Fire smoke in the stratosphere: a new climate forcer (StratoFIRE)

Progress report
(Including deliverables D1.1, D2.1, D2.2, D2.3, D3.1)

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1. Abstract

Large-scale wildfires have been making global headlines over the recent years, highlighting the importance of fire and its feedback within the Earth System. The most extreme manifestation of a fire-weather interaction is the formation of pyrocumulonimbus (pyroCb) clouds. PyroCbs are thunderstorm-like clouds developed by powerful wildfires under favorable meteorological conditions. Observations over the last years highlight that: a) pyroCbs are surprisingly frequent in the mid-latitude summer, b) pyroCBs can inject as much smoke, water, and reactive gases into the stratosphere as volcanic eruptions, c) without fast removal in the stratosphere, the smoke flies high for months and spreads over the globe, and d) a warming climate favors more frequent and severe smoke injections. PyroCb firestorms have thus emerged as new semi-seasonal source of aerosols in the stratosphere.

Smoke is largely composed of organic and black carbon, numerous reactive gases, and other aerosol precursors. Black carbon (BC) is of particular interest as it is the strongest absorber of shortwave light. Absorption by BC heats the plume causing shelf-lofting to higher altitudes, which prolongs the smoke lifetime and amplifies radiative and chemical perturbations. The global and regional radiative effects and feedbacks associated with stratospheric smoke are uncertain, partly because smoke ageing in the stratosphere is not well constrained. Apart from radiative perturbations, smoke may also accelerate ozone destruction via a) heterogeneous chlorine chemistry, b) moistened stratosphere and water vapor photolysis, c) chlorine activation on polar stratospheric clouds (PSCs), and d) changes in circulation. These mechanisms are known from studies of volcanic aerosols, but their chemical reactivity might differ for smoke, given the different nature of smoke aerosols.

These recent developments call for a comprehensive characterization of the multi-faced role of smoke to the variability of the lower-stratosphere and the global climate. StratoFIRE is aiming exactly at reducing some of those uncertainties. StratoFIRE is an ELIDEK project running from 2022-2025 to provide evidence that the lower stratosphere may act as a mediator connecting extreme wildfires, smoke, and global climate. In the three years of this project we aim to i) monitor stratospheric smoke with a variety of ground-based and space-borne instruments, with particular emphasis given to continuous measurements at PANGEA observatory (PANhellenic GEophysical observatory of Antikythera) ii) develop novel methodologies to infer emissions, optical properties and lifetime of smoke and quantify its corresponding radiative forcing and iii) apply this new information to global climate models to assess the climatic relevance of the stratospheric smoke intrusions.

This is the first progress report of the project StratoFIRE delivered to ELIDEK in month 12, including Deliverable Items D1.1, D2.1, D2.2, D2.3, D3.1.

2. D1.1: Progress report

2.1. Overview

StratoFIRE started on July 2022. This is the first-year progresses report, describing the work so far, key accomplishments and dissemination activities.

Key accomplishments

- Characterization of smoke plume of the Australian 2019/2020 wildfires in a variety of satellite products (related to Deliverables D2.2)
- Preparatory simulations with EMAC in ARIS HPC environment.
- Determination of smoke injection height using satellite observations and climate simulations (related to deliverable D3.1)

Figure 1 describes the workflow of the Project and highlights in green the deliverables included in this report.

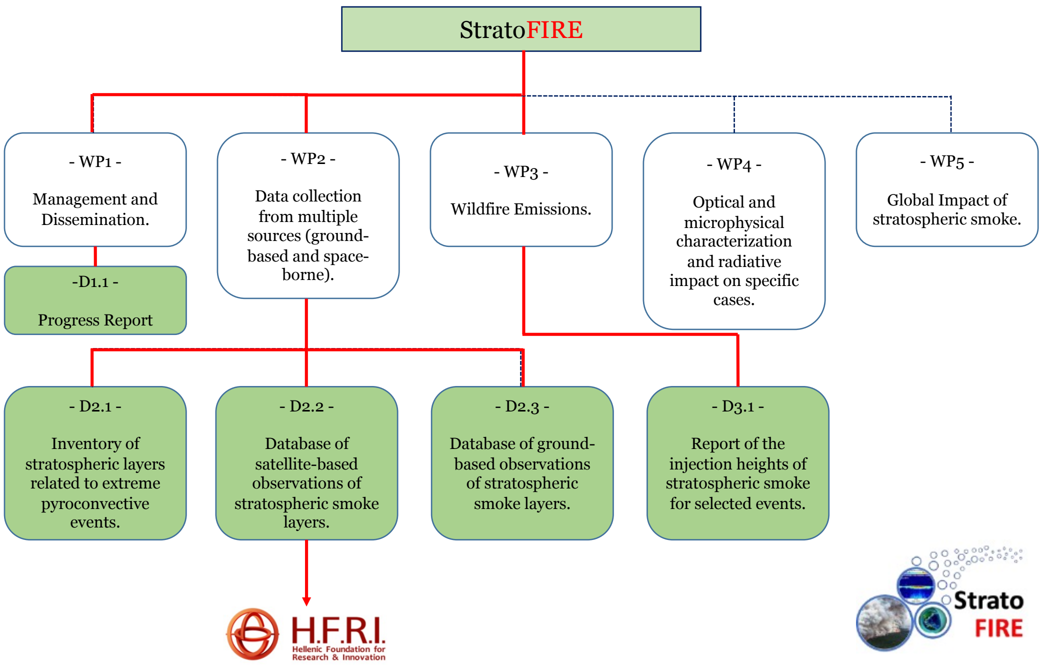


Figure 1 Workflow of StratoFIRE and the deliverables included in this progress report.

Deliverables are separated in two categories: a) reports, such as D1.1 and D3.1 and b) demonstrations, that include description of the datasets and demonstration of some of the research carried out so far in the StratoFIRE. All deliverables are available through the website of the project.

2.2. Risk Management

No serious obstacles are foreseen at this stage. We note some delays because of the necessary reorganization of the team. Reasons and the new team have been detailed to ELIDEK.

2.3. Spinoff Activities

We applied for computing time to the GRNET ARIS HPC. The first round was used to develop the EMAC model and run preparatory simulations. Computing time from the second round will be used to run some production runs in association to WP5.

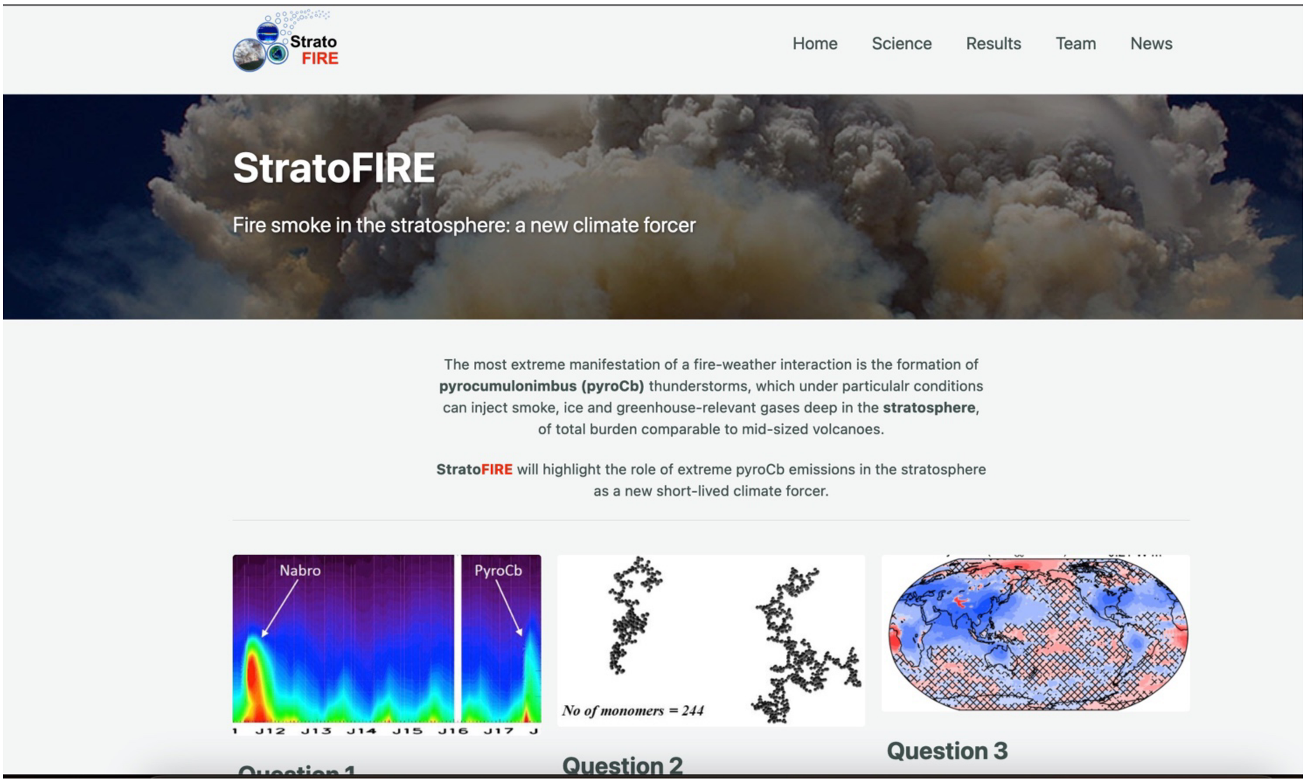
- 14th Call for Proposals for Production Projects (2022-2023), we secured 1200000 CPU hours
- 12th Call for Proposals for Production Projects (2023-2024), we secured 1200000 CPU hours

