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Knowledge Transfer with Citizen Science: Luft-Leipzig Case Study

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Abstract: Community-based participatory research initiatives such as "hackAir", "luftdaten.info", "senseBox", "CAPTOR", "CurieuzeNeuzen Vlaanderen", "communityAQ", and "Healthier Air, Healthier Children" campaign among many others for mitigating short-lived climate pollutants (SLCPs) and improving air quality have reported progressive knowledge transfer results. These research initiatives provide the research community with the practical four-element state-of-the-art method for citizen science. For the preparation-, measurements-, data analysis-, and scientific support-elements that collectively present the novel knowledge transfer method, the Luft-Leipzig project results are presented. This research contributes to science by formulating a novel method for SLCP mitigation projects that employ citizen scientists. The Luft-Leipzig project results are presented to validate the four-element state-of-the-art method. The method is recommended for knowledge transfer purposes beyond the scope of mitigating short-lived climate pollutants (SLCPs) and improving air quality.

Keywords: knowledge transfer; short-lived climate pollutants; air quality; black carbon; particulate matter; citizen science

1. Introduction

In the last decade, numerous community-based participatory research initiatives have emerged for improving public health and for fighting global warming [1]. Fighting global warming is a challenge that requires efforts from the individual level bridged with related policy initiatives. Since the start of industrialization, the world has warmed by about 0.85 degrees [2], and the average global mean temperature is expected to rise by at least 2 °C from pre-industrial levels by 2050. Temperatures in Europe have been rising even faster than the global average. Over the last 30 years, the average mean temperature in Europe rose by 0.48 °C, whereas the average global temperature rose by 0.27 °C (IPCC). Dust, allergens, black carbon, water vapor, and other particles as well as gases in the atmosphere are constantly interacting and forming new mixtures, often with the influence of heat and ultraviolet radiation. Many direct human health effects of these airborne agents have been well characterized. Some of these agents also have greenhouse properties, contributing to the overall global warming. Rising temperatures and air pollution are thus inextricably intertwined. Single air pollutants and/or climate forcers have been policy issues for a long time and started to be addressed over thirty years ago. One of the first major and internationally binding agreements addressing air pollution was, for example, the Geneva Convention on "Long-range, Transboundary Air Pollution" signed in 1979. Several other initiatives and agreements addressing individual air pollutants, including some of the substances labeled as short-lived climate pollutants (SLCPs) today, followed. These pollutants include the greenhouse gases methane and hydrofluorocarbons, and anthropogenic black carbon. However, addressing the exact substances, including black carbon (BC), and labeling it as "SLCPs" is relatively new and dates back to the publication of

two seminal reports in 2011: "The Integrated Assessment of Black Carbon and Tropospheric Ozone" published by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) and the publication of "Near-term Climate Protection and Clean Air Benefits: Actions for Controlling Short-Lived Climate Forcers" published by UNEP the following year [3].

The primary air pollutant of concern for human health is fine particulate matter (PM) [4]. Fine particles belonging to the short livable pollutant category can be carried deep into the lungs where they can cause inflammation and a worsening of the condition of people with heart and lung diseases. In addition, they may carry surface-absorbed carcinogenic compounds into the lungs [4].

Whilst reducing SLCPs offers an important opportunity to reduce the rate of warming in the coming decades, it has to be acknowledged that over the long term, mitigating SLCPs only makes a modest contribution to climate change mitigation. Nevertheless, in the recent decade, policymakers, industry, and academia have made numerous advancements in terms of air pollution monitoring networks, low-cost sensors, and interdisciplinary projects that include various communities in research design for awareness building. The participation of various communities, including the public, in science and research, has gained importance in policy and research alike [4,5].

The first recorded use of the term citizen science (CS) in the form that we currently use can be traced to three decades ago, according to the researchers of the Oxford English Dictionary. The term appeared in an issue of the MIT Technology Review from January 1989 [6]. CS involves public participation in scientific exploration and possibly other activities designed to advance the public's understanding of their environment, including local air quality. CS initiatives that focus on air quality often use low-cost sensors to measure concentrations of different pollutants. A wide variety of small, portable, and lower-cost monitoring devices are being developed by industry, universities, and individuals to potentially enhance air quality monitoring means. Low-cost sensor networks make it possible to monitor most of the hazardous pollutions in outdoor air that have been applied for various CS projects in the past years in Europe and overseas [7]. Although CS has been around for almost three decades, the clear definitions and research set-ups vary among the scientific community [6].

This paper describes the latest air quality and SLCP knowledge transfer projects set-ups in the "State-of-the-art of Knowledge Transfer Project Set-ups with Citizen Science" chapter by seven related project methods. Based on the seven initiatives, conclusions for a novel method are drawn, and the method is visualized in the "Method" chapter. This four-step method is validated by the Luft-Leipzig case study, whereas all four steps are explained in detail. The exact data collection protocols and sensors specifics are presented in a separate paper. This study contributes to science by defining a novel method for sustainability knowledge transfer projects, which are explained in the next sections.

2. State-of-the-Art of Knowledge Transfer Project Set-Ups with Citizen Science

The "citizen science" term is used for SLCP and air quality monitoring projects or an ongoing program of scientific work in which individual volunteers or networks of volunteers, many of whom may have no specific scientific training, perform or manage air quality research-related tasks such as observation, measurement, data validation, or computation [8]. It reflects a contemporary understanding of science that allows societal engagement through participatory methods. Involving various citizen communities into scientific processes can create spatially and temporally very complex, and in part, completely new and novel data sets that require both web-based and analog infrastructures [9] as well as new lightweight wearable SLCP monitoring devices.

A project called "CurieuzeNeuzen Vlaanderen (Curious Noses Flanders)" launched in 2018 in Europe. It has been described as "the largest citizen science project on air quality to date." [10]. The initiative's goal was to create a detailed map of nitrogen dioxide (NO_2) concentrations in Flanders (the northern region of Belgium), both in urban and rural areas.

Participants received prior information about the project via media and could sign up to participate for a small fee (10 Euro). Each participant installed a simple, standardized measurement device on a street-facing window of their house, apartment, or building. Two diffusion tubes determined the mean concentration of nitrogen dioxide (NO2) in the ambient air over one month (May 2018). Quality assurance was provided, and the data collected from the diffusion samplers were scientifically controlled and calibrated with NO2 measurements at reference monitoring stations operated by the Flemish Environment Agency (VMM). The community collected the data and did not scientifically validate or analyze NO2 data themselves. Scientific support in the project data analysis part was not executed as the data were collected to help test a computer model for air quality in the region.

The Health and Environment Alliance (HEAL) conducted a measurement project with passive samplers as part of its "Healthy Air, Healthier Children" campaign. Fifty elementary schools in Warsaw, Berlin, London, Paris, Madrid, and Sofia participated in HEAL's air quality survey inside and outside elementary school from March to May 2019, monitoring particulate matter (PM), nitrogen dioxide (NO_2), and carbon dioxide (CO_2) [11]. The air quality crowdsourcing study design approach started with a one-day seminar where each participating school was visited by a project representative, to explain the activity and then monitor PM and CO_2 concentrations for a period of $\pm$ 20 min. Project partners along with teachers and often the help of students installed the diffusion tubes. In the second phase of the study design, the measurements took place outside the school entrance and inside the schools' classrooms. The measurements were performed for 3–4 weeks using diffusion tubes which were provided to each participating school together with a project poster board. Data analysis was carried out by researchers. Once again, as in "CurieuzeNeuzen Vlaanderen" [10], the interpretation of the air quality measurement weeks results was not carried out by the wider community but by project scientists [11].

