VOLUNTEERED GEOGRAPHIC INFORMATION FOR MAPPING URBAN CLIMATE AND AIR QUALITY: TESTING AND ASSESSING 'SNIFFER BIKES' WITH LOW-COST SENSORS

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ABSTRACT:

Impacts of climate change and air pollutants are a growing concern. Reliable and accessible monitoring systems to assess air quality and climate extremes are essential to inform decision-makers and increase awareness of citizens. Approaches from Volunteered Geography play a pivotal role both in research and empowerment by new low-cost technologies. Recently, the spread of GeoICT and micro-sensors are offering opportunities for mobile environmental mapping. In general, official stations acquire data with high accuracy and reliability; in contrast low-cost mobile devices increase the spatio-temporal resolution of air sampling but with lower accuracy. Aims of study are i) assessing accuracy of temperature values from Sodaq Air and MeteoTracker devices; ii) assessing accuracy on PM 2.5 acquisition for Sodaq Air; iii) geovisualizing three months of environmental monitoring in the city of Padua. Accuracy assessment for air temperature was performed by using a calibrated thermometer; PM 2.5 from Sodaq Air were compared with an official air quality station. Preliminary results on dynamic mobile mapping indicate that temperature values from MeteoTracker present good accuracy, while those from Sodaq Air showed bias of approximately +2.5 °C. Air quality data from the latter seems to present, in this phase of development, some limitations, since comparative analysis with official air quality station indicates 93% of overestimation, on average. On the other hand, the environmental campaign with mobile mapping devices at urban scale highlights the capability of geovisualizing hotspots and densifying georeferenced data acquisition over space and time. Further software/hardware implementation and applied research are required with various devices in different environmental conditions to improve data quality and reliability.

1. INTRODUCTION

1.1 Citizen science and mobile mapping devices for environmental monitoring

Local climates and air quality of urban systems currently represent two crucial aspects both for public health and for the adoption of effective mitigation strategies to contrast climate extremes such as heat waves. According to the European Environmental Agency (Yatkin et al., 2022a) air pollution is the major health concern as 96% of urban dwellers were exposed in 2020 to levels of particulate matter (PM) higher than the World Health Organization limits; moreover, the increase in frequency and magnitude of extreme heat waves related to climate change is exacerbating the Urban Heat Island (UHI) phenomenon. Effects of air pollution and extreme UHI are associated with a wide range of diseases and the increase of mortality in urban areas (Dosio, 2018; IPCC, 2021).
Generally, urban microclimates and air quality assessment are performed from public authorities by using static monitoring stations equipped with certified and calibrated reference sensors; they are adopted for the reliable assessment of temperature (T) and relative humidity (RH) as well as regulatory air pollutants such as CO_2, CO, NO_x, O_3 and $PM_{10\text{-}2.5}$ (Castell 2015; Bulot et al., 2019; Karagulian et al., 2019; Yatkin et al., 2022b). Such static monitoring stations are usually of relevant size, and they require accurate calibrations and professional maintenance. Moreover, due to the high costs, ranging from 5,000 to 30,000 €, installation and use of certified static stations are at present limited, also for public authorities. As result, they accomplish with generation of official accurate environmental data but, due to their very low spatial sampling density, they are not capable to provide information about localized gradients of relevance for health protection of urban population (Castell et al., 2017; DeSouza et al., 2020).
On the other hand, the advances in technological development of micro-sensors, together with the integration and the pervasive spread of ICT and geospatial technologies (GIS, WebGIS, GPS, GeoAPP for smartphone) are at present providing new opportunities both for public authorities and non-expert citizens for urban climate and air quality mapping and monitoring (Strobl, 2009; Bulot et al., 2019; Karagulian et al., 2019; Yatkin et al., 2022b).
Different projects were therefore implemented, by assembling sensors into a platform to have a mobile device mapping (Liu et al., 2015; Sun et al., 2019; De Oliveira et al., 2019; Magi et al., 2020).
In general, individual micro-sensors are assembled in a control board that incorporates other essential components: GPS module, accelerometer, data storage, network antenna for wireless connectivity, communication ports, battery. Typologies and number of assembled sensor platforms are rapidly increasing worldwide, with a consistent decrease in costs for final users and increase in ease of use. They can be designed as unplugged portable devices or as mobile mapping sensor platforms with the integration of GPS receiver. At present,

