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First Results of the Application of a Citizen Science-Based Mobile Monitoring System to the Study of Household Heating Emissions

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Abstract: This work aims at understanding whether a citizen science-based monitoring system could be adequate to detect the effects, in terms of air quality, of solid and liquid fuel combustion for household heating. Citizen science is known to be able to improve the coverage and resolution of measurements at a very low cost. On the other hand, it also has severe limitations. Since low-cost sensors are to be used, measurements are problematic in terms of precision and accuracy. In order to test these aspects, we developed a system named COCAL that supports all the phases of air quality monitoring, from data acquisition, georeferencing, transmission, and processing up to web mapping. In this work, we focus on particulate matter. To address the limitations of the citizen science approach, we carefully tested all the parts of the system and, in particular, the performances of the low-cost sensors. We highlighted that their precision is acceptable, while their accuracy is insufficient. Measurements taken within such a paradigm cannot be used, therefore, as reference values. They can be used, instead, as relative values, in order to identify and to map trends, anomalies and hotspots. We used COCAL extensively in the city of Trieste and were able to identify different behaviors in different areas of the city. In the city center, PM values increase constantly during the day. In the rural suburbs of the city, we observed that PM values are low during the day but increase very rapidly after 5 p.m. It is important to note that, in the city center, household heating is based almost completely on natural gas. In the rural areas, household heating is generally based on wood burning stoves or liquid and solid fuel. A possible explanation of the different behavior between the two areas can then be related to commuters living in the rural areas but working in the city center. When they return home in the evening, they switch on the heating systems triggering the release of large quantities of particulate matter. We were able to map peaks of particulate matter values and highlight that they are initially located within the village centers to later propagate to the areas around them. The possibility of mapping air quality with the coverage and resolution we were able to obtain within a citizen science approach is very encouraging. This can be very helpful in understanding the impact that liquid and solid fuel combustion can have on the environment and human health. In addition, we think that this opportunity can be very important considering the current geopolitical situation where a (hopefully only temporary) shift toward pollutant fuels is expected in the near future.

Keywords: air quality; particulate matter; low-cost sensors; citizen science; crowdsourcing; liquid fuels; solid fuels; residential wood combustion

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1. Introduction

It is well known that exposure to air pollution increases the risk of pulmonary infection and cardiovascular diseases [1]. The World Health Organization (WHO) reported that in 2016 around 7 million people died as a result of air pollution exposure [2], and concerns are raised regarding the possible correlation between COVID-19 occurrence and air quality [3].

The most common causes of the deterioration of air quality are fossil fuel or biomass combustion, automobile exhaust fumes, wind-blown dust, and industry and construction emissions, while indoor pollutants are released while cooking or heating, from cigarette smoke or household cleaning.

Household heating can have a deep impact on health and the environment in general. The EU strategy for heating and cooling [4] maintains that, notwithstanding the efforts to move to clean, low-carbon energy, the sector still uses 75% of fossil fuels. Only half of this is from natural gas; 15% is estimated to be coal, and 10% is oil.

Biomass is the most widely used renewable energy for heating. It represents some 90% of all renewable heating fuels but remains below 11% of the overall sources of heating fuels.

Not all fuels perform the same way in terms of emissions of pollutants. Natural gas, which is primarily composed of methane (CH4), is the cleanest fuel. The combustion of natural gas contributes to the formation of smog and acid rain, but particulate matter (PM) emissions are typically low [5].

Liquid fuel combustion produces large quantities of PM and high concentrations of sulfur and heavy metals. Coal is one of the most problematic fuels. Its combustion produces high levels of pollutants such as oxides of nitrogen and sulfur, trace elements, and high levels of fine PM [6].

More recently, biomass combustion and, in particular, residential wood combustion (RWC) received attention as an important source of pollution [7,8]. Its characteristic of being recognized as a form of eco-friendly fuel is mainly due to its "carbon neutrality". The amount of CO_2 released into the atmosphere from burning wood and wood pellets is, in fact, approximately the same as the CO_2 absorbed by the tree through photosynthesis while it is growing. If we consider instead the aerosols produced during RWC, similarly to other solid fuels, this emits large amounts of PM, black carbon, nitrogen oxides, carbon monoxide, sulfur dioxide, lead, mercury, and polycyclic aromatic hydro-carbons (PAHs). PAHs, in particular, are known to be mutagenic and carcinogenic and are classified as persistent toxic compounds [9].

Another important issue to consider in studying the generation of pollutants due to RWC is the technologies of stoves and boilers. Quoting [4], in Europe, a large part of them were installed before 1992, have an efficiency of 60% or less, and are older than their technical life. Replacement of old appliances is typically made under pressure when the system breaks down. Owners do not have, then, the time to obtain information on new technologies and continue to use old and less efficient ones. Air pollutant sources are not homogeneously distributed geographically. Lim et al. [10], for example, maintain that there are differences between low-income and high-income countries and between urban and rural areas. Champion et al. [11] report on the consequences for the health of using high-volatile bituminous coals, and several other authors, such as [12], studied air pollutants in highly industrialized countries such as China.

In Europe, the EU [13] highlighted the large differences across individual countries as well as in comparison to the EU average values. In Sweden, for example, household heating is largely based on biomass burning, Poland focuses on coal, while Italy and Hungary rely mainly on natural gas. This latter is typically supplied to buildings via underground distribution pipelines owned by a utility company. However, not all territories can be easily reached by the pipeline network. In Italy, for example, considering that a large portion of the territory lies in mountainous or inaccessible areas, a certain portion of the national territory is actually not reached by the national natural gas distribution network [14]. There, liquid or solid fuels are predominantly used.

According to the Italian Ministry of Ecological Transition data sheets [15], in 2021, Italy imported approximately 72 billion cubic meters (bcm) of natural gas. The demand is met by importing approximately 90% of the total supply [16]. The Italian storage system is entirely based on depleted natural gas fields and has a capacity of 16.7 Bcm [17].