An example where the community could carry out air quality measurements, as well as data analysis, is "hackAIR". This CS approach was an open technology platform to access, collect, and improve information on air quality in Europe [12]. It was created by six European organizations as part of an EU-funded project on Collective Awareness Platforms for Sustainability and Social Innovation (2016–2018). Since 2018, the same low-cost diffusion tubes can be used to contribute with PM data collection to a "senseBox" project that took over the userbase from "hackAir" once the project funding ended in 2018. The project "senseBox" was developed at the Institute for Geoinformatics at the University of Münster as part of a research project funded by the German Federal Ministry of Education and Research (BMBF). The senseBox is a do-it-yourself kit for stationary and mobile sensor stations and aims to reach as many citizens as possible. The "senseBox" is intended to enable users such as schools and student labs to integrate the contents of the "senseBox" into their curriculum. The "hackAir" (later "senseBox") study design consists of four elements. Firstly, information was shared with the project community on how to build your diffusion tubes in workshops with project scientists. After that, the participants could carry out (unlimited time) PM measurements and thirdly validate and analyze their data. These two CS initiatives differ from the first two CS projects explained above by the non-passive approach of just air quality data gathering. Scientific support was provided in "hackAir" and is provided in "senseBox" CS projects, respectively, as the fourth element during the measurement phase and data interpretation phase.

The CS project "CAPTOR" was launched in 2016. Using low-cost measurement devices, citizens supported tropospheric ozone monitoring in three European testbeds. Metal oxide and electrochemical sensing devices with Arduino or Raspberry Pi. Sensor validation and calibration were carried out at regulatory-grade air quality monitoring stations in each of the testbeds [13]. This CS project offered a passive participation option for the citizens. The devices themselves were installed by project team members. "CAPTOR" hosts were provided with background information on ozone in informal conversations with the project team and via the "CAPTOR" project website, but consuming this information
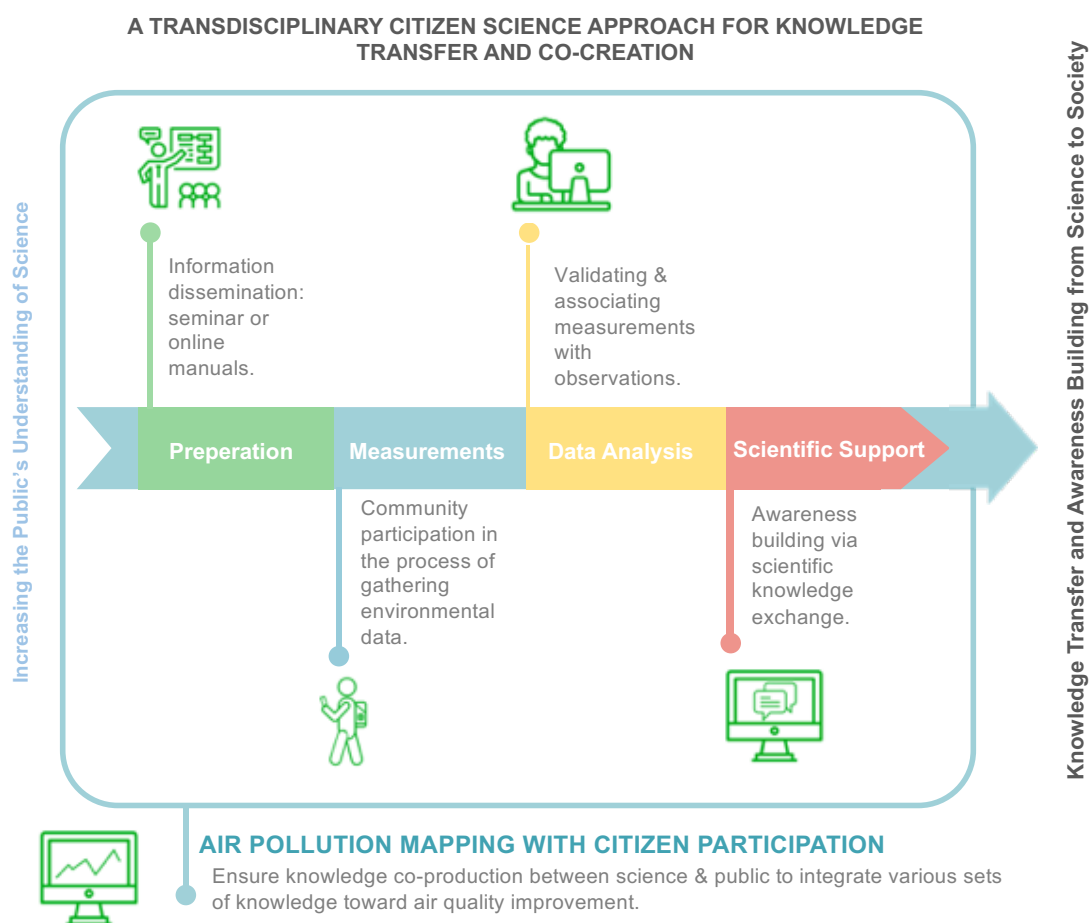
was voluntary. The sensors were installed by scientists, and the measurements took place for 2–3 years [13].

A controversial CS study design approach to "CAPTOR" is the "luftdaten.info" design where sensing and air quality mapping rely heavily on community active participation. The CS project is the project that is led by "OK Lab Stuttgart" for PM measurement. This project development started in 2014. Citizens install self-built measuring devices on the outside wall of their house that they finance themselves (approximately 40 euro). From the transmitted data, luftdaten.info generates a constantly updating particulate matter map. The design starts with workshops where participants obtain the necessary information on data collection protocols, network specifics, and know-how on sensor development. The measurement phase for the PM sensing community in unlimited and scientific support is offered in form of community gatherings as well as by online means [12].

A CS example from the United States with a four-element study design is "communityAQ"; the project has been active since 2009. It allows participants to monitor air quality at stationary sites with the community air monitor (CAM) or on-the-go with the mobile personal air monitor (PAM). The CAM and PAM provide participants with complementary technology for any air-monitoring scenario. The data collection process is supported with smartphone apps and interactive online data visualizations. Air pollution data collected by communities and students from both mobile indoor and outdoor surveys and stationary gauges are displayed on maps and in graphs. Outreach programs have reached approximately 200,000 students at more than 350 schools. Through these programs, students have been responsible for uploading more than 12 million ozone measurements and more than 2000 mobile treks. The community can download their data and compare it to others' measurements. Scientific support is available throughout the process via a platform where there are Moodle programs for study and awareness-building purposes [14].

3. Method

Citizen science project method for mitigating climate warming and fighting air pollution is dependent on the project goals. The above-listed air-quality-related citizen science initiatives present an overview of various study designs all for the goal of better air quality and for fighting global warming. Nevertheless, there are various channels for those ambitious goals. In the case of "CAPTOR", the project goal was not to educate the community. The "CAPTOR" aimed at advancing existing knowledge on the usage of low-cost sensors for ozone measurement and to learn about the impact of the involvement of citizens as sensor hosts. Similarly, the "CurieuzeNeuzen Vlaanderen" aimed at creating a detailed pollution map and using the citizens just as sensor hosts. Knowledge transfer was not the goal of these two CS projects. If, however, the aim of the CS initiative is awareness building and knowledge transfer, a more excessive involvement of the community into data analysis and interpretation processes is presented by "hackAir", "senseBOX", "Healthy Air, Healthier Children", and "communityAQ". In the latter case, information dissemination (workshops or online manuals), citizen measurement phases, data analysis and validation, and scientific support are necessary CS study design elements. Based on the current air pollution CS projects state-of-the-art, the study design for knowledge transfer purposes is summarized below in Figure 1.