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prices of low-cost sensors range from 20 to 100 €, while integrated platforms from 150 to 2,000 € (Table 1). Increasing attention is given to mobile sensor platforms as they can play a pivotal role in supporting environmental monitoring by increasing the spatial and temporal sampling density of different environmental indicators of the urban territory with aggregated georeferenced data, providing data support to official monitoring networks. Furthermore, spatially-explicit data based on individual urban mobility can be analyzed by a geographic approach to enhance a deep understanding on when, where and why citizens experience exposure to UHI and air pollution, enabling to investigate multiple factors based on their spatio-temporal relationships (Park et al., 2020; Schilt et al., 2023). Moreover, Volunteered Geography Information as a bottom-up approach can play an important role to involve citizens in the processes of acquiring large amounts of data at urban and metropolitan scales for scientific purposes, while simultaneously increasing awareness of crucial environmental issues such as climate change and air pollution (Sîrbu et al., 2015).
The technological opportunities from low-cost sensor platforms currently represent a paradigm shift on how and who is monitoring on the territory local climates and air quality: from static and top-down to mobility-based and community level approaches (Castell et al., 2017; Park et al., 2020).

Sensor name	Size Mm	Sensitivity to particle size	Measure range	Response Time	Price
PMS 5003	50x 38x 21	50% for 0.3 µm; 98% for 0.5 µm	0–500 $\mu g/m^3$	≤10’’	42€
Shinyei PPD42 NS	59x 45x 22	1 µm	\	\	29€
Nova Fitness SDS01 1	71x 70x 23	70% for 0.3 µm; 98% for 0.5 µm	0–999.9 $\mu g/m^3$	< 10’’	35€
Aranet	104x 67x 37	\	0–1000 $\mu g/m^3$	1,2,5’	240€

Table 1. Overview of selected sensors for particulate matter data acquisition.

1.2 Aims of the research

The current availability on the global market of low-cost sensor platforms is providing a promising technological opportunity for bottom-up environmental monitoring to complement official network and to increase citizen awareness on crucial issues on urban sustainability. However, in most cases mobile assembled devices are directly commercialized by manufacturers with poor or completely without technical information about performances of their sensing platforms. In various cases, names of integrated sensors as well as error and accuracy characteristics, nor data quality, are publicly available. Therefore, for professional, scholars or non-expert citizens is critical to know if data quality of sensor platforms is suitable for the intended purposes (Castell et al. 2017).
The main objective of this study is to assess the general performances of two commercialized mobile sensor platforms for mapping urban climate and air quality; specific aims are the followings: i) assessing accuracy of temperature values in static and dynamic mode from Sodaq Air and MeteoTracker devices; ii) assessing accuracy on PM 2.5 acquisition for Sodaq Air; iii) geovisualizing UHI and PM 2.5 hotspots during three months of air temperature and PM 2.5 monitoring at urban scale, in the city of Padua. The former specific objective was performed by testing four mobile sniffer bikes Sodaq AIR, installed in the zero-emission transportation (bikes and electric scooters) of four researchers of the Laboratory GIScience and Drones for Good (University of Padua).

2. MATERIALS AND METHODS

2.1 Materials

In this subsection five different devices used in this study are presented: three mobile devices, one fixed weather station and one air quality fixed stations.

2.1.1 Sodaq Air: Sodaq Air is a low-cost mobile device developed by Sodaq that measures PM 2.5 concentration, temperature and humidity of the air. It can be installed on bicycles and electric scooter and works without the need of a smartphone. Aggregated data can be visualized in real time in the KnowYourAir web GIS (https://knowyourair.net). It is equipped with the following sensors:

- LIS2DE12 (accelerometer)
- SPS30 (particle sensor)
- SHT31 (temperature and humidity sensor)
- UBLOX M8Q (GNSS module)

Components and device are shown in Figure 1.

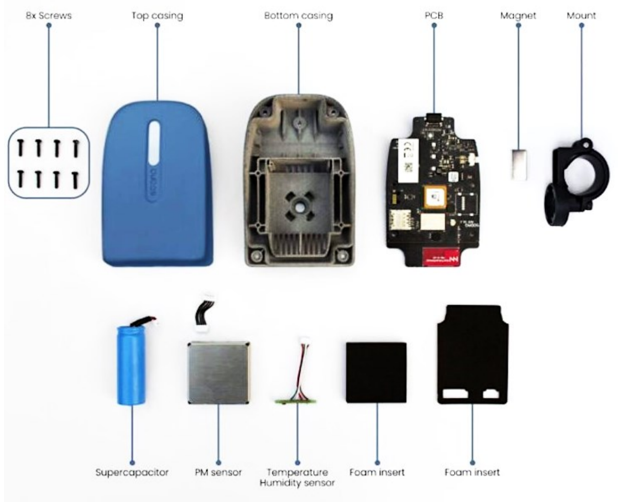

Figure 1. Sodaq AIR: main components (source: https://sodaq.com/products/air/)