The current (August, 2022) international geopolitical situation is problematic for natural gas, where supplies rely on imports from Russia. To contrast this situation and to respond to the climate crisis, the EU is planning a massive scaling up and speeding up of renewable energy through the REPowerEU Plan. This aims, for example, at doubling the solar photovoltaic capacity and accelerating the development of hydrogen-based technologies [18]. However, this will take time. Several experts forecast, in the short term, a burst of coal and other more polluting fuels until enough solar and wind energy are available [19].

This trend will probably be different in urban or rural areas. In the countryside, the availability of RWC stoves and boilers will shift the balance in favor of polluting fuels. In the city centers, instead, large multi-story buildings with natural gas-based central heating systems will not be able to switch to other types of fuels.

These forecasts raise concerns about air quality in rural areas. Current monitoring methods can be inadequate. Specific techniques are then to be developed that can reconstruct the distribution of pollutants with high coverage and resolution.

Participatory Citizen Science

Participatory citizen science (CS) is a wide concept that encompasses the possibility of outsourcing some activities normally restricted to the scientific community to a wider group of volunteers that generally are not experts in the subject. This approach dates back to the seminal work of Irwin at the end of the '90s [20], who postulated that enrolling laypeople in scientific research it is possible to reach two main goals. On the one hand, people become aware and informed on scientific topics. On the other hand, researchers can count on additional resources for their work.

From a scientist's point of view, a very important driver to entering the participative paradigm is the reduction of costs. Some research activities such as observation and measurements, image coding, or the transcription of documents require personnel, logistics, and funding that, through time, have been progressively difficult to obtain. The availability of volunteers (also called citizen scientists) able to perform such simple tasks can be decisive. This is why this approach gained progressively more and more momentum. Crowd and citizen science-based projects have already resulted in a significant volume of research outputs. These have been studied from a bibliometric point of view by authors such as [21]. Other authors attempted to quantify the financial value of crowd contributions [22].

CS did not go unnoticed by governmental and funding organizations. The US Federal Government recognized CS as a key element in its Crowdsourcing and Citizen Science Act of 2016 (15 USC 3724) [23]. The EU highlighted the importance of CS in its green paper on CS [24]. Private companies have also developed an interest in CS. This is witnessed, for example, by the support to Zooniverse by Google [25].

CS has been applied in a wide spectrum of scientific fields, such as astrophysics [26] or archaeology [27], epidemiology [28], or socio-linguistics [29]. CS is particularly suitable for the environmental sciences [30–33]. This approach has also been used by our team in other projects devoted to monitoring the marine environment [34–36].

From the citizen scientist's and general public's point of view, CS can be very useful in raising awareness of environmental issues. In addition, CS can be particularly important to contrast 'fake news' that very easily and quickly circulates in social media [37].

2. Materials and Methods

This work aims at exploring the possibility of using unconventional methods to map the distribution of air pollutants emitted by household heating. In particular, we are interested in understanding how air pollution can be related to the use of liquid and solid fuels and the consequences that this can have on the environment and human health. As mentioned above, this can be particularly urgent considering the current geopolitical situation, where a trend toward an increase in the use of solid fuels is forecasted by several authors.

Air quality monitoring is a consolidated activity fulfilled by governmental environmental agencies through ground-based monitoring systems. These stations use high-accuracy and precision devices that are deployed in a network of sparse stations. The costs of such instrumentation and its logistics can be very high so that the coverage of phenomena using such technologies is necessarily limited. In addition, these stations are generally more densely distributed in urban areas rather than in rural ones.

The set of discrete point measurements is then inter/extrapolated using statistical [38] and/or modeling techniques [39] in order to attain a larger geographic and temporal distribution. These results can be problematic where the environment is characterized by high gradients.

In order to address these problems, we studied the possibility of introducing a CS-based participatory approach. CS is known to improve geographic and temporal coverage but can introduce severe limitations. To test advantages and disadvantages of CS-based monitoring, we developed a system named COCAL (a dialectal term for the seagull bird) that covers all the technological aspects of the problem. The system allows measurements, transmission, integration, processing, and real-time web-based visualization of air quality maps.

COCAL system is described in detail in another work [40]. We will here describe its features and functionalities that are relevant for mapping pollution emitted by household heating. We will also report on the limitations of the approach and the first results we were able to obtain.

2.1. The Cocal System

CS can be declined in slightly different ways. In this work, we focus on what is generally referred to as crowdsensing. Within this approach, citizen scientists are mostly engaged in data collection. COCAL uses mobile vehicles of volunteers in an opportunistic way in order to host the sensing and transmission boxes developed within the project.

COCAL boxes have already been extensively installed on private cars, vans, and buses. Buses, in particular, guarantee large geographic and time coverage of an area, while private cars are less easy to organize.

During acquisition, measurements are geolocated and then transmitted to a central facility. There, data are stored and processed in order to produce a map of the distribution of pollutants in the designated area.

One of the key aspects of the crowdsensing approach, also anticipated by the use of the term 'crowd', is the need to use as many simultaneous acquisition platforms as possible. This allows us to improve time and spatial coverage of data. If we were to use standard techniques such as filters and gravimetric mass detection, this could lead to an increase in costs which would make the initiative impossible to carry out. These technologies are, in fact, very expensive and need trained personnel and controlled procedures in order to correctly operate them. To overcome these problems, we need low-cost hardware.

Unfortunately, low-cost hardware is known to perform rather poorly. This is particularly true in the case of low-cost sensors (LCS), gauges, or measurement devices in general. LCS are affected by low precision and accuracy, which can drastically reduce the quality of the expected results.

In order to mitigate these effects, statistics is the most commonly used approach [41]. Statistical methods need redundancy of data, which calls for the use of a large number of simultaneous acquisition platforms. This motivates even further the need for low-cost hardware.

