EYE-CLIMA
Verifying emissions of climate forcers

Preliminary emissions and uncertainties of BC globally

DELIVERABLE 3.7

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Summary

Black carbon (BC) is a product of incomplete combustion and the main absorbing component of atmospheric aerosols. It has a positive radiative forcing and is also an atmospheric pollutant harmful to human health. Improving knowledge of its emissions is needed for implementation of policy to mitigate climate change and for clean air.

This deliverable presents the first results of atmospheric inversions to improve estimates of BC emissions globally. Two atmospheric transport models are used for BC in EYECLIMA, a Lagrangian particle dispersion model, FLEXPART, and a Eulerian global chemistry transport model, TM5-MP, which are used with the Bayesian inversion frameworks, FLEXINVERT and TM5-MP-CTDAS, respectively. Ground-based observations of elemental carbon (EC) and equivalent black carbon (eBC) have been collected and used to optimize the emissions via atmospheric inversions. However, observations are relatively scarce over South America, Africa and Asia. This is in contrast to Europe, which has abundant observations meaning that the emissions in Europe are better constrained than other regions of the world (see the preliminary deliverable on the European inversions D3.8).

Global inversions have been performed for 2017 and have shown an overestimate of BC emissions in China and an underestimate in India and Indonesia compared to the prior emissions. However, there is a lack of available observational data in these regions and improving data coverage here would increase the confidence in the inversion results.

This deliverable provides only preliminary results and the effort continues in collecting additional observations to use them to improve the inversion estimates as well as extending the inversion to cover the full period to be studied from 2015 to 2023. These will be reported in D3.11.

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1. Introduction

Black Carbon (BC) is a product of incomplete combustion, which negatively impacts human health and has the highest absorbing properties of any aerosol species and, therefore, is very relevant to climate. However, in the IPCC 6th Assessment Report (AR6) the uncertainty in its contribution to global warming is evaluated to be very high as BC not only influences radiative forcing but also modulates cloud formation, the climate impact of which is difficult to assess. In addition, BC is an aerosol with large uncertainties in its emission due to the uncertainty in the emission factors. To constrain the emissions, accurate and abundant observations are needed. Unfortunately, it is not possible to make measurements of BC directly. Usually, equivalent BC (eBC) is determined by using the aerosol absorption coefficient (AAC). Another approach is to use thermo-optical or laser-based methods. Inter-comparisons have shown that these methods do not give the same results and can vary by a factor of 3, indicating a need to better describe BC.

Globally, BC emissions are estimated at 6 million tons per year. Most anthropogenic emissions are found in India whereas most natural emissions are found in Equatorial Africa. In order to study BC concentrations and trends on a global or regional basis, often a combination of satellite observations and surface stations is used. In this manner, significant spatial and temporal variability influenced by regional emission sources, policy interventions, and measurement approach, can be revealed. For example, for China (Zhao et al., 2024) a comprehensive analysis combining satellite data from the Ozone Monitoring Instrument (OMI), a top-down inversion method, and an exposure–response model examined BC trends from 2000 to 2020. Zhao et al. (2024) found that bottom-up inventories likely underestimated BC emissions, particularly in less-developed western regions. National emissions rose by 8% during 2000–2010 but declined by 26% from 2010–2020 due to pollution control measures. While some industrial provinces saw emissions rebound after initial reductions, more urbanized regions experienced sustained decreases.

Furthermore, in Northern China high-resolution wintertime observations from Shijiazhuang between 2018 and 2020 showed a marked decrease in BC concentrations from over 9 $\mu g/m^3$ to 3.5 $\mu g/m^3$, reflecting the success of air quality policies (Wang et al., 2021). Source attribution indicated a shift from biomass burning dominance in 2018 to fossil fuel combustion in the subsequent years. With the help from trajectory analyses, it was confirmed that both local emissions and regional transport from nearby industrial areas, like central Shanxi, contributed to the observed BC levels. The study also noted the importance of considering both climate and air quality synergies in mitigation strategies, as some BC reduction measures may conflict with CO_2 emission goals.