2.1.2 MeteoTracker: MeteoTracker is a small low-cost mobile weather station developed by Iotopon (Antoniciello, 2021). It can be installed both on bikes and on the roof of cars. It is activated by movement, and is connected to internet via a mobile app. All data acquired by MeteoTracker are displayed in an online dashboard (https://app.MeteoTracker.com/). The sensors installed in the device are:

- HDC2022 (temperature and humidity sensor)
- BMP290 (pressure)

Meteotracker device is presented in Figure 2.

Figure 2. Meteotracker device
(source: https://meteotracker.com)

Lutron TM-947SD: Lutron TM-947SD is a professional calibrated digital thermometer. It's used in this study to measure the reference temperature to be compared with the two low-cost devices presented above. Technical specifications can be found in the Lutron website (https://www.lutroninstruments.eu/with-datalogger/thermometer-lutron-tm-947sd/).

2.1.3 Davis weather station: Davis vantage pro 2 weather station (https://www.davisinstruments.com/pages/vantage-pro2) installed on the roof of DICEA department of University of Padua is approved by Meteonetwork standards (Giazzi et al., 2022) and a dashboard of weather variables is available in the Meteonetwork platform (https://meteonetwork.eu/it/weather-station/vnt470-stazione-meteorologica-di-portello) with two records per hour. This weather station's time series is used as a background, in order to understand spatial variability of air temperature collected by mobile devices in the city of Padua.

ARPAV PM 2.5 Station: To test Sodaq Air devices accuracy on PM 2.5 concentration we used as reference values the validated data from official regional environmental protection agency station located in Monselice (Province of Padua, Italy) with geographic coordinates: 45,240859; 11,7454834. This air quality station provides gravimetric determination of the PM 2.5 fraction of particles in air every two hours (https://www.arpa.veneto.it/dati-ambientali/dati-in-diretta/aria/qualita-aria-dati-in-diretta).

2.2 Methods

The two mobile devices presented in section 2.1.1 and 2.1.2 have been tested, both in static and dynamic mode for temperature (both of them) and for air quality (Sodaq Air only). The tests were carried in Veneto region (north-east Italy), one of the worst areas in Europe for PM 2.5 atmospheric concentration (Pivato et al., 2023) and are detailed in subsections 2.2.1-3. Moreover, a preliminary 3-months survey of urban climate and air quality in Padua with mobile devices is presented in subsection 2.2.4.

2.2.1 Air quality – Static mode testing: Two Sodaq Air devices have been tested for PM 2.5 atmospheric concentration against an official PM 2.5 concentration station of the Regional Environmental Protection Agency (ARPAV) is located. The test was carried during 4 hours the 22nd of February 2023, from 8 am to 12.00 pm. Two Sodaq Air devices were located in the gate that fence ARPAV's station at 2 meters high from the ground. ARPAV's PM 2.5 sensor provide the value of PM 2.5 concentration every two hours, while the Sodaq Air devices collects data every 5 minutes in static mode.

2.2.2 Temperature – Static mode testing: One Sodaq Air and one MeteoTracker devices were tested for air temperature, both indoor and outdoor in Sandrigo, Italy (geographic coordinates: 45.6594035, 11.5972374). The test was carried between 3.30 pm and 4.30 pm the 14th of December 2022. The first half hour the test was carried indoor, and at 4.00 pm the devices were moved outdoor. Air temperature values from the two devices were tested against a Lutron TM-947SD calibrated thermometer. Sodaq Air, MeteoTracker and Lutron sensing frequency is every 5 minutes, 3 and 10 seconds respectively. A second test was carried the 18th of February 2023 for Sodaq Air only, after a firmware update.

2.2.3 Temperature - Dynamic: Sodaq Air and MeteoTracker were also tested in dynamic outdoor mode against the Lutron TM-947SD thermometer, in Sandrigo, the 20th of December 2022. The Lutron thermometer was located outdoor, while a bicycle was equipped with Sodaq Air and MeteoTracker.