Another important issue to consider is the need to lift volunteers from the responsibility of hosting expensive devices. It is very important, in fact, to keep their motivation high, while it is easy to imagine how the risk of misuse or of breaking costly apparel can be problematic for them.

Each COCAL acquisition box contains air quality and environmental sensors, GPS, GSM/LoRa/WiFi/Bluetooth connectivity, and the electronics to gather, pack, and transmit data. Georeferencing, formatting, timestamping, and possible caching of data are conducted in the microcontroller. Software, which in other initiatives can be a problem, is not an issue in COCAL since it has been developed completely within the project. Its cost, therefore, is not affected by the number of installations. Sampling rate of the acquisition is 10 s.

Data is transmitted mostly through GSM mobile phone networks, while LoRa can be used for long-distance transmission, and WiFi/Bluetooth is mainly used during testing and maintenance.

Data is tunneled to a central hub where all processing takes place. A 200 m by 200 m by 1 h regular grid is superimposed on the distribution of measurements. The median value of all the points contained in each cell is calculated and assigned. The grid then becomes the map of the distribution of PM in the designated area.

Data products follow a full open-data policy and are made available in almost real-time through a web portal https://cocal.ogs.it (accessed 2/8/2022). This has been developed within the project and is compliant with Inspire, ISO, and OGC standards.

Summing up, the overall cost of the initiative is mostly determined by the cost of the sensors in the COCAL box. To reduce this to its minimum, we use only PM10, PM2.5, Relative Humidity (RH), Temperature and Pressure LCSs.

2.1.1. Low-Cost Sensor Performances

To measure particulate matter, we use LCSs based on laser scattering. This relates the diameter and number of particles contained within an airflow with the waveform of the light scattered by those particles. This technique allows real-time and continuous measurements of PM but introduces some issues.

It is important to note, for example, that this class of sensors does not allow any chemical analysis, such as those that can be obtained with chromatography or spectrometry. These analyses can be important to distinguish contributions from traffic or from biomass burning.

It is also important to highlight that these sensors lack sample conditioning devices. This has the effect that environmental conditions and relative humidity (RH), in particular, can affect hygroscopic growth of particles. This can impose a bias on measurements [42].

In this work, we use the SDS011 PM sensors from Nova fitness Co. These sensors allow us to measure at the same time both PM2.5 and PM10. During PM measurements, we also monitor environmental conditions such as RH, temperature, and pressure through an external (to the COCAL box) waterproof Dallas Semiconductor DS18B20 and an internal Bosch BME280 sensor.

Detailed analysis, in controlled laboratory conditions, of the performances of the SDS011 sensors can be found in [42,43]. In that work, several issues have been highlighted, such as a general trend to underestimate PM values and a delay in timing of measurements. On the other hand, [42] claims that the performances of SDS011 sensors are reasonably similar to other LCS. Being SDS011 sensors are extremely inexpensive, they can be considered, therefore, a proper choice for CS.

Several authors [44,45] advise on the importance of LCS calibration. [46] underscore the need for testing sensors in real-life conditions, not only in the lab.

To follow this advice, we decided to test accuracy and precision of SDS011 sensors in comparison with a reference station, following [47] and US EPA protocols.

We already performed something similar in another work [40]. There, we co-located several LCSs with a reference station operated by the regional environmental agency ARPA-FVG and located in the city center. Results of these tests showed that the precision of sensors was acceptable, while the accuracy of the LCS sensors was rather poor. Here we try to understand whether this can be the case also for a non-urban environment.

Unfortunately, in the area of study, there is no official reference station to compare data to. We decided, then, to co-locate 3 LCS with a high-quality Lighthouse 3016 IAQ handheld PM probe and compare results from this experiment with those obtained in [40].

Of course, the limitations of this approach are substantial. In fact, even if we use a high-quality PM sensor, this uses a similar technology to that used in the LCS and, therefore, cannot be considered an absolute reference. The experiment lasted 3 weeks. The sampling rate of the Lighthouse probe was set to 3 min. It was possible to collect approximately 10K measurements. The sampling rate of the LCS was set to 1 min. This resulted in approximately 30K points per each LCS. Later, LCS measurements were synchronized with the reference instrumentation averaging them within each 3-min sampling bin.

Results of these tests show interesting features. Comparing the time series of the LCSs (Figure 1, red, green, blue) and that of the high-quality sensor (Figure 1 in black), it is possible to see that the LCSs correctly follow the trend measured by the high-quality sensor. On the other hand, LCSs generally underestimate PM values, as was anticipated by [42].

In the case of precision, the results of the tests were encouraging and identical to those obtained in [40]. Standard deviation resulted in 2.15 μg/m^3 for PM10 and 1.17 μg/m^3 for PM2.5, which is within the recommended values of 5 μg/m^3. The Coefficient of variation was also reasonably within the recommendations being 24.70% for PM10 and 22.77% for PM2.5, while the limit is set by E.P.A. to 30%.