For India, measurements from fifteen sites in the India Meteorological Department's BC observation network during 2016–2018 demonstrated high variability across the subcontinent (Kumar et al., 2020). Northern India and the Indo-Gangetic Plain recorded the highest BC mass concentrations, with annual means exceeding 13,000 ng/m^3 in Delhi. In contrast, coastal and background stations in southern India observed much lower concentrations. A source apportionment analysis using the Aethalometer model revealed that fossil fuel combustion dominated BC contributions year-round, though biomass burning played a notable seasonal role, especially in winter. Seasonal analyses showed the highest concentrations post-monsoon and in winter, which are attributed to increased domestic fuel use and stagnant meteorology, while monsoon rains reduced concentrations through wet scavenging. These results highlight the spatial heterogeneity of BC in India and the importance of addressing both fossil and biomass sources.

Also for India, satellite-based approaches further extend our understanding of BC distributions. A study using the Cloud and Aerosol Imager-2 (CAI-2) aboard GOSAT-2 validated satellite retrievals of BC over India against ground-based data from the ARFINET (Gogoi et al., 2023) network. The results showed

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good agreement, with RMSE values below 1 µg/m³ and high correlations during winter and pre-monsoon months. These satellite observations revealed regional BC hotspots and allowed for the extrapolation of spatiotemporal patterns globally. Areas with intense biomass burning showed elevated BC concentrations, supporting the use of satellite products for continuous monitoring of anthropogenic and fire-related emissions.

Another satellite study utilized the Earth Polychromatic Imaging Camera (EPIC) on DSCOVR to analyze smoke aerosols over North America and central Africa, focusing on BC and brown carbon (BrC) content (Choi et al., 2020). Using the MAIAC algorithm, researchers retrieved aerosol optical properties and inferred BC and BrC volume fractions with high spatial and temporal resolution. The results demonstrated that smoke over North America, primarily from wildfires, exhibited high aerosol layer heights and substantial BrC content, whereas smoke in central Africa, largely from savanna burning, showed stronger absorption and higher BC fractions. Regional differences in aerosol optical depth and single-scattering albedo were closely linked to the type of burning and local meteorological conditions. These findings provide critical observational constraints for climate modeling and reinforce the role of satellite data in assessing the radiative impacts of light-absorbing aerosols.

Together, these studies highlight that BC concentrations and their impacts vary widely across regions and time periods. They illustrate the importance of integrating surface observations, source apportionment techniques, and satellite remote sensing to characterize BC emissions and their effects on air quality, health, and climate.

In EYECLIMA, we aim to constrain the global BC emissions by using two different inversion frameworks. One framework is TM5-MP-CTDAS and consists of the TM5-MP Eulerian atmospheric transport model, which also simulates aerosol microphysics. A data assimilation system has been developed for TM5-MP using the Ensemble Kalman filter method based on the Carbon Tracker Data Assimilation Shell (CTDAS). The other is the FLEXPART-FLEXINVERT framework and consists of the FLEXPART model, which models aerosol species using a parameterization of scavenging that has been tested both for mid-latitude and Arctic stations.

Both systems will use observations of eBC concentration from the ACTRIS database and the NOAA/ESRL Federated Aerosol Network. Although BC emissions will be estimated globally, the posterior emissions are expected to be more accurate over Europe due to the density of the observational network there. In TM5-MP, the radiative absorption of BC will also be modelled and validated against data from the global AERONET database (https://aeronet.gsfc.nasa.gov/) of total column AAOD, from which BC can be also derived. Inversions will be performed globally at 1°×1° (TM5-MP) and 2°×2° (FLEXPART) resolution and monthly from 2015 to at least 2023.

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2. Method

2.1 FLEXPART transport modelling

To investigate atmospheric transport patterns and connect them to potential source regions to be used for the inversion, simulations were conducted using the Lagrangian particle dispersion model FLEXPART (Pisso et al., 2019; Bakels et al., 2024). FLEXPART simulates the trajectories of a large ensemble of virtual particles released into the atmosphere and accounts for key atmospheric processes including turbulence-induced dispersion, deep and shallow convection, as well as both dry and wet deposition. Each released particle was tracked within the model domain for a duration of 30 days, ensuring coverage of long-range transport events. FLEXPART has been extensively evaluated for various tracers, including black carbon (BC), particularly in Arctic regions, which adds robustness to its application in this study. The model was run continuously with hourly resolution for one period (2017), using 30 observation locations, 15 situated within Europe and 15 distributed globally outside of Europe.