2.2.4 Survey campaign: From the 5th of October 2022 three bicycles and one electric scooter were equipped by four researchers with Sodaq Air devices and surveyed air quality and air temperature in the city of Padua (Italy) during daily mobility. The electric scooter was also equipped with MeteoTracker starting from 25th of November 2022. The survey ended the 31st December, since two Sodaq Air devices were broken.
Air temperature values collected by Sodaq Air and MeteoTracker devices were compared with data from the fixed urban weather station located in the historical center of Padua (https://meteonetwork.eu/en/weather-station/vnt470-portello-meteorological-station) presented in section 2.1.4. We subtracted from the temperature surveyed by mobile devices the closest value - in terms of time of acquisition - of the fixed urban weather station, to better understand the spatial variability of air temperature inside the city. A 60 m-diameter hexagonal fishnet in the surveyed area was made, in order to represents the average value of temperature anomaly and PM 2.5 concentration. All the analysis were conducted with Excel, R and QGIS softwares.

3. RESULTS AND DISCUSSION

3.1 Air quality – static

Two Sodaq Air devices were tested against one official ARPAV air quality station for PM 2.5 concentration. Results of the tests are presented in Figure 3. PM 2.5 concentration values detected and performed by the two Sodaq Air devices are always higher than the official ARPAV station, with an average overestimation of 93%. It is worth to note that the two Sodaq Air devices have a significant average difference in PM 2.5 concentration values during the 4-hour test, with an average difference of 12.6 µg/m3. Even if the official ARPAV air quality station is based on a gravimetric PM 2.5 survey and provide the average concentration during 2 hours, the differences with the optical sensor measurements of Sodaq Air are significant.

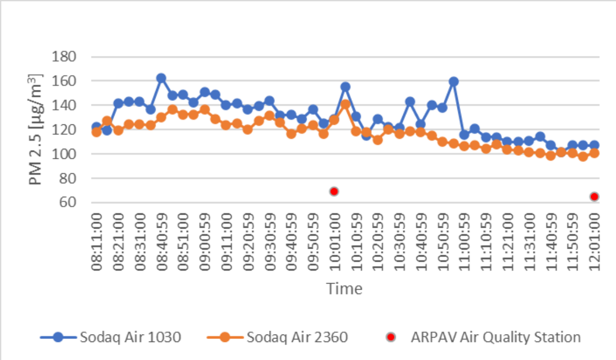

Figure 3. Atmospheric PM 2.5 concentration (μg/m^3) detected by two Sodaq Air devices and the official ARPAV air quality station in Monselice (Province of Padua, Italy) between 8 am and 12 pm the 22nd of February 2023.

3.2 Temperature – static tests

The static tests for temperature accuracy of the two mobile devices against Lutron TM-947SD calibrated thermometer is presented in Figure 4. The tests indicate a reliable performance of MeteoTracker during the first outdoor part of the test. Since MeteoTracker is designed for a dynamic use, it is therefore not capable to register temperature variation when moved indoor in the second half of the test.
Sodaq Air in the first outdoor part of the test provided from 3 to 5 °C higher than the calibrated Lutron TM-947SD; when moved to indoor environment, the response time to detect the actual air temperature was about 30 minutes. Sodaq Air is designed both for static and dynamic acquisitions, however it seems to have some limitation in detecting rapid temperature changes.

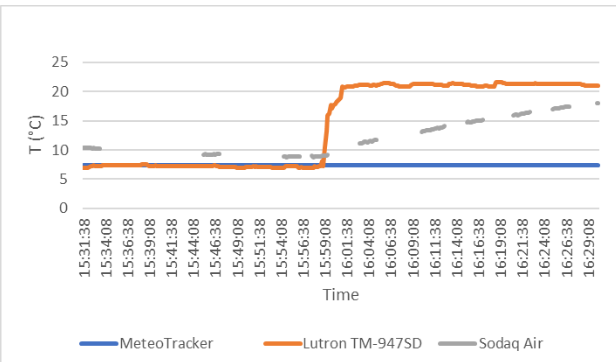

Figure 4. Outdoor and indoor air temperature surveyed by Sodaq Air, MeteoTracker and Lutron TM-947SD in static mode the 14th of December 2022.

After a software update the Sodaq Air device performance increased in term of accuracy in the static mode; however, it is still slow in registering rapid temperature changes as in the experiment presented in Figure 5, in which the sensors were moved from indoor to outdoor with a drop of 9 °C. It is important to highlight that the new Sodaq Air software updates improved also the sampling frequency, which is now more regular (Figure 5).