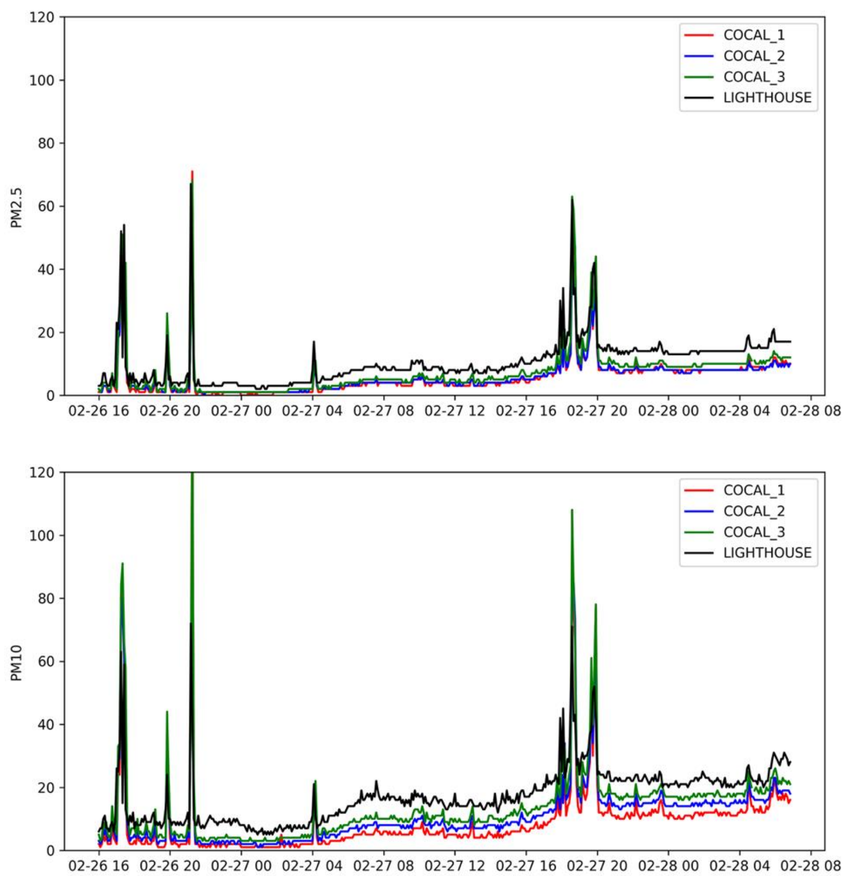

Figure 1. A subset of the time series from which we compared the behavior of LCS (colored lines) with the high-quality PM sensors (black).

The tests aiming at assessing the accuracy of LCS have been instead more problematic. Results of these tests are summarized in Table 1 and must be compared with US E.P.A. standards.

Table 1. Accuracy of LCS (PM10) following [47].

	LCS 1	LCS 2	LCS 3
Coefficient of Determination (R^2)	0.19	0.27	0.52
Slope (m)	0.79	0.79	0.90
Intercept (b)	−6.95	−5.32	−4.52
Root Mean Square	21.28	19.12	16.71
Error (RMSE)	79.67	71.59	62.43
Normalized Root Mean Square Error (NRMSE)	0.19	0.27	0.52

These standards recommend that R2 should be higher than 0.70, slope (m) should be approximately 1 ± 0.35, the intercept (b) should be between −5 and +5, RMSE should be lower than 7 μg/m^{3,} and NRMSE less than 30%.

Analyzing the results in Table 1, it can be said that even if the precision of LCS is acceptable, the accuracy of the LCS is largely insufficient. These conclusions are similar to those obtained in [40].

3. Results

3.1. Designated Area

The designated area for this first test study is the urban and hinterland area of the city of Trieste (northeastern Italy). The city faces the Adriatic Sea and is surrounded by the Karst plateau. This is the northwesternmost part of the External Dinarides and forms an NW–SE oriented anticlinorium with a maximum height of about 350 m above the sea. Urban development in the area followed the economic trends of the city. In the past, Trieste was the most important port of the Austro-Hungarian Empire. Recently, due to tourism and a revitalization of the port, the city experienced a new phase of expansion. In between these phases, the city experienced a period of contraction.

The center of the city and the suburbs are built mostly in large multi-story buildings. In the outskirts of the city, detached and semi-detached buildings are becoming more and more common. In the rural areas of the Karst tableau, this type of building is the most common one.

Household heating in the city center and the suburbs is based on natural gas. In the Karst, it is mainly based on wood stoves and liquid fuels since often the natural gas network does not reach these areas.

In the perspective of this work, it is, therefore, possible to distinguish three main zones in the designated area (Figure 2) and namely: (i) the city center, where air quality is conditioned mainly by the traffic while PM Emissions related to household heating should be low since heating is based mainly on natural gas; (ii) the Karst plateau, where the traffic is minimal, but household heating is based on solid or liquid fuels; and (iii) the city outskirts where PM emissions can be due to traffic, solid or liquid fuels combustion but also to other sources. This third zone, in fact, coincides with a highly industrialized area which makes the situation more complicated. To identify the sources of air pollution in this area, it would be necessary to study the PM chemical composition. This is not possible with the sensors we use.

In the city center and the Karst area, a chemical analysis is not necessary since sources of PM are different and clearly identified.

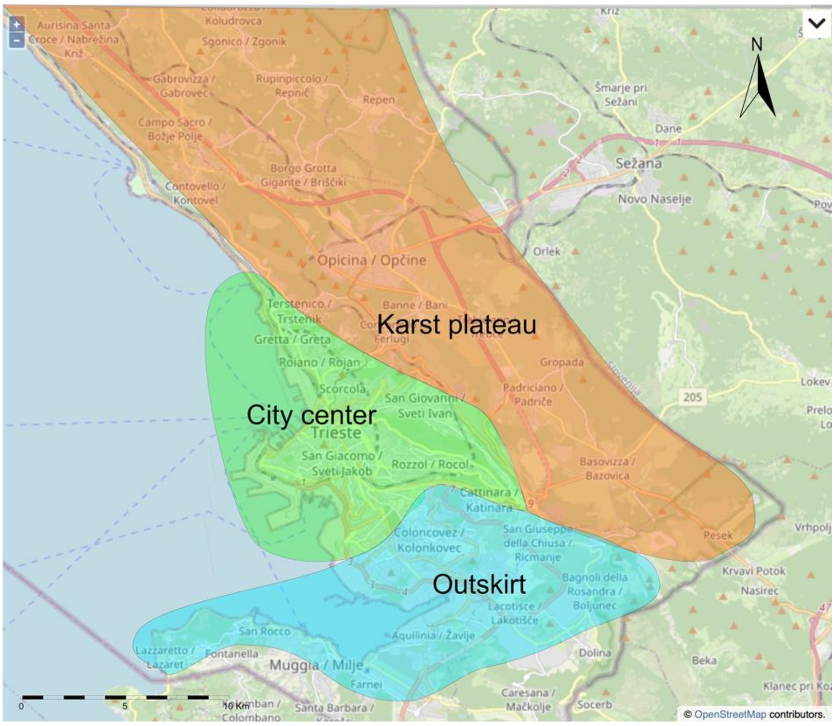

Figure 2. The city of Trieste, where we highlighted in different colors the extension of the three types of areas considered in this work; (i) the city center, where household heating is based mainly on natural gas and PM source is conditioned mostly by the traffic(green); (ii) the Karst plateau where traffic is rather low and where household heating is based mainly on solid and liquid fuel burning (brown); (iii) the outskirts of the city where the contribution of different sources of PM (traffic, heating, industries) are difficult to separate (blue).