A TRANSDISCIPLINARY CITIZEN SCIENCE APPROACH FOR KNOWLEDGE TRANSFER AND CO-CREATION

Increasing the Public's Understanding of Science

Information dissemination: seminar or online manuals.

Validating & associating measurements with observations.

| Preperation | Measurements | Data Analysis | Scientific Support |

Community participation in the process of gathering environmental data.

Awareness building via scientific knowledge exchange.

Knowledge Transfer and Awareness Building from Science to Society

AIR POLLUTION MAPPING WITH CITIZEN PARTICIPATION
Ensure knowledge co-production between science & public to integrate various sets of knowledge toward air quality improvement.

Figure 1. The four-element-CS air quality sensing study design recommended by state-of-the-art method aiming at knowledge transfer.

The next chapters present how the four-element CS study design was applied in the Luft-Leipzig case study, which, as the name suggests, was conducted in Leipzig, a city of 600,000 inhabitants in eastern Germany. Firstly, the aim of the case study, as well as its details, is explained. Secondly, each of the four elements is clarified by the Luft-Leipzig CS initiative. For public preparation and measurement elements, detailed descriptions of the procedures are given. For data analysis and scientific support/interpretation modeling, results from the urban microscale model CAIRDIO [15] are presented for the whole Luft-Leipzig dataset and not for individual participants data. Data collection and sensor technology specifics are presented in a separate publication as the goal of this publication is to present a novel method that is validated by the Luft-Leipzig case study. In the discussions and results chapter, we recap the Luft-Leipzig CS project lessons learned and the novel four-element CS study design for knowledge transfer purposes.

4. Luft-Leipzig Case Study Results

In 2017, a knowledge transfer and co-creation project WTimpact was launched. WTimpact aimed to find out more about what citizens learn in such projects and how citizen science projects can be optimally designed. Part of WTimpact was the Luft-Leipzig CS project that aimed at air quality awareness building and for crowdsourcing mobile air quality measurements. For that, the citizen science method was applied, which is explained in Figure 1. The participants were selected according to various criteria. Within the framework of the project, participants who were older than 18 and who lived in Leipzig or the neighboring municipalities were accepted. In total, 50 female and 48 male participants took part in the campaign from all age groups (the youngest participant being 18 years

old). The Luft-Leipzig CS initiative was successful with 98 selected participants in four various field phases following the four-element air quality CS study design. In the next chapters, the implementation of the four elements of the knowledge transfer project study design is presented in detail by the Luft-Leipzig case study.

4.1. Preparation

The applied citizen science study design began with preparing the community for the experiment. On the website of Leibniz Institute for Tropospheric Research (TROPOS), information was given out to the public about the project launch. A separate website was set up with a poster and postcard where the boundary conditions for participation and the schedule for the planned measurement campaign were given. Information dissemination on the Luft-Leipzig project was most extensively conducted at workshops carried out in TROPOS. Studying project-related information was requested of all selected citizens as a prerequisite for contributing, and receiving the sensor was participation in the workshops.

Participants were invited to a workshop and received intensive training as most of the volunteers were non-experts. In the Luft-Leipzig case study, aerosol-physics and meteorology scientists gave air pollution measurement-related scientific information as well as the use of the instruments and platform in a seminar scheduled on one day and lasting approximately one afternoon. The maximum group size was planned to be 10 community members. Weekends were preferred for the workshops because our target audience was citizens aged 18 and older, and most participants had limited capacity to attend seminars at TROPOS on weekdays. The seminars were designed in such a way that all necessary information could be given out with the sensor on the same day. The workshop covered the main principles of air quality measurements in the Leipzig area and the protocols of data curation. The team introduced themselves to encourage the participants to actively seek support and help on the forum platform. Together with lending out the sensor and filling out the protocols, a whole afternoon was planned for the weekend.

In each of the field phases, three workshops were planned and carried out on Sunday afternoons to introduce TROPOS, the project, the project staff at the institute, and the PM and BC measuring backpack to the participants. Due to the limited number of participants (the aim was to have 100 participants), each of these workshops could be conducted for 8–10 participants. This relatively small group allowed the TROPOS staff and the participants to get to know each other personally and thus to lower the inhibition threshold in case of questions and problems and to stimulate the discussion between each other.

4.2. Measurements

Each volunteer was lent the PM10 and BC sensor set for one week for carrying out measurements. No financial commitment was requested from the participants. No pre-given location for citizen measurements was set by the project, and therefore, the volunteers could carry out measurements whenever and wherever they wanted. It was recommended to carry out at least one hour of air quality sensing per day. Citizens could make notes on the mobile device on notable observations as trucks driving by or passing BBQ areas. The measurements took place from April 2019 until February 2021. All participants together performed slightly more than 1000 h of measurements in the greater Leipzig area (of approximately 300 km^2), which corresponds to a data set of more the 3 million data points.

The measurement field phases took place throughout the year, except during the vacations in high summer. The first measurements field phase, in which 23 participants took part, ran from the beginning of April to the end of June 2019. This first phase was followed by a 3 month break, which was used to further improve both the hardware and software. The second field phase then lasted from early September 2019 to mid-December 2019, with 25 participants taking part. There was a break again over Christmas and the turn of the year. The third field phase started in January 2020 and was scheduled to run until April. However, due to the outbreak of the COVID-19 pandemic, the measurement phase could not be successfully carried out to the end but had to be stopped in mid-March. Even

before that, the method for participant training needed to be changed. It was no longer possible to conduct workshops due to the required spacing rules. Therefore, during the third field phase, a change was made to individual training. Due to the early termination of the campaign, the targeted number of participants could not be reached. In the third field phase, 19 citizen scientists participated. Although only three field phases were originally planned; the fourth phase was therefore appended. The fourth field phase started in September 2020, i.e., after the relaxations of lockdown rules during the pandemic, and was continued almost until the end of the project in February 2021. Even during the fourth field phase, increasing constraints had to be faced due to the ongoing COVID-19 pandemic. Specifically, both acquiring motivated participants and instructing them was a major challenge. Therefore, throughout the fourth field phase, participants were also trained in one-on-one briefings as it was already conducted at the end of the third one. Although the field phase had to be designed longer than the previous ones, it was finally completed in February 2021 with 31 participants. The summarized measurement data are presented in the next chapter.

4.3. Data Visualization and Analysis

The data evaluation and visualization include two stages. One was the analysis by the citizen scientists themselves; the other was the evaluation of the whole data set by the scientists. After one week of measurements, the volunteers could validate their data collected with the expert community and discuss notes taken during measurements in the forum. However, for data protection reasons, each participant only had access to their measurement data, and the evaluation of the entire data set was thus reserved for the scientists. In this section, the joint BC and PM measurement results of the Luft-Leipzig 98 participants are presented and plotted alongside the official, stationary measuring station Leipzig Mitte data operated by Saxon State Office for Environment, Agriculture, and Geology (LfULG) and correspond to average daily values. Firstly, as SLCP and air quality are dependent on weather conditions, meteorological data throughout the four field campaigns are presented in the below graph.