2.4. Dissemination

2.4.1. StratoFIRE webpage

We designed the project's website to be hosted on the NOA server. This is important to communicate project results because the News section will provide information about smoke events (e.g. the very recent Alberta 2023 wildfires), which can could be forwarded to the StratoFIRE Facebook account. The bebpage describes the objectives of the project and provides a premier on pyroCBs and climate under the Science Tab. Furthermore, it lists the members of the team. The website is **https://stratofire.space.noa.gr/**

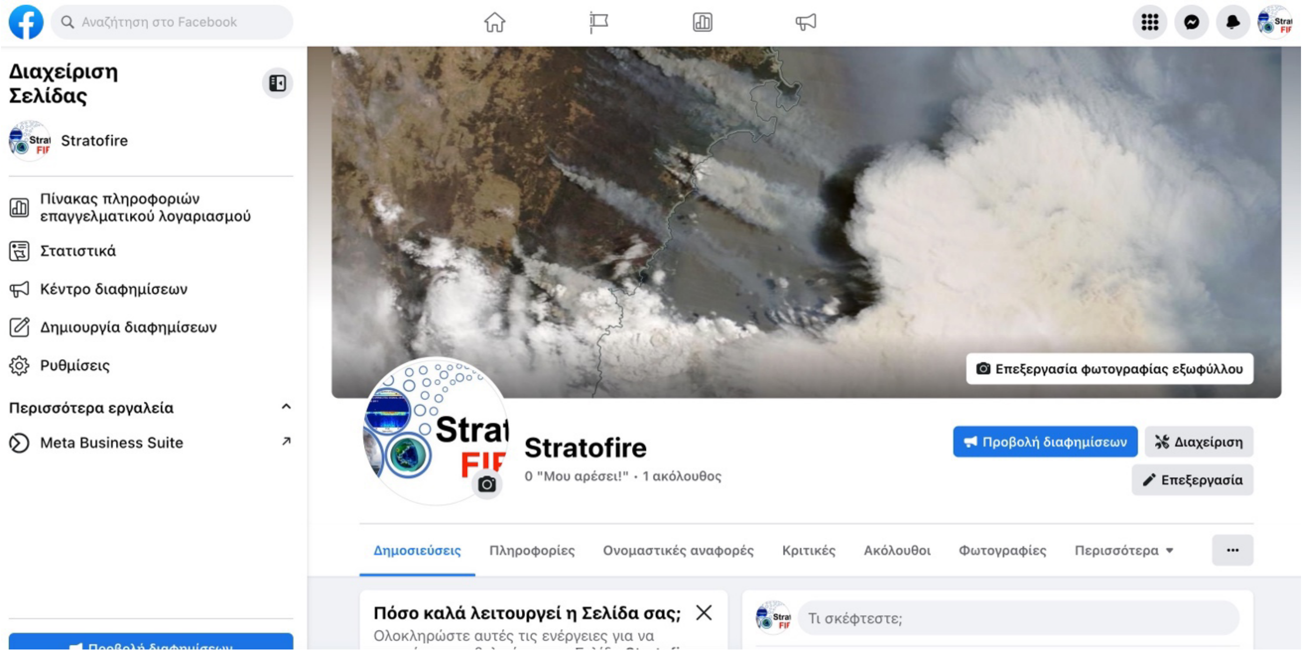
<u>It must be emphasized that all deliverables and datasets will be available to the public through the Results tab.</u>



Picture 1 The webpage of the StratoFIRE accessible through stratofire.space.noa.gr .

2.4.2. StratoFIRE on Facebook

News and research are posted on the Facebook account.



Picture 2 The Facebook account of StratoFIRE.

2.5. Meetings and Conferences

- Drakaki E. et al., Advancing WRF-Chem regional simulations via Aeolus wind assimilation in the framework of the JATAC campaign, Aeolus Science Conference 2023, Rhodes, Greece, 22-26 May, 2023
- Misios S., Chrysanthou A., Tsigaridis K., Amiridis V., StratoFIRE: modelling wildfire smoke in the stratosphere, submitted to 16th International Conference on Meteorology, Climatology and Atmospheric Physics –COMECAP 2023 (25 up to 29 September 2023)

3. D2.1: Inventory of stratospheric layers related to extreme pyro-convective events.

3.1. Overview

Utilizing the Cloud Aerosol Lidar with Orthogonal Polarization (CALIOP) on board the Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO, see also D2.2), we were able to identify smoke aerosols from pyroCBs during intense wildfire events that reached into the stratosphere. CALIOP accurately measures the altitude of the event plumes with a very high vertical resolution in the stratosphere ranging between 60 - 300m. These are detailed in the following Table 1 as in Tackett et al. (2023). Although CALIOP has been taking measurements since 2006, we focus on the last decade to make sure that there is an overlap between various satellite and ground-based remote sensing products used for the purposes of WP2.

From the events listed in Table 1 below, we focus on the most recent two, demonstrating the degree of the impact of wildfire-associated pyroCb leading to enhanced stratospheric aerosol loading. The Pacific Northwest (PNW) event relates to smoke-infused thunderstorms coming about in the British Columbia, Canada as well as in the Washington state, United States on 12 August 2017, injecting between 0.1 -0.3 Tg of aerosol mass into the stratosphere (Peterson et al., 2018) and its plume was measured two days later from CALIPSO over north-east Canada at 12-14km. CALIPSO observations have shown that the smoke-infused plume reached Europe and circumnavigated the globe by the end of the month, affecting the entire Northern hemisphere stratosphere poleward of 30°N.

The most recent major wildfire event over the past decade took place in Southern Australia between 29 December 2019 – 4 January 2020 known as the Australian New Year (ANY) event. Multiple pyroCbs were developed over much of the continent leading to a massive injection of smoke into the stratosphere. The estimated mass of the aerosol injection is almost three times more than the PNW event ranging between 0.2 – 0.9 Tg (Khaykin et al., 2020). The smoke plumes during the first two weeks from the event were measured by CALIOP at 11-22 km, in much of the Southern Pacific Ocean, meaning that the plume was directed eastward, ultimately reaching altitudes of over 30km in February 2020. The smoke injection alongside water vapour deep into the stratosphere was accompanied by strong positive temperature anomaly due to enhanced absorption of solar radiation from the smoke particles. The impact of the ANY event highlighted the role of dynamics and heterogeneous chemistry to the observed mid-latitude and polar ozone depletion later that year (Solomon et al., 2022).

Event Name
Australian New Year (ANY) event, *Dec 2019–Jan 2020*
Pacific Northwest (PNW) event, *Aug 2017*
North American wildfires, *Jul 2014*
Australian bushfires, *Dec 2006*
Black Saturday Australian bushfires, *Feb 2009*
Siberian wildfires, *May 2012*

Siberian wildfires, *Jun 2007*	
Canadian wildfires, *Jul–Aug 2007*	

Table 1 Wildfire-associated smoke events reaching into the stratosphere as classified from the CALIOP v4.5 aerosol typing algorithm and sorted by the number (descending) of unique stratospheric aerosol layers in CALIOP.

Upon identifying the wildfire events that reach into the stratosphere, we use the Ozone Mapping and Profiler Suite Limb Profiler (OMPS-LP) on board the Suomi National Polar-orbiting Partnership (Suomi-NPP) measuring limb-scattered sunlight and provides aerosol extinction ratios at 6 different wavelengths spanning from mid-visible to near infrared as well as ozone profiles in 2012 (Pan et al., 2019). Additionally, we utilize the Aura Microwave Limb Sounder (MLS) version 5 (Livesey et al., 2006) which provides profiles of a suite of atmospheric trace gases, including ozone, water vapor, reservoir and reactive chlorine species, and several markers of biomass burning pollution.

In the section below we present some key figures pertaining to the two wildfire events detailed above. Figure 2 shows the Microwave Sounding Unit channel 4 (MSU4) vertical weighted average of the 745nm extinction ratio (aerosol/molecular) of the OMPS-LP for full available period 2012-2022 at the time of writing. Not accounting for the massive extinction ratio increase due to the Hunga Tonga–Hunga Ha'apai submarine volcanic eruption in February 2022, the ANY wildfires injection of sulphate aerosols into the stratosphere produces a longer-lived surge in the extinction ratio that is if not of a similar magnitude, stronger than the Calbuco eruption in mid-2015 and the Raikoke eruption in mid-2019.

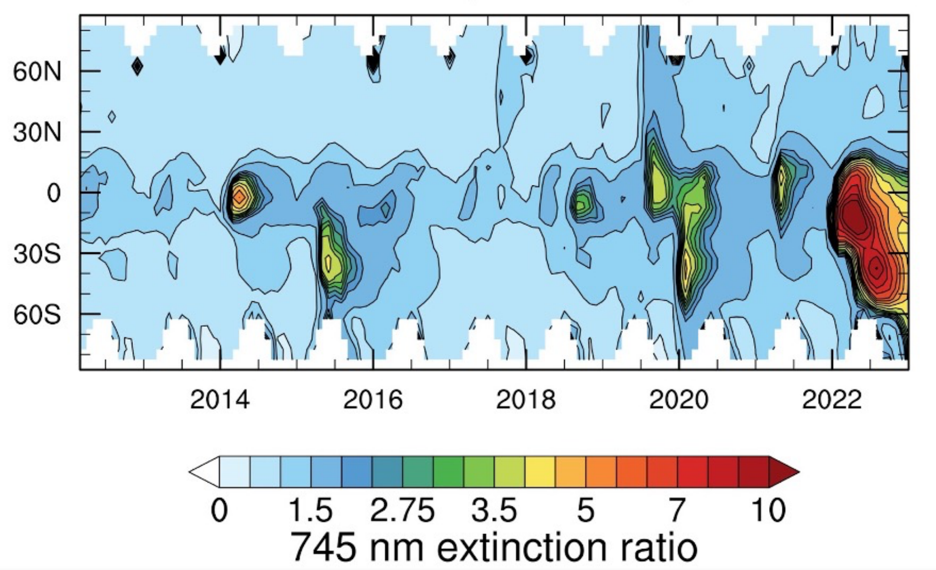


Figure 2 OMPS-LP level 3 monthly mean extinction ratio at 745 nm.

