event despite both being major pyroCb perturbations. The long-term evolution of the three major wildfire perturbations investigated here was associated with the formation of smoke-charged



vortices (SCV), although their stability differed substantially among events. The vortex generated by the ANY fires remained remarkably stable and long-lived, sustaining the confinement and radiatively driven self-lofting of the Australian smoke (Khaykin et al., 2020; Ohneiser et al., 2023), whereas the PNE vortex was comparatively less stable (Lestrelin et al., 2021) and the PWO vortex exhibited a markedly unstable evolution (Vieille et al., 2026). These differences in SCV stability directly influence the degree and persistence of self-lofting: a stable vortex maintains a concentrated smoke plume, thereby sustaining radiative heating and diabatic ascent, whereas a less stable vortex favours plume dilution and progressively weakens the radiative heating responsible for self-lofting. Vortex stability therefore contributes to controlling both the magnitude and duration of self-lofting and, ultimately, the stratospheric residence time of smoke aerosols.

Overall, return and e-folding times provide complementary metrics for comparing the long-term impact of stratospheric aerosol perturbations. The relationships with perturbation magnitude and injection altitude show that neither parameter alone determines aerosol persistence. Instead, the large event-to-event variability reflects the combined influence of initial aerosol loading and injection conditions together with subsequent microphysical and dynamical evolution. The role of these processes is further investigated in Part II, where the early optical properties and evolution of individual volcanic and wildfire plumes are examined in greater detail.

Data availability

EarthCARE ATLID data are available at <https://earth.esa.int/eogateway/catalog/earthcare-l1-products> (last access: 5 June 2026); OMPS V2.0 data is available at https://snpp-omps.gesdisc.eosdis.nasa.gov/data/SNPP_OMPS_Level2/OMPS_NPP_LP_L2_AER_DAILY.2 (last access: 5 June 2026); GloSSAC data are available at https://asdc.larc.nasa.gov/project/GloSSAC/GloSSAC_2.22 (last access: 5 June 2026); NDACC lidar data are available at <https://ndacc.larc.nasa.gov> (last access: 5 June 2026). The CALIOP L1CC dataset is available on Zenodo at DOI: 10.5281/zenodo.22790686.

Author contributions

SK conceived the study. OS performed the analysis and wrote the manuscript. SK and SGB revised the manuscript. AF prepared CALIOP L1C product. TS, YJ and IM provided Lauder lidar data. All authors contributed to the final manuscript.

Competing interests:

The contact author has declared that none of the authors has any competing interests.



Acknowledgements

We thank the personnel of lidar stations (OHP and Lauder) for conducting lidar measurements. The French lidar stations operate under support of French Institut National des Sciences de l'Univers (INSU) of the Centre National de la Recherche Scientifique (CNRS) and of Centre National d'Etudes Spatiales (CNES). Lidar observation at Lauder is funded in part by the
 820 GOSAT (Greenhouse gases Observing SATellite) series project.

Financial support

This project has received financial support from the CNRS through the MITI interdisciplinary programs This research has also been supported by the Agence Nationale de la Recherche (ANR grant no. PyroStrat 21-CE01-335 0007-01) as well as by the Centre National d'Etudes Spatiales (CNES grant no. EXTRA-SAT and EARTHCARE).

