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Swiss Made Measurement Techniques for Carbonaceous Aerosols

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Abstract: Carbonaceous aerosols (CA) represent a chemically and physically diverse class of airborne particles. Their relevance for climate and health is significant, but poorly understood. Conventional metrics, such as particulate matter (PM_{10} or $PM_{2.5}$), are insufficient to capture their impact. More specific indicators, such as elemental and organic carbon (EC and OC) and equivalent black carbon (eBC), often suffer from methodological artefacts, limited compatibility, and insufficient time resolution. In this work, we present an overview of the techniques and measurement systems developed by members of our group at FHNW for improved *in situ* quantification and characterization of CA. Photoemission-based sensors provide a real-time signal that serves as a proxy for particle-bound polycyclic aromatic hydrocarbons (PAHs), which include well known carcinogenic substances. Photothermal methods, such as photothermal interferometry (PTI) and photoacoustic spectroscopy (PAS), are used for direct observation of light absorption — an optical property directly linked to climate effects — without artefacts inherent to filter-based measurements. The fast thermal carbon totalizator (FATCAT) provides robust, unattended measurement of total carbon with high time resolution and generates fast-thermograms that reveal volatility and refractivity. Collectively, these methods address key limitations of current CA monitoring and support the long-term goal of integrating relevant metrics into air quality monitoring and climate observation networks.

Keywords: Air quality monitoring · Carbonaceous aerosol · Photoemission spectroscopy · Photothermal spectroscopy · Total carbon

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1. Introduction

1.1 *Historical Context*

The realization that carbonaceous aerosols (CA) are harmful has evolved gradually over the past century, as scientific understanding and environmental awareness have grown. Early concerns were mostly about visible smoke and soot emissions, but major events like the Great Smog of London in 1952—which caused thousands of deaths—highlighted the severe health risks of particulate pollution.[1,2] By the 1970s to 1990s, scientific research began to distinguish between different types of carbonaceous aerosols, revealing their roles in both climate change and public health.

By the early 2000s, black carbon (BC) was identified as the second most important contributor to global warming after CO_2, due to its ability to absorb sunlight and reduce snow albedo.[3] Nevertheless, the radiative forcing of BC is more complex and uncertain than that of long-lived greenhouse gases. Factors such

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as mixing state, atmospheric lifetime, and spatial distribution significantly influence its climate impact and contribute to the associated uncertainties.[4]

More recent epidemiological studies linked CA exposure to cardiovascular and respiratory diseases, and premature mortality.[5,6] A new study[7] has confirmed that lung cancer is significantly more prevalent among people living in areas with high levels of air pollution. Paisi *et al.*[8] quantified the excess mortality attributed to CA in Europe, showing they may be twice as toxic as inorganic particulate matter ($PM_{2.5}$) components. According to the World Health Organization (WHO), air pollution caused approximately 6.7 million deaths globally in 2019, combining both ambient (outdoor) and household air pollution.[9] This includes deaths from heart disease, stroke, chronic obstructive pulmonary disease, lung cancer, and pneumonia.

In November 2024, the revised EU Ambient Air Quality Directive designated black carbon and elemental carbon as pollutants of emerging concern, requiring measurements at monitoring supersites to support research on their health and environmental impacts.[10]

In Switzerland, research on atmospheric aerosols began in the 1970s with a focus on sulfates and broadened in the 1980s to other aerosol types.[11] In the late 1970s, Prof. Siegmann started his pioneering work at ETH Zurich in the field of aerosol photoemission.[12,13] He and his team also applied this technique to identify combustion aerosols like diesel soot.[14,15] Over the years, this has enabled the development of innovative automatic sensors that are used to characterize air pollution, in particular for the detection of particle-bound polycyclic aromatic hydrocarbons (PAHs), which enhance the photoelectric yield if present at the particle surface.[16,17] PAHs are produced in any incomplete combustion of organic fuels, like combustion engines, cigarette smoke, and wood burning, and include well known carcinogenic substances.[18] Already back then, Prof. Siegmann publicly stated that the exposure to vehicle emissions caused human lung cancer[19] (Fig. 1).