3.2. The Australian New Year event

A closer look to the ANY event as seen from the latitude/altitude cross sections of the extinction ratio at 745 and 510 nm in Figure 2, reveals that the plume at lower altitudes (up to ~13km) was confined in the mid-latitudes and then made its way towards the south pole by February/March 2020. However, higher up the sulphate plume moved equatorward within the first six months surpassing altitudes of 20km. The highest point of the plume impacts as measured by OMPS-LP was located at the same latitude of the initial injection at an altitude of ~31-32km.

The plume of the ANY massive pyroCbs injected into the stratosphere a large quantity of water vapour as seen in Figure 3. MLS data show that a positive anomaly of up to ~ 1ppm (~20-25%) was observed in altitudes below 20km that persisted for more than six months. This positive water vapour anomaly moved equatorwards soon after the event and crossed the tropics to reach the Northern Hemisphere (NH) mid-latitudes within six months of the event showcasing the climate impacts of wildfire stratospheric injections of this scale. The MLS data also show a minor O3 depletion in the lower stratosphere (LS) Southern Hemisphere (SH) mid-latitudes that was not-linked to transport processes; instead associated with enhanced and newly activated ClO concentrations albeit an unprecedented and prolonged HCL depletion (>50%) highlighting the impact of heterogeneous chemistry onto the smoke particles that reached the stratosphere (Santee et al. 2022).

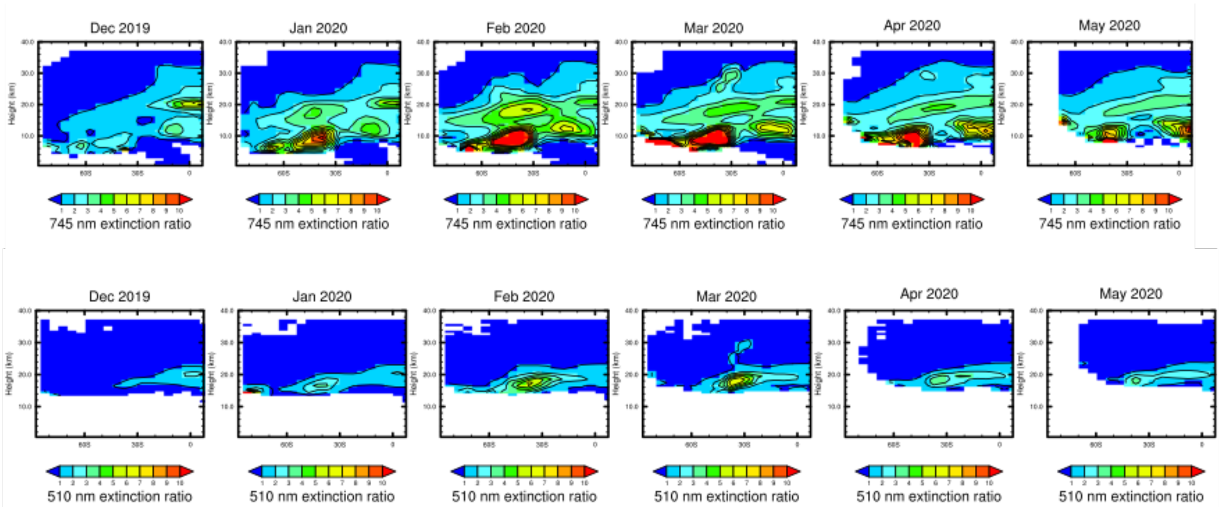


Figure 3 Latitude/altitude cross sections of OMPS-LP level 3 monthly mean extinction ratio at 745 nm (top row) and 510 nm (bottom row) for the first 6-months of the ANY wildfire event.

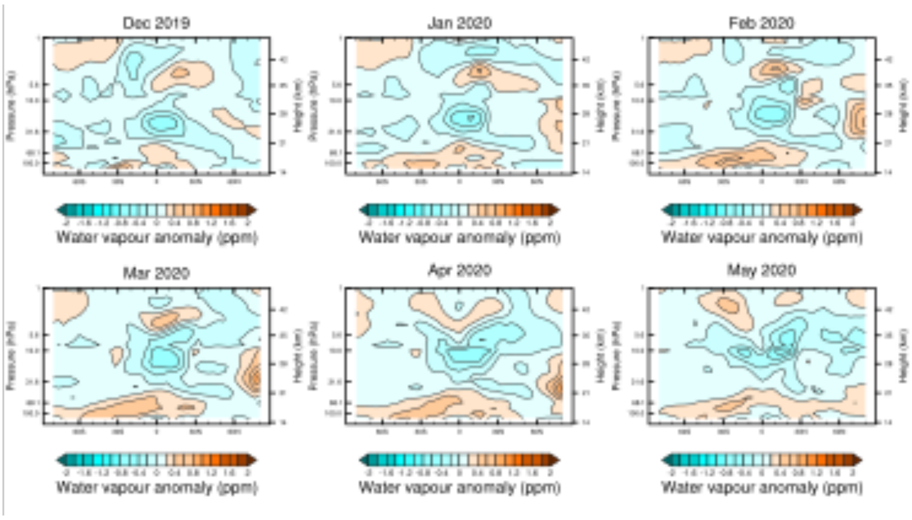


Figure 4 Latitude/pressure cross sections of MLS v5 level 3 monthly mean water vapor anomalies (wrt 2005-2019 climatology) for the first 6-months of the ANY wildfire event.

3.3. The Pacific NorthWest event

In a similar fashion to the analysis presented for the ANY wildfire event, Figure 5 shows the OMPS-LP extinction ratio for two wavelengths for the PNW event. The eruption in August 2017, injected smoke particles into the stratosphere at altitudes up to ~20km. The extinction ratio at 745 nm reached its maximum value (~2.5) in September 2017 as it moved upwards and polewards after a short period of time. The magnitude of this event is not quite comparable to ANY however, it showcases that even smaller scale pyroCbs exhibit the capacity to significantly impact the stratosphere across shorter time-scales. Finally, as seen in the MLS water vapour data in Figure 6, the water vapour anomaly amplitude reached values of 0.5 ppm which is roughly within the envelope of interannual variations in the lower stratosphere. Unlike ANY event the relatively enhanced water vapour in the vicinity dissipated rather quickly and it was well confined below the 20 km altitude level as expected due to the lower injection height of the smoke plume.

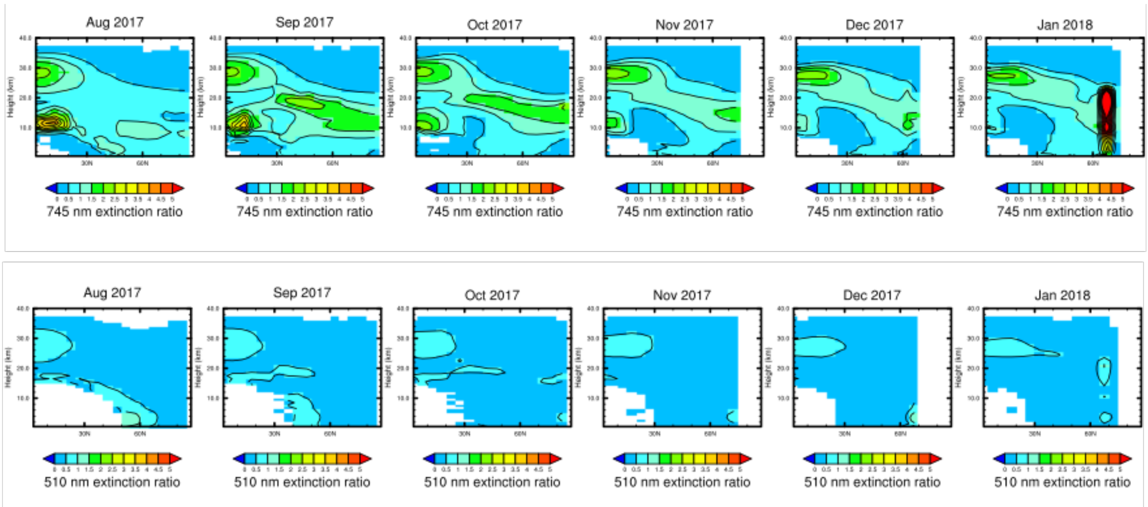


Figure 5 Latitude/altitude cross sections of OMPS-LP level 3 monthly mean extinction ratio at 745 nm (top row) and 510 nm (bottom row) for the first 6-months of the PNW wildfire event.