2.2 FLEXINVERT inversion framework

To quantify surface emissions and evaluate source strengths, the output from FLEXPART was integrated within the FLEXINVERT (Thompson & Stohl, 2014) inversion framework. FLEXINVERT is a Bayesian atmospheric inversion system that utilizes the source-receptor relationships (SRRs) computed by FLEXPART to constrain spatially and temporally resolved emissions based on observational data. The system links the modelled SRRs to prior emissions estimates to model concentrations, that are then compared to measured concentrations and applies a regularized least-squares optimization to estimate the most probable fluxes, taking into account both prior emission information and the uncertainties associated with the observations and the transport model. In this study, FLEXINVERT was configured to assimilate the three-hourly observational data in conjunction with the hourly-resolved footprint matrices from FLEXPART, providing an optimized estimate of source strengths across the domain. This framework allows for robust quantification of emissions and identification of potential source regions, particularly valuable in regions with sparse observational coverage or complex atmospheric transport dynamics.

2.3 TM5-MP transport modelling

The TM5-MP global chemistry transport model is used to investigate the atmospheric transport of BC in the global atmosphere. It explicitly accounts for aerosol microphysics. Inversions of BC will be made globally using the TM5-MP model, (Williams et al., 2017) with full chemistry and aerosol microphysics, using the M7 module (Vignati et al., 2004). The model has been extensively evaluated for various tracers and contributes to CMIP simulations. TM5-MP uses ERA5 meteorology and as starting (a priori) emissions we used the CMIP6 emission inventory (Feng et al., 2020), which covers emissions from both anthropogenic activities and biomass burning events. Inversions will be also performed using anthropogenic emissions provided by GAINS, combined with CMIP6 biomass burning emissions. The model is used as the forward model using a 1°×1° horizontal resolution and 34 vertical levels for these preliminary simulations for the year 2016. The model uses a dynamic timestep of 30 min and 15 min for chemistry and aerosol microphysics.

2.4 TM5-MP-CTDAS inversion modelling

TM5-MP is integrated with the Carbon Tracker Data Assimilation Shell (CTDAS) that is using the Ensemble Kalman filter method and a fixed-lag assimilation window method (Van Der Laan-Luijkx et al., 2017) for BC inversions. In CTDAS, the forward model output using these emissions is compared with the EC and eBC observations worldwide obtained by filter-based techniques and aethalometers from the EBAS (https://ebas.nilu.no) and IMPROVE (Malm et al., 1994) databases, that were thus assimilated by CTDAS. Scaling factors for emission corrections are computed per HTAP region. An assimilation window

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of 1 week with a fixed-lag of 2 weeks is applied for the first test simulations. The lag window will be optimized for the final simulations. An ensemble of 50 members is used for the assimilation for each of the 17 HTAP regions in which emissions are optimized. The model uses 50 station locations in Europe and 173 outside Europe most of them in the USA, both eBC and EC observations.

2.5 Observations

Within the EYECLIMA project, equivalent black carbon (eBC) data for Europe were compiled from aethalometer instruments retrieving AAC (see deliverable D1.10 and Fig. 1 of this report). To ensure consistency across different measurement protocols and instruments, the data were harmonized into a unified and quality-controlled dataset representing homogeneous BC concentrations. The resulting time series vary in length and continuity, with many stations exhibiting temporal gaps due to data availability and operational interruptions (see Fig. 2).

For this deliverable, we have collected data from individual sites globally, which are in addition to the data used for the European inversions (described in D3.8). These sites and their geographical location are listed in Table 1. Also used in this deliverable, are eBC data from the Federated Aerosol Network (FAN) with 11 sites globally. The locations of the stations are shown in Fig. 4.

Among the available sites, background monitoring stations were found to be the most suitable for the analysis, as they are less influenced by local pollution sources and provide a more representative signal of regional and long-range transported BC. These observations served as the target values in the inversion framework, enabling the optimization of emission estimates and evaluation of the modelled atmospheric transport and scavenging processes.

