Impact of wildfires on stratospheric aerosol composition and dynamics from ground-based and satellite lidars

Sergey Khaykin[a], Tetsu Sakai[b], Ben Liley[c], Richard Querel[c], Isamu Morino[d], Yoshitaka Jin[d], Tomohiro Nagai[b], Osamu Uchino[b], Sophie Godin-Beekmann[a]

[a] *LATMOS, CNRS, Sorbonne Université/UVSQ, Guyancourt, France,*
E-mail : sergey.khaykin@latmos.ipsl.fr
[b] *Meteorological Research Institute (MRI-JMA), Tsukuba, Japan*
[c] *National Institute of Water & Atmospheric Research (NIWA), Lauder, New Zealand*
[d] *National Institute for Environmental Studies (NIES), Tsukuba, Japan*

Abstract: The severity of wildfires has remarkably increased over the last decade in both hemispheres and there is an emerging realization of their effect on climate and ozone layer via stratospheric emissions. Here we exploit a synergy of satellite and ground-based lidar observations to characterize the stratospheric impact of major wildfire outbreaks in terms of bulk aerosol composition change and generation of self-lofting smoke-charged vortices (SCV). We use long-term lidar observations at Observatoire de Haute-Provence (OHP) (Southern France) and Lauder (New Zealand) to constrain the magnitude and longevity of smoke aerosols in the stratosphere. The CALIOP satellite lidar observations of backscatter and depolarization are used to characterize the evolution of smoke plumes' optical properties and to contrast them with those of volcanic plumes.

1. Introduction

Intense wildfires release tremendous amounts of heat into the atmosphere, which gives rise to extreme thunderstorms termed Pyrocumulonimbus (PyroCb). These storms, augmented by the energy of combustion, can generate vigorous convective updrafts injecting smoke into the stratosphere, where the residence time of aerosol is not limited by cloud scavenging and precipitation. Recent studies [1, 2] have shown that that PyroCb injections into the stratosphere combined with solar heating of highly-absorptive smoke plumes leads to generation of synoptic-scale anticyclones (termed SCV – Smoke-Charged Vortex) that can persist in the stratosphere for months providing dynamical confinement to the aerosol plume. The confinement maintains the aerosols at high concentration, which provides a high degree of internal heating and leads to diabatic rise of the plume. Such self-lofting prolongs the stratospheric residence time and radiative effects of carbonaceous aerosols whilst altering their meridional dispersion [3].

Here we present examples of ground-based and satellite lidar profiling application for the study of PyroCb-induced perturbations of stratospheric composition and dynamics.

2. Data sets

The Observatoire de Haute-Provence (OHP) located in southern France (43.9° N, 5.7° E, 683 m) is one of the NDACC stations. The longest continuous lidar aerosol records at OHP are provided by two independent instruments: a stratospheric ozone lidar (LiO3S) with an off-line channel of 355 nm and a Rayleigh-Mie lidar for temperature and aerosol measurements (LTA) operating at 532 nm. Both LiO3S and LTA lidar systems have provided routine measurements for over 3 decades with a mean measurement rate of 10-12 acquisition nights per month. A detailed description of the instruments, aerosol retrieval and error budget are provided in [4].

The Lauder Atmospheric Research Station of the National Institute of Water and Atmospheric Research (NIWA) located in South Island of New Zealand (45.0° S, 169.7° E, 370 m), which is also one of the NDACC stations, has been operating at 532 nm since 1992 on a regular basis with a mean measurement rate of 1 or 2 nights per week. It has a capability of both scattering ratio and particle depolarization ratio measurements. A more detailed description of the instruments, aerosol retrieval and error budget are provided by [5,6].

The Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) is a two-wavelength polarization lidar on board the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) mission that performs global profiling of aerosols and clouds in the troposphere and lower stratosphere [7]. We use the total and perpendicular attenuated backscatter level 1B product V4.51.

The Stratospheric Aerosol and Gas Experiment (SAGE) III provides stratospheric aerosol extinction coefficient profiles using solar occultation observations from the International Space Station (ISS) [8]. These measurements, available since February 2017, are provided for nine wavelength bands from 385 to 1550 nm.

3. Results

3.1 Wildfire-induced stratospheric aerosol perturbations

Figure 1 shows time series of stratospheric aerosol optical depth (sAOD) observations by NDACC lidars at OHP and Lauder observatories since 2008. These stations, quasi-antipodally located on the globe, represent respectively the northern and southern midlatitudes. The lidar series are compared with zonally-averaged SAGE III sAOD data.