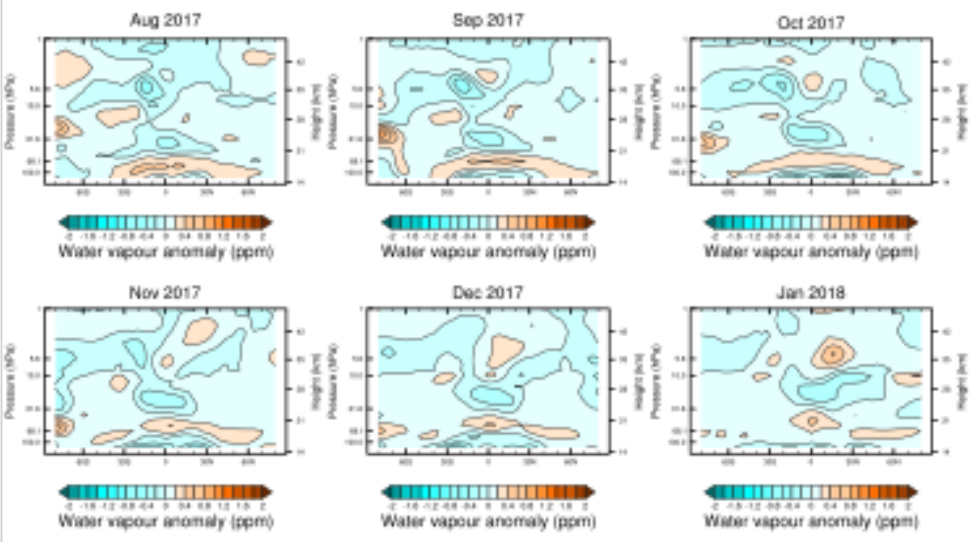


Figure 6 Latitude/pressure cross sections of MLS v5 level 3 monthly mean water vapor anomalies (wrt 2005-2019 climatology) for the first 6-months of the PNW wildfire even

4. D2.2 Database of satellite-based observations of stratospheric smoke layers.

4.1. Overview

StratoFIRE WP2 aims to (a) detect major events of stratospheric aerosol transport and identify the cases related to pyroCb injections and (b) to provide to WP3, WP4, and WP5 the necessary ground-based and satellite observations for the stratospheric aerosol layers, with focus on the specific extreme smoke events (e.g., Canadian 2017, Australian 2019-2020) as well as any future event within the project period.

Towards addressing StratoFIRE Scientific Questions, identification of the major stratospheric perturbations in both hemispheres resulting from extreme smoke events is of high importance. In addition, space-borne datasets have to be extensively used to provide a broader spatiotemporal characterization of specific events and the estimation of the PyroCb source strength/emissions at the tropopause, with focus on specific extraordinary stratospheric smoke cases, inventoried in StratoFIRE WPs.
Towards these objectives, StratoFIRE will make use of several satellite-based observations to probe the upper troposphere - lower stratosphere, during individual intense pyroconvective events, as documented, categorized and inventoried in global pyroCb databases in D2.1.

The present section provides an overview of satellite-based observations used in the StratoFIRE, namely:

- GLOSSAC, which is used in D3.1
- OMPS
- MLS
- CALIPSO-CALIOP, which is a cornerstone of the StratoFIRE WP2 satellite-based observational component

In the following we provide a short introduction to each dataset and describe the files which are distributed by the project.

4.2. GLOSACC

The Global Space-based Stratospheric Aerosol Climatology, or GloSSAC, is a 43-year climatology of stratospheric aerosol properties focused on extinction coefficient measurements by the Stratospheric Aerosol and Gas Experiment (SAGE) series of instruments through mid-2005 and later from mid-2017 and on the Optical Spectrograph and InfraRed Imager System (OSIRIS) and the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) data thereafter (Thomason et al., 2018). SAGEIII/ISS data is also incorporated in GloSSAC to extend the climatology to the present and to test the approach used to correct OSIRIS/CALIPSO data particularly during the time when overlap measurements are available. Data from other space instruments and from ground-based, air and balloon borne instruments to fill in key gaps in the data set. The end result is a global and gap-free data set focused on aerosol extinction coefficient at 525 and 1020 nm and other parameters on an 'as available' basis.

The StratoFIRE database includes the GloSSAC version 2.2, which has been extended through December 2021. A description of the dataset and the updates compared to previous versions is given here:
https://asdc.larc.nasa.gov/documents/glossac/quality_summaries/GloSSAC_Product_Quality_Summary_v2.2.pdf. The source of the original file is:
https://asdc.larc.nasa.gov/project/GloSSAC/GloSSAC_2.2

Description of the dataset

File name: StratoFIRE_GloSSAC_V2.2_Glossac_Aerosol_Extinction_Coefficient_1979-2021_zm_mm.nc

Time Period and resolution: 1979-2021, monthly

Domain: Zonal averaged, 80 height levels

Variables:

StratoFIRE_GloSSAC_V2.2_Glossac_Aerosol_Extinction_C...	StratoFIRE_GloSSAC_V2.2_Glossac_Aerosol_Extinction_Coefficient_19...	Local File
alt	alt	1D
Glossac_Aerosol_Extinction_Coefficient	GloSSAC Aerosol Extinction Coefficient	Geo2D
lat	Latitude	1D
time	time	1D
wavelengths_glossac	GloSSAC Measurement wavelength	–

Table 2 List of all variables in StratoFIRE_GloSSAC_V2.2_Glossac_Aerosol_Extinction_Coefficient_1979-2021_zm_mm.nc

4.3. OMPS

The Ozone Mapping and Profiler Suite (OMPS) on board the Suomi National Polar-orbiting Partnership (NPP) satellite launched in October 2011 consists of the sensors designed to acquire ozone profiles and total ozone measurements (Pan et al., 2019). The three spectrally overlapping sensors scan the air masses and measure the scattering of solar irradiance within 10 minutes. Two out of the three sensors are part of the nadir module; The Total Column Nadir Mapper (TC-NM) measures total column ozone while the Nadir Profiler (NP) measures ozone vertical profiles. The third and last sensor called Limb Profiler (LP) measures vertical ozone profiles (in UV and VIS spectral ranges) spanning from the upper troposphere to the mesosphere with a higher vertical resolution that ranges between 2-3 km.

The StratoFIRE database includes the OMP version 2.0, which has been extended through December 2021. A description of the dataset and the updates compared to previous versions is given here: https://asdc.larc.nasa.gov/documents/glossac/quality_summaries/GloSSAC_Product_Quality_Summary_v2.2.pdf. The the original MPS-NPP LP L2 Aerosol Extinction Vertical Profile swath multi-wavelength daily 3 slit Collection 2 V2.0 data are accessible from the Goddard Earth Sciences Data and Information Services Center (GES DISC), https://doi.org/10.5067/CX2B9NW6FI27

Description of the dataset

File name: STRATOFIRE_OMPS-NPP_LP_L3_AER_MONTHLY_v1.0_201203_202301_mm.nc

Time Period and resolution: 2012/03-2023/01, monthly

Domain: Global, 41 height levels

Variables:

OMPS-NPP_LP_L3_AER_MONTHLY_v1.0_201203_202301.nc	Suomi-NPP OMPS Limb Profiler Gridded Aerosol Data	Local File
Altitude	Altitude	1D
ExtinctionAvg	Extinction coefficient average	Geo2D
ExtinctionStDev	Extinction coefficient standard deviation	Geo2D
ExtinctionStErr	Extinction coefficient standard error	Geo2D
ExtRatioAvg	Aerosol to molecular extinction ratio	Geo2D
ExtRatioStDev	Aerosol to molecular extinction ratio standard deviation	Geo2D
ExtRatioStErr	Aerosol to molecular extinction ratio standard error	Geo2D
Latitude	Latitude	1D
Longitude	Longitude	1D
NumDensAvg	number density average	Geo2D
NumGoodScreen	Number of screened samples	Geo2D
NumSamples	Number of possible samples	Geo2D
Pressure	Background pressure average	Geo2D
ScatteringAngle	Scattering angle average	Geo2D
StratColumn	Aerosol stratospheric column optical depth	Geo2D
Temperature	Background temperature average	Geo2D
time	time	1D
TropopauseAltitude	Tropopause altitude average	Geo2D
Wavelength	Wavelength	1D

Table 3 List of all variables in STRATOFIRE_OMPS-NPP_LP_L3_AER_MONTHLY_v1.0_201203_202301_mm.nc

4.4. MLS

The Microwave Limb Sounder (MLS) aboard the Aura satellite is part of the Earth Observing System (EOS) and since August 2004, provides daily daytime/night-time measurements of ozone profiles (~3500 profiles each day) on a global scale as well as trace gases from the upper troposphere to the upper mesosphere (~90km). Aura MLS vertically scans the Earth's atmosphere limb in five broad regions of the electromagnetic spectrum ranging between 118 GHz and 2.5 THz and measures thermal radiance emissions. Contrary to similar instruments that measure emissions in a direction perpendicular to the spacecraft flight direction, MLS scans the atmosphere directly ahead of the Aura satellite which follows a sun-synchronous near-polar orbit with ascending equatorial crossing time of ~13:45 local time (LT). The MLS retrieves water vapour from the 190 GHz radiometer and ozone from the 240 GHz spectral band using optimal estimation approach with a high vertical resolution that spans between 2.5-3km from the upper troposphere to the lower mesosphere and a 5km vertical resolution in the upper mesosphere.