As already described above, the participants of the project were not given any strict guidelines for the measurements. In the workshops and later in the individual instructions, only general hints were introduced. Likewise, advice and recommendations from the scientists' point of view were given in response to queries. In the end, however, the participants were free to decide for themselves where and how long they wanted to plan their measurements. This waiver of strict guidelines was made as a compromise not to overburden the participants.

Despite the lack of strict regulations for the participants concerning the measurements, data were taken almost all over the city of Leipzig as seen in Figure 2, showing the coverage of measurements in the city area. For the illustration and the further analysis of the measurement data (except if mentioned separately), indoor measurements were excluded. One reason for the good coverage is certainly that the participants also came from all parts of the city. It can be expected that a high number of measurements took take place in the vicinity of the respective place of residence.
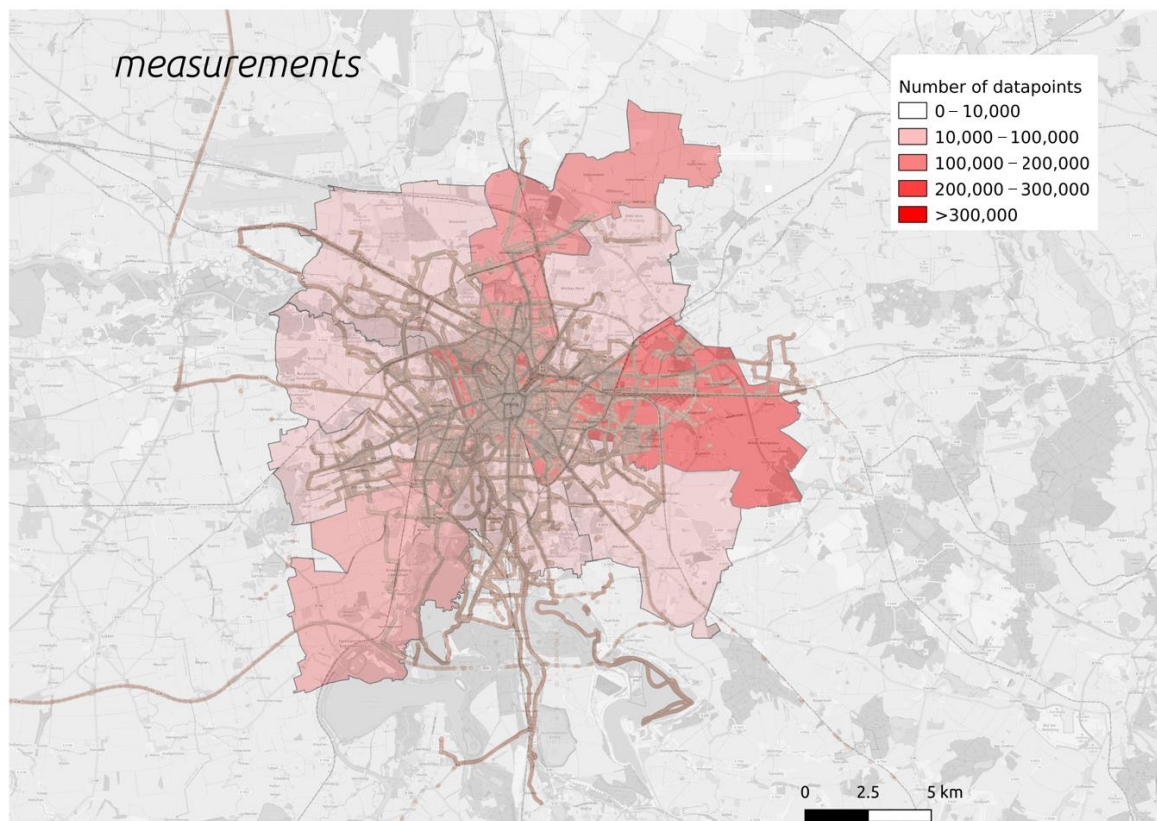
**Figure 2.** City of Leipzig coverage of the project measurements.

It can be further assumed that the choice of the measurement routes depends on additional factors, including weather conditions, that may play an important role. Figure 3 shows the distribution of measurements depending on the respective air temperature. The air temperature was also measured with the mobile backpack. It is noticeable that especially on days with high temperatures, measurements were taken in the recreational areas around the city center of Leipzig (the location of the measuring station Leipzig-Mitte is also marked in Figure 3). This is particularly obvious around the lake district in the southeast and east of Leipzig. By contrast, measurements were taken at a significantly lower mean temperature in the districts around the city center (especially in the district Grünau in the southwest, in Möckern in the northwest, or Schönefeld/Paunsdorf in the east). It may be concluded that participants used "nice and warm" weather (high temperatures) for leisure activities where they had the measurement backpack with them (hikes and bicycle tours). Since high temperatures mainly occur in the summer half-year, a certain spatial division over the course of the year should be also visible. Thus, while in the winter half-year, the participants measured mainly in the urban area "in front of the house", in the summer half-year, there was a significant proportion of measurements in the urban background during the measurements during leisure activities. It is, therefore, to be expected that a seasonal effect can be observed in the CS air quality measurement data.
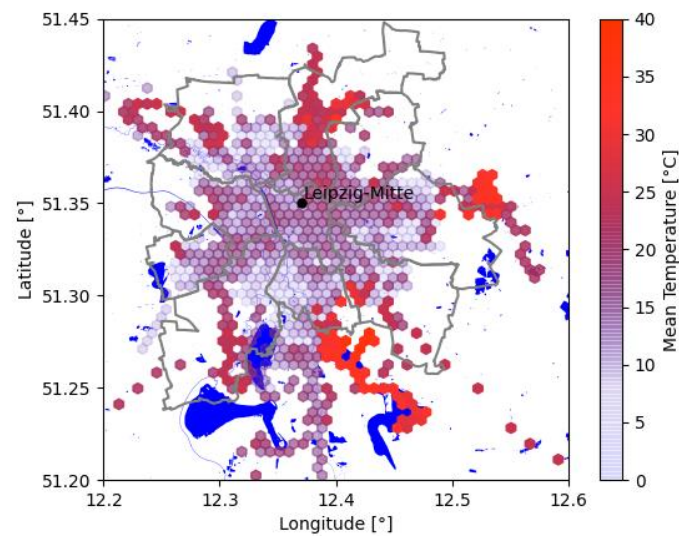
Figure 3. Map showing the mean temperature during the citizen measurements.