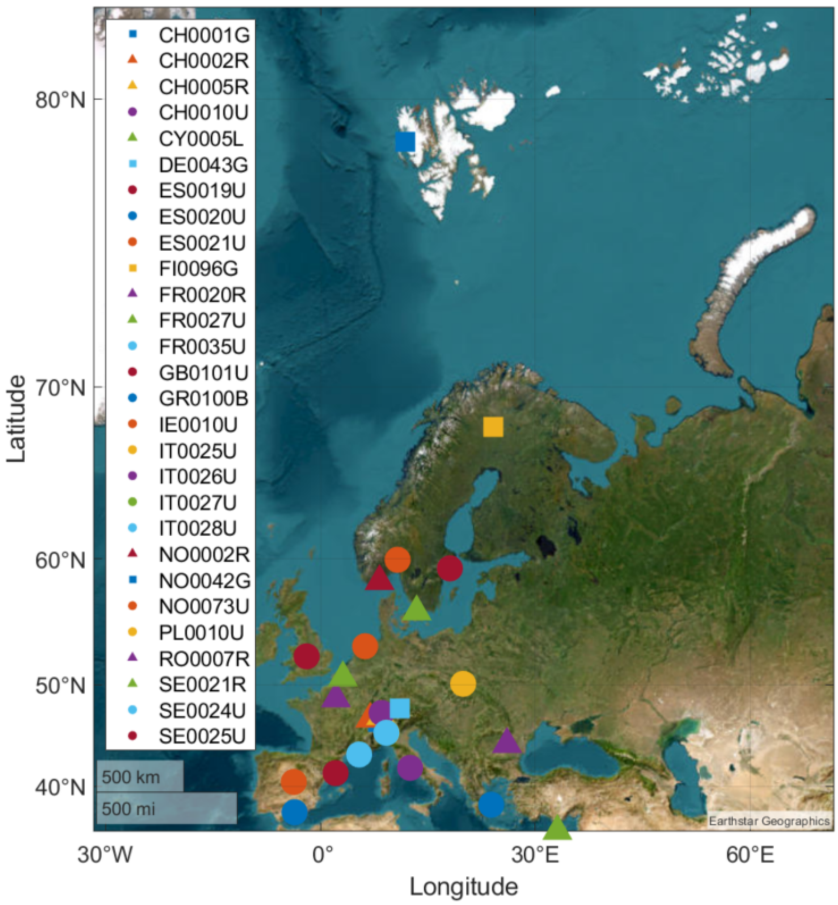

***Figure 1**: Location of the European measurement stations used in EYE-CLIMA, the round markers indicate background stations, while the triangle are sub-urban stations.*