3.2. Cocal System Deployment

Within this preparatory work, five COCAL boxes have been installed on buses of the local transportation authority, Trieste Trasporti, while four COCAL boxes have been deployed on voluntary private cars.

Soon we realized that acquisitions made using private cars were deeply conditioned by volunteers' personal availability. This, unfortunately, was generally rather limited, so we were often forced to add data infills using our cars.

On the contrary, bus-based measurements were much more reliable, continuous, and with high time and geographic coverage. In the designated area, the bus service starts at 5 a.m and stops at midnight. The five-hour gap during the night is generally not critical. Data available from governmental environmental agencies and numeric simulations show, in that time range, a smooth decrease in PM concentrations [48]. Only very rare anomalous events relevant to air quality studies have been identified in the period considered for this work. The operating time range of the bus service guarantees that most PM emissions related to human activities can be correctly considered.

Buses, where the COCAL box has been installed, follow predefined bus line routes. This, in theory, can bias geographic coverage. In reality, each bus often changes its route. This allows to improve coverage and reduces possible biases. In addition, it allows the extension of the surveyed areas without the need to increase the number of acquisition boxes.

The COCAL system was developed and tested in 2020. It became fully operational in March 2021 and has been active ever since without interruptions.

Figure 3 shows the geographic density map of the dataset acquired so far. The distribution in the designated area is very high, although not homogeneous. This largely depends on the distribution of the public transportation network. Bus lines, in fact, are denser in the city center. In the outskirts of the city and the Karst, buses are less frequent, and the routes are sparser.

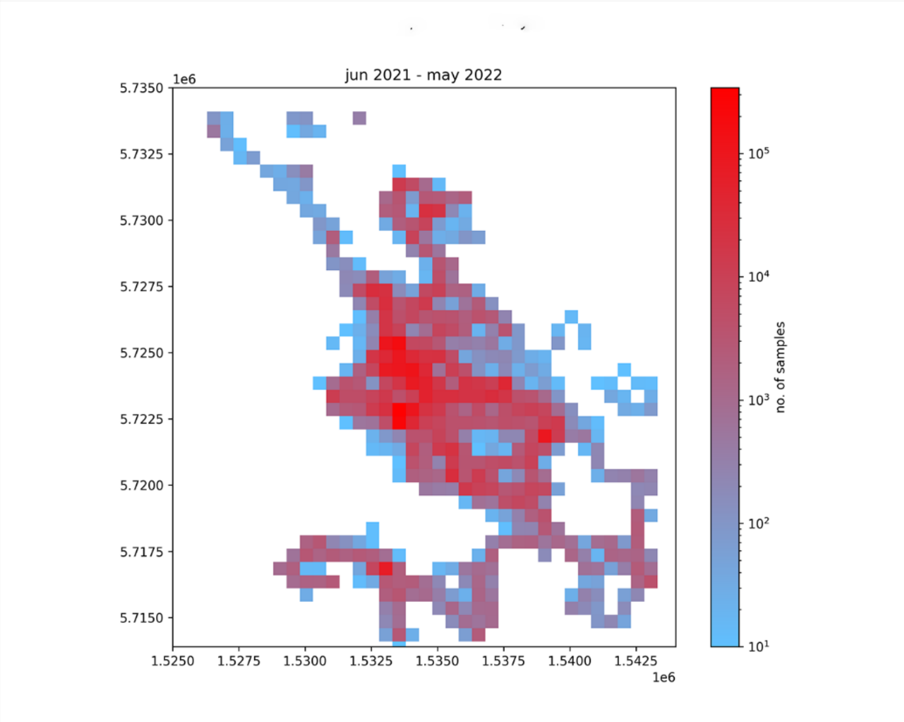

Figure 3. Acquisition density map in the designated area.

3.3. First Indications of Differential Behavior

The large amount of data gathered allowed us to pinpoint several interesting and unexpected features of the distribution of PM in the designated area.

The first goal to achieve was to understand if the various zones of the designated area behave differently in terms of atmospheric loading of particulate matter.

In this perspective, we superimposed on the data a regular grid of 500 m by 500 m cells. We then gathered data in four-time subsets corresponding approximately to summer, autumn, winter, and spring seasons. Within each cell, we then calculated the third quartile of the distribution of PM values for each time subset (Figure 4).

As expected, during summer, the third quartile distribution is at its minimum (the plot is green almost everywhere), while during winter time, values are at their top (red pixels). What is interesting is that, during winter, the distribution is not homogeneous. In fact, while the southern part of the city experiences high PM values, the city center seems to show lower values.

In order to compare the center, the outskirts of the city, and the Karst zone, we need to focus on the village of Opicina/Opčine (highlighted in light blue in Figure 4). This zone is particularly important because it is the only one in the Karst zone that is sufficiently covered by the public transportation network (see Figure 3).

In summer, this zone behaves very similarly to the rest of the region.