The Figure 4 displays the time series of meteorological parameters over the entire CS project period from 2019 to 2021. The data originate from the official, stationary measuring station Leipzig Mitte operated by LfULG which was not collected by citizens and is publicly available. The data presented correspond to average daily values. The periods of the field phases are highlighted in gray. The figure above shows the typical annual cycle of the meteorological parameters. Furthermore, it can be seen that, except for summer, all seasons could be covered at least once by Luft-Leipzig citizen measurements. The citizen measurements are displayed as "PM10-Backpack" against the publicly available measurement station data below.
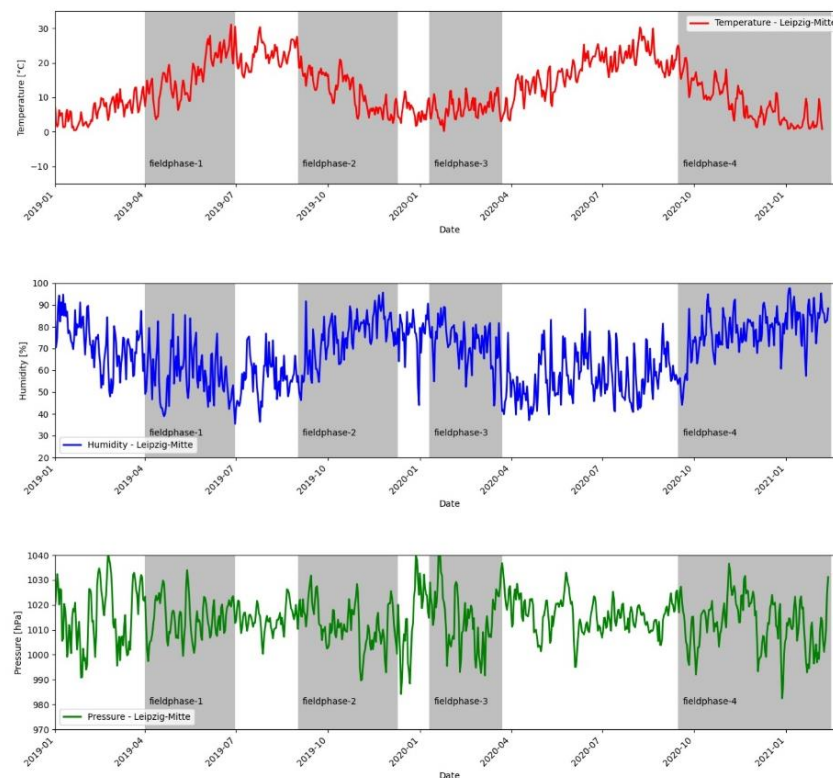
Figure 4. Time series of temperature, relative humidity, and pressure during the entire period of all field campaigns. Meteorological data were measured at Leipzig-Mitte (source: Saxon State Office for Environment, Agriculture and Geology, LfULG, Dresden, Germany).

The below-plotted Figure 5 shows the temporal course of the hourly mean values of the PM10 concentration, which were observed employing a tapered element oscillating microbalance (TEOM) instrument at the stationary Leipzig measuring stations (Leipzig-Mitte, Leipzig-Lützner Straße, and Leipzig West). Furthermore, a time series of values from the background station "Collm" is also shown in Figure 5. The background concentration is shown as a daily mean value to smooth the graph. Finally, the figure shows the data measured by the citizen scientists and represented by hourly mean values. Again, the time periods of the field phases are recognizable, as well as the broad scattering of the measured values, which already here indicating a high spatial and temporal variability.
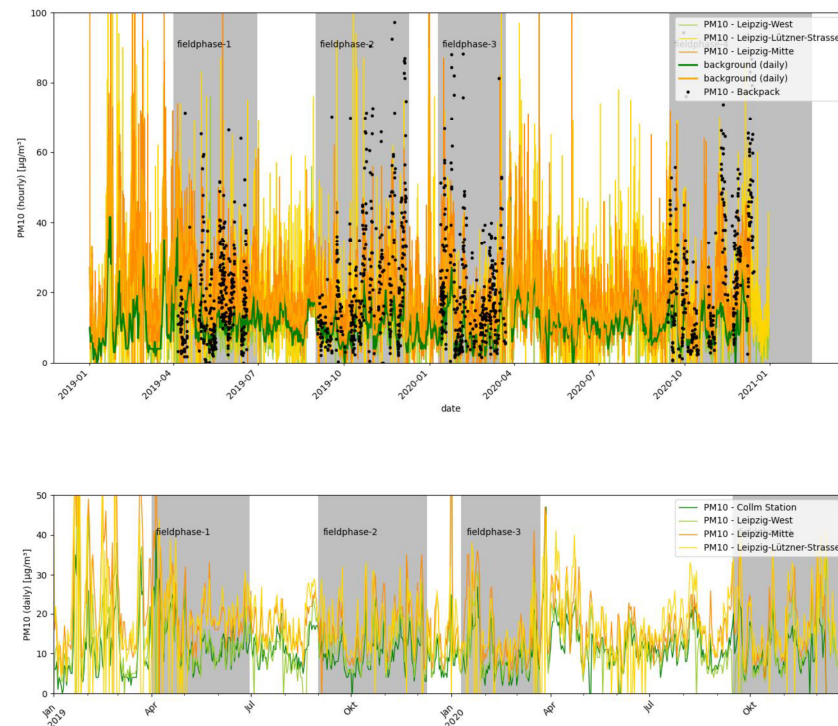
Figure 5. Time series of PM10 mass concentration during the entire period of all field campaigns. The upper panel show data on an hourly basis, the lower panel gives averaged daily values. PM10 reference mass concentrations were measured at Leipzig-Mitte and Collmberg (Collm.) station (source: Saxon State Ministry for Energy, Climate Protection, Environment, and Agriculture, LfULG, Dresden, Germany), the black dots represent hourly averaged backpack measurements performed by the citizen scientist.

Urban concentrations of SLCP (PM, NOx, and BC) often show a typical diurnal pattern with maxima during peak traffic hours. A distinction can be made between weekdays and holidays (or weekends). Figure 6 below summarizes the average daily variations of the measured PM10 and BC mass concentrations for both the stationary measuring stations and the citizen measurements. The maxima in the morning and afternoon hours are visible. As also shown in Figure 6, the diurnal variation is also reflected by citizen scientists' measurements (again, the average was calculated using overall measurements, i.e., excluding values marked as indoor measurements and all field phases).
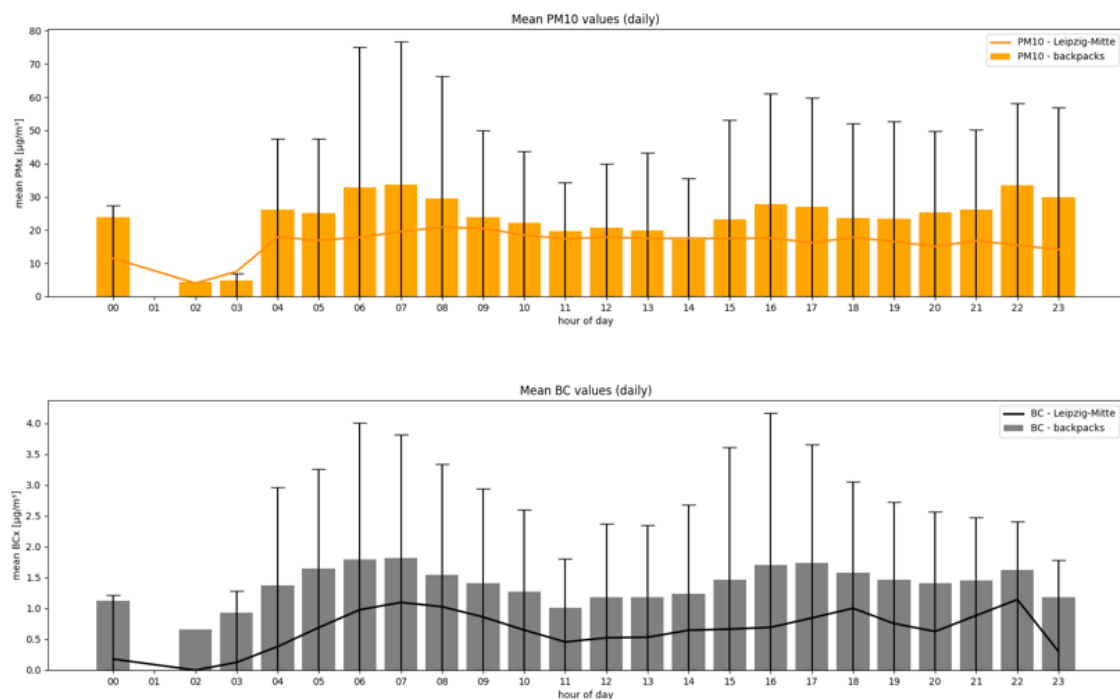
Figure 6. Diurnal variation of the measured PM10 and BC mass concentrations (fixed stations compared to backpack measurements performed by the citizen scientists). Data source for the stationary data: LfULG.