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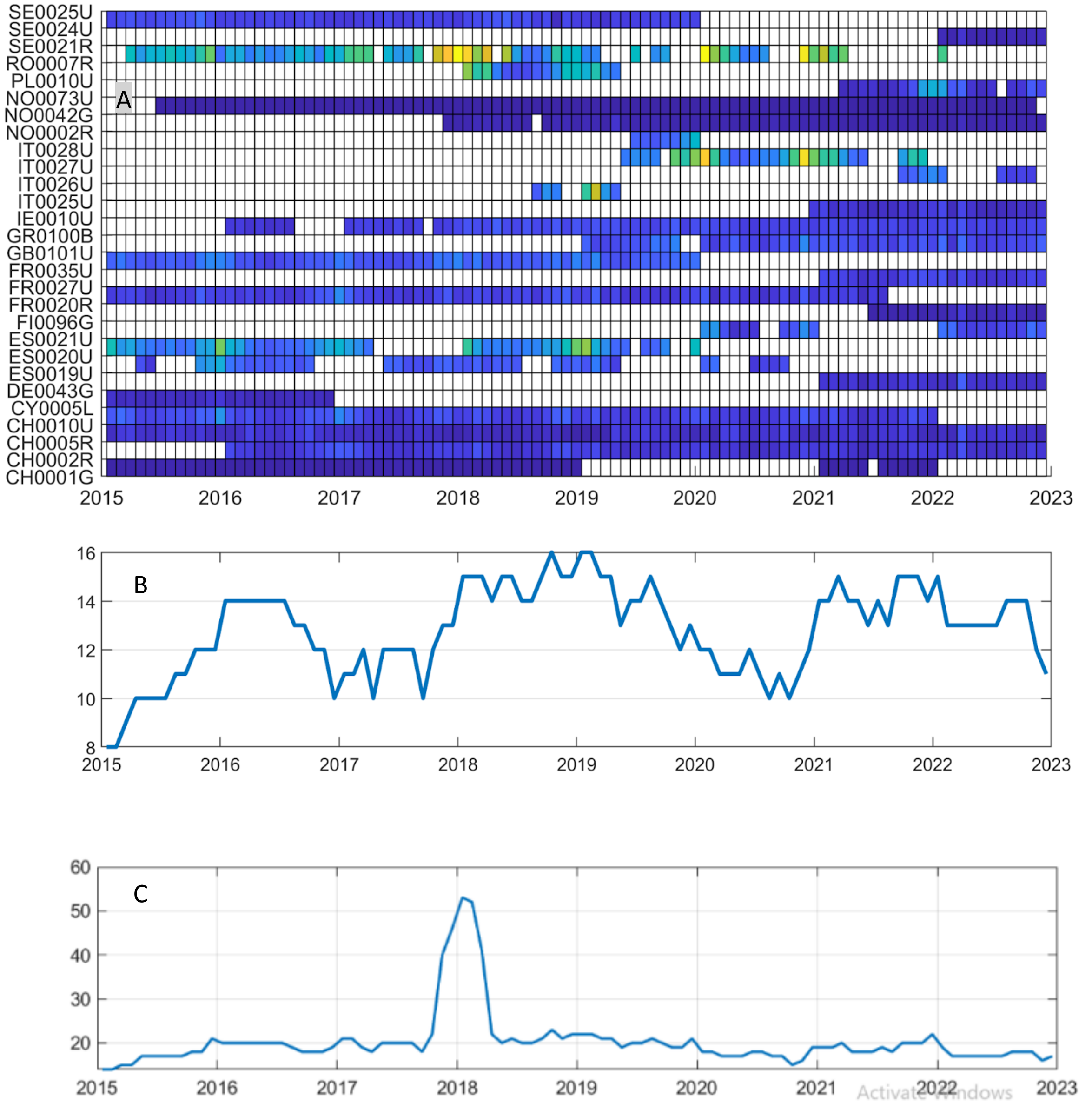

***Figure 2**: Availability and average concentrations of BC observations for the European EYECLIMA network. Panel (A) shows the available monthly observations for the stations abbreviated in the y-axis. The middle panel (B) shows the number of available stations per month. Panel (C) are additional observations spread over Europe shown in order to visualize the abundance of observations in 2018, which is due to a special EMEP campaign and can be used for validation. The stations available for this 3-month campaign in this year is for clarity, not shown in panel (B).*

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***Table 1**: Station name, region and available period for eBC observations used for the global EYECLIMA BC inversions.*

City, country	Years available	Geographical region
Fukue, Japan	2009-2023	Asia
Curibata, Brazil	2008-2015	South America
Altzomoni, Mexico	2015-2019	South America
Juriquilla, Mexico	2015-2019	South America
Snow mountain, China	2019-2020	China
Rwanda	2014-2019	Africa
Bely	2019-2022	Russia
Baranova	2019-2022	Russia
Dehli	2020-2024	India

2.6 Global BC Emissions from anthropogenic sources and from wildfires

In this project, we are using global anthropogenic BC emissions at 0.5° resolution created for EYECLIMA and the HTAP experiments. Emissions are available for the years 1995, 2000, 2005, 2010, 2015 and 2020 for 8 different source categories (agricultural waste burning, domestic heating, shipping, industry and energy production). We assume emissions are constant for each 5 years period. Anthropogenic emissions include also seasonal cycle in the domestic burning sector.