In winter, it experiences PM values that are higher than the city center and comparable to the outskirts of the city

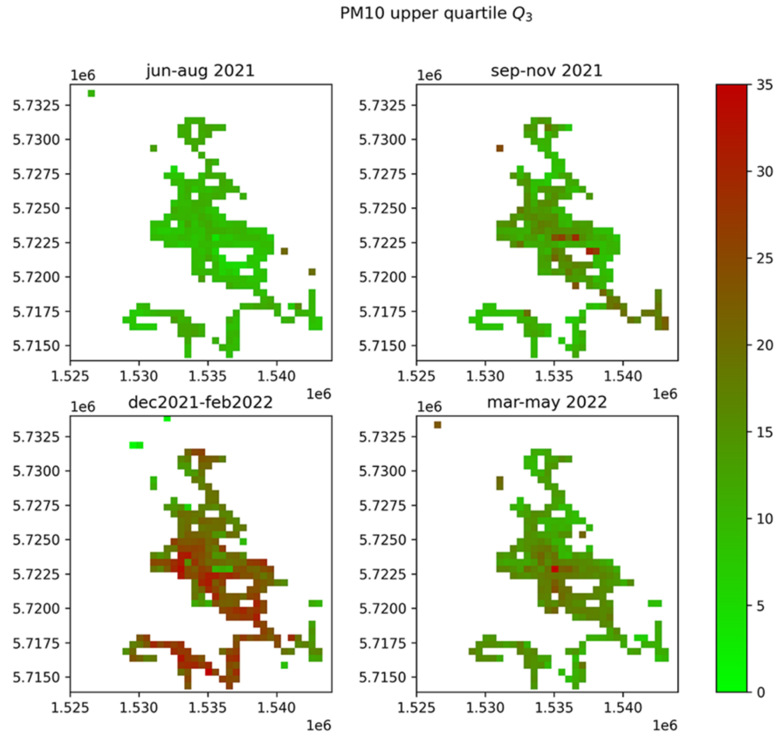

Figure 4. Comparison of third quartile distribution in the four seasons with the village of Opicina highlighted in light blue.

These first indications suggested that further analysis should be performed to understand how and why this behavior emerges.

We focussed on the winter period (when the phenomenon appeared) and defined three equidimensional (4 km by 4 km) subzones: one in the city center, one in the outskirts, and one around the village of Opicina (Figure 5 left).

In order to study the evolution of particulate matter in each zone during the day, we extracted subsets of all available measurements upon their position and timing. Three time ranges have been considered, namely: from 9 a.m. to 1 p.m., from 1 p.m. to 5 p.m., and from 5 p.m. to 9 p.m.

With those subsets, we were able to create a matrix of nine violin plots representing the distribution of values in the three areas in the three periods of the day. The nine plots can be seen in Figure 5 right.

The differences between the three subzones are very relevant. In particular, comparing PM distributions in the village of Opicina and in the city center, it is possible to highlight a very interesting trend.

During the day, in the city center, PM values increase steadily and relatively slowly.

In the village of Opicina, instead, PM values remain almost constant and are considerably lower than in the city center.

In the evening, the trend changes abruptly.

While in the city, the situation remains the same, in the village of Opicina, instead, PM values rise quickly, becoming higher than in the urban area and showing frequent peaks above 80 μg/m^3.

The third subzone, corresponding to the outskirts of the city, performs worse in terms of air quality. PM concentrations increase steadily during the day, showing higher values than in the other two zones. It is interesting to notice that in the range between 1 p.m. and 5 p.m., although extending towards higher PM values, the distribution of measurements seems to shrink between 15 μg/m^3 and 30 μg/m^3.

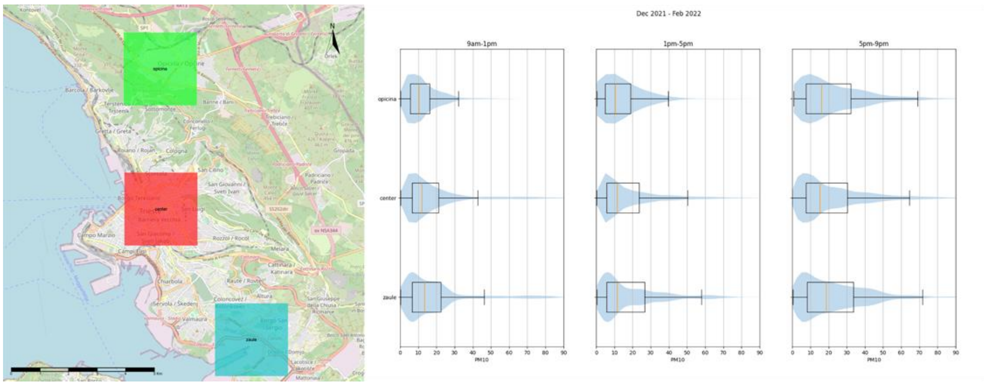

Figure 5. Map of the designated area highlighting the three subzones that have been considered for the analysis (**left**) Matrix of violin plots showing the trends of PM distribution during three time intervals of the day from December to February 2022 (**right**).

3.4. Daily Pattern in the Karst Using a Fixed Monitoring Station

The pattern highlighted above suggested monitoring what happens throughout each day and across several days in a single fixed position in the Karst.

In this perspective, we installed a COCAL box at a fixed location in the village of Trebiciano/Trebče for two weeks (Figure 6 left, in red).

The results are very interesting and show that in the time range between 5 p.m. and 11 p.m., strong PM peaks are very common. During the rest of the day, lower values are experienced instead. This can be easily seen in Figure 6 (right), where the heatmap shows the magnitude of PM as color. The position of each measurement in the graph was a function of the day and of the hour of the day when it was acquired. It is easy to recognize a band characterized by high values in the evening.