Urban concentrations of air pollutants are influenced by anthropogenic sources. Due to a large number of local sources and the often-limited mixing, a strong small-scale variability of concentrations can be observed. Characterizing this small-scale variability is therefore one of the potential essential applications of low-cost, mobile measurements executed by citizens and in the state-of-the-art air quality CS studies designed for the last element- the scientific interpretation and support component.

4.4. Scientific Interpretation and Support

The air SLCP data collected by citizen scientists in Leipzig was accompanied by mathematical modeling to carry out scientific support. An urban air-quality forecast for Leipzig and eastern central Germany was provided to the volunteers via interactive web mapping for experimental planning and the interpretation of observations, based on simulations with the multi-scale chemistry-transport model COSMO-MUSCAT [16]. In addition, for further interpreting the small-scale variability of air pollution, the novel urban micro-scale dispersion model CAIRDIO [15] was applied in hindcast mode as presented here. This kind of modeling that applies data from the past represents a high level of scientific support that a citizen could receive from the scientific community for knowledge transfer and awareness building, similarly to "CAPTOR" to "CurieuzeNeuzen Vlaanderen" CS projects, where the last element did not necessarily include public engagement. To qualify as a knowledge transfer study design element, the results, however, of the last step have to be made publicly available for citizens (e.g., via open-access publications or project website). The Leipzig case study the scientific modeling of the citizen data was executed and presented to the public as a result of the first three study design elements.

The supplement of data from urban air quality models combined with citizen measurement data can add important information to the interpretation of citizen measurements, e.g., interesting questions arising from citizen measurements are the significance of different sources (source apportionment) and the influence of varying meteorological conditions, as well as the complex urban topography, which ultimately led to the observed air pollutant concentrations. These questions can be well addressed using Eulerian dispersion models, which solve the fluid-dynamic equations under the imposition of realistic meteorological

boundary conditions [17,18]. Moreover, with multi-scale modeling approaches, it is also possible to discriminate local contributions from the long-range transport of atmospheric pollutants [19]. This question is important to assess when evaluating local mitigation efforts. Putting it the other way around, air quality simulations also strongly benefit from mobile measurements, as the latter can provide important clues on the proper representation of local air pollution sources in the model, which is often quite uncertain [20]. Measurements can thus be used to adjust emission inventories to account for more realistic scenarios [21].

Here, we present an exemplary modeling study to complement Luft-Leipzig citizen measurements of PM10 taken during an early-autumn weekend in 2020 with data from a high-resolution air-quality model. The simulated time span covers the evening hours of 12 September 2020, a period which was marked by warm and dry weather and thus favorable for outdoor activities, including barbequing (BBQ). During this period, citizen measurements are available within the city district Leipzig Gohlis along a track that traverses diverse neighborhoods, including garden plots, within surprisingly very high PM10 concentrations (>50 μg/m^3) that were measured (see Figure 7).
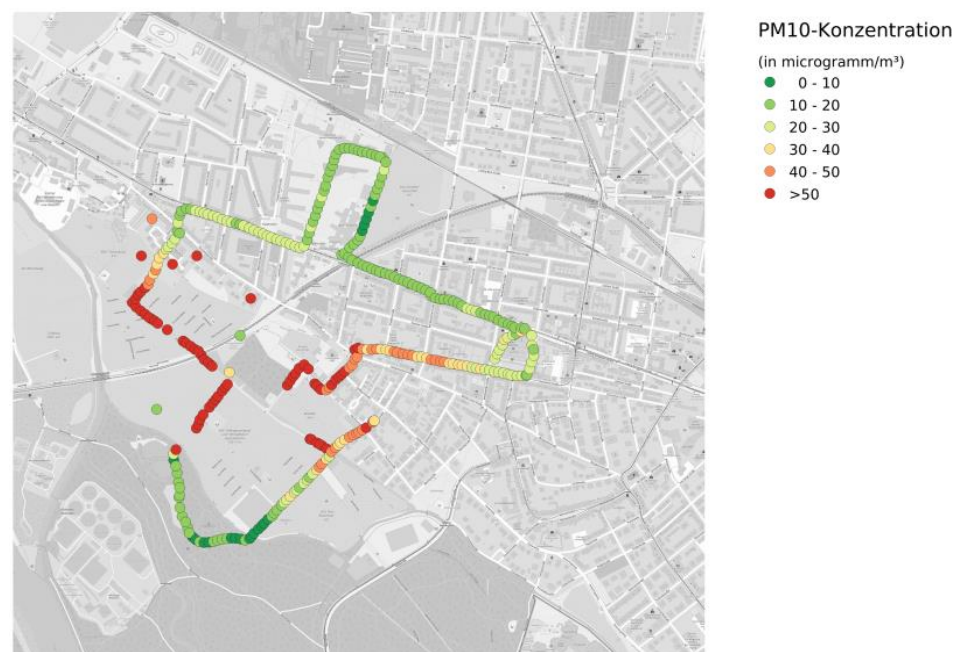
Figure 7. Citizen measurements within the city district Leipzig Gohlis along a track that traverses diverse neighborhoods, including garden plots, within very high PM10 concentrations.

The modeling study uses the newly developed large-eddy simulation-based dispersion model CAIRDIO, which is suitable to simulate PM10 emissions and dispersion patterns on spatial scales ranging from a few meters to tens of meters. Figure 8 gives an overview of the simulation domain, which mostly covers the area depicted in Figure 7, and also shows prescribed line emissions for roads and railways. Road emissions are provided by LfULG, while railway emissions and area sources for other domestic and industrial activities (not shown) are provided by the Federal Environmental Agency UBA. Boundary conditions for meteorology and back-ground PM10 concentrations are interpolated from simulation results with the weather and air-chemistry transport model COSMO-MUSCAT, which was deployed on scales ranging from entire Europe (14 km spatial resolution) down to the urban-background scale (550 m spatial resolution).
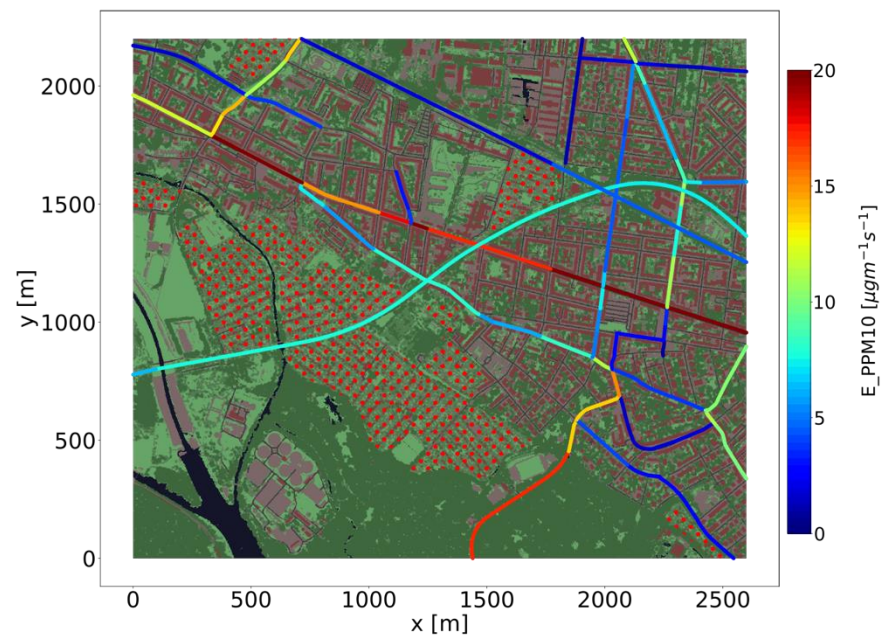
Figure 8. CAIRDIO simulation domain with 10 m horizontal resolution depicting part of the city district Leipzig Gohlis. Prescribed line emissions of primary particulate matter (PPM10) for major roads and railways are overlaid on the image and are based on data from the LfULG and UBA. Garden plots are marked by red-dotted patterns, for which stochastically flaring-up point sources are assumed to represent barbequing activity in model run WBBQ.

