WILDFIRE SMOKE IN THE STRATOSPHERE OVER EUROPE– FIRST MEASUREMENTS OF DEPOLARIZATION AND LIDAR RATIOS AT 355, 532, AND 1064 NM

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ABSTRACT

Canadian wildfire smoke was detected in the troposphere and lower stratosphere over Europe in August and September 2017. Lidar measurements from various stations of the European Aerosol Research Lidar Network (EARLINET) observed the stratospheric smoke layer. Triple-wavelength (355, 532, and 1064 nm) lidar measurements of the depolarization and the lidar ratio are reported from Leipzig, Germany. The particle linear depolarization ratio of the wildfire smoke in the stratosphere had an exceptional strong wavelength dependence reaching from 0.22 at 355 nm, to 0.18 at 532 nm, and 0.04 at 1064 nm. The lidar ratio increased with wavelength from 40±16 sr at 355 nm, to 66±12 sr at 532 nm, and 92±27 sr at 1064 nm. The development of the stratospheric smoke plume over several months was studied by long-term lidar measurements in Cyprus. The stratospheric smoke layers increased in altitude up to 24 km height.

1. INTRODUCTION

In summer 2017, a record-breaking amount of wildfires in western Canada emitted a huge amount of biomass burning smoke into the atmosphere. Pyrocumulonimbus events occurred due to the strong heat release and lifted the smoke up into the stratosphere [1]. Smoke transport from North American forest fires to Europe is known since a long time [2, 3]. However, for the first time a significant amount of smoke was detected in the stratosphere over Europe, where the light-extinction coefficients were 20 times stronger than after the Pinatubo eruption in 1991 [4]. The smoke in the stratospheric as well as in the troposphere reached Europe about 10 days after injection into the atmosphere over western Canada [5]. On 22 August 2017, the smoke layers were detected over Leipzig and measured with several lidar systems [6]. The stratospheric smoke layers remained for several months over Europe. In Cyprus the stratospheric smoke layers were detected till January 2018.

This abstract describes the first measurement of the lidar ratio and the depolarization ratio at all three typical lidar wavelengths (355, 532, and 1064 nm) to give a full characterization of the optical properties of stratospheric smoke. Furthermore, the stratospheric smoke as a long-term phenomenon is discussed.

2. LIDAR SYSTEMS

BERTHA (Backscatter Extinction lidar-Ratio Temperature Humidity profiling Apparatus) [7] is the first lidar which measures the extinction coefficient at 1064 nm [8, 9] and the depolarization ratio at 355, 532, and 1064 nm [10]. It takes 20-30 minutes to change from the extinction to depolarization measurement at 1064 nm. With the short delay, 3+3+3 measurements (3 backscatter coefficients, 3 extinction coefficients, 3 depolarization ratios) can be realized for the first time.

Long-term observations in Cyprus and other European sites were performed with an autonomous 3+2+2 Polly^{XT} lidar [11] in the framework of PollyNET [12] and CyCARE (Cyprus Clouds, Aerosol and pReciptation Experiment, October 2016 to March 2018, Limassol, Cyprus).