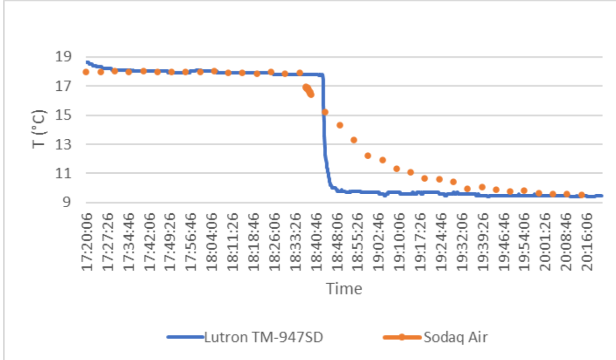

Figure 5. Indoor and outdoor air temperature surveyed by Sodaq Air and Lutron TM-947SD in static mode the 18th of February 2023.

3.3 Temperature – dynamic tests

Dynamic outdoor tests for air temperature measurement accuracy were performed for Sodaq Air and MeteoTracker against the Lutron calibrated thermometer the 20th of December 2022. The results are presented in Figure 6. MeteoTracker performed well in measuring air temperature compared to Sodaq Air: the former is in line with the observation of the Lutron, while the latter presents an overestimation in air temperature by 2-3 °C. The changes in temperature are well detected by both the mobile device, since the correlation between the two time series is 0.91. Sodaq Air is overestimating air temperature respect to MeteoTracker with an average bias of +2.6°C, but the trends maintained, since the standard deviation between MeteoTracker observations and Sodaq Air bias-corrected observations is 0.28 (Figure 6).

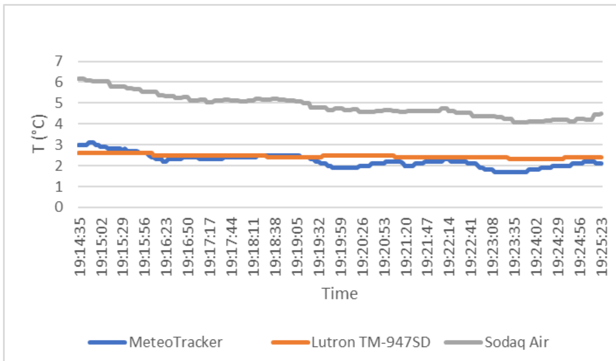

Figure 6. Outdoor air temperature surveyed by Sodaq Air, MeteoTracker and Lutron TM-947SD in dynamic mode the 20th of December 2022.

3.4 Air quality and temperature survey campaign

Between October and December 2022 an air quality and urban climate survey campaign was performed by using four Sodaq Air devices and one MeteoTracker device. The survey allowed to collect 27,427 points data for Sodaq Air, and 48,000 for MeteoTracker, for a total length of 735 km. The results of the survey are presented in the following subsections.

3.4.1 Air quality map: The PM 2.5 observations from four Sodaq Air devices are presented in Figure 5. The map geovisualize the average values of air PM 2.5 concentrations, the daily mobility in the city of Padua for the last three months of 2022. It is possible to observe that, in general, higher values of PM 2.5 concentration are in correspondence of the most trafficked roads. In particular, the internal ring road travelled during morning and evening rush hours are the ones with highest average values. On the other hand, in the inner historical city center where there is a restriction for car circulation, air quality is in general better than the non-restricted areas. Since in the city there are no official fixed air quality stations with appropriate temporal resolution, it was not possible to calculate the difference with the background values of PM 2.5 concentration. The legend of the map in Figure 7 represents the deciles of the distribution, that ranges from 0.4 to 362.7 μg/m^3. It is worth to note that the upper 60% of the distribution exceeds 27.1 μg/m^3, while the legal limit, according to the Directive 2008/50/EC of the European Parliament, is set below 25 μg/m^3 on average on a yearly basis (European Parliament, 2008).

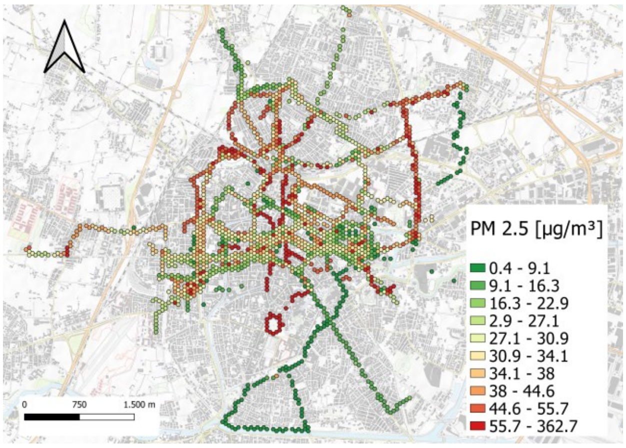

Figure 7. Average atmospheric PM 2.5 concentration (μg/m^3) in Padua, (Italy) surveyed with four Sodaq Air devices between October and December 2022.