Simulation results using the aforementioned standard emission dataset are shown in Figure 9a–d (run without BBQ fires—WOBBQ) during the time span from 18:30 to 20:00 CEST. From 18:30 to 19:30 CEST, PM10 concentrations are mostly low (10 $\mu g/m^3$–20 $\mu g/m^3$), apart from higher concentrations along the Georg-Schumann road crossing the domain from west to east, where concentrations reach up to 60 $\mu g/m^3$ at exceptional spots. During this period, the prevailing wind direction is from the west with mostly pristine inflowing background concentrations. Between 19:00 and 19:30 CEST, a marked and abrupt wind shift to northwesterly directions occurs with an approaching cold front. With the wind turning, the more polluted air mass is carried into the city district. The origin of these now much higher PM10 concentrations (~40 $\mu g/m^3$) is from non-local sources, and the PM10 is mostly composed of secondary aerosol. When compared to the mobile measurements in Figure 7, at first, the model results cannot explain the measured spatial variability and levels of PM10 concentrations: for the first half of the simulation period, the observed high PM10 concentrations within the garden plots (>50 $\mu g/m^3$) are absent in the model. After the wind shift, modeled concentration fields are much higher, but they lack the observed spatial gradients. Most probably, the citizen measurements were taken before the wind shift occurred, when a quite pristine background was present. Locally strong pollution sources within the garden plots presumably associated with BBQ activity led to the high PM10 concentrations within and further downwind of the garden plots to the east. The sharp gradients along the southern and western boundaries of the garden plots agree with a mostly pristine background and westerly to southwesterly winds.

To account for the BBQ activity in the model, which is not covered by the standard setup, a second model run with BBQ fire emissions (WBBQ) was conducted by making the following assumptions for additional local garden plots emissions as BBQ is an activity usually conducted in evening hours under good weather conditions in green areas. Based on their typical pattern on satellite images, a total area of 75.2 ha of garden plots was identified, which can be divided into 1928 parcels of approximately 390 m^2 (see shaded areas in Figure 9). Of those parcels, one third are randomly chosen to be active during the evening, i.e., they contain a point source, which flares up for one single time during

the evening. The highest probability for a source to flare up is during the typical dining hours between 18:00 and 20:00 local time. After activation of a source, its emission rate gradually increases to reach the peak emission rate, which lasts for one hour, before it gradually decreases again, with a total source-active time of 2 h. The peak emission rate of 40 g/h PM10 is a rough upper estimate for a single charcoal-fueled grill, when considering PM-emission factors of up to 10–40 g/kg for uncooked meat [22].

Model results of this second run WBBQ are depicted in Figure 9e–h. Compared to the original run WOBBQ, plumes of locally high PM10 concentrations (>50 μg/m³) originating inside the garden plots are advected to the east into residential areas. Building rows were aligned perpendicular to the flow block the dispersion, while the plumes protruded more easily along wind-parallel street canyons into residential areas. In addition, the observed sharp gradients to the south and west of the garden plots are well represented in the model. Thus, the air-pollution pattern in this run considering BBQ activity matches observations much better than the pattern seen in the run WOBBQ. After the shift in wind direction, the influence of BBQ activity on the residential areas becomes less significant due to the plumes being transported more to the south and the generally higher background PM10 concentrations.
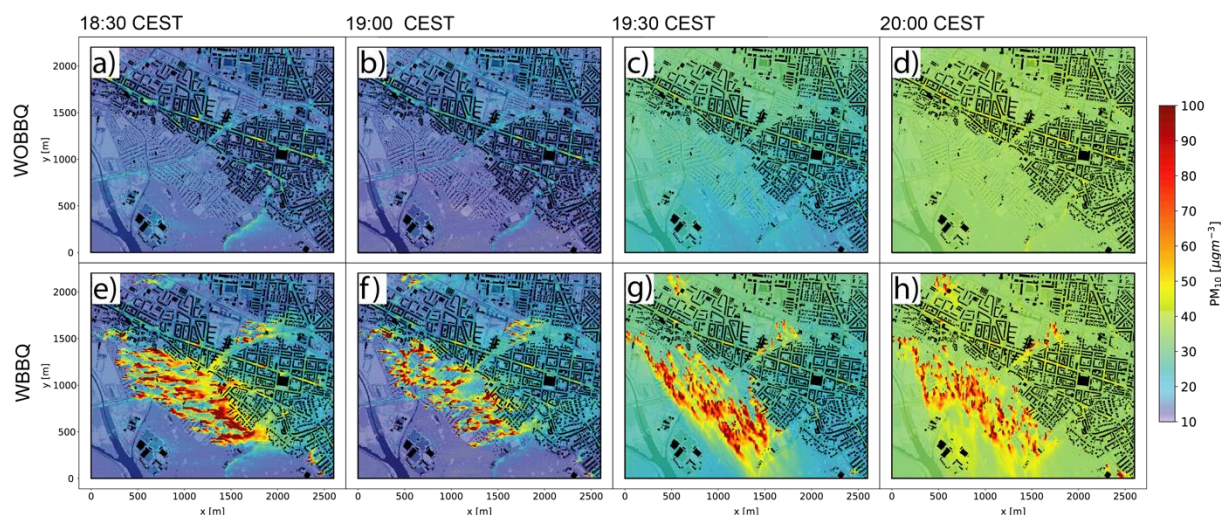
Figure 9. Panel plot of modeled half-hourly PM10 maps at 2.5 m height from 18:30 to 20:00 CEST. (**a**–**d**) show model results of the run using the standard emission inventory, (**e**–**h**) of the run using additional local emissions for BBQ activity.

The disagreement between the model run WOBBQ and the mobile measurements points out an important limitation of air-quality models using standard emission inventories. Only with the availability of the mobile measurements showing high PM10 concentrations within garden plots, BBQ activity could be considered as an important factor for local air quality, whose representation proved to be important in the model during the simulated period. To conclude, this modeling example highlights the beneficial synergic effects of using combined model and mobile measurements data to study local air quality.