The International Agency for Research on Cancer (IARC) classified diesel engine exhaust as probably carcinogenic to humans (Group 2A) in 1988, and as carcinogenic to humans (Group 1) in 2012, while gasoline exhaust has been classified as possibly carcinogenic to humans (Group 2B) since 1989.[20] These particles often carry PAHs and metals, which contribute to oxidative stress, DNA damage, and inflammation — key mechanisms in cancer development. This led to stronger environmental policies and emission controls worldwide.

1.2 *Carbonaceous Aerosols: Properties and Definitions*

CA are a diverse class of fine airborne particles containing carbon in different forms, including elemental carbon (such as graphitic or amorphous carbon) and a wide variety of organic compounds. Soot is a subset of CA consisting of fractal-like structures of carbonaceous spherical primary particles (typically 10–50 nm in diameter) formed during incomplete combustion. It originates largely from anthropogenic sources such as the combustion of fossil fuels and biomass burning.

In addition to primary emissions, CA also forms through atmospheric processes. Specifically, secondary organic aerosol (SOA) forms when volatile organic compounds — emitted by plants, combustion processes, or industrial processes — react with atmospheric oxidants like ozone, nitrogen oxides or hydroxyl radicals.[21] These reactions yield low-volatility compounds that condense into the particle phase, contributing to the organic fraction of CA.

Total Carbon (TC), Organic Carbon (OC), and Elemental Carbon (EC) are key indicators used to describe the composition of carbonaceous aerosols. TC represents the total amount of carbon in particulate form within an aerosol sample, typically measured in micrograms per cubic meter ($\mu g/m^3$). OC is the fraction of TC associated to organic compounds. EC is the complementary fraction of OC, defined as the non-organic, refractory portion of TC. BC has historically been used to describe the light-absorbing component of carbonaceous aerosols.

While EC is usually monitored with thermal methods, BC mass concentration (MBC) is derived from the measured light absorption coefficient b_{abs} using a conversion constant:

$$M_{\mathrm{BC}} = {b_{\mathrm{abs}}}/{\mathrm{MAC}} \tag{1}$$

where MAC denotes the mass absorption cross-section (common unit: m^2/g). MAC depends on the wavelength of light, as well as on the size, morphology, and composition of the absorbing particles. Therefore, Petzold *et al.*[22] recommend to use the term equivalent black carbon (eBC) when black carbon mass is derived from b_{abs} and to state the measurement wavelength and MAC values used for the conversion. Brown carbon (BrC) is defined as the light-absorbing organic carbon in airborne particles, which tends to appear brown rather than black. Wood combustion is an important source of BrC.[23]

Autoabgase fordern ebenso viele Todesopfer wie Autounfälle

ETH-Studie: Rauchen und Autoabgase hauptverantwortlich für Lungenkrebs

In der Schweiz ist es heute ebenso wahrscheinlich, von den Autoabgasen vergiftet wie bei einem Autounfall getötet zu werden. Dieses Fazit einer bisher noch unveröffentlichten Studie von Hans-Christoph Siegmann, dem derzeitigen Vorsteher des Laboratoriums für Festkörperphysik der ETH Zürich, wäre wahrscheinlich noch schlimmer ausgefallen, hätte man alle wichtigen Schadstoffe der Autoabgase berücksichtigt. Siegmann hat sich dabei vor allem auf die unsichtbaren, mit krebserzeugenden Stoffen besetzten Teerteilchen aus den Autoabgasen konzentriert. Die Zürcher Ergebnisse: Strassenbenützer und Autofahrer sind diesen Teerteilchen am meisten ausgesetzt; in einer verkehrsreichen Stadtregion treten innerhalb der Wohnung doppelt so hohe Konzentrationen auf wie in einer verkehrsärmeren Stadtrandregion; im Winter ist die Dichte der Teilchen bis viermal höher als im Sommer, und bei regnerischem oder nebligem Wetter können sie sogar um das Zehnfache zunehmen.