825 References

- Ansmann, A., Baars, H., Chudnovsky, A., Mattis, I., Veselovskii, I., Haarig, M., Seifert, P., Engelmann, R., and Wandinger, U.: Extreme levels of Canadian wildfire smoke in the stratosphere over central Europe on 21–22 August 2017, *Atmos. Chem. Phys.*, 18, 11831–11845, <https://doi.org/10.5194/acp-18-11831-2018>, 2018.
- Aquila, V., Oman, L. D., Stolarski, R. S., Douglass, A. R., and Newman, P. A.: The response of ozone and nitrogen dioxide
 830 to the eruption of Mt. Pinatubo at southern and northern midlatitudes, *J. Atmos. Sci.*, 70, 894–900, <https://doi.org/10.1175/JAS-D-12-0143.1>, 2013.
- Baars, H., Ansmann, A., Ohneiser, K., Haarig, M., Engelmann, R., Althausen, D., Hanssen, I., Gausa, M., Pietruczuk, A., Szkop, A., Wang, D., and Reichardt, J.: The unprecedented 2017–2018 stratospheric smoke event: decay phase and aerosol properties observed with EARLINET, *Atmos. Chem. Phys.*, 19, 15183–15198, <https://doi.org/10.5194/acp-19-15183-2019>,
 835 2019.
- Butchart, N.: The Brewer–Dobson circulation, *Rev. Geophys.*, 52, 157–184, <https://doi.org/10.1002/2013RG000448>, 2014.
- Carn, S. A. and Prata, F. J.: Satellite-based constraints on explosive SO₂ release from Soufrière Hills Volcano, Montserrat, *Geophys. Res. Lett.*, 37, L00E22, <https://doi.org/10.1029/2010GL044971>, 2010.
- Cashman, K. V. and Sparks, R. S. J.: How volcanoes work: a 25-year perspective, *Geol. Soc. Am. Bull.*, 125, 664–690,
 840 <https://doi.org/10.1130/B30720.1>, 2013.
- Corradini, S., Merucci, L., Prata, A. J., and Piscini, A.: Volcanic ash and SO₂ in the 2008 Kasatochi eruption: retrievals comparison from different IR satellite sensors, *J. Geophys. Res.-Atmos.*, 115, D00L21, <https://doi.org/10.1029/2009JD013634>, 2010.



- Donovan, D. P., van Zadelhoff, G.-J., and Wang, P.: The EarthCARE lidar cloud and aerosol profile processor (A-PRO): the
845 A-AER, A-EBD, A-TC, and A-ICE products, *Atmos. Meas. Tech.*, 17, 5301–5340, <https://doi.org/10.5194/amt-17-5301-2024>,
2024.
- Fernald, F. G.: Analysis of atmospheric lidar observations: some comments, *Appl. Opt.*, 23, 652–653,
<https://doi.org/10.1364/AO.23.000652>, 1984.
- Godin-Beekmann, S., Porteneuve, J., and Garnier, A.: Systematic DIAL lidar monitoring of the stratospheric ozone vertical
850 distribution at Observatoire de Haute-Provence, *J. Environ. Monit.*, 5, 57–67, <https://doi.org/10.1039/B205880D>, 2003.
- Haarig, M., Ansmann, A., Baars, H., Jimenez, C., Veselovskii, I., Engelmann, R., and Althausen, D.: Depolarization and lidar
ratios at 355, 532, and 1064 nm and microphysical properties of aged tropospheric and stratospheric Canadian wildfire smoke,
Atmos. Chem. Phys., 18, 11847–11861, <https://doi.org/10.5194/acp-18-11847-2018>, 2018.
- Hunt, W. H., Winker, D. M., Vaughan, M. A., Powell, K. A., Lucker, P. L., and Weimer, C.: CALIPSO lidar description and
855 performance assessment, *J. Atmos. Ocean. Tech.*, 26, 1214–1228, <https://doi.org/10.1175/2009JTECHA1223.1>, 2009.
- Illingworth, A. J., Barker, H. W., Beljaars, A., et al.: The EarthCARE satellite: the next step forward in global measurements
of clouds, aerosols, precipitation, and radiation, *Bull. Am. Meteorol. Soc.*, 96, 1311–1332, <https://doi.org/10.1175/BAMS-D-12-00227.1>, 2015.
- Jaross, G., Bhartia, P. K., Chen, G., Kowitt, M., Haken, M., Chen, Z., Xu, P., Warner, J., and Kelly, T.: OMPS Limb Profiler
860 instrument performance assessment, *J. Geophys. Res.-Atmos.*, 119, 4399–4412, <https://doi.org/10.1002/2013JD020482>, 2014.
- Jégou, F., Berthet, G., Brogniez, C., et al.: Stratospheric aerosols from the Sarychev volcano eruption in the 2009 Arctic
summer, *Atmos. Chem. Phys.*, 13, 6533–6552, <https://doi.org/10.5194/acp-13-6533-2013>, 2013.
- Kar, J., Vaughan, M. A., Lee, K.-P., et al.: CALIPSO lidar calibration at 532 nm: version 4 nighttime algorithm, *Atmos. Meas.*
Tech., 11, 1459–1479, <https://doi.org/10.5194/amt-11-1459-2018>, 2018.
- 865 Karagulian, F., Clarisse, L., Clerbaux, C., Prata, A. J., Hurtmans, D., and Coheur, P. F.: Detection of volcanic SO₂, ash, and
H₂SO₄ using the Infrared Atmospheric Sounding Interferometer (IASI), *J. Geophys. Res.-Atmos.*, 115, D00L02,
<https://doi.org/10.1029/2009JD012786>, 2010.
- Khaykin, S. M., Godin-Beekmann, S., Keckhut, P., Hauchecorne, A., Jumelet, J., Vernier, J.-P., Bourassa, A., Degenstein, D.
A., Rieger, L. A., Bingen, C., Vanhellemont, F., Robert, C., DeLand, M., and Bhartia, P. K.: Variability and evolution of the
870 midlatitude stratospheric aerosol budget from 22 years of ground-based lidar and satellite observations, *Atmos. Chem. Phys.*,
17, 1829–1845, <https://doi.org/10.5194/acp-17-1829-2017>, 2017.
- Khaykin, S., Legras, B., Bucci, S., Sellitto, P., Isaksen, I., Tencé, F., Bekki, S., Bourassa, A., Rieger, L., Zawada, D., Jumelet,
J., and Godin-Beekmann, S.: The 2019/20 Australian wildfires generated a persistent smoke-charged vortex rising up to 35
km altitude, *Commun. Earth Environ.*, 1, 22, <https://doi.org/10.1038/s43247-020-00022-5>, 2020.
- 875 Khaykin, S., Sicard, M., Leblanc, T., Sakai, T., Balugin, N., Berthet, G., Chevrier, S., Chouza, F., Feofilov, A., Gantois, D.,
Godin-Beekmann, S., Haddouche, A., Jin, Y., Morino, I., Kadygrov, N., Lecas, T., Liley, B., Querel, R., Taha, G., and
Yushkov, V.: Global transport of stratospheric aerosol produced by Ruang eruption from EarthCARE ATLID, limb-viewing