The StratoFIRE database includes the MLS version 5.0, which has been extended through December 2022. A description of the dataset is given here: https://mls.jpl.nasa.gov/data/v5-0_data_quality_document.pdf The original MLS Level 3 data described here can be obtained from the NASA Goddard Space Flight Center Earth Science Data and Information Services Center (GES-DISC, see https://disc.gsfc.nasa.gov/)

Description of the dataset

File name: STRATOFIRE_H2O_MLS_v5_2005-2022_mm.nc

Time Period and resolution: 2005-2022, monthly

Domain: Global, 55 pressure levels

Variables:

STRATOFIRE_H2O_MLS_v5_2005-2022.nc	N/A	Local File
H2O_PressureGrid	H2O_PressureGrid	—
lat	Latitude	1D
lev	Pressure	1D
lon	Longitude	1D
std_dev	Standard Deviation of Water	Geo2D
time	Time	1D
value	Average Value of Water	Geo2D

4.5. CALIPSO-CALIOP

The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) mission (Winker et al., 2010) is a joint satellite project, developed, operating and maintained in close and ongoing collaboration between the National Aeronautics and Space Administration (NASA), the United States space agency, and the Centre National D'Études Spatiales (CNES), the French space agency. The satellite CALIPSO was launched on April 28th, 2006, to be integrated in the Afternoon-Train (A-Train) constellation of sun-synchronous polar-orbit satellites hosting a suite of three Earth-observing instruments, in a near-nadir-looking configuration: a single channel 645 wide field-of-view camera (WFC), a three channel (8.65, 10.6, 12.05 μm) Imaging Infrared Radiometer (IIR), and the principal payload, the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) lidar (Hunt et al., 2009). The primal instrument, CALIOP, is a dual-wavelength polarization-sensitive elastic backscatter Nd:YAG lidar, that transmits linear polarized light pulses at 532 and 1064 nm, and accordingly, makes separate range-resolved measurements of the backscattered signals by atmospheric features, and specifically, of the parallel and perpendicular components of the backscattered photons at 532 nm with respect to the polarization plane of CALIOP emitted beam, and the total backscatter intensity at 1064 nm.

Because CALIPSO dataset is the cornerstone of the StratoFIRE WP2 satellite-based datasets, we provide an extensive description of main characteristics of the satellite platform and the dataset of interest.

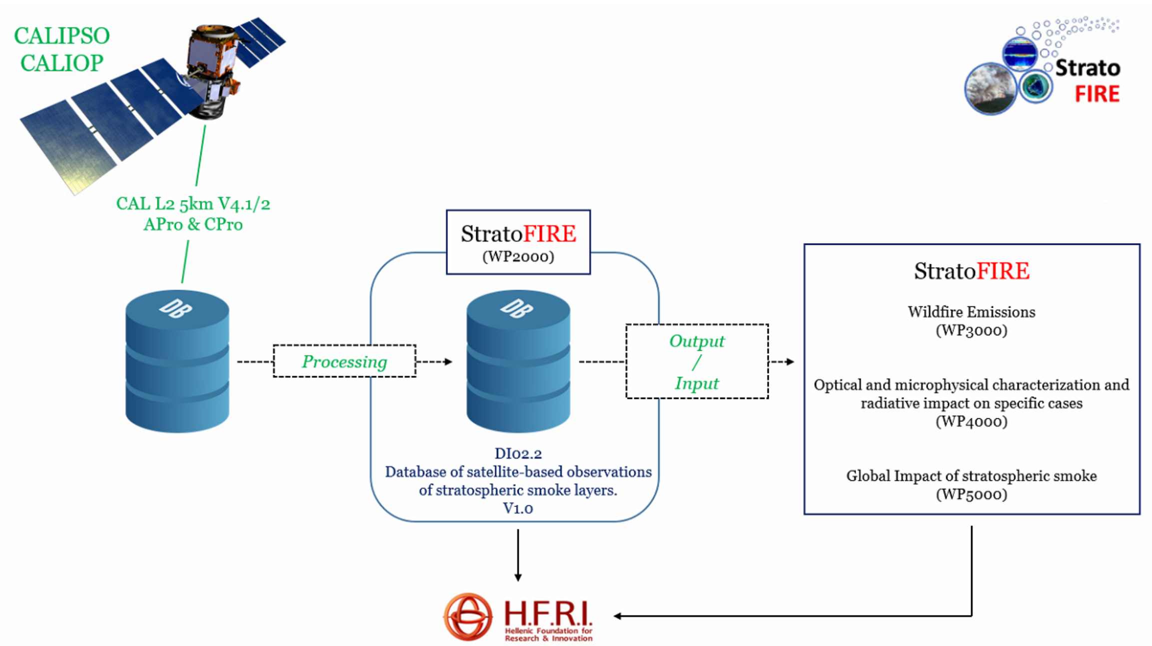


Figure 7 StratoFIRE Work Logic for CALIPSO-CALIOP.

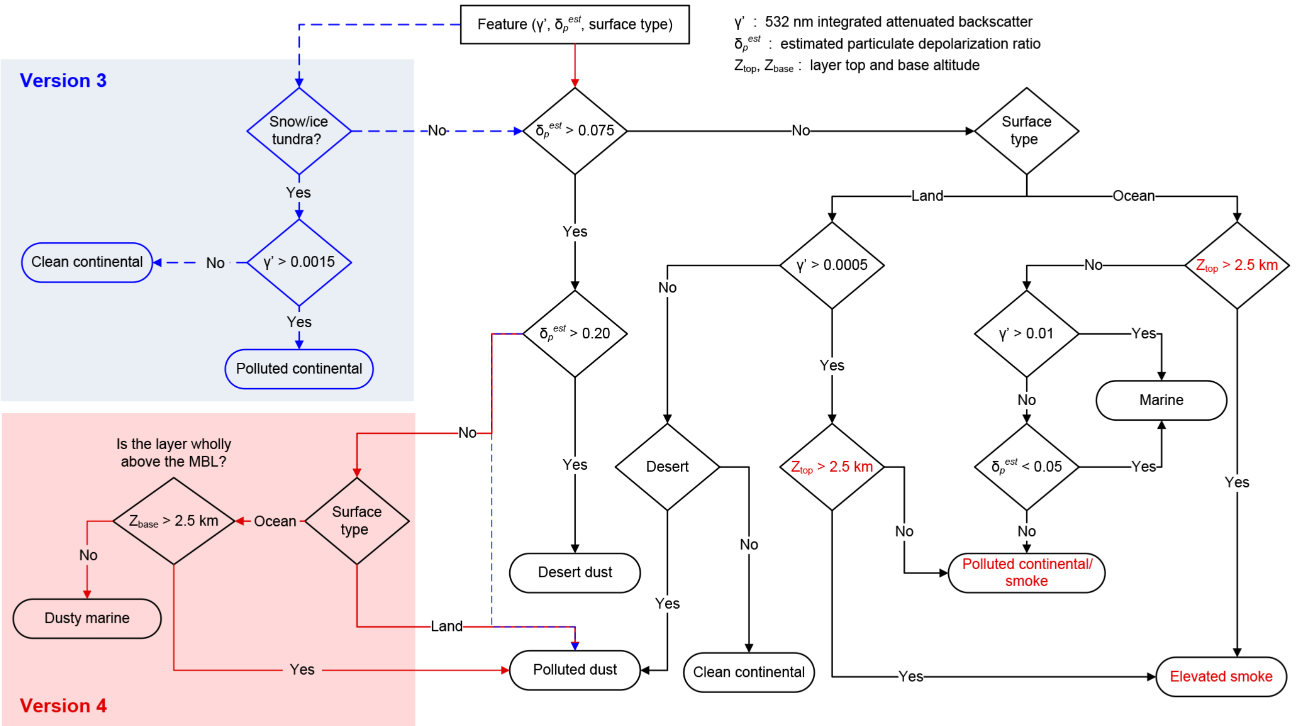


Figure 8 Flowchart of the CALIPSO aerosol subtype selection scheme for tropospheric aerosols (source:(Kim et al., 2018)).

CALIOP measurements and products are provided in different levels of processing. The received measurements of attenuated backscatter from molecules and particles are provided in 1/3 km horizontal and 30 m vertical resolution and reported in CALIOP Level 1 data products. Subsequently, CALIOP Level 1 measurements are processed to CALIOP Level 2 products, following a sophisticated chain of algorithms that perform a sequence of functions, including the fundamental for the retrievals daytime and nighttime calibration of the three receiver channels, layer detection and cloud-aerosol discrimination. In addition, in the process to retrieve particulate extinction profiles, an intermediate aerosol classification and Lidar Ratio selection algorithm for feature detection classifies atmospheric features between "clear-air", "tropospheric aerosol", "stratospheric aerosol", "cloud", "surface", "subsurface", "totally attenuated", and aerosol and cloud features of "low/no confidence". The algorithm modules further classify atmospheric features categorized as "tropospheric aerosol" between "marine", "dust", "polluted continental/smoke", "clean continental", "polluted dust", "elevated smoke" and "dusty marine" (Kim et al., 2018) – (Figure 10), and in the case of "stratospheric aerosol" between "PSC aerosol", "volcanic ash", and "sulfate/other"– (Figure 11).