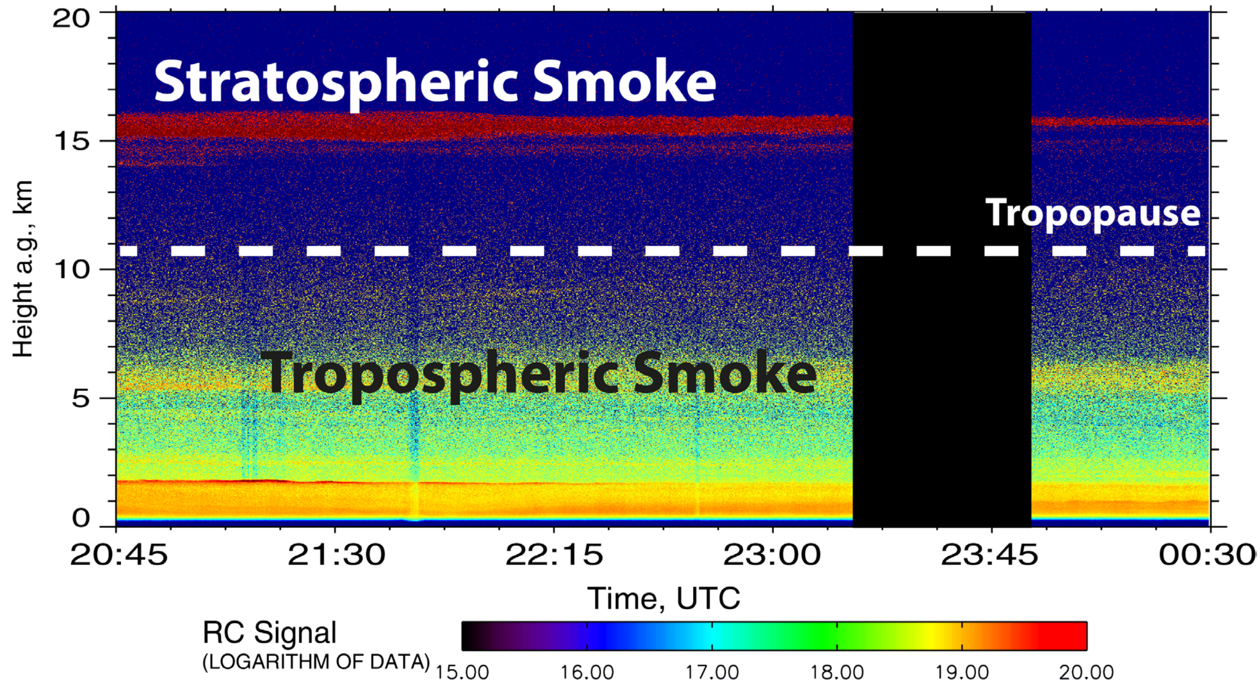

Figure 1 *BERTHA measurements of stratospheric and tropospheric smoke layers over Leipzig on 22 August 2017. The change from the 1064 nm extinction measurement to the 1064 nm depolarization-ratio measurement including calibration caused the gap in the measurements (23:15-23:50 UTC). The range corrected signal at 532 nm (cross polarized) is shown.*

3. RESULTS

3.1 3+3+3 measurements of stratospheric and tropospheric smoke

On 22 Aug 2017 smoke layers reached continental Europe and were measured in Leipzig with 3 lidar systems. Tropospheric smoke layers occurred mainly between 5 and 6.5 km height and a second much stronger smoke layer was found in the stratosphere between 15 and 16 km height (see Fig. 1) well above the local tropopause at 10.8 km height.

The extinction-to-backscatter ratio (lidar ratio) and the particle linear depolarization ratio (PLDR) were measured at 355, 532, and 1064 nm. The profiles of the optical properties are not shown here, but they can be found in Haarig et al. (2018) [6]. At this point, we focus on the main findings and the comparison of the smoke characteristics after the tropospheric and stratospheric transport way.

The lidar ratio of the long-range transported smoke increased with wavelength without a significant difference between the smoke in the troposphere and stratosphere as shown in Fig. 2a. A higher lidar ratio in the visible than in the UV is a clear indication for smoke in contrast to pollution [3]. The lidar ratio at 1064 nm was measured for the first time and could replace former estimates [e.g., 13]. The spectral dependence of the lidar ratio was a result of the strong wavelength dependence of the particle backscatter coefficient and a weak spectral dependence of the extinction coefficient [6].

The particle linear depolarization ratio shown in Fig 2b had values below 5% in the troposphere, which is in line previous observations of aged smoke [e.g., 14]. The particles were obviously compact and of almost spherical shape. In contrast, high values of the PLDR were observed in the stratosphere, 22% at 355 nm, 18% at 532 nm, and 4% at 1064 nm, indicating non-spherical particles. Observations of the same stratospheric smoke layer over Lille, France, confirmed this strong wavelength dependence [15]. A similar case was observed by [16] in the upper troposphere (around 8 km height).

The strong wavelength dependence of the PLDR of the stratospheric smoke compared to the tropospheric smoke points to significant different conditions during transport or already during the emission process. The fast lifting of the smoke particles during the pyrocumulonimbus event or the extremely dry conditions in the stratosphere

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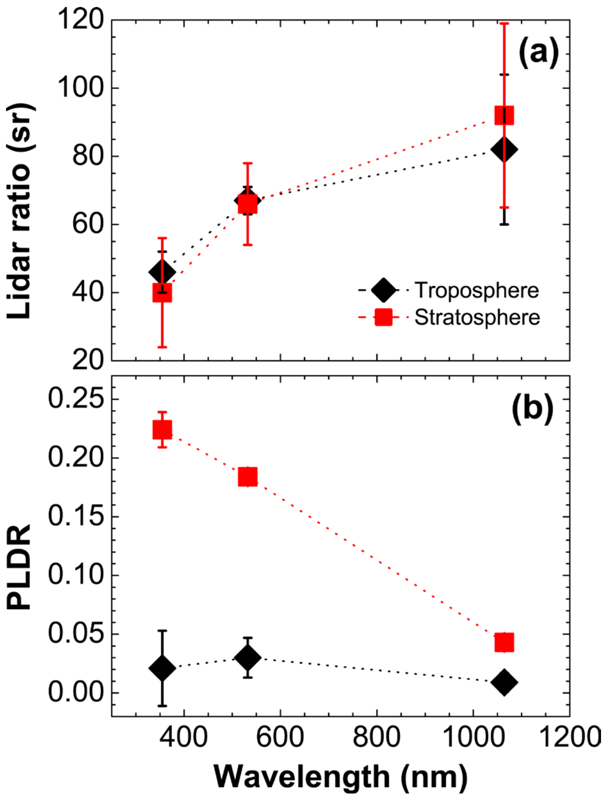

Figure 2 *Spectral behavior of the lidar ratio (a) and particle linear depolarization ratio (b) of smoke in the troposphere (black diamonds, 5 – 6.5 km height) and stratosphere (red squares, 15 – 16 km) over Leipzig on 22 August 2017.*

might be possible explanations for the less spherical smoke particles in the stratosphere.