Fig. 1. "Car exhaust fumes claim as many lives as car accidents". Newspaper clipping (Tages-Anzeiger, February 14th, 1984, Switzerland) covering the findings of Prof. Siegmann about the carcinogenicity of vehicle emissions, several years before their classification by the IARC.

1.3 *What Metrics Should be Used to Assess the Effects of Carbonaceous Aerosols?*

As far as the impact on the climate is concerned, the situation is relatively clear and undisputed: the key factors to determine the radiative forcing potential of CA are the optical properties such as wavelength-dependent absorption and scattering coefficients.[24]

Health impacts, however, depend on multiple factors, and the appropriate metrics for assessing potential health risks remain under debate:

- Particle number or surface area concentration are increasingly considered relevant for ultrafine particles, which in ambient air are often dominated by carbonaceous components.[25–27]
- Chemical composition metrics, such as the concentration of PAHs or reactive oxygen species (ROS), are important due to their known toxicity and carcinogenicity.[28–30]
- Although mass-based metrics like PM_{10} and $PM_{2.5}$ have been widely used for several decades, they are not well suited for assessing the health impacts of CA. Specific subfractions of CA often contribute little to total mass, yet may exert disproportionately high toxicological effects.[31]

Recent studies suggest that EC and BC are better indicators of health risks than total $PM_{2.5}$. For example, EC has been associated with up to ten times greater cardiopulmonary mortality risk compared to total $PM_{2.5}$ in some epidemiological studies.[32] However, the variability in EC/BC measurement methods and the lack of standardization complicate their use in regulatory frameworks.[33–36]

2. Measurement Techniques for *Carbonaceous Aerosols*

Within this manuscript we will discuss the use of photoemission as a proxy for the presence of PAHs and an indicator of health effects, as well as measurement methods for TC, OC, EC, and eBC, focusing on our work towards the development of such methods. These metrics are directly linked to combustion sources and can better reflect the toxicological potential of CA. We consider them therefore to be good indicators, provided that there are also sensitive and robust measurement methods for their continuous assessment.

In addition to these methods, incandescence-based techniques are an alternative metric for the measurement of BC. This technique makes use of a high-intensity IR laser to heat the particles to their boiling temperature and quantify them through the thermal emission radiation.[37] Incandescence measurements are very sensitive, but the instrument signal is related to the refractory black carbon (rBC) particle mass and size, and it is not a light absorption measurement (*i.e.* no spectral information can be retrieved).

In mass spectrometry instruments, sampled aerosols are first vaporized and ionized. The resulting ions are then separated based on their mass-to-charge ratio (m/z). Although these techniques are expensive, they offer detailed, high-resolution chemical speciation of organic and inorganic aerosols in real time.[38]

2.1 *Characterization of Particles by Photoemission*

In the photoelectric aerosol sensor, particles are exposed to ultraviolet light, which results in the emission of electrons when the photon energy exceeds the work function (*i.e.* the photoelectric effect). The subsequent rapid extraction of electrons from the gas is facilitated by a small electric field, which functions as an ion trap (Fig. 2). The charged particles are captured in a filter, and the produced current (in fA to pA) is measured by a sensitive current amplifier. While a time resolution of 1s is typical for most applications, photoemission with pulsed light sources has also been used to study processes occurring on millisecond timescales.[39] An alternative detection method is employed by Nishida *et al.*[40] who measure the current by emitted electrons in an electric field.

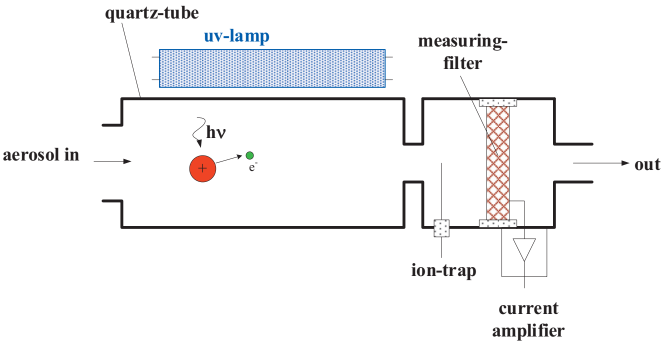

Fig. 2. Schematic of the photoelectric aerosol sensor.[41] Particles irradiated with UV light emit electrons, which are trapped in a weak electric field (ion-trap); the charged particles are collected on a filter, and the resulting current is measured by an electrometer (current amplifier).