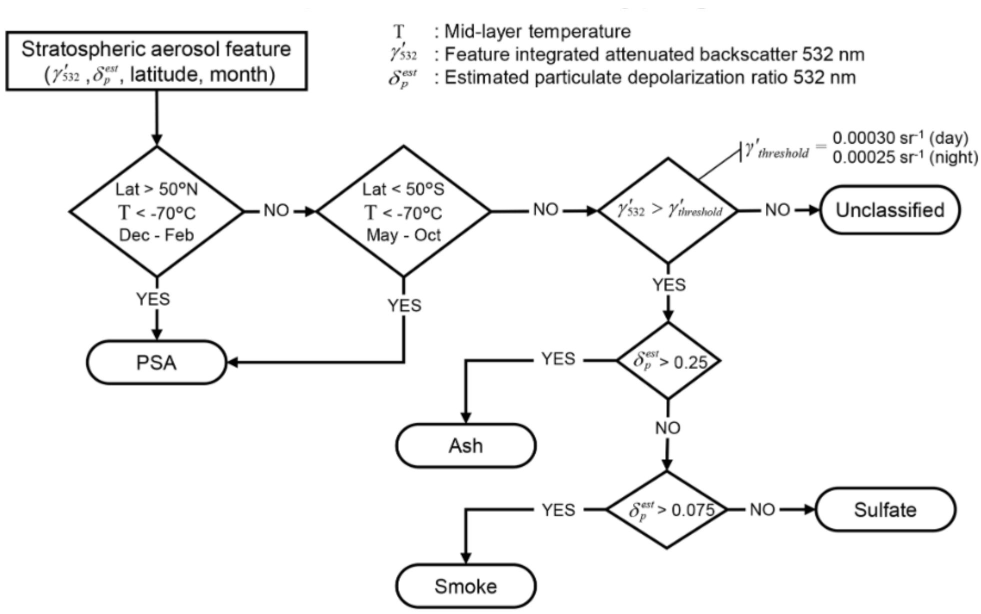
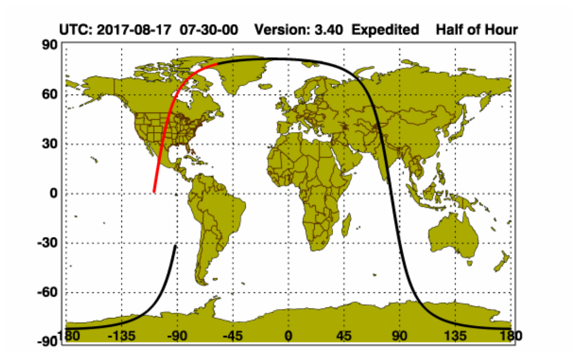
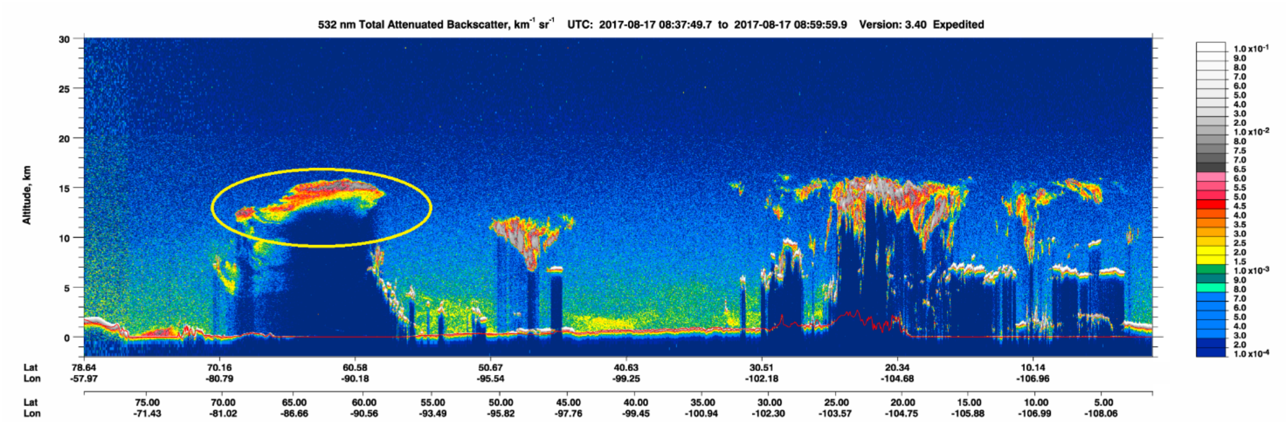
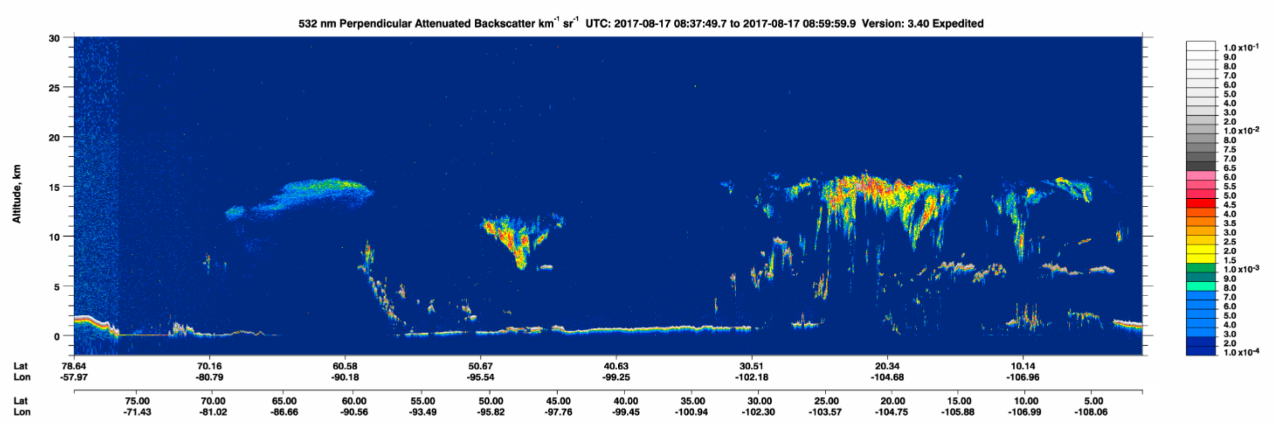


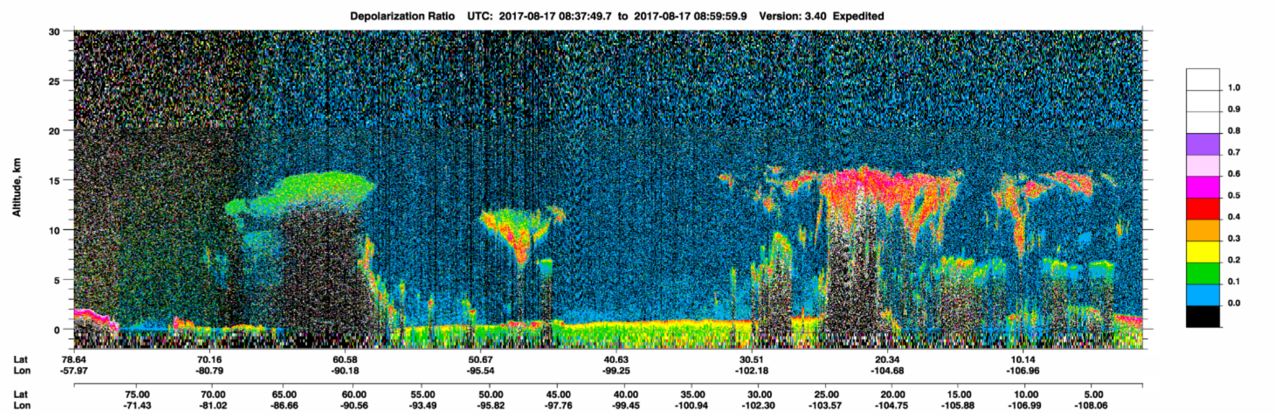
Figure 9 Flowchart for stratospheric aerosol subtyping in the V4.5.

During the massive Pacific Northwest (PNW) event in August 2017, smoke injected into the lower stratosphere. An example CALIOP observation of one of the earliest smoke plumes detected from the event (Torres et al., 2020) is shown in the panels of Figure 12. More specifically, Figure 12 provides the CALIPSO overpass (Fig. 12a), the total attenuated backscatter 532nm (Fig. 12b), the perpendicular attenuated backscatter at 532nm (Fig. 12c), the volume depolarization ratio at 532nm (Fig. 12d), and the feature type classification for the selected example scene (Fig. 12e).






532 nm Perpendicular Attenuated Backscatter km-1 sr-1 UTC: 2017-08-17 08:37:49.7 to 2017-08-17 08:59:59.9 Version: 3.40 Expedited
Altitude, km
Lat
Lon
78.64 -57.97
70.16 -80.79
60.58 -90.18
50.67 -95.54
40.63 -99.25
30.51 -102.18
20.34 -104.68
10.14 -106.96
75.00 -71.43
70.00 -81.02
65.00 -86.66
60.00 -90.56
55.00 -93.49
50.00 -95.82
45.00 -97.76
40.00 -99.45
35.00 -100.94
30.00 -102.30
25.00 -103.57
20.00 -104.75
15.00 -105.88
10.00 -106.99
5.00 -108.06


Depolarization Ratio UTC: 2017-08-17 08:37:49.7 to 2017-08-17 08:59:59.9 Version: 3.40 Expedited
Altitude, km
Lat
Lon
78.64 -57.97
70.16 -80.79
60.58 -90.18
50.67 -95.54
40.63 -99.25
30.51 -102.18
20.34 -104.68
10.14 -106.96
75.00 -71.43
70.00 -81.02
65.00 -86.66
60.00 -90.56
55.00 -93.49
50.00 -95.82
45.00 -97.76
40.00 -99.45
35.00 -100.94
30.00 -102.30
25.00 -103.57
20.00 -104.75
15.00 -105.88
10.00 -106.99
5.00 -108.06