The wildfire emissions are taken from GFAS/CAMS at daily resolution extracted from a 0.1° raster and aggregated to 0.5° to match the anthropogenic emissions. The average annual total is 6 Tg/year. However, at high latitudes the wildfire emissions dominate the anthropogenic emissions. The most severe fires are found in boreal regions in Canada and Siberia. The extreme maximum in Canadian fires in 2023 had direct impact on air quality in Canada and the United states. Due to the high latitudes the fires also have an impact on the Arctic.

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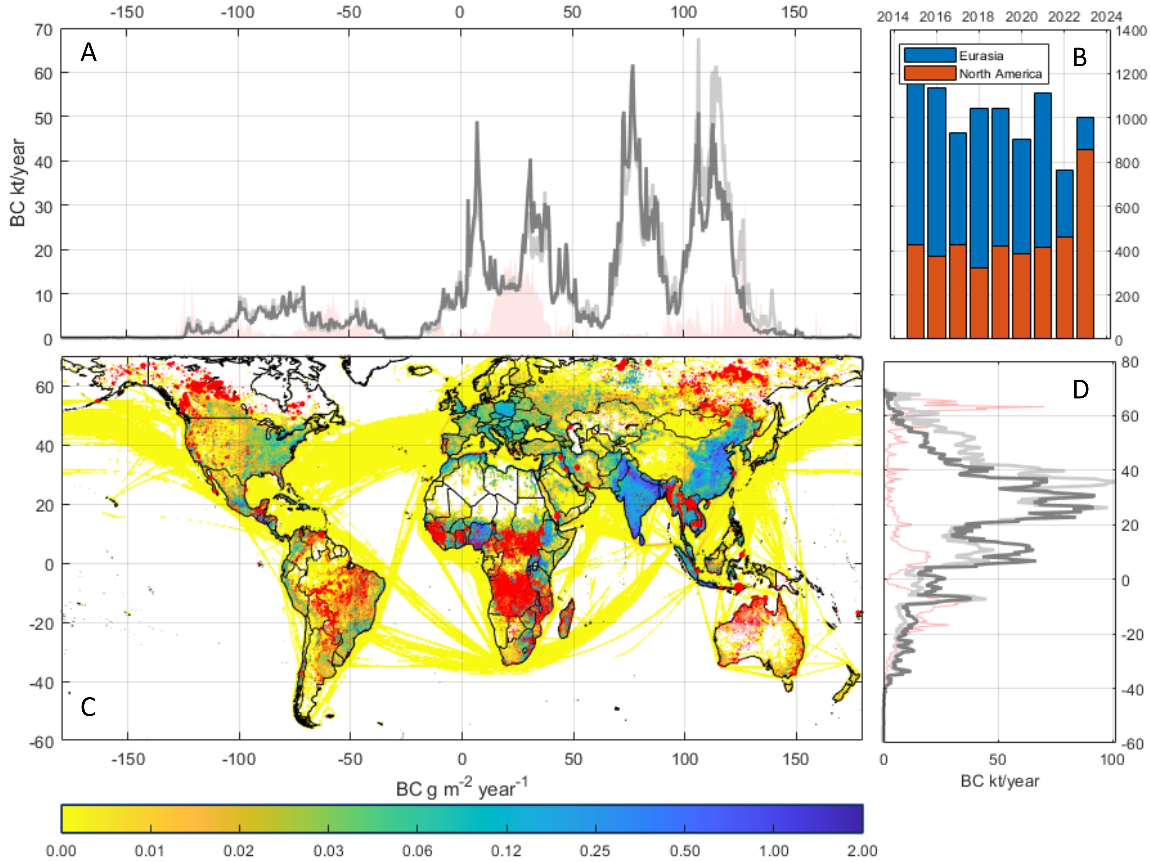

Figure 3*: Source strength and spatial distribution of anthropogenic BC emissions. Panels (A) and (D) show the accumulated emission flux for each 0.5° longitude and latitude band, respectively, for the areas shown in panels (C) (grey) and (B) (red). The geographical variability of BC emissions from wildfires between Eurasia and North America for the study period of 2015-2023 is shown in panel (B).*

Regionally, the highest anthropogenic BC emissions are found in Asia, particularly South and East Asia. India and China are among the largest emitters due to their high population densities, extensive use of solid fuels, and growing transportation and industrial sectors. Sub-Saharan Africa also contributes significantly, primarily from residential biofuel use and open biomass burning, such as savanna and agricultural fires. Southeast Asia and parts of Latin America (notably the Amazon basin) experience large episodic emissions from agricultural and forest fires. In contrast, Europe and North America have relatively lower emissions, primarily due to stricter emission standards and cleaner technologies, although urban areas with heavy diesel traffic can still be hotspots (Fig. 3).