As photoemission involves the absorption of a photon by the particle bulk material and the subsequent emission of an electron through the particle surface, the resulting charge on the particles is dependent on both bulk and surface properties.[41] The emission probability is particularly elevated for particles emanating from incomplete combustion. A substantial number of empirical studies have demonstrated a close correlation between emission probability and EC concentration in the context of diesel engines. In the context of ambient air studies, the PAS signal has been demonstrated to exhibit a correlation with the total concentration of particle-bound PAHs.[42,43] As the work function is highly sensitive to the state of the surface, it is possible to detect the adsorbates of fractions of a monolayer.[44] The application of photoelectron emission for surface analysis is demonstrated by Nishida *et al.*[40] and Olszok *et al.*[45] Li and Chen[46] conducted a comparative analysis of the charging efficiency of photoelectric charging versus bipolar and corona charging.

In terms of optical design, wavelengths in the range of λ = 200 to 220 nm are optimal for combustion particles. Shorter-wavelength sources, like Xe_2 excimer lamps (170 nm), are less selective. Additional information can be achieved if more than one wavelength is used.[47]

In an alternative setup a photoelectrically active surface can be irradiated in the vicinity of aerosol particles. The emitted electrons can then attach to the particles, leading to a negative charge on them. In contrast to direct photoemission this indirect process does not depend on the particle composition.[48] A recent design of a miniature sensor is introduced by Zhou *et al.*[49] The availability of UV-LEDs of appropriate wavelength may soon offer the possibility to develop very small and cheap sensors.

While, to our knowledge, no studies have directly used photoemission to quantify health effects, the strong correlation between photoemission signals and particle-bound PAHs provides a link to toxicological relevance. Beyond ambient air monitoring, photoemission has also been used in targeted field studies, such as the detection of high-emitting vehicles (‘super polluters’) under real-world conditions.[50] Such applications highlight the value of photoemission-based sensors to identify combustion-related sources with potentially elevated health relevance.

2.2 *Filter Based Light Absorption*

The predominant method of measuring aerosol light absorption is to collect aerosols on a fibrous filter tape and detect the resulting reduction of light transmittance through the loaded filter in comparison to the unused filter tape. Filter-based instruments convert the measured reduction of filter light transmittance directly into absorption coefficients and eBC concentrations.

Unfortunately, these low-tech methods have significant drawbacks as they suffer from large systematic errors caused by the modification of particle properties upon deposition in the filter: depending on the instrument and filter type, the apparent absorption of the filtered aerosol can be up to a factor of 5 higher than the corresponding value of the unfiltered (airborne) particles.[51] There are various optical interactions between the deposited particles and the filter medium, which can enhance or lower the apparent absorption and modify the wavelength dependence.

The scientific community is well aware of these filter based artefacts and various correction algorithms exist which are based on many assumptions and simplifications.[51–53] The consequence of this is that the corrected measurements of eBC are still prone to large systematic errors which can amount to ±30–70%.[54] The advantage of filter-based techniques is that they are straightforward, allow for unattended operation, and are relatively cheap. In addition, they have a low limit of detection (LoD) due to the enrichment of the absorbing species on the filter over time: The LoD can reach $b_{abs} < 0.05\ Mm^{-1}$ (which corresponds to a few ng/m^3 eBC) when the data is integrated over a sufficiently long time (hours).