5. Discussions

The limitations for creating a commonly accepted method as presented in this paper are the various scientific goals of knowledge transfer projects. To date, no common definition or method for CS exists as many types of infrastructures exist with different functionalities [11]. It is important to note that the aims of the project can vary, and the above-presented study design can be modified according to individual CS project needs. Most CS initiatives for raising public awareness include each of the four elements that were presented in detail by the Luft-Leipzig case study. The study design should start with public preparation element where information is disseminated in the form of workshops (in the case of "Healthy Air, Healthier Children" campaign, "senseBOX", "luftdaten.info",

"hackAir", Luft-Leipzig, and the USA example—"communityAQ") or the SLCP, and air quality-related information is disseminated via online channels only ("CurieuzeNeuzen Vlaanderen"), and it is possible that consuming the information is voluntary ("CAPTOR"). However, a certain amount of information has to be made available for the public to carry out CS projects.

The second common element in almost all CS projects is the element that involves public participation in scientific exploration. The duration of the measurements phase can last from one week (Luft-Leipzig) to several years ("CAPTOR"), and this element of the study design has to be designed for specific project goals. It must be noted that it is both possible to offer the sensors for no costs (e.g., "CAPTOR" or Luft-Leipzig) or for low costs ("CurieuzeNeuzen Vlaanderen" 10 euro or "luftdaten.info" approximately 40 euro).

The third element is data analysis, which can be carried out by community and/or scientist. If the goal of the study is to educate the public about SLCP and air quality and to contribute to knowledge transfer based on state-of-the-art methods, the public is in one way or another integrated into data analysis processes. In other words, the community can visualize, download, validate, edit, and/or compare their observations with others or at least carry out one of the mentioned functions.

The fourth element common in study designs for CS knowledge transfer studies is the scientific support component. This is defined by scientific work with the community data that is made available for the citizens so new knowledge can be generated. In the "CAPTOR" or "CurieuzeNeuzen Vlaanderen" CS project, the scientific support element consisted of experts validating the data and making the SLCP and air-quality-related data available with the support of mathematical modeling or even developing advanced AI algorithms based on community data and presenting it to the public without requesting citizen commitment to modeling or AI algorithms development. Alternatively, active community involvement in analysis and data interpretation can be integrated into the fourth element as well as performed in "senseBOX" or "communityAQ". There, expert assistance (scientific support) is offered in the form of interpreting the air-quality-related data. The complexity of the scientific goals determines how much citizens can be involved in the final scientific element. Due to data protection laws, it must be noted that in EU the individual GPS data publishing is not allowed, and therefore joint results can be presented in reports and publications and web-outlets.

If community participation should be wide-reaching and people from various backgrounds are targeted, developing advanced air quality AI algorithms or implementing CAIRDIO modeling together with the public could be an extensive resource. Therefore, the state-of-the-art of air quality CS research presents various opportunities for scientific support and data modeling or interoperations element, which nevertheless is part of each air-quality-related CS initiative.

For future research, it is suggested to develop the four steps further, more in detail, and to specify each step for various scientific goals. For example, if the goal is not knowledge transfer and data curation with citizen participation, the concluded method of this study should be validated by setting up a case study and by drawing conclusions based on the case study results if the four steps are enough or too much for achieving specific scientific goals. Nevertheless, for a common definition of a CS method, it is important to make sure that the process is applicable beyond a specific case study.

6. Conclusions

The active role of citizens and their direct involvement is essential to address climate change. Changes in citizen's behaviors toward more sustainable patterns can happen through knowledge transfer, awareness building, citizen science, observation and monitoring of their environmental impacts, and civic involvement [23]. Bridging policy and individual action to mitigate climate change via emission reduction is the key [24].

In this paper, selected CS projects addressing SLCP monitoring were investigated. The state-of-the-art method, that was identified is presented in Figure 10. The four-element

study design was strategized based on six European air-quality-related CS projects and one American one. This method was applied for the Luft-Leipzig case study and the four steps presented in detail for each of the elements, namely project related information dissemination for the target community (workshops); measurements (air quality sensing); curation of the whole citizen dataset with scientific support (data visualization and analysis; and fourthly scientific interpretation of citizen measurements results via mathematical models. Each participant selected for the Luft-Leipzig CS project went through the four elements mapped above. In total, 50 female and 48 male participants took part in the campaign from all age groups (the youngest participant being 18 years old). The Luft-Leipzig CS initiative was successful with 98 selected participants in four various field phases. The measurement elements of the knowledge transfer project Luft-Leipzig established a dataset of more than three million SLCP related data points that enabled the scientist to plot the air quality map of Leipzig (the third element) and finally scientifically support the citizens with CAIRDIO modeling to further describe the variability of citizen measurements results by presenting the BBQ effect.
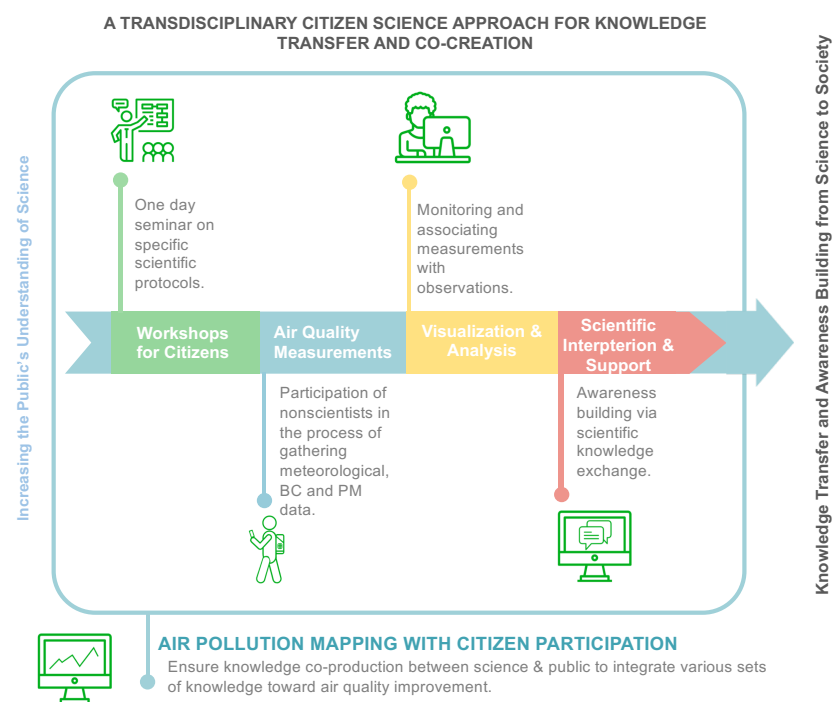
Figure 10. A novel method for SLCP mitigation projects that employ citizen scientists, validated by the Luft-Leipzig case study and recommended for knowledge transfer purposes.

The four-element study design for the Luft-Leipzig project is presented above in Figure 10. With the four elements, it is possible to contribute to SLCP mitigation science and knowledge transfer alike. This study design is suggested for forthcoming CS initiatives aiming at knowledge transfer and SLCP mitigation. As the international CS community is in the process of defining public participation in scientific projects [25], studies contributing to defining the design and methods of a specific area of focus (e.g., air quality and SLCP mitigation) contribute to further improving the value of CS. Establishing criteria and guidelines for a scientific topic related CS research set-ups helps ensure that CS projects are rigorous, help the field flourish, and, where applicable, encourage policymakers to take CS project data and results seriously. This paper contributes to science with a novel four-element study design for public involvement in SCLP mitigation knowledge transfer projects that can be applied beyond the Luft-Leipzig case study.

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