3.4.2 Sodaq Air temperature anomaly map: Urban temperature anomaly values recorded by four Sodaq Air devices during the survey campaign are presented in Figure 8. The map shows air temperature anomaly surveyed by Sodaq Air devices respect to the background temperature observed by the urban fixed weather station presented in section 2.1.4. The inner historical city centre of Padua and the most trafficked roads during rush hours are the areas where temperature anomalies are higher. Higher temperature anomalies in the city center are probably caused by UHI effect, exacerbated by high density of impermeable surfaces and lack of green spaces (Pristeri et al., 2020; Todeschi et al., 2022; Peroni et al., 2022, Pappalardo et al., 2023). On the other hand, residential and peripherical streets are the ones with lower air temperature anomalies.

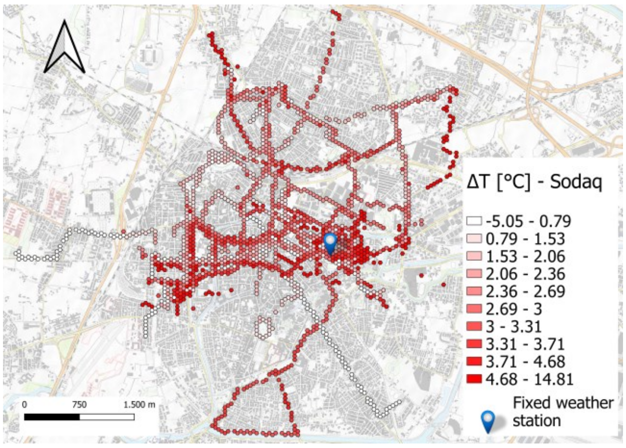

Figure 8. Average temperature anomaly (°C) observed by four Sodaq Air devices respect to Davis fixed weather station between October and December 2022.

3.4.3 MeteoTracker temperature anomaly map: MeteoTracker survey is presented in Figure 9. The map geovisualize the average temperature anomaly observed by one MeteoTracker device in November and December 2022. Similarly, to the results obtained with Sodaq Air, the map reveals that higher temperature anomalies are found in the most trafficked roads and in the inner city center. In the highlighted area in Figure 9 it is possible to observe a significant difference in average temperature (~3°C) between two adjacent one-way roads divided by the ancient city wall: the right one travelled from South to North in the morning and the left one from North to South in the evening. Possible reasons of this phenomenon might be: i) the traffic jam is more concentrated in the morning, while car traffic is more fluent (Schaffer, 2019); ii) the walls that surrounds the S-N creates an Urban Canyon Effect (Andreou and Axarli, 2012) and iii) the canal on the side of the N-S road cools down the air temperature (Moyer and Hawkins, 2017). One difference with the survey conducted with Sodaq Air is that MeteoTracker has a smaller temperature range (-1.7 – 4.9 °C) than the Sodaq Air one (-5.0 – 14.8 °C).

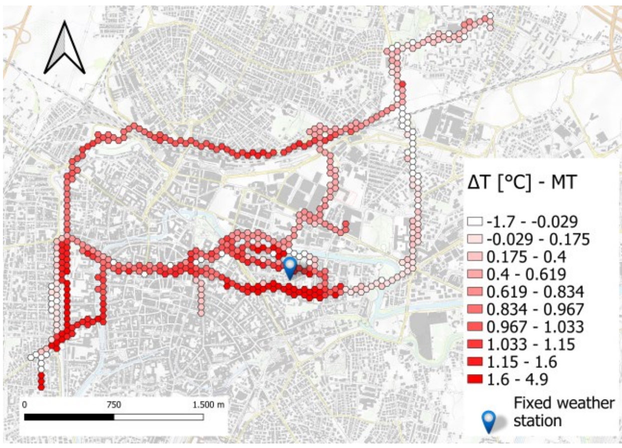

Figure 9. Average temperature anomaly (°C) observed by one MeteoTracker device respect to Davis fixed weather station in November and December 2022.

4. CONCLUSIONS

Different typology of mobile mapping devices for environmental monitoring are at present commercialized worldwide. This study highlights the importance of scientific testing to improve the reliability and the usability of the devices both for supporting the accurate, but punctual data acquired from official public networks, and to generate usable data from mobile mapping performed by Volunteered Geography and Citizen Science approaches. By testing two different types of "sniffer bikes" (namely, Sodaq Air and MeteoTracker), our study performed tests and accuracy assessment for mapping UHI and PM 2.5, both in static and dynamic mode as well as at urban scale. Preliminary results suggest that MeteoTracker is able to provide reliable air temperature values, while Sodaq Air seems to have some limitations, both in response time and absolute temperature detections. In addition, comparative analysis between Sodaq Air and official ARPAV station suggests that detection of PM 2.5 presents some critical elements, with an overestimation of almost two times. This might be related to environmental conditions as well as some limitations in hardware/software design.