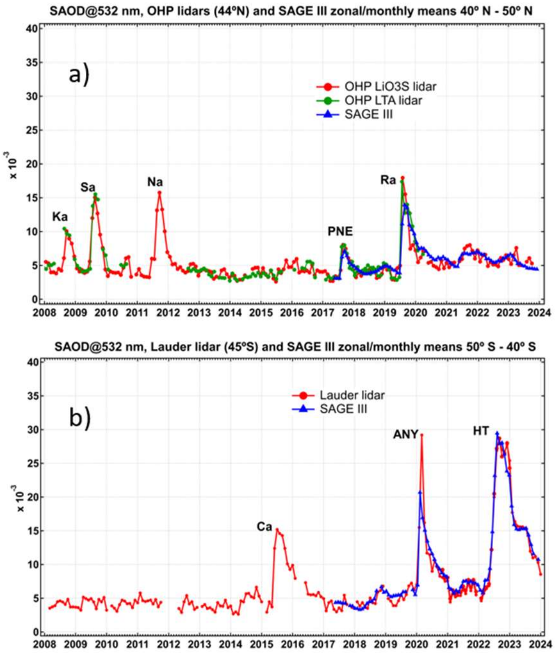

Figure 1. Time series of monthly-mean aerosol optical depth at 532 nm of the stratospheric overworld (380 K - 33 km) from ground-based lidars at a) OHP (LiO3S and LTA lidars) and b) Lauder station compared to the corresponding monthly/zonal-mean values from ISS/SAGE III satellite observations within 40°N - 50°N and 50°S - 40°S latitude bands. The literal notations indicate the most significant volcanic eruptions: Ka - Kasatochi, Sa - Sarychev, Na - Nabro, Ra - Raikoke, Ca - Calbuco, HT - Hunga; and wildfire events: PNE - Pacific Northwest Event (BC, Canada) and ANY - Australian New Year super outbreak.

The OHP sAOD time series reveals several perturbations due to moderate volcanic eruptions (2008 Kasatochi, 2009 Sarychev, 2011 Nabro and 2019 Raikoke) as well as by the Canadian PyroCb wildfire outbreak in August 2017 (PNE – Pacific Northwest Event) [9], which is readily comparable in magnitude to the Kasatochi (Ka) perturbation. With that, the full decay of the PNE perturbation (8-9 months) appears to be longer than that of Kasatochi (6-7 months), which can be explained by self-lofting of PNE-generated smoke in the stratosphere, prolonging its stratospheric residence time.

At the southern midlatitudes (Fig. 1b), the most significant volcanic sAOD perturbations were generated by the 2015 Calbuco (Ca) and the 2022 Hunga (HT) eruptions. On par with them is the record-breaking 2019/20 Australian New Year (ANY) wildfire outbreak, that produced one of the strongest sAOD perturbation in the last three decades [1]. The self-lofting of the primary smoke plume up to 35 km altitude led to prolonged decay of sAOD during more than 1 year. The sharp peak in Lauder sAOD in February 2020 largely owes to the lidar observations during the transit of the largest SCV bubble over New Zealand.

3.2 SCV transit over Lauder

The largest SCV during the ANY outbreak, produced by a cluster PyroCb event on 31 December 2019 persisted for 3 months, travelled 66,000 km and ascended up to 35 km before its final collapse [1]. Over the course of January 2020, the vortex has traveled across the Pacific and made a U-turn over the tip of South America whilst ascending through a directional wind shear. On the way back across the southern Pacific, the SCV was passing over the Lauder station. Figure 2 shows a 5-day time curtain of volume depolarization during that time, reflecting the transit of the rotating smoke bubble. The shape of the smoke bubble from a stationary perspective suggests a tilt and bottom-side elongation of the plume. The meridional wind anomaly from operational twice-daily radiosoundings at a nearby station in Invercargill (not shown) is found structurally coherent with the smoke plume's shape. A very similar shape of the same smoke plume was observed by lidar at Punta Arena in southern Chile [10], during the U-turn phase of the SCV.