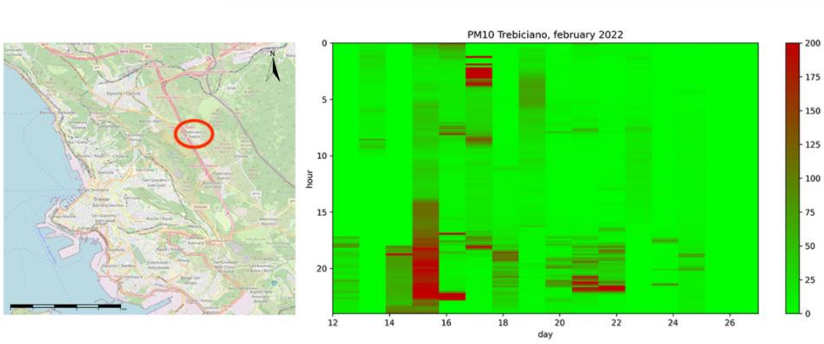

Figure 6. Heatmap of PM values in the village of Trebiciano in the Karst tableau (highlighted in red in the map on the left). The heatmap shows the distribution of PM values throughout the day (24 h) in two weeks. It is possible to identify a band characterized by high values between 5 p.m. and 11 p.m.

3.5. CS Survey

Data acquired in the Karst so far was obtained within a limited area only. As mentioned above, this is due to the fact that the public transportation network on which COCAL boxes have been installed so far is not sufficiently extended in the Karst zone.

In order to study the behavior of PM trends and patterns in a larger area, we organized a specific car-based CS survey that took place on 26 January 2022.

The survey involved four simultaneous acquisition platforms. These allowed us to cover extensively all the designated areas and large parts of the Karst zone from early morning to late in the evening. Integrating those data with those from the bus network, we were able to obtain a very large dataset and a very good time and geographic coverage.

Figure 7 shows the integrated dataset. To ease the comparison with the previous experiments (Section 3.3), data are gathered in the same 4 h intervals of Figure 5 (from 9 a.m. to 1 p.m. (a), from 1 p.m. to 5 p.m. (b) and from 5 p.m. to 9 p.m. (c)). It is possible to follow how the quality of the air in the whole area degrades during the day from lower PM values to higher PM values.

It is also possible to notice how, in the evening (later than 5 p.m.), the situation worsens more rapidly in the Karst zone in comparison to the city center.

Figure 8 (right) shows a zoom on the PM distribution in the South East sector of the Karst zone between 5 p.m. and 9 p.m. It is possible to see how higher values concentrate in the areas of the villages while far from them, PM values decrease rapidly. On the left of Figure 8, it is possible to see a photo taken from the viewpoint identified with the eye icon on the map. The direction of the photo is toward the South. The photo shows the villages of Padriciano/Padriče and Gropada/Grpeč with a white cloud that extends on them, and that can be associated with the recorded high PM values.

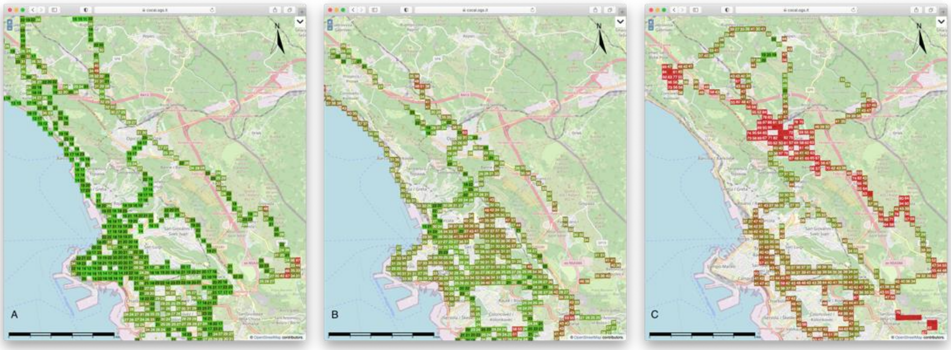

Figure 7. Snapshots from the COCAL web portal showing the distribution of PM measurements in the designated area during the experiment. For ease of reading, data are gathered in 4 h intervals (**A**) 9 a.m. to 1 p.m., (**B**) 1 p.m. to 5 p.m., (**C**) 5 p.m. to 9 p.m.

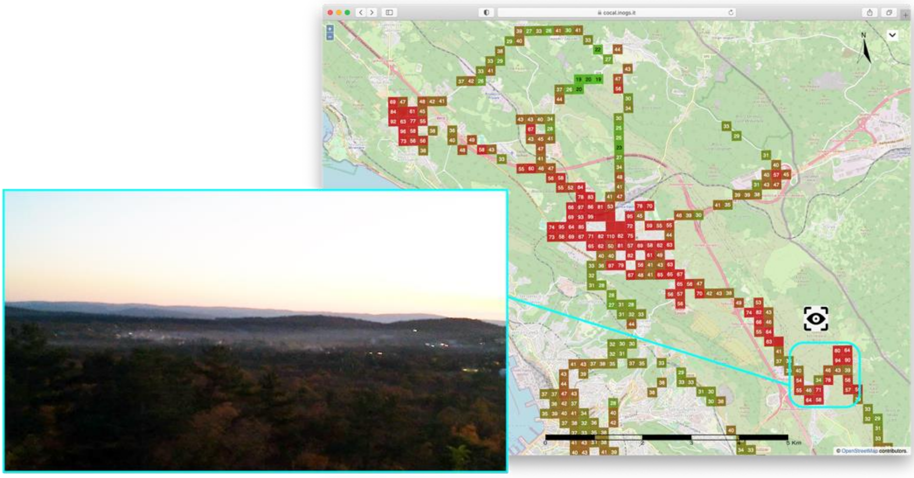

Figure 8. Map of the distribution of PM between 5 p.m. and 9 p.m. in the area of Padriciano/Padriče and Gropada/Grpeč (right). On the left, a photo taken at 6 p.m. towards the South, from the position identified on the map with the icon of an eye. The photo captures the emissions in the area highlighted in light blue on the map.

4. Discussion

This work aims at understanding whether a CS monitoring system could detect the effects, in terms of air quality, of RWC or other solid and liquid fuel combustion for household heating.