On the other hand, mobile mapping devices showed the potential in massifying sampling over space and time for local climates and air quality monitoring at urban scale, allowing to identify, by geovisualization and dynamic maps, potential hotspots for mitigation measures of UHI and air pollutants.

Massifying air temperature data acquisition with mobile mapping devices would allow more reliable UHI analyses, since nowadays the most common way of assessing temperature anomalies is from satellite thermal images that quantify land surface but not air temperature (Tsin et al., 2016; Yin et al., 2020).

Finally, beyond the panacea of low-cost devices with prices not so accessible for normal citizens (and even less for urban population of the so-called Global South), there is an urgent need for the implementation and testing of open-source technologies and mobile sensor platforms (both hardware and software) for democratize the use of such important ground-based environmental monitoring systems.

REFERENCES

Andreou, E., Axarli, K., 2012: Investigation of urban canyon microclimate in traditional and contemporary environment. Experimental investigation and parametric analysis. *Renewable Energy*, 43, 354-363.

Antoniciello, G., 2021: MeteoTracker, piccola ma promettente stazione meteo portatile. *Nimbus*, 86, pp. 6-9.

Bulot, F.M., Johnston, S.J., Basford, P.J., Easton, N.H., Apetroaie-Cristea, M., Foster, G.L., Morris, A.K., Cox, S.J., Loxham, M., 2019: Long-term field comparison of multiple low-cost particulate matter sensors in an outdoor urban environment. *Scientific reports*, 9(1), 1-13.

Castell, N., Dauge, F.R., Schneider, P., Vogt, M., Lerner, U., Fishbain, B., Broday, D., Bartonova, A., 2017: Can commercial low-cost sensor platforms contribute to air quality monitoring and exposure estimates?. *Environment international*, 99, 293-302.

Castell, N., Kobernus, M., Liu, H.Y., Schneider, P., Lahoz, W., Berre, A.J., Noll, J., 2015: Mobile technologies and services for environmental monitoring: The Citi-Sense-MOB approach. *Urban climate*, 14, 370-382.

De Oliveira, R.H., Carneiro, C.D.C., De Almeida, F. G. V., de Oliveira, B.M., Nunes, E.H.M., dos Santos, A.S., 2019: Multivariate air pollution classification in urban areas using mobile sensors and self-organizing maps. *International Journal of Environmental Science and Technology*, 16(10), 5475-5488.

DeSouza, P., Anjomshoaa, A., Duarte, F., Kahn, R., Kumar, P., Ratti, C., 2020: Air quality monitoring using mobile low-cost sensors mounted on trash-trucks: Methods development and lessons learned. *Sustainable Cities and Society*, 60, 102239.

Dosio, A., Mentaschi, L., Fischer, E.M., Wyser, K., 2018: Extreme heat waves under 1.5 C and 2 C global warming. *Environmental Research Letters,* 13(5), 054006.

European Parliament, 2008: Directive 2008/50/EC. *Official Journal of the European Union.*

Giazzi, M., Peressutti, G., Cerri, L., Fumi, M., Riva, I.F., Chini, A., Ferrari, G., Cioni, G., Franch, G., Tartari, G., Galbiati, F., Condemi, V., Ceppi, A., 2022: Meteonetwork: An Open Crowdsourced Weather Data System. *Atmosphere*, 13(6), 928.

IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change *Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA,* 2391 doi:10.1017/9781009157896.

Karagulian, F., Barbiere, M., Kotsev, A., Spinelle, L., Gerboles, M., Lagler, F., Redon, N., Crunaire, S., Borowiak, A., 2019: Review of the performance of low-cost sensors for air quality monitoring. *Atmosphere*, 10(9), 506.

Liu, X., Li, B., Jiang, A., Qi, S., Xiang, C., Xu, N., 2015: A bicycle-borne sensor for monitoring air pollution near roadways. *2015 IEEE International Conference on Consumer Electronics-Taiwan.* 166-167.

Magi, B.I., Cupini, C., Francis, J., Green, M., Hauser, C., 2020: Evaluation of PM 2.5 measured in an urban setting using a low-cost optical particle counter and a Federal Equivalent Method Beta Attenuation Monitor. *Aerosol Science and Technology*, 54(2), 147-159.