- satellites and ground-based lidar observations, *Atmos. Chem. Phys.*, 26, 607–629, <https://doi.org/10.5194/acp-26-607-2026>, 2026.
- 880 Kloss, C., Berthet, G., Sellitto, P., et al.: Transport of the 2017 Canadian wildfire plume to the tropics via the Asian monsoon circulation, *Atmos. Chem. Phys.*, 19, 13547–13567, <https://doi.org/10.5194/acp-19-13547-2019>, 2019.
- Kovilakam, M., Thomason, L. W., Ernest, N., Rieger, L., Bourassa, A., and Millán, L.: The Global Space-based Stratospheric Aerosol Climatology (version 2.0): 1979–2018, *Earth Syst. Sci. Data*, 12, 2607–2634, <https://doi.org/10.5194/essd-12-2607-2020>, 2020.
- 885 Kremser, S., Thomason, L. W., von Hobe, M., et al.: Stratospheric aerosol—Observations, processes, and impact on climate, *Rev. Geophys.*, 54, 278–335, <https://doi.org/10.1002/2015RG000511>, 2016.
- Lestrelin, H., Legras, B., Podglajen, A., and Salihoglu, M.: Smoke-charged vortices in the stratosphere generated by wildfires and their behaviour in both hemispheres: comparing Australia 2020 to Canada 2017, *Atmos. Chem. Phys.*, 21, 7113–7134, <https://doi.org/10.5194/acp-21-7113-2021>, 2021.
- 890 Lopes, F. J. S., Silva, J. J., Antuña Marrero, J. C., Taha, G., and Landulfo, E.: Synergetic Aerosol Layer Observation After the 2015 Calbuco Volcanic Eruption Event, *Remote Sens.*, 11, 195, <https://doi.org/10.3390/rs11020195>, 2019.
- Loughman, R., Bhartia, P. K., Chen, Z., et al.: The Ozone Mapping and Profiler Suite (OMPS) Limb Profiler (LP) Version 1 aerosol extinction retrieval algorithm: theoretical basis, *Atmos. Meas. Tech.*, 11, 2633–2651, <https://doi.org/10.5194/amt-11-2633-2018>, 2018.
- 895 Martinsson, B. G., Friberg, J., and Sporre, M. K.: A global view of the stratospheric background, volcanic and wildfire aerosol in the CALIOP era (2006–2023), *Atmos. Chem. Phys.*, 26, 8999–9016, <https://doi.org/10.5194/acp-26-8999-2026>, 2026.
- McCormick, M. P., Thomason, L. W., and Trepte, C. R.: Atmospheric effects of the Mt Pinatubo eruption, *Nature*, 373, 399–404, <https://doi.org/10.1038/373399a0>, 1995.
- Noel, V., Chepfer, H., Hoareau, C., Reverdy, M., and Cesana, G.: Effects of solar activity on noise in CALIOP profiles above the South Atlantic Anomaly, *Atmos. Meas. Tech.*, 7, 1597–1603, <https://doi.org/10.5194/amt-7-1597-2014>, 2014.
- 900 Ohneiser, K., Ansmann, A., Witthuhn, J., Deneke, H., Chudnovsky, A., Walter, G., and Senf, F.: Self-lofting of wildfire smoke in the troposphere and stratosphere: simulations and space lidar observations, *Atmos. Chem. Phys.*, 23, 2901–2925, <https://doi.org/10.5194/acp-23-2901-2023>, 2023.
- Omar, A. H., Winker, D. M., Vaughan, M. A., et al.: The CALIPSO automated aerosol classification and lidar ratio selection algorithm, *J. Atmos. Ocean. Tech.*, 26, 1994–2014, <https://doi.org/10.1175/2009JTECHA1231.1>, 2009.
- Peterson, D. A., Campbell, J. R., Hyer, E. J., et al.: Wildfire-driven thunderstorms cause a volcano-like stratospheric injection of smoke, *npj Clim. Atmos. Sci.*, 1, 30, <https://doi.org/10.1038/s41612-018-0039-3>, 2018.
- Pitts, M. C., Poole, L. R., and Gonzalez, R.: Polar stratospheric cloud climatology based on CALIPSO spaceborne lidar measurements from 2006 to 2017, *Atmos. Chem. Phys.*, 18, 10881–10913, <https://doi.org/10.5194/acp-18-10881-2018>, 2018.