2.3 *Photothermal Techniques (PAS & PTI)*

Reliable characterization of BC particles calls for alternative approaches that eliminate artefacts introduced by filter-based measurements. A more accurate method is to measure aerosol light absorption 'directly', through the photothermal processes (see Fig. 3), with the particles in their natural, suspended state. A commonly used *in situ* technique is photoacoustic spectroscopy (PAS), which relies on the photoacoustic effect discovered in 1880[55] and first applied for aerosol detection in 1977.[56,57] In this method, suspended aerosol particles are exposed to intensity-modulated laser light.[58] The modulated light induces periodic heating and cooling of the particles, leading to pressure oscillations in the surrounding gas, which are detected by a microphone. The pressure waves and the signal to noise ratio can be enhanced using an acoustic resonator which enhances the desired frequencies and dampens others. Longitudinal-resonator PAS instruments have been designed for vehicle emission monitoring.[59,60] A version of this development is widely applied to study on-road emissions from combustion engines.

Even though a few photoacoustic instruments can achieve LoD of $b_{abs} \sim 0.1\ Mm^{-1}$ (60 s average),[62] corresponding to an eBC concentration of ~10 ng/m^3, most instruments have considerably higher LoDs.[63] An interesting recent development is presented by Fischer and Smith:[64] The cavity-enhanced MultiPAS-IV instrument uses 4 wavelengths to characterize ambient aerosol absorption. The resonant acoustic frequency is around 1.5 kHz, and the sensor achieves an LoD corresponding to 30–50 ng/m^3 eBC (60 s). A comparable LoD is achieved by the single-path system PAAS-4λ presented by Schnaiter *et al.*[65] It combines four laser wavelengths in a single acoustic resonator operated at 3.2 kHz. The system is specifically designed for long-term, unattended field deployment, as demonstrated in a 1.5-year campaign at a remote station in the Finnish Subarctic. Keller *et al.*[66] have developed a small pumpless photoacoustic instrument that can be used for indoor smoke detection, however this instrument is not sensitive enough for ambient measurements.

An interesting photoacoustic technique, known as quartz-enhanced photoacoustic spectroscopy (QEPAS), uses a quartz tuning fork simultaneously as a resonator and transducer to detect the modulated pressure waves.[67] An advantage of QEPAS over traditional PAS with resonant cells is that the resonance frequency depends on the tuning fork dimensions and is not greatly affected by temperature, pressure or gas composition.

So far, QEPAS has mostly been used to detect gas-phase species. However, this technique has also been demonstrated to work for laser entrapped single particle spectroscopy measurements[68] (particles with diameters larger than 300 nm) and for high concentrations of soot particles (>$10^3\ \mu g/m^3$) from tailpipe emissions.[69] Comparisons with gas-phase applications[70] suggest that the LoD can be further reduced by several orders of magnitude. Ultimately, the fundamental LoD of a QEPAS setup is defined by the intrinsic thermal noise of the system.[71] These developments highlight the potential of QEPAS as a compact and selective tool for high-concentration environments or targeted applications. Further research should focus on improving sensitivity and exploring its use in specialized monitoring scenarios.

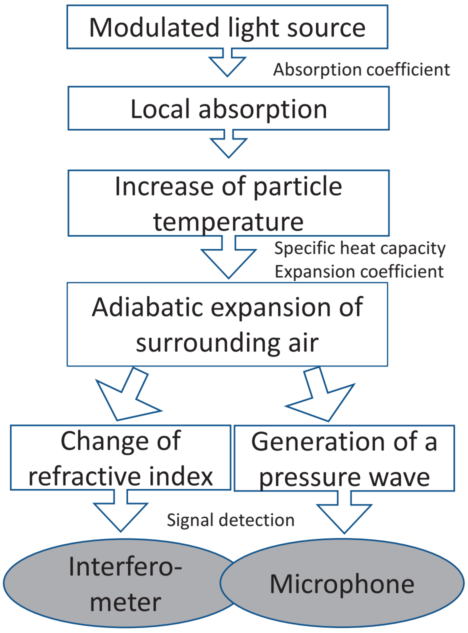

Fig. 3. Fundamental photothermal processes and their detection methods, adapted and expanded from Ref. [61].

