Collective Mobile Sensing for Urban Health

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As urban citizens, we are often exposed to highly polluted environments. However, despite the growing access to sensing technologies, urban environmental data is still not openly available to the public. Lack of availability of air pollution data not only abstracts the sensitivity of environmental issues for the citizens, but also diminishes the overall understanding of the relationship between urban parameters and pollutant concentrations.

In response to these challenges, this paper argues that, in order to better understand urban environmental conditions, we must first work with high-resolution spatio-temporal air pollution data. We argue that collective mobile sensing methods with the use of low-cost and technically accessible devices have the potential to provide sufficient spatio-temporal air pollution data. We must then investigate alternative visualization strategies for better analysis of multivariable spatial data such as, air pollution. The goal is to enhance public awareness and motivate subsequent initiatives to improve and promote urban health.

This paper presents a case study developed and implemented at the University of Southern California in the city of Los Angeles. Collective mobile sensing is performed through student engagement and the use of bikes and UAV technologies. The results are displayed and analyzed through three visualization strategies i) GIS analysis ii) 3D spatio-temporal analysis and iii) video filtering analysis.

1. INTRODUCTION

With the advent of rapid urbanization, and increasing concern for urban health (WHO 2014), the formulation of urban strategies to improve urban air quality are becoming critical. This is especially true for dense urban environments where air quality is most compromised (Britter and Hanna 2003). Urban air quality is influenced by ambient wind, atmospheric stability, solar radiation and anthropogenic pollutant emissions. Thermal pollution and chemical pollutant concentrations peak in cities, as opposed to the countryside, due to high and localized anthropogenic emissions, as well as to the topographical and surface materials properties of the urban fabric (Oke 1988). Luke Howard, a British meteorologist, was one of the first scientists who addressed this evidence in the 1830s (Howard 1838); and since then, the research on urban air quality has been ongoing.

In the last decade, many cities have adopted policies to control the emission of pollutants to the atmosphere as well as to promote sustainable urban developments (Transport of London 2015, NYSDOT 2011). However, due to the lack of availability of urban air quality data, these regulations often fail to respond to specific local needs. Therefore, to be able to better monitor air quality, we must gather higher spatial resolution urban environmental data to capture the variability of the heat and contaminant concentration levels across the city (Llaguno-Munitxa and Bogosian 2015). Such high resolution environmental data cannot be obtained from weather stations or current sensory networks (Oke 2006). Thus, to capture air quality data at a finer spatial resolution, an exploration of alternative modes of data acquisition is necessary.

This paper argues that collective mobile environmental data gathering is an ideal method for achieving high spatial resolution environmental data. Citizen engagement in the process of environmental data collection, will result in obtaining a large number of geotagged databases which will inform research on urban microclimatology as well as the formulation of urban policies. This assertion is supported by a case study conducted in the city of Los Angeles which focuses on the acquisition of high spatial resolution urban air quality data, utilizing readily available environmental sensors coupled to mobile devices. Custom air quality sensor kits are mounted to bikes for acquisition of pedestrian level microclimate data. The same sensor kits are attached to a number of Unmanned Aerial Vehicle (UAV) for the vertical air quality measurements.

To rationalize the collected field measurements in relation to existing urban parameters, three visualization strategies have been proposed. Firstly, Geographical Information System (GIS) analysis is performed to enable a visual overlay of the recorded environmental data and existing urban data. Secondly, 3-dimensional spatio-temporal analysis is performed for the visualization of complex environmental datasets. Lastly, video filtering analysis is performed by layering the captured data on footages of the mobile sensing trajectories. All three visualization strategies aim to facilitate the rationalization of the collected data for an easier translation of the results to the citizens and planning strategists where urban sustainability is promoted.

The working methodology advocated here emphasizes the importance of spatial resolution for understanding urban microclimates and takes advantage of accessibility to sensors and mobile devices to develop a collective mobile urban sensing methodology. This method not only provides finer grain data for environmental scientists, but also elevates citizens' health consciousness and climate change literacy through active participation. Furthermore, the proposed visualization strategies would facilitate correlations between the collected data and further urban parameters. The goal is to amplify the reading of the climatic data for the formulation of locally informed urban policies and increased sensitivity towards the built environment.