The annual cycle of BC emissions and concentrations is strongly influenced by seasonal human activities and meteorological conditions. In regions with strong winter heating demand, such as northern India, China, and Eastern Europe, BC levels peak during the colder months due to increased residential combustion. Similarly, biomass burning seasons in tropical and subtropical regions, such as the dry season in central Africa or the pre-monsoon season in South Asia, are associated with pronounced increases in black carbon emissions. Wildfire-prone regions in North America, Siberia, and Australia exhibit seasonal spikes during the respective summer or dry seasons, when high temperatures and drought conditions promote fire activity.

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2.7 Deviations from the Description of Work

Technical issues with the global simulations of TM5-MP-CTDAS have been faced during this period and the global inversions with this modelling framework are still in progress. The results of this inversion framework will be reported in the next and final deliverable on global BC emissions (D3.11).

3. Results

3.1 Global black carbon inversion

We performed a global inversion using FLEXPART-FLEXINVERT for the year 2017 with the 17 stations that were available for this year. This was the required pilot study for EYECLIMA. Fig 4 shows the correction to the prior emissions through the inversion. As can be seen in Fig 4, the inversion increased the emissions in India, where the prior emissions were already very high (see Fig. 3), and decreased the emissions in China. Due to a lack of available observations in India and China, the emissions there are constrained by observations at stations in Japan and Korea, which receive air masses from these regions and hence are sensitive to the emissions there.

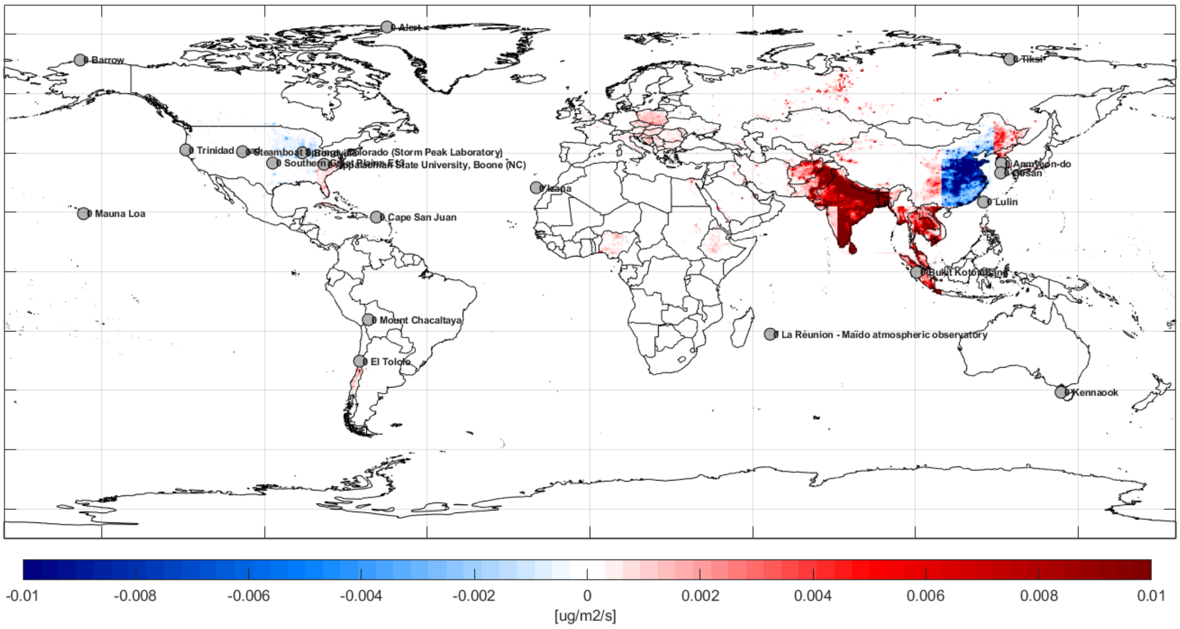

***Figure 4**: Global inversion results for the year 2017. The blue regions indicates a downward correction of the EYE-CLIMA prior emissions estimate and the red areas indicate an increase. The grey dots indicate the observations that have been used for the inversion in this year.*