The spectral behavior of the optical properties benefiting from the measurements at 1064 nm indicated the absence of coarse mode particles (radius > 500 nm). The particles must be small compared to the wavelength of 1064 nm. Lidar inversion calculations led to an effective radius of 0.17±0.06 µm (troposphere) and 0.32±0.10 µm (stratosphere) [6].

3.2 Evolution of the smoke layer with time

The injection of significant amounts of wildfire smoke into the stratosphere was a phenomenon of intercontinental scale. In August 2017 the smoke was released in Western Canada and traveled via Greenland to Europe. This process was studied from space with CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation) [5]. Most of the EARLINET stations between Norway and Crete observed the stratospheric smoke layer in late August and early September 2017 (Baars et al., 2019 in prep).

The stratospheric smoke layers were a long-lasting phenomenon. The measurements with a Polly^{XT} at Cyprus revealed that the smoke layers were present in the stratosphere for more than 5 months till January 2018. Figure 3 shows the vertical extend of the smoke layers over Limassol, Cyprus. Color-coded are the backscatter coefficient and the depolarization ratio.

In September 2017, the stratospheric smoke passed Limassol in several layers between 17 and 23 km height. These layers were characterized by a high depolarization ratio (> 16% at 532 nm) and a strong backscatter coefficient (Fig. 3). The smoke layers got diluted with time leading to a lower backscatter coefficient at a larger vertically

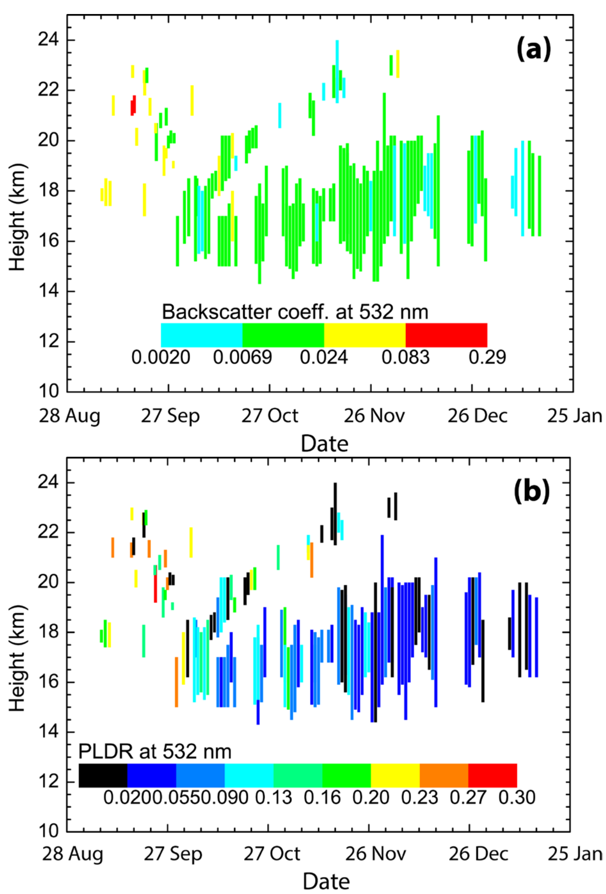

Figure 3 *The stratospheric smoke layer over Cyprus between August 2017 and January 2018. The vertical extend is marked with the bars, color coded with the particle backscatter coefficient (a) on a logarithmic scale and the particle linear depolarization ratio at 532 nm (b) on a linear scale.*

extend. The decrease of the particle depolarization ratio with time (Fig. 3b) is not easy to explain. Either the smoke particle got more spherical or their size decreased with time. Both, spherical particles and small particles cause low depolarization ratios. Or the later arriving smoke particles have a different history of emission and transport (slower transport speed).

Between September and November 2017, part of the stratospheric smoke increased in height up to 24 km. Compared to the tropospheric smoke which was washed out after a few weeks, the stratospheric smoke stayed for more than 5 months in the atmosphere and contributed significantly to the stratospheric aerosol load.

4. CONCLUSION AND OUTLOOK

Unique 3+3+3 lidar observations could be performed during the record-breaking stratospheric smoke event occurring over Europe in August 2017. The extension of the spectral range towards the near infrared (1064 nm) in terms of extinction and depolarization ratio measurements adds valuable information about the particle size and shape characteristics.

The observations at Cyprus show the advantage of continuous lidar measurements over longer time periods. The temporal evolution of the stratospheric smoke layers over the Eastern Mediterranean revealed that the smoke stays for several months in the stratosphere [17].

Wildfire smoke can have a major contribution to the stratospheric aerosol load in the same order of magnitude or even stronger than volcanic aerosol. The radiative fluxes, chemical processes, and even heterogeneous ice formation in the upper troposphere were influenced over a period of weeks to several months.

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