1.1 AIR POLLUTION

The Great Britain, as the first industrial nation, was the first place where pollution regulation measures were considered (Thorsheim 2006). Given the necessity for the study of the pollutant concentration in cities, in 1912, The Committee for the Investigation of Atmospheric Pollution was set up by the Meteorological Foundation. Research that promoted the establishment of the first air quality policy in the UK– the Clean Air Act of 1956- soon to be followed by the US clean air act in 1963. Currently, the legislations established by the National Ambient Air Quality Standards (NAAQS) (under the Environmental Protection Agency (EPA)) set the regulations for carbon monoxide, nitrogen dioxide, sulfur dioxide, ozone, particulate lead, and suspended particulate mass. However, despite these regulations, over 70 communities throughout the United States have violated the NAAQS standards (Chow et al. 1993).

While the relationship of high particulate matter (PM) concentrations in ambient air with health problems have been widely documented (Dockery et al. 1993, Kunzli et al. 2001), research on particle matter (PM) concentration and composition in urban environments is considered one of the most critical fields of research (Schauer 1996). Specifically, the combination of high concentrations of traffic in areas with dense architectural configurations, have shown to heavily compromise air quality in urban street canyons (Dingenen et al. 2005, Britter and Hanna 2003). Air pollution concentration levels are also being strongly influenced by the urban surface properties such as, the surface structure, surface materiality and the land coverage (Stewart and Oke 2012). Architectural scale features can also influence the pollutant concentrations by affecting airflow patterns, turbulence intensities and atmospheric instabilities in urban environments (Llaguno-Munitxa, Bou-Zeid, and Hultmark 2016, Kastner-Klein, Berkowicz, and Britter 2004). Therefore, not only the implementation of urban policies which introduce vehicle restrictions could contribute to an improvement of urban air quality, but also the introduction of urban policies that attend to the architectural characteristics and understand the role of urban surface properties, would greatly improve air quality in our cities.

Pedestrian level pollution concentrations have been collected in several cities across the world to evaluate atmospheric concentrations as well as thermal pollutions (Chandler 1965, Berry, Colls, and Weter 2003, Nasrallah et al. 2003, Velasco et al. 2005, Vogt et al. 2006). While to a much lesser extent, vertical concentration profiles have been developed and reported (Rotach et al. 2005). One example is studies on the vertical variability of CO_2 concentrations amongst other parameters for a neighborhood in Basel, Switzerland. Similarly (Kanda, Moriwaki, and Kimoto 2005) developed field measurements to collect the variability in the wind velocity and temperature profiles in a 29m tall tower in a residential area in Tokyo.

Previous studies have shown that pollutant concentration gradients vary significantly in time and space. Therefore, urban field measurements should be gathered at a range of different sites and at sequential time intervals which attend the characteristic eddy turn over times in order to reflect upon the air quality trends within a given area. As described by (Oke 2007), "there is a growing need for meteorological data in urban areas in support of air pollution research and management". However, cost and technical complications associated with field experiments are to be taken into account. Furthermore, the cost and technical difficulties become more aggravated for obtaining vertical profile measurements. Another important constraint to take into account is that weather stations generally provide the necessary temporal resolution to capture the steady and unsteady flow characteristics; however, the spatial resolution of the data obtained from weather stations generally proves insufficient to perform urban analysis (Llaguno-Munitxa and Bogosian 2015). Therefore, it is not surprising that the influence of urban geometry on pollutant concentration has been mainly developed through wind tunnel experiments and numerical simulations.

In this context, the use of sensor networks and remote sensing technologies are becoming more widespread for a higher spatial resolution acquisition of the urban air quality data. However, these remote sensing methods are still costly and require expertise. Furthermore, the increasing accessibility to easy to use and low cost sensors is motivating the manufacturers to incorporate sensors into everyday objects which encourages the general public to engage in urban sensing projects. The urban sensing methodology proposed in this paper is framed in this context. The case study which will be introduced in the following sections, promotes an urban sensing strategy based on collective mobile sensing to capitalize on the benefits of crowd sourced sensing as well as mobile platforms for attaining higher environmental resolution data of our cities.

1.2 COLLECTIVE SENSING

The increasing availability of low-cost sensing platforms and their integration into everyday personal devices are contributing to the recognition of the value of ubiquitous sensing for environmental research (Campbell et al. 2006, Goodchild 2007, Resch, Blaschke, and Mittlboeck 2010). The advantages of accessing crowd sourced sensing data, does not only contribute to the collection of a higher spatial resolution urban environmental data, but could also reduce the operation cost compared to traditional field measurements. Thus, crowd-sourced sensing can contribute to a growing social awareness and the understanding of urban environmental parameters and its relationship to public health. This assertion increases the role of Citizen Science (CS) i.e. crowd-sourced experiments to perform urban environmental data research initiatives.