Another approach consists of measuring the particle light absorption using an interferometer instead of a microphone. Such photothermal interferometers (PTI) have been used for decades for the sensitive detection of trace gases (*e.g.* Refs. [72–74]) and aerosol absorption (Refs. [75–82]). Like PAS, absorption is determined directly by measuring the absorbed energy of a light source. In PTI, however, the induced temperature change in the air is detected *via* the change in the refractive index of the air. The advantage over PAS is that PTI is based on first principles and does not require resonance frequency tracking. However, PTI is also affected by the cross-sensitivity of the interferometer to external vibrations.

In 2015, the FHNW aerosol group began developing new sensor concepts using PTI to measure traces of light-absorbing species. We have developed a novel single-beam photothermal interferometer[83] that uses only one laser beam for pumping and probing. The current LoD is around 1 $\mu g/m^3$ eBC with a 1-minute time resolution. This technique was refined for measuring eBC for metrological traceability,[84] as it can be National Institute of Standards and Technology (NIST) traceably calibrated with known quantities of light-absorbing gases (*e.g.* 1 ppm NO_2).

Standard PTI devices use free-beam lasers and are therefore relatively large, complex to adjust and expensive. Considering that the PTI measurement volume (*i.e.* the cross-section of the lasers where the excitation takes place) can be extremely small (< 1 mm^3), miniaturization using waveguide structures and integrated photonic circuits is an obvious choice for further development.[85] We have presented the first experimental proof of concept for a waveguide-based PTI with custom-designed photonic integrated circuit (PIC) components.[86] It demonstrates the promising advantages and new possibilities offered by this miniaturization step. However, the corresponding current LoD is still too high for use in the environment (10 µg/m^3 eBC, 60 s).

2.4 *Thermal Methods*

Thermal methods are widely used to quantify the carbon content of aerosol particles, typically separating it into OC and EC fractions. In standard thermal-optical analysis,[33] aerosol samples are collected on quartz filters and subjected to controlled heating, following a pre-established thermal protocol in two stages: the first is in an inert atmosphere to volatilize OC, and the second is in an oxidizing atmosphere to combust EC. The OC–EC separation is determined operationally, often using optical monitoring (transmittance or reflectance) to correct for pyrolyzed OC, which would otherwise be misclassified as EC.

While this approach is common in both monitoring and research contexts, it suffers from several inherent limitations.[34] The OC–EC split is protocol-dependent, with results varying significantly across heating protocols (*e.g.* EUSAAR2 *vs*. NIOSH870), instruments, and laboratories. Artefacts due to pyrolysis, gas-phase absorption, or filter substrate effects can introduce large uncertainties. Moreover, interpretation of fractions is difficult as OC and EC are based on instrument response to heating conditions and do not provide a clean separation in terms of volatility or molecular components.[87]

On the other hand, TC is a more robust, and traceable metric that captures the totality of the carbonaceous material regardless of volatility or chemical structure.[35,88] Recently, simplified field instruments have been created to monitor TC through rapid thermal oxidation without separation into OC–EC fractions,[89] including the fast thermal carbon totalizator (FATCAT) developed by the aerosol group of the FHNW.[90]

FATCAT offers several advantages over conventional thermal analysis instruments. It samples aerosols on a sintered metallic filter, a distinctive feature of FATCAT that eliminates the need for frequent filter replacement. This design enables long-term unattended operation and avoids common issues seen in quartz-filter-based instruments, such as leakage and filter displacement which can compromise long-term field measurements.

FATCAT achieves a low LoD of approximately 0.3 µg/m^3 TC for a one-hour sampling interval, making it suitable for ambient concentrations. The quantification method is traceable to NIST standards, relying on non-dispersive infrared (NDIR) detection of CO_2 combined with a calibrated mass flow controller. The instrument's autonomous performance has been demonstrated during an extended deployment at the Global Atmosphere Watch (GAW) station at the Jungfraujoch observatory (see Fig. 4).

In addition to quantifying TC, FATCAT provides a novel analytical output in the form of fast thermograms — real-time profiles of CO_2 evolution during the rapid heating cycle (60 s). Unlike conventional thermal–optical methods that rely on discrete temperature steps and inert/oxidizing gas switches, FATCAT produces a continuous signal that reflects the volatility and refractoriness of the aerosol constituents without imposing a discrete operational fraction-separation.