Moyer, A.N. and Hawkins, T.W., 2017. River effects on the heat island of a small urban area. Urban Climate, 21, pp.262-277.

Pappalardo, S.E., Todeschi V., Zanetti C., 2023: Mapping urban heat islands and heat-related risk during heat waves from a climate justice perspective: a case study in the municipality of Padua (Italy) for inclusive adaptation policies. *Landscape and Urban Planning,* in press.

Park, H.S., Kim, R.E., Park, Y.M., Hwang, K.C., Lee, S.H., Kim, J.J., Choi, J.Y., Lee, D.G., Chang, L.S. and Choi, W., 2020: The potential of commercial sensors for spatially dense short-term air quality monitoring based on multiple short-term evaluations of 30 sensor nodes in urban areas in Korea. *Aerosol and Air Quality Research*, 20(2), 269-380.

Peroni, F.; Pappalardo, S.E.; Facchinelli, F.; Crescini, E.; Munafò, M.; Hodgson, M.E.; De Marchi, M., 2022: How to map soil sealing, land take and impervious surfaces? A systematic review. *Environ. Res. Lett.* 2022, 17, 053005.

Pivato, A., Pegoraro, L., Masiol, M., Bortolazzo, E., Bonato, T., Formenton, G., Cappai, G., Beggio, G. and Giancristofaro, R.A., 2023: Long time series analysis of air quality data in the Veneto region (Northern Italy) to support environmental policies. *Atmospheric Environment*, 298, 119610.

Pristeri, G.; Peroni, F.; Pappalardo, S.E.; Codato, D.; Castaldo, A.G.; Masi, A.; de Marchi, M.: 2020: Mapping and assessing soil sealing in Padua municipality through biotope area factor index. *Sustainability*, 12, 150.

Schaffer, K.G., 2019: Measuring Temporal and Spatial Exposure of Urban Cyclists to Air Pollutants Using an Instrumented Bicycle (No. GT-01-09). *In Conference on Health and Active Transportation,* 182.

Schilt, U., Barahona, B., Buck, R., Meyer, P., Kappani, P., Möckli, Y., Meyer, M., Schuetz, P., 2023: Low-Cost Sensor Node for Air Quality Monitoring: Field Tests and Validation of Particulate Matter Measurements. *Sensors*, 23(2), 794.

Sîrbu, A., Becker, M., Caminiti, S., De Baets, B., Elen, B., Francis, L., Gravino, P., Hotho, A., Ingarra, S., Loreto, V., Molino, A., 2015: Participatory patterns in an international air quality monitoring initiative. *PLOS one*, 10(8), 0136763.

Strobl, J., 2009: Geo-ICT: Connecting physical and virtual geographies. *Geospatial Technology and the Role of Location in Science*, 187-199.

Sun, C.Y., Kato, S., Gou, Z., 2019: Application of low-cost sensors for urban heat island assessment: A case study in Taiwan. *Sustainability*, 11(10), 2759.

Todeschi, V., Pappalardo, S.E., Zanetti, C., Peroni, F., De Marchi, M., 2022: Climate Justice in the City: Mapping Heat-Related Risk for Climate Change Mitigation of the Urban and Peri-Urban Area of Padua (Italy). *ISPRS International Journal of Geo-Information*, 11(9), 490.

Tsin, P.K., Knudby, A., Krayenhoff, E.S., Ho, H.C., Brauer, M. and Henderson, S.B., 2016: Microscale mobile monitoring of urban air temperature. *Urban Climate*, *18*, 58-72.

Yatkin, S., Gerboles, M, Borowiak, A and Signorini, M., 2022a: Guidance on low-cost air quality sensor deployment for nonexperts based on the AirSensEUR experience. *Publications Office of the European Union, Luxembourg.* doi:10.2760/180094.

Yatkin, S., Gerboles, M., Borowiak, A., Davila, S., Spinelle, L., Bartonova, A., Dauge, F., Schneider, P., Van Poppel, M., Peters, J., Matheeussen, C., 2022b: Modified Target Diagram to check compliance of low-cost sensors with the Data Quality Objectives of the European air quality directive. *Atmospheric Environment*, 273, 118967.

Yin, Y., Tonekaboni, N.H., Grundstein, A., Mishra, D.R., Ramaswamy, L., Dowd, J., 2020: Urban ambient air temperature estimation using hyperlocal data from smart vehicle-borne sensors. *Computers, Environment and Urban Systems*, 84, 101538.