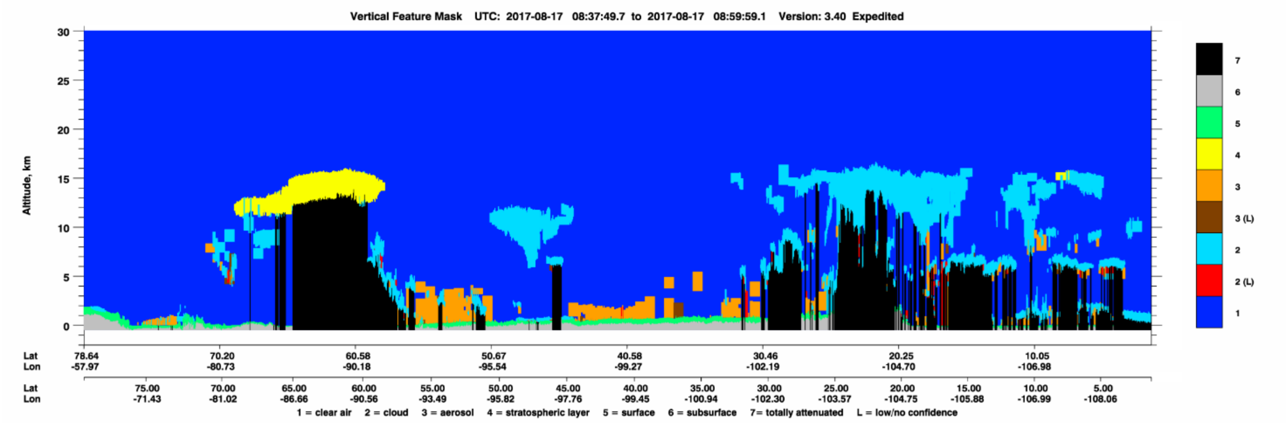


Figure 10 PyroCb smoke plume from the PNW event on 17th of August 2017 in the proximity of Quebec Province, Canada. During the massive PNW event smoke injected into the lower stratosphere: CALIPSO overpass (Fig. 12a), the total attenuated backscatter 532nm (Fig. 12b), the perpendicular attenuated backscatter at 532nm (Fig. 12c), the volume depolarization ratio at 532nm (Fig. 12d), and the feature type classification for the selected example scene (Fig. 12e).

Description of the dataset

File name: collection of netcdf files. Example: StratoFIRE_lat_c_-7.5_lon_c_-137.5_062006-052021.nc

Time Period and resolution: 06/2006-05/2021, tracks

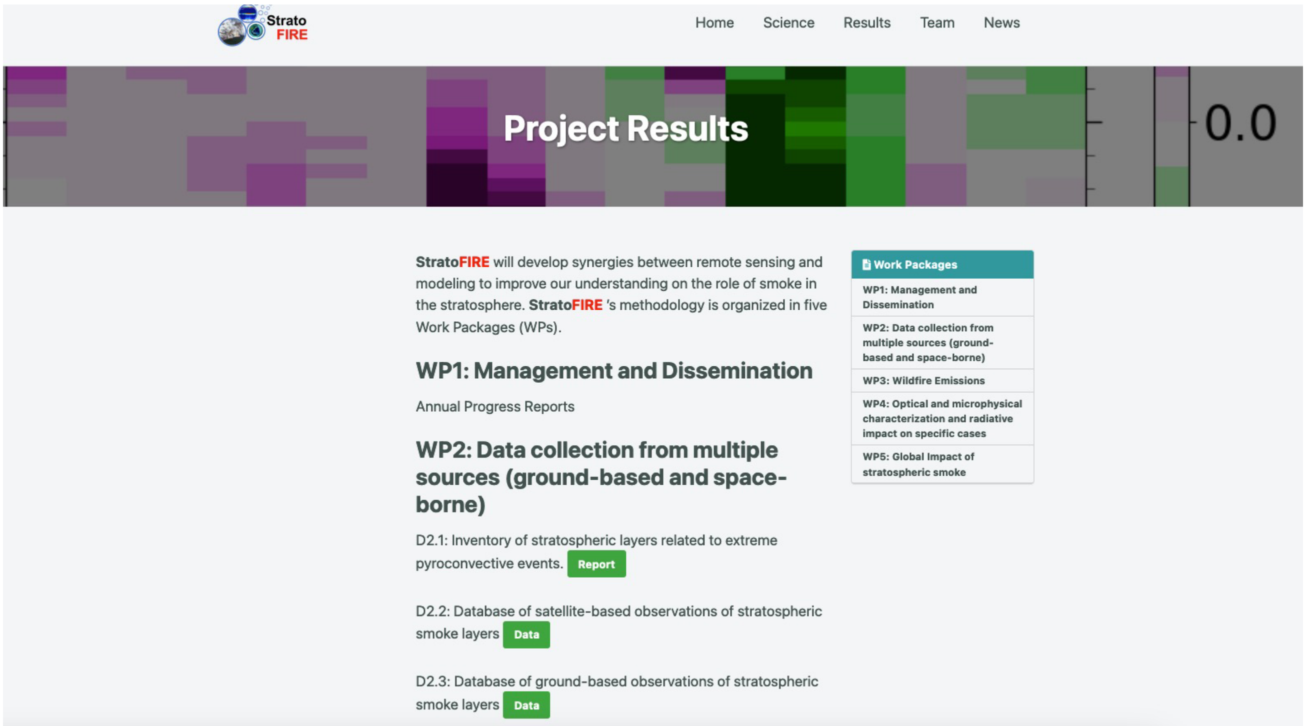
Domain: Global, 399 height levels

Variables:

StratoFIRE_lat_c_7.5_lon_c_-97.5_062006-052021.nc	StratoFIRE_lat_c_7.5_lon_c_-97.5_062006-052021.nc	Local File
Backscatter_Coefficient_532nm_mean	Backscatter Coefficient 532nm – mean	2D
Backscatter_Coefficient_532nm_SD	Backscatter Coefficient 532nm – SD	2D
Extinction_Coefficient_532nm_mean	Extinction Coefficient 532nm – mean	2D
Extinction_Coefficient_532nm_SD	Extinction Coefficient 532nm – SD	2D
Height	km	1D
Tropopause_Height_mean	Tropopause Height – mean	1D
Tropopause_Height_SD	Tropopause Height – SD	1D

4.6. Database access

Access to the HFRI- StratoFIRE D2.2 dataset is provided via the project's Webpage. The user should go to Results tab and the select the deliverables of each work package, as demonstrated in Picture 3.



Picture 3 The satellite-based database of D2.2 is accessible from the webpage.

5. D2.3: Database of ground-based observations of stratospheric smoke layers.

5.1. Overview

StratoFIRE WP2 aims to (a) detect major events of stratospheric aerosol transport and identify the cases related to pyroCb injections and (b) to provide to WP3, WP4, and WP5 the necessary ground-based and satellite observations for the stratospheric aerosol layers, with focus on the specific extreme smoke events (e.g., Canadian 2017, Australian 2019-2020) as well as any future event within the project period.

StratoFIRE will make use of two sites of ground-based lidar observations to probe the upper troposphere - lower stratosphere, during individual intense pyroconvective events. It must be mentioned that the number of sites and the spatial and temporal coverage of the ground-based data are significantly lower compared to D2.2 satellite products.

The present section provides an overview of satellite-based observations used in the StratoFIRE, namely:

- Leipzig EARLINET
- PANGEA EARLINET

In the following we provide a short introduction to each dataset and describe the files which are distributed by the project.

5.2. Leipzig EARLINET

The highest smoke load over EARLINET stations has been reported at Leipzig, Germany for the Pacific- Northwest event (Ansmann et al., 2018). Measurements at the Leibniz Institute of Tropospheric Research (TROPOS) were conducted with the BERTHA (Backscatter Extinction lidar-Ratio Temperature Humidity profiling Apparatus) multi-wavelength polarization Raman lidar system. The system measures the total and cross-polarized component of the elastic backscattered light at 355, 532 and 1064 nm, which are used to derive the PLDR at these wavelengths. It is also able to perform independent measurements of the aerosol extinction coefficient at 387, 607 nm and (after optics re-arrangement) at 1058 nm, and thus has a capability to provide 10 the LR profiles at 355, 532 and 1064 nm. On August 22, the profiles of the stratospheric smoke backscatter and extinction coefficients at 355, 532 and 1064 nm and the smoke PLDR at 355 and 532 nm were derived from two-and-a- half-hour averaging of the lidar signals between 20:45 and 23:17 UTC. The PLDR value at 1064 nm was calculated using a forty-minute averaging between 23:50 and 00:30 UTC. The gap between the end of the first measurement and the beginning of the second, corresponds to the necessary time for the rearrangement of BERTHA optics.
Layer-integrated values of PLDR and LR for the stratospheric smoke layer are derived, which show values typical for aged Canadian smoke at 355 nm (40 ± 16 sr) and 532nm (66 ± 12 sr). Low signal-to-noise ratio at the plume height prevented detailed retrievals of particle extinction coefficient at 1058 nm. Thus, for the LR values at 1064 nm only few measurement points could be derived. This yields a LR value of 92 ± 27 sr at 1064 nm.

Description of the dataset

File name: collection of dat files.

Time Period: 22-Aug-2017

Domain: Leipzig

Variables: backscatter coefficients, extinction coefficients and depolarization ratio

5.3. PANGEA EARLINET

The PANGEA observatory of NOA in the remote island of Antikythera, is located across the travel path of different air masses, providing continuous monitoring of essential climate variables in the Eastern Mediterranean. The Aerosol Remote Sensing facility of ACTRIS (Aerosol, Clouds, and Trace Gases Research Infrastructure; actris.eu) is collecting continuous observations of aerosols and clouds since 2018.

The parameters used are collected from the Polly^{XT}-NOA lidar (part of EARLINET). The Polly^{XT}-NOA lidar is a multi-wavelength Raman-polarization system with 24/7 operational capabilities, providing vertical distributions of the particle backscatter coefficient (β) at 355, 532, and 1064 nm, the extinction coefficient (α) at 355 and 532 nm and the particle depolarization ratio (δp) at 355 and 532 nm.