- 910 Powell, K. A., Hostetler, C. A., Vaughan, M. A., et al.: CALIPSO lidar calibration algorithms. Part I: Nighttime 532-nm parallel channel and 532-nm perpendicular channel, *J. Atmos. Ocean. Tech.*, 26, 2015–2033, <https://doi.org/10.1175/2009JTECHA1242.1>, 2009.
- Prata, F., Young, S., Siems, S., and Manton, M.: Lidar ratios of stratospheric volcanic ash and sulfate aerosols retrieved from CALIOP measurements, *Atmos. Chem. Phys.*, 17, 8599–8618, <https://doi.org/10.5194/acp-17-8599-2017>, 2017.
- 915 Ridley, D. A., Solomon, S., Barnes, J. E., et al.: Total volcanic stratospheric aerosol optical depths and implications for global climate change, *Geophys. Res. Lett.*, 41, 7763–7769, <https://doi.org/10.1002/2014GL061541>, 2014.
- Robock, A.: Volcanic eruptions and climate, *Rev. Geophys.*, 38, 191–219, <https://doi.org/10.1029/1998RG000054>, 2000.
- Sakai, T., Nagai, T., Nakazato, M., et al.: Stratospheric aerosol backscatter and depolarization ratio observed with ground-based lidar at Tsukuba, Japan, and Lauder, New Zealand, *J. Geophys. Res.-Atmos.*, 130, e2024JD041329, <https://doi.org/10.1029/2024JD041329>, 2025.
- 920 Sasano, Y. and Browell, E. V.: Light scattering characteristics of various aerosol types derived from multiple wavelength lidar observations, *Appl. Opt.*, 28, 1670–1679, <https://doi.org/10.1364/AO.28.001670>, 1989.
- Sellitto, P., Podglajen, A., Belhadji, R., et al.: The unexpected radiative impact of the Hunga Tonga eruption of 15 January 2022, *Commun. Earth Environ.*, 3, 288, <https://doi.org/10.1038/s43247-022-00618-z>, 2022.
- 925 Siddaway, J. M. and Petelina, S. V.: Transport and evolution of the 2009 Australian Black Saturday bushfire smoke in the lower stratosphere observed by OSIRIS on Odin, *J. Geophys. Res.-Atmos.*, 116, D06203, <https://doi.org/10.1029/2010JD015162>, 2011.
- SPARC: Assessment of Stratospheric Aerosol Properties (ASAP), SPARC Report No. 4, WCRP-124, WMO/TD-No. 1295, <https://aparc-climate.org/publications/sparc-report-no-4/>, 2006.
- 930 Surono, Jousset, P., Pallister, J., Boichu, M., Buongiorno, M. F., Budisantoso, A., Costa, F., Andreastuti, S., Prata, F., Schneider, D. J., et al.: The 2010 explosive eruption of Java's Merapi volcano – a “100-year” event, *J. Volcanol. Geoth. Res.*, 241–242, 121–135, <https://doi.org/10.1016/j.jvolgeores.2012.06.018>, 2012.
- Taha, G., Loughman, R., Zhu, T., Thomason, L., Kar, J., Rieger, L., and Bourassa, A.: OMPS LP Version 2.0 multi-wavelength aerosol extinction coefficient retrieval algorithm, *Atmos. Meas. Tech.*, 14, 1015–1036, [https://doi.org/10.5194/amt-14-1015-](https://doi.org/10.5194/amt-14-1015-2021)
- 935 2021, 2021.
- Thomason, L. W., Ernest, N., Millán, L., Rieger, L., Bourassa, A., Vernier, J.-P., Manney, G., Luo, B., Arfeuille, F., and Peter, T.: A global space-based stratospheric aerosol climatology: 1979–2016, *Earth Syst. Sci. Data*, 10, 469–492, <https://doi.org/10.5194/essd-10-469-2018>, 2018.
- Vernier, J.-P., Thomason, L. W., and Kar, J.: CALIPSO detection of an Asian tropopause aerosol layer, *Geophys. Res. Lett.*, 38, L07804, <https://doi.org/10.1029/2010GL046614>, 2011.
- 940 Vernier, J.-P., Fairlie, T. D., Deshler, T., et al.: In situ and space-based observations of the Kelud volcanic plume: the persistence of ash in the lower stratosphere, *J. Geophys. Res.-Atmos.*, 121, 11104–11118, <https://doi.org/10.1002/2016JD025344>, 2016.