Initial laboratory studies have shown that thermogram shape and timing can be used to distinguish between different CA sources, such as soot, wood smoke, or secondary organic material.[90] The field campaign at the high alpine site Jungfraujoch confirmed that the thermograms can be used in ambient condition to discriminate between different CA sources like local fossil fuel emissions and long-range transport from wildfires aerosols (Fig. 5).

3. Summary and Conclusions

Decades of research highlight the importance of carbonaceous aerosols in the context of both health and climate forcing. However, our understanding of its effects has been hindered by the use of inappropriate monitoring metrics. Regulatory monitoring has historically focused on mass-based metrics such as PM_{10} and $PM_{2.5}$. While these are straightforward to measure, they fail to capture the optical, chemical, and toxicological diversity of aerosols, particularly in the case of CA.

Although our understanding of CA has advanced significantly, no single metric has emerged as universally relevant for evaluating climate effects or toxicological potential. For climate, radiative forcing is closely tied to optical properties like light absorption and scattering. For health effects, however, multiple candidates have been proposed, including particle number and surface area, specific subfractions like eBC, as well as specific compounds such as PAHs and ROS. Each of these requires dedicated measurement infrastructure which, in the best case, has only recently been implemented in monitoring networks (*e.g.* NABEL in Switzerland[91]). Other important fractions like TC, EC, and OC are measured offline using 24-hour filter samples. Due to the lack of an automatic analysis, only a small subset of collected filters is systematically processed, limiting the availability of high-resolution historical data. This presents a challenge for epidemiological

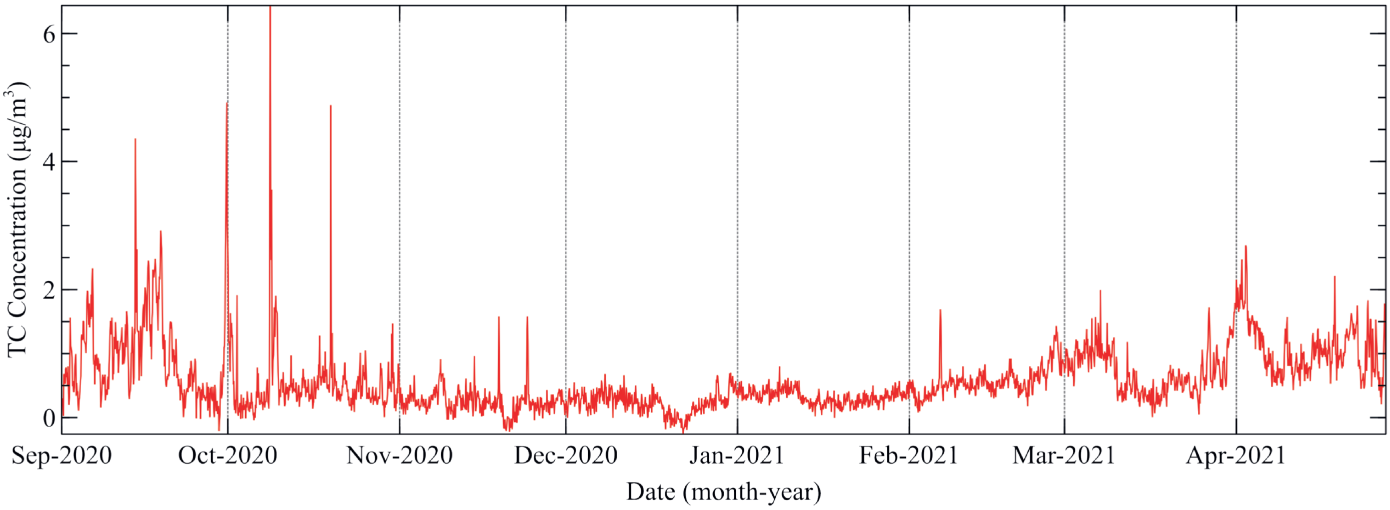

Fig. 4. Unattended long-time measurement series of the total carbon concentration by means of FATCAT at the Jungfraujoch GAW monitoring site with a time resolution of two hours. The sharp spikes represent single episodes of high concentrations due to local emissions or atmospheric long-range transport of, *e.g.* wildfire plumes. Required user intervention during the measurement period was only due to replacement of the analysis gas cylinder every 4 months.