"The human sensors", as described by (Resch 2013), can contribute to the gathering of higher spatial resolution urban environmental data to address urban questions such as public safety, environmental monitoring, traffic management, or public health. (Boulos et al. 2011). There are various citizen science initiatives that have proved to be beneficial to complement scientific analysis. (Mellanby 1974) compiled the water quality data collected by school children to estimate the water pollution in rivers and streams in Britain and concluded that the results compared favorably with the existing official data and gave more details than had previously been recorded. (Davies et al. 2011) reflected upon the OPAL (Open Air Laboratories) program, a UK-wide citizen science initiative that focuses on topics such as air or water pollution. (Davies et al. 2011) considered the initiative not only to be beneficial for scientific research but also for community awareness. Similarly, the crowd-sourced air quality monitoring initiative "iSpex add-on" described by (Snik et al. 2014), coupled a spectrum of light measuring device to smart phones, and engaged various participants in the scanning of the sky to capture the differences in the particle concentration across different cities around Europe. The Amsterdam Smart Citizen Lab (Henriquez, Kresin, and De-Sena 2015) is also an interesting example where through a collaborative platform where scientist and urban citizens meet, urban environmental topics such as noise pollution or air quality are being researched.

As of today, despite the growing number of citizen science initiatives as well as the increasing affordability of the sensors and technical hardware required to perform the measurements, the availability of urban environments data is still limited. Furthermore, prior urban sensing citizen science initiatives have generally resorted to static-direct sensing strategies which often prove limiting in terms of spatial resolution when compared to data acquired from other technologies such as Light Detection and Ranging (Lidar) or Radio Detection And Ranging (Radar). Lidar technologies for example, can gather topographical information (NOAA 2012), data on airborne pollutant concentration, temperature or wind speed (Noh et al. 2016, Noel et al. 2004) to very high temporal and spatial resolutions. However, given the technical requirements and financial expenses associated with the deployment of these technologies, their use is still limited which contributes to the lack of availability of high resolution urban environmental data. With the ambition to develop a low cost, and citizen friendly sensing methodology, the case study argues for the use of the collective mobile urban sensing methodology. That is, a citizen involvement project where through mobile sensing, the acquisition of high spatial resolution urban environmental data is sought.

1.3 MOBILE SENSING

Mobile sensing has historically proved to be a valid methodology for the urban scale (Schmidt 1927, Peppler 1929, Chandler 1965). Amongst the newly implemented initiatives, the Copenhagen Wheel project (Outram 2010) utilizes the dynamic energy of physical effort to power environmental CO, NOx, temperature, noise (dB), humidity, and location sensors. Public transport mediums such as, trains and buses have been utilized in projects such as, the Open Sense project in Zurich (Li 2012), where the environmental sensing kits were attached to the city trams.

Mobile 3-dimensional mapping of the environment have received less attention given the technical difficulties associated with the acquisition of spatial data. For example, tethered balloons have been used in the past to dynamically capture the vertical gradient profiles (Tropea, Yarin, and Foss 2007). In the last years however, as the Unmanned Aerial Vehicle (UAV) technologies are becoming more utilized for various purposes such as mail delivery, forest monitoring, security, or video recordings amongst others, given the flexibility and affordability they offer, they are being regarded as a potential mobile platform to perform environmental analysis. As it will be described in the case study that follows, we have implemented bikes and UAV technologies to perform 3-dimensional environmental mappings of neighborhoods.

Through collective mobile sensing, high spatial resolution urban environmental data can be collected to develop research on topics such as the correlation of the urban heat island effect with the characteristics of the urban fabric, or the association between air quality and social and urban parameters. However, given the complexity and lack of cohesion in the available data, relating urban environmental data with further urban parameters often proves challenging. Therefore one of the main barriers scientists looking for strategies to improve urban sustainability encounter, is the lack of mechanisms that facilitate the correlation between the wide diversity of available data. In addition, little attention has been regarded to the development of spatio-temporal visualization techniques for environmental analysis. Therefore, we propose that an integrated urban environmental visualization would not only provide assistance for scientific analysis, but could also inform the general public.