On the one hand, this can be evaluated in terms of the limitations of the paradigm and of the instrumentation used. On the other hand, this can be understood by analyzing data acquired by the actual implementation of a system that follows the CS approach.

Limitations in the CS paradigm are associated with the use of LCS and the possible introduction of biases during the acquisition of data.

The use of LCS is connatural with CS. We analyzed the performances of the LCS used within this work and found that their precision is acceptable, but their accuracy is insufficient. This is in accordance with the large literature existing on the use of PM LCSs, such as [49] for indoor monitoring, [50] for outdoor monitoring, or [51] for mobile monitoring. Our results are also in accordance with studies, such as [42,43,52], where several LCS models are compared, including the SDS011 sensor used in this work.

From these results, we understood that LCS can then be used to map relative values and distribution of PM, but only with great caution to assess their absolute values. It is important to highlight that we have studied the performances of the LCS in real-life environments [46] characterized by emissions from RWC and solid and liquid fuels [53].

From the perspective of this work, it should be possible, then, to map, at least qualitatively, the evolution in time and space of the distribution of air quality in an area. It should be possible, also, to compare different zones of the designated area in order to highlight specific trends and behaviors.

Other possible known limitations of the CS paradigm are related to spatial bias due to opportunistic sampling [54,55]. Within this preliminary work, we installed COCAL boxes on mobile volunteer platforms such as cars and buses. This, theoretically, should allow an increase in spatial and temporal coverage. We realized, however, that this can also raise issues. Volunteers' cars resulted, in fact, being a rather unreliable platform because they only seldom were actually accessible. In addition, these surveys suffered from uneven and biased distribution of measurement due to volunteers' personal habits and schedules. Public transportation was, instead, extremely reliable and robust.

Buses follow the network of urban city lines. This can be considered a form of spatial bias, but our results show that even with a very small number of acquisition boxes, it is possible to cover large portions of the designated area.

The other way to assess if a CS-based monitoring system is suitable for the purpose of this work is to consider the data it actually acquires. If the data show trends and anomalies that could be related to RWC or solid and liquid fuel combustion, then the tool could be considered helpful.

In this perspective, our team developed COCAL and deployed it in the city of Trieste. The system allowed us, since March 2021, to gather a very large amount of data on the air quality in the designated area. The analysis of such data allowed us to highlight several interesting and unexpected features. Among them are the peculiar daily and seasonal behavior of the various zones of the city. Geographic, diurnal, and seasonal variations in the atmospheric loading of pollutants have been reported by many authors [10–12,56]. Winter is particularly relevant for RWC and solid and liquid fuels burning. Several authors [57–59] analyzed the PM time series related to the emissions of these types of fuels. These works have been performed mostly in rural areas of less developed countries. In these studies, a simple trend is identified that shows lower values during the night and higher values during the day. Our observations instead show, in the rural areas of the Karst, low concentrations during most of the day with a rapid increase in the emission of PM at approximately around 5 p.m. In the city center, PM concentrations increase steadily during the day. A possible explanation for this phenomenon could be related to household heating. The Karst area is, in fact, less populated during the day since most of the people work in the city center. In the evening, when people return to their houses, they switch on their heating systems. This will be in line with [60], which claims that emissions from firewood stoves considerably depend on the user´s behavior and habits.

As mentioned above, the distribution of fuels for household heating is not the same in the city center and in the hills. In the first case, heating is mostly based on natural gas with lower PM emissions, while in the hills, this is based on RWC or other solid and liquid fuels, which produce higher emissions of PM. To corroborate this hypothesis, during a specific CS survey, we were able to map several PM hotspots corresponding perfectly to the locations of the villages in the Karst tableau.

Of course, the atmospheric loading of particulate matter is a very complex phenomenon. This can be strongly influenced by multiple environmental parameters, such as humidity or winds. In particular, the Karst area is characterized by frequent events of strong and cold northern to northeastern katabatic wind called *"Bora" [40].* Rainfall can also improve air quality through the below-cloud aerosol scavenging process by precipitation [61,62].

All this leaves space for other possible interpretations of the data and calls for a more extensive study of the area and RWC and solid and liquid fuel emissions.

5. Conclusions and Future Work

This preliminary work demonstrated that a CS-based system, such as the one we developed, could be very efficient in mapping air quality trends and hot spots in urban and rural areas. Our work demonstrated, on the other hand, that measurements taken with LCS cannot be used as reference values.

We took into consideration the area of the city of Trieste and its surroundings. We demonstrated that the distribution of PM in the Karst tableau has a peculiar trend. During the day, the air quality is generally rather good, while after 5 p.m., the situation worsens very quickly. PM emissions originate in the village centers and tend, in a few hours, to extend to the surrounding areas. Peaks can be very high, often exceeding 80 $\mu g/m^3$.

A possible explanation of the phenomenon could be associated with the return to their houses of people commuting from the city center in the evening.

The high PM values recorded can be explained in light of the types of fuels used there. Since the natural gas network often does not reach those areas, RWC or other types of liquid and solid fuels are commonly used. This is rather worrying, considering the current geopolitical situation, where an increase in the use of solid fuels is forecasted; if that happens to other areas, the air quality is anticipated to degrade considerably.

From this perspective, CS-based monitoring technologies can be very helpful. While monitoring problematic areas, in fact, they can provide means to improve time and geographic coverage and increase resolution.

Once demonstrated that this approach is feasible and advisable, our future work will focus first on the further development of COCAL in the designated area. We estimate that by tripling the number of devices on the public transportation network, with the addition of a smaller but supportive number of volunteer cars, it would be possible to obtain a very good spatial and temporal coverage. We also plan to apply the system in other areas so that new issues and topics might emerge.

We are also planning to integrate in the system, data, and measurements from governmental reference stations. This will allow us to automatically correct CS data in order to obtain more realistic PM distributions.

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