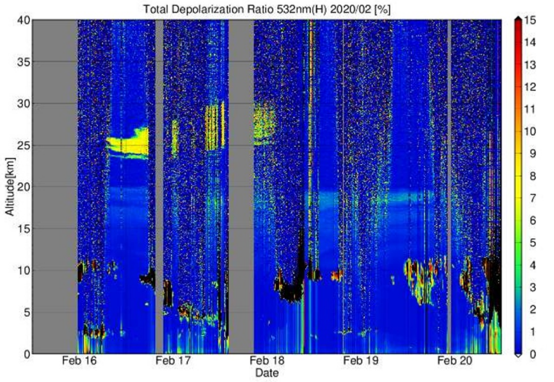

Figure 2. Height-resolved vertical profiles of total depolarization ratio at 532 nm from Lauder lidar observations during the SCV transit over New Zealand in February 2020.

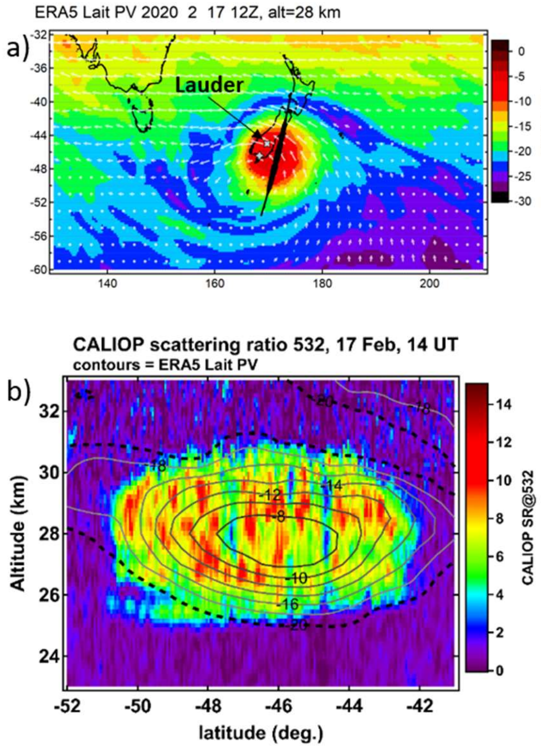

Figure 3. a) ERA5 Lait potential vorticity at 28 km level on 17 February 2020 17 UTC. Grey starts indicate the locations of Lauder and Invcargill stations. Black curve across the PV anomaly, reflecting the SCV indicates CALIPSO lidar ground track on the same day. The thicker segment of the CALIPSO ground-track marks the along-orbit extent of the aerosol plume. b) Corresponding CALIPSO vertical section of scattering ratio across the SCV bubble overlayed by ERA5 PV contours.

During its transit over Lauder, the SCV was sampled by CALIOP in close proximity to the station. Figure 3a display a map of ERA5 Lait Potential Vorticity (PV), revealing the vortical structure together with CALIPSO ground track across the vortex. The corresponding vertical section of CALIOP scattering ratio with PV contours overlayed is shown in Fig. 3b. The vertical section reveals fine-scale inhomogeneities in the aerosol concentration inside the plume, which might be linked to the dynamics of the rotating bubble but remain yet to be understood.

3.2 Evolution of the SCV aerosol composition

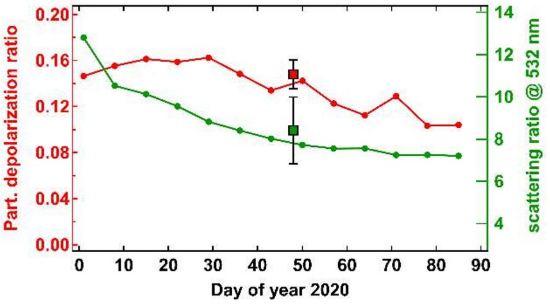

Figure 4. Weekly-averages of particulate depolarization (red curve) and scattering ratio (green curve) of the SCV aerosol bubble from CALIPSO 532 nm observations. Red and green squares represent the respective Lauder lidar measurements on 17 February 2020. The error bars indicate one standard deviation of the lidar-derived optical parameters within the aerosol layer.

The evolution of the average particulate depolarization and scattering ratio of the confined aerosol bubble from CALIOP observations is presented in Fig. 4. They are found in close agreement with the optical parameters provided by the Lauder lidar on 17 February 2020. Interestingly, both depolarization and scattering ratio are subject to little change over the SCV lifetime, which may be attributed to the dynamical confinement preventing from mixing with the ambient air. Such behavior can be contrasted with that of volcanic plumes, characterized by a high depolarization in the fresh plumes (due to presence of ash), which rapidly drops to near-zero values as the ash particles obtain sulfuric coating [11].