4. Conclusion and outlook

There are abundant BC observations in Europe to perform an inversion. In contrast, over Asia and the southern hemisphere there are fewer stations available. While over South America, we could collect observations from 2015-2019, the Indian networks had data available only after 2020. This makes it impossible to get an accurate description of the geographical distribution and temporal evolution of the BC emissions.

When considering other observations than the aerosol absorption coefficient then two other global networks would be available. One is the SPARTAN network (The Surface PARTiculate mAtter Network). SPARTAN is a global, long-term initiative focused on analyzing the chemical and physical characteristics of aerosols collected through filter-based sampling at locations around the world (https://www.spartan-

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network.org/; Snider et al., 2016). It provides open-access data on particulate matter concentrations and composition, specifically targeting PM2.5 and PM10. The network aims to support the validation and refinement of remote sensing models and to aid efforts in air quality management. Currently, SPARTAN operates 29 monitoring sites across the globe. Aerosol samples are typically collected over 8-day intervals, from which the chemical constituents are subsequently analyzed.

The other dataset is a global EC dataset which has been published in October 2025 and was compiled by Putoud et al. 2025 (https://www.sciencedirect.com/science/article/pii/S1352231025003139#da0010).

In addition, we initiated collaboration with scientists in India and China and this will result in a denser network and a better uncertainty reduction in the final inversions for the EYE-CLIMA project.

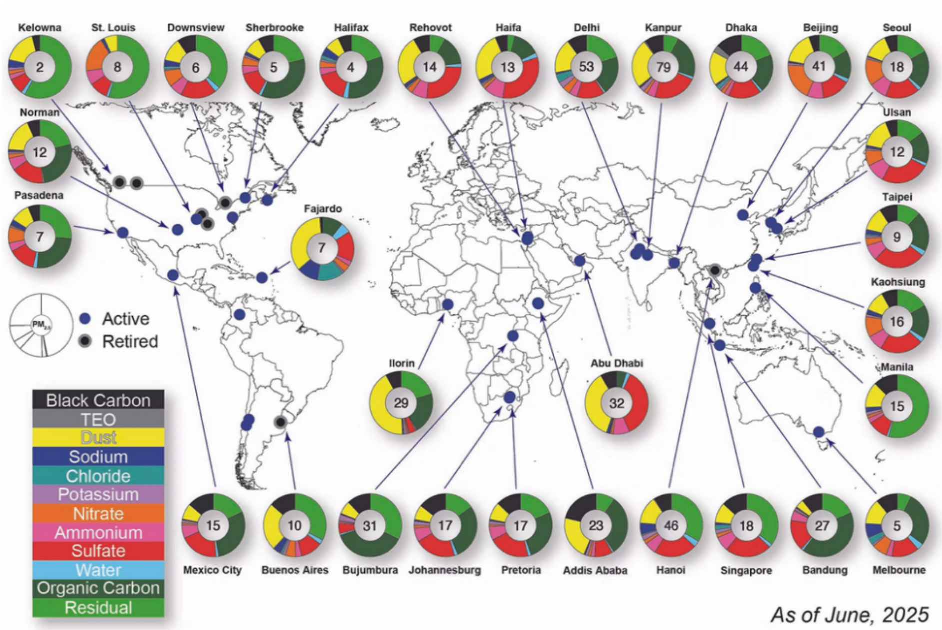

***Figure 5**: Image from https://www.spartan-network.org/data. Location of the sites used for the analysis of the aerosol composition as well as relative contribution of the different sectors to the total aerosol observed. The black colour indicates black carbon.*

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https://eyeclima.eu

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