In this context the presented case study, on the one hand proposes a data acquisition system based on collective mobile sensing aiming for the acquisition of high spatial resolution urban environmental data ,and on the other hand, proposes novel data representation strategies to enhance legibility and facilitate analysis of the acquired environmental data.

1.4 ENVIRONMENTAL VISUALIZATION STRATEGIES

The practice of formulating scientific data into microclimatic maps has historically contributed to the establishment of a dialogue between city climatology and urban planning processes. Originally proposed by Rudolf Geiger, the Klimaatlas (Geiger 1927, Geiger 1965), was devised as a synthetic tool to correlate environmental and planning data. The Klimaatlas allowed connecting meteorological studies to urban growth projections and policies.

In the last decade there have been number of projects which have focused on the online compilation of the crowd sourced environmental data and making it accessible to the general public. The Air Quality Egg was launched in 2012 where by distributing egg-shaped sensing kits, local air quality data was stored and processed in a remote platform called Xively (formerly known as Cosma and Pachube) which promoted an Internet of Things (IOT) approach to utilizing the air quality database. Similarly, the Smart Citizen initiative in Barcelona was launched in 2013, which promoted a custom kit for gathering crowd sourced environmental data along with an online interface to share and display the collected data. These initiatives have been successful in making the data accessible and visible to the public. However, their main objective has been to locally sense the environment, and not much focus has been placed on the resolution of the overall urban scale analysis and visualization. Open Sense project in Zurich (Li et al. 2012), addresses this problem of lack of spatial resolution by promoting mobile sensing techniques. Open Sense aims at investigating community-based air quality sensing using wireless sensor network technology attached to ground transportation methods. While, Open Sense achieves high-resolution spatio-temporal data, its analysis and visualization techniques have remained traditionally 2-dimensional. However, advancements in web and mobile GIS applications, as well as computational power and computer vision techniques, are opening new potentials for information processing and analysis. Therefore, the case study presented in the section to follow aims at the development of an integrated visualization of the city and environmental data. The goal is to establish environmental data visualization strategies which unveil the complex relationship between urban parameters and the recorded measurements.

2 CASE STUDY

We have developed and implemented a pilot project on the campus of University of Southern California in Los Angeles. With this case study, we aimed at not only initiating a collective mobile sensing workflow for air pollution documentation, but also investigating various methods of pollution data visualization to trigger rethinking urban policies and practices in the citizens.

2.1 CUSTOM SENSING KIT

Our devised workflow proposes a real-time data gathering methodology based on mobile sensing which utilizes accessible low-cost technologies for environmental sensing coupled to mobile devices. A custom sensing kit is designed which contains three sensors: temperature, humidity and CO_2. The sensing kit also contains a GPS module for geotagged collected data. These custom air quality sensor kits along with a GoPro camera are mounted to bike helmets for acquisition of pedestrian level pollution data. The same sensing kits are attached to UAVs for the vertical air quality measurements. The UAVs are equipped with a built-in GPS and Gyroscope boards and a Wi-Fi spy aerial vision camera. These built-in systems allow tracking and documentation of the experiment (see Figure 1). Flight elevation was set from the ground level to 120 ft. to record the

a)

Data Interpretation	Data Collection
"GPS1_Time_Stamp" Year, Month, Day, Hours, Minute, Seconds, Milliseconds, log to the SD if GPS	GPS1, 2015, 10, 26, 22, 33, 2, 0, fix_1
"GPS2_Info" Latitude, N, Longitude, W, Altitude, Speed, Int satellites	GPS2, 3401.225097, N, 11817.194335, W, 2.80, 1.02, 7
"DHT (Distributed Hash Table)" Humidity, Temp_Celsius, Temp_Fahrenheit, HeatIndex	DHT, 43.80, 24.90, 76.82, 78.31
"CO_2 Sensor Type" CO_2 level Parts Per Million	K30, 417

b)

c)

d)

Figure 1: a) Portable sensor kit (Humidity/Temperature + CO_2 sensors with GPS shield and microcontroller). b) An instance of collected data on the University of Southern California campus. c) Custom air quality sensing kits are mounted to bike helmets for horizontal sensing. d) Custom air quality sensing kits attached to Unmanned Aerial Vehicle (UAVs) for vertical sensing.

variability between the street canyon and over the Urban Canopy Layer (UCL).