4. Summary

The severity of wildfires has remarkably increased over the last years in both Northern and Southern hemispheres and there is an emerging realization of their effect on climate through emissions of biomass burning aerosol into the stratosphere.

We showed that the hemispheric-scale perturbations of stratospheric aerosol burden by the largest wildfire outbreaks rival those by moderate volcanic eruptions and may exceed them in terms of the longevity of perturbation. The latter can be attributed to the self-lofting capacity of absorbing carbonaceous aerosols, prolonging their stratospheric residence time and hence their effects on radiative balance and ozone chemistry.

Dynamical confinement of the PyroCb stratospheric plumes by SCV is one of the key prerequisites for an efficient self-lofting as it maintains the aerosols at high concentration thereby providing a sufficient degree of internal heating. In this context, it is crucial to better constrain the dynamical behaviour of stratospheric wildfire plumes in order to reliably assess their long-term impact on ozone chemistry, stratospheric circulation, and global climate. The high-resolution ground-based and satellite lidar observations remain indispensable for an accurate characterization of the smoke plumes' optical properties and their evolution, whilst uncovering fine-scale dynamics of the SCV, which is necessary for understanding their structure, genesis and lifecycle.

5. References

[1] Khaykin, S., Legras, B., Bucci, et al..: The 2019/20 Australian wildfires generated a persistent smoke-charged vortex rising up to 35 km altitude, Nature Communications Earth and Environment, 1, 22, (2020)

[2] Kablick, G. P., Allen, D. R., Fromm, M. D., and Nedoluha, G. E.: Australian pyroCb smoke generates synoptic-scale stratospheric anticyclones, Geophys. Res. Lett., 47, e2020GL088101 (2020)

[3] Yu, P., Toon, O., Bardeen, C., Zhu, Y., Rosenlof, K., Portmann, R., et al. . Black carbon lofts wildfire smoke high into the stratosphere to form a persistent plume. Science, 365(6453), 587–590 (2019)

[4] Khaykin, S. M., Godin-Beekmann, S., Keckhut, P., Hauchecorne et al., Variability and evolution of the midlatitude stratospheric aerosol budget from 22 years of ground-based lidar and satellite observations, Atmos. Chem. Phys., 17, 1829-1845 (2017.)

[5] Nagai, T., Liley, B., Sakai, T., Shibata, T., and Uchino, O.: PostPinatubo evolution and subsequent trend of the stratospheric aerosol layer observed by mid-latitude lidars in both hemispheres, SOLA, 6, 69–72, doi:10.2151/sola.2010-018 (2010)

[6] Sakai, T., O. Uchino, T. Nagai, B. Liley, I.Morino, and T. Fujimoto (2016), Long-term variation of stratospheric aerosols observed with lidars over Tsukuba, Japan, from 1982 and 19 Lauder, New Zealand, from 1992 to 2015, J. Geophys. Res. Atmos., 121, 10,283 – 10,293 (2016)

[7] Winker, D. M. et al. The CALIPSO mission: a global 3D view of aerosols and clouds. Bull. Am. Meteorol. Soc. 91, 1211–1230 (2010).

[8] Cisewski, M. et al. The stratospheric aerosol and gas experiment (SAGE III) on the International Space Station (ISS) Mission. Proc. SPIE 9241, Sensors, Systems, and Next-Generation Satellites XVIII, 924107 (2014)

[9] Peterson, D. A., Campbell, J. R., Hyer, E. J., Fromm, M. D., Kablick, G. P., Cossuth, J. H., and DeLand, M. T.: Wildfire-driven thunderstorms cause a volcano-like stratospheric injection of smoke, npj Clim. Atmos. Sci., 1, 30 (2018)

[10] Ohneiser, K., Ansmann, A., Kaifler et al.: Australian wildfire smoke in the stratosphere: the decay phase in 2020/2021 and impact on ozone depletion, Atmos. Chem. Phys., 22, 7417–7442 (2022)

[11] Khaykin, S.M., de Laat, A.T.J., Godin-Beekmann, S. et al. Unexpected self-lofting and dynamical confinement of volcanic plumes: the Raikoke 2019 case. Sci Rep 12, 22409 (2022)

Acknowledgements

This research has been supported by the ANR PyroStrat project (21-CE01-0028-01) as well as the CNES EECLAT and Extra-SAT projects. We thank the personnel of lidar stations for conducting the lidar measurement. Lidar operation at Lauder is supported in part by the GOSAT series project.