With the observations, and using well known methodologies, we can separate spherical and non-spherical particles in mixed aerosol layers, towards aerosol characterization. In addition, using parameterizations based on AERONET retrievals we can estimate vertical distributions of aerosol concentrations for different aerosol species (e.g., dust, smoke, and marine) from 200 m above the ground up to ~16 km .

Description of the dataset

File name: collection of dat files.

Time Period and resolution: 2020-present,

Domain: Antikythera

Variables: backscatter coefficients, extinction coefficients and depolarization ratio

5.4. Database access

Access to the HFRI- StratoFIRE D2.3 dataset is provided via the project's Webpage. The user should go to Results tab and the select the deliverables of each work package, as demonstrated in Picture 3.

6. D3.1: Report of the injection heights of stratospheric smoke for selected events

6.1. Introduction

The largest known stratospheric smoke injection was associated with the fierce Australian wildfires in the New Year of 2019/2020 (ANY hereafter). Many pyroCbs injected over 1 million tons of smoke particles into the stratosphere, reaching altitudes up to 35 kilometers. The mass and reach of this aerosol injection exceeded all volcanic aerosol injections over the last 30 years. Satellite- and ground-based measurements subsequently detected self-lofting, significant stratospheric warming, and a considerable reduction in mid-latitude ozone that lasted several months. During November-December 2020, the Antarctic ozone hole reached a decadal high in magnitude and persistence, along with record-low polar temperatures and a strong polar vortex. The magnitude of the rec-ord-high ozone depletion event in 2020 corresponds to a ~10-year delay in ozone recovery.

6.2. Injection heights: model vs satellites

Wildfires need to be investigated with respect to their relation to weather, climate, and society. Here, we use the EMAC Earth System Model to simulate atmospheric and climatic responses to the ANY wildfires. The model is configured with a) aerosol microphysics, b) chemistry with heterogenous reactions, c) a scheme for PSCs, and d) comprehensive chemistry-radiation-dynamics interactions. EMAC links together all the key mechanisms between the stratosphere and surface, which makes it possible to quantify how strato-spheric smoke affects the global radiative balance, circulation, ozone concentrations, and surface UV levels and precipitation patterns.

As a first step, we carry out sensitivity simulations to examine the sensitivity of the stratospheric aerosol loading to injection height of the smoke (Table 2). The model is running with nudged meteorology from ERA5 till 28 December 2019 and freely thereafter till the end of 2020. We emit 0.9 Tg of smoke composed by 97.5% organic carbon and 25 % Black Carbon. The particles are emitted in the insoluble Aitken mode.

Simulation	Description
Free_13Km	Nudging ends 28 Dec 2019. Emission 11-13 Km
Free_14Km	As Free but emission between 11-14 Km
Free_15Km	As Free but emission between 11-15 Km
Free_16Km	As Free but emission between 11-16 Km

Table 4 List of the sensitivity simulations with the EMAC model.

Figure 13 shows aerosol extinction coefficients (1/Km) averaged from 20S to 60S at 14, 18 and 22 Km. Superimposed in dots are extinction coefficients from the monthly mean GLOSSAC merged aerosol dataset and SAGE-ISS observations. Our model generally shows a faster increase in the extinction coefficients in the fist months after the ANY pyroCBs whether observations indicate a more gradual buildup, peaking in March 2020. Similar behavior is simulated in 20 Km. At 24 Km the model underestimates considerably the magnitude of the aerosol extinction by the injected smoke in all sensitivity runs. Regarding the emission height, we find that a maximum injection of smoke at 16 Km gives the best similarity to the observed extinction.

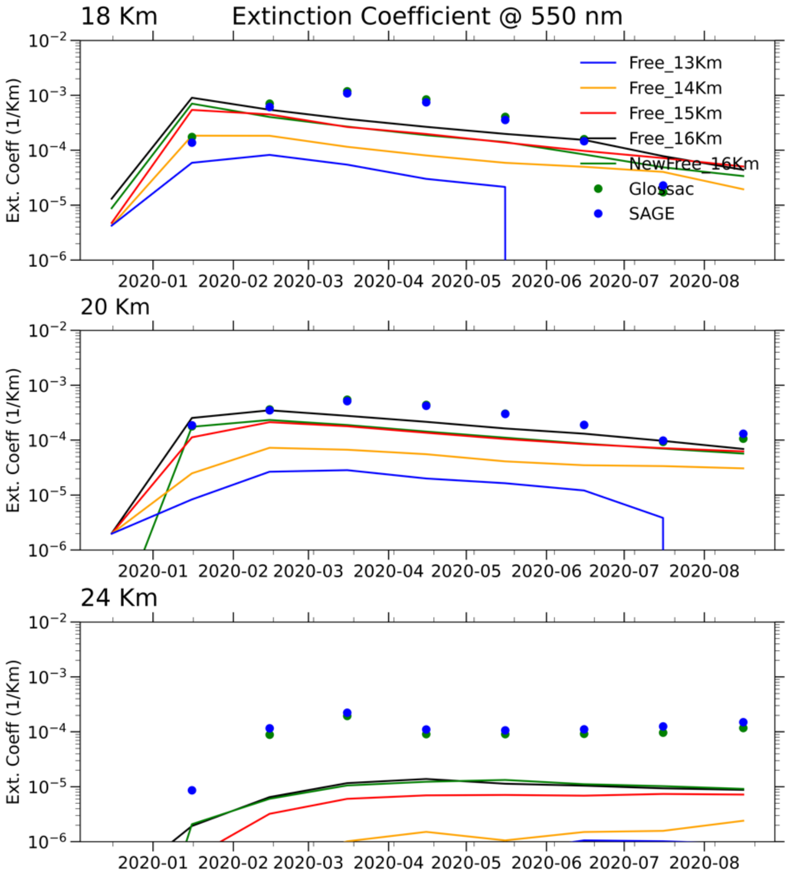


Figure 13 Extinction coefficients (lines) averaged between 20S-60S in the simulations with EMAC. Dots indicate extinction coefficients from SAGE (blue) and Glossac (green) datasets. Units in 1/Km.

Figure 14 compares the time evolution of the stratospheric aerosol optical depth (SAOD) from the ANY wildfires assuming different emission heights. We find that an injection height at 13 Km perturbs aerosols in the stratosphere for 5 months only. In contrast, an injection at 16 Km height causes an aerosol perturbation in both hemispheres. In the Southern Hemisphere, SAOD is perturbed even in the following year with values above 0.001. Interestingly, smoke penetrates in the Northern Hemisphere and reaches the Arctic in June-July 2020.

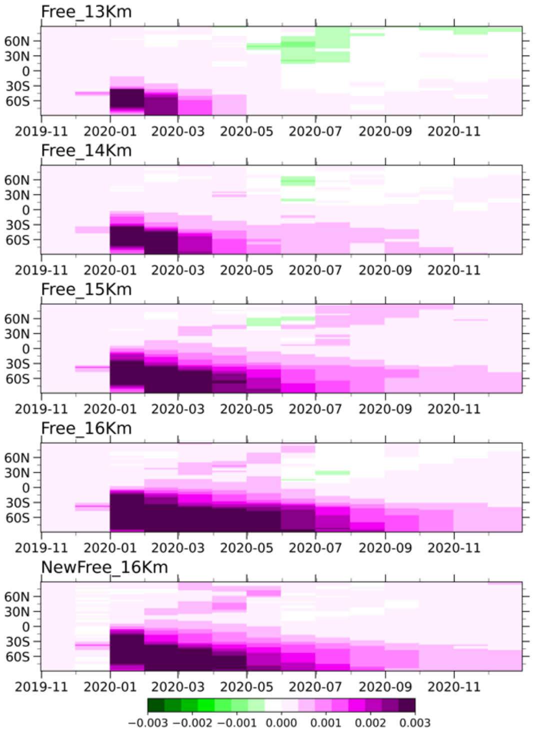


Figure 14 Latitude-time cross sections of stratospheric aerosol optical depth in the EMAC sensitivity simulations.

In the first set of simulations presented here, we examined the sensitivity of the SAOD to the injection height of the smoke plume. The best agreement with observations is found by assuming a maximum injection height at 16 Km. The next step will be to quantify the radiative perturbations in the stratosphere and the global radiative forcing after ANY. Smoke, however, presents rather different properties from the liquid, spherical, less light-absorbing sulfuric acid droplets of volcanic origin that are usually found at strato-spheric altitudes. StratoFIRE will explore a detailed characterization of the optical and microphysical properties of stratospheric smoke, which at present remain poorly understood mainly due to the sparsity of the remote sensing /in-situ observations in the LS. This uncertainty complicates considerably any assessment about the radiative impacts of stratospheric smoke.

7. Acronyms and Abbreviations

APro	Aerosol Profile.
A-Train	Afternoon Train.
CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarization.
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation.
CNES	Centre National D'Études Spatiales.
DI	Deliverable Item.
Fig.	Figure.
HFRI	Hellenic Foundation for Research & Innovation.
IAASARS	Institute for Astronomy, Astrophysics, Space Applications & Remote Sensing.
IIR	Imaging Infrared Radiometer.
L1	Level 1.
L2	Level 2.
NASA	National Aeronautics and Space Administration.
NOA	National Observatory of Athens.
PNW	Pacific Northwest.
PyroCb	Pyrocumulonimbus.
StratoFIRE	Fire smoke in the stratosphere: a new climate forcer.
V01	Version 01.
V04	Version 04.
WFC	Wide field-of-view camera.
WL	Work Logic.
WP	Work Package.

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