The experiments were conducted during the month of March, 2016. Measurements were taken number of times to obtain data at sequential time intervals that attend the characteristic eddy turn over times to reflect upon the air quality characterization within the given area. The gathered data was analyzed and visualized following three strategies: GIS analysis, 3D spatio-temporal analysis, and video filtering analysis.

2.2 GIS ANALYSIS

An essential aspect of our sensing kit is the GPS module which enables geotagging of the collected data. When using geolocations, it becomes possible to overlay the collected data on GIS based files that entails roads, green areas, location of trees, building geometries, and topographical information.

As shown in Figure 2, our process begins by utilizing GIS data to plot geotagged acquired data on the existing urban context. We then proceed to utilizing GIS for parameterizing urban properties such as, green areas, impervious surfaces and building masses, around the acquisition trajectories as shown in Figure 3. The correlation of the acquired measurements and the urban parameters, show that maximum CO_2 concentrations mainly peak in road intersections. Building masses and greenery also influence the distribution of pollutant concentrations both in the pedestrian level and in the vertical profiles. The vertical readings are also sensitive to building and urban volumes and textures. Therefore, the analysis of vertical gradients though the use of UAV technologies is crucial for a better understanding of the relationship between urban morphology and air pollution. For further analysis, the collectively gathered air quality data is compared against the metropolitan scale GIS data to identify air quality trends and their relationship to urban design attributes. The acquired data is translated to GIS file types to not only analyze the findings but also share the information with the community for further analysis and verifications.

2.3 3D SPATIO-TEMPORAL ANALYSIS

Graphs have always been utilized to assist scientific visualization and analysis processes. Traditional 2-dimensional graph types such as, pie, bar or scatter plot, are limiting for working with multivariable data such as air pollution, unless one looks at each variable in isolation of the rest. For this case study, it is important to choose a method that best portrays the spatial characteristics of the acquired time based data. This objective resonates well with Edward Tufte's statement about time-based data representation, as he states that "An especially effective device for enhancing the explanatory power of time-series displays is to add spatial dimensions to the design of the graphic" (Tufty, 2001). Therefore, we utilize the existing GIS data to construct a high spatial resolution 3D model of the University of Southern California campus which then acts as the context for the air pollution data visualization. The next step is to plot the acquired geotagged data with the use of point, line, color and text. Figure 4 displays samplings of the temperature and CO_2 parameters on the University of Southern California campus. Each reading is first plotted with a geotagged point. The temperature is represented as text tags. The CO_2 concentration is reflected with the line length and color. The red colors represent higher CO_2 measurements, and the light blue colors display the lowest CO_2 concentrations. The different colors in the numbers represent readings following 3 different trajectories.

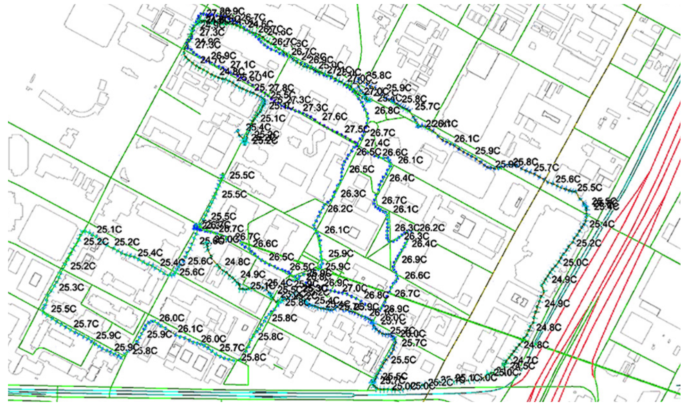


Figure 2: Geotagged temperature data layered on GIS data of University of Southern California campus.

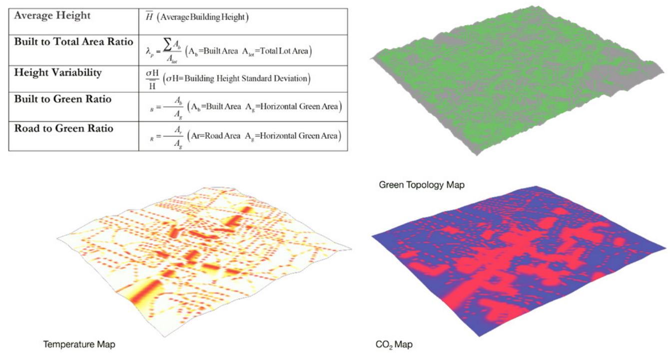