- 945 Wehr, T., Kubota, T., Tzeremes, G., et al.: The EarthCARE mission – science and system overview, *Atmos. Meas. Tech.*, 16,
3581–3608, <https://doi.org/10.5194/amt-16-3581-2023>, 2023.
- Winker, D. M., Hunt, W. H., and McGill, M. J.: Initial performance assessment of CALIOP, *Geophys. Res. Lett.*, 34,
2007GL030135, <https://doi.org/10.1029/2007GL030135>, 2007.
- Winker, D. M., Vaughan, M. A., Omar, A., Hu, Y., Powell, K. A., Liu, Z., Hunt, W. H., and Young, S. A.: Overview of the
CALIPSO mission and CALIOP data processing algorithms, *J. Atmos. Ocean. Tech.*, 26, 2310–2323,
950 <https://doi.org/10.1175/2009JTECHA1281.1>, 2009.
- Yu, P., Toon, O. B., Bardeen, C. G., Zhu, Y., Rosenlof, K. H., Portmann, R. W., Thornberry, T. D., Gao, R.-S., Davis, S. M.,
Wolf, E. T., de Gouw, J., Peterson, D. A., Fromm, M. D., and Robock, A.: Black carbon lofts wildfire smoke high into the
stratosphere to form a persistent plume, *Science*, 365, 587–590, <https://doi.org/10.1126/science.aax1748>, 2019.