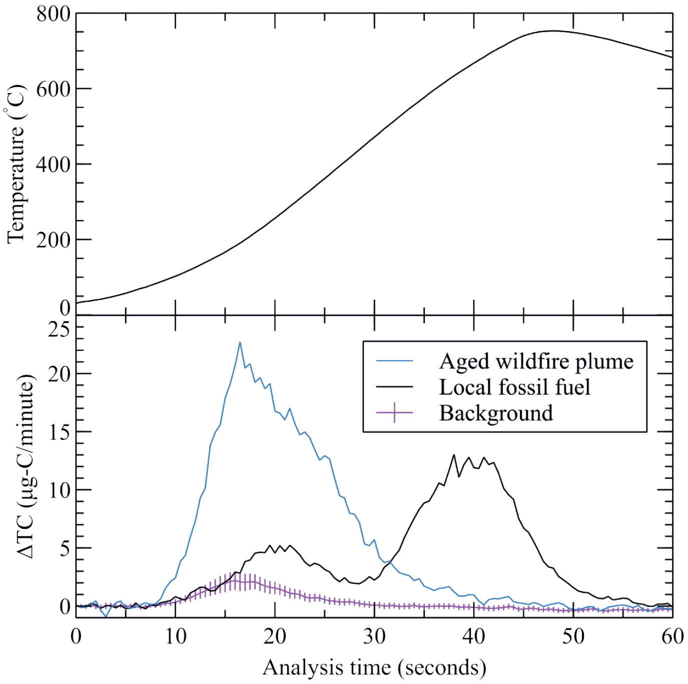

Fig. 5. Evolution of the filter temperature (top panel) during a 60-second analysis cycle performed by FATCAT, along with exemplary thermograms from the 2020 measurement campaign at the Jungfraujoch observatory (see Fig. 4). The thermograms correspond to two-hour sampling periods on October 8th (aged wildfire plume) and October 19th (local fossil fuel emissions). The fossil fuel emissions contain a high fraction of refractory material which evolves at higher temperatures compared to the wildfire plume. As reference, we include an average thermogram for all samples collected between midnight and 6am (UTC) between November 2020 and February 2021 (error bars: standard deviation). We consider this to be the atmospheric background corresponding to higher volatility OC that evolves at low temperatures.

studies that aim to link health outcomes to exposure beyond what is captured by PM mass alone.

In this context, the Swiss-Made measurement systems presented here aim to address key limitations in current monitoring systems:

- The **photoemission-based sensors** provide a real-time proxy for particle-bound PAHs, which include known carcinogenic substances that are otherwise difficult to measure. As new UV-LED technologies emerge, these sensors could experience an upswing and could even be used as miniature, portable exposure monitoring devices.
- **Photothermal techniques**, such as PAS and PTI, allow direct *in situ* measurement of light absorption, overcoming the artefacts of filter-based methods. Ongoing, miniaturization efforts (QEPAS and waveguide-based PTI) points towards future opportunities for including these measurement systems in denser monitoring networks beyond traditional fixed monitoring sites.
- **Thermal methods**, like FATCAT, offer robust, unattended quantification of TC with high time resolution. In addition, the fast thermograms generated during analysis offer insight into composition and thermal stability. For example, they can be used to identify individual sources, complementing or even offering an alternative to EC/OC measurements.

Together, these methods reflect our efforts towards providing robust and reliable tools suitable for long-term monitoring. We hope that, in the long run, these developments will support the advance of scientific understanding of the environmental and health impacts of carbonaceous aerosols, ultimately aiding future air quality guidelines and policymaking.

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Author Contributions

All coauthors contributed to the writing of this manuscript and to the interpretation and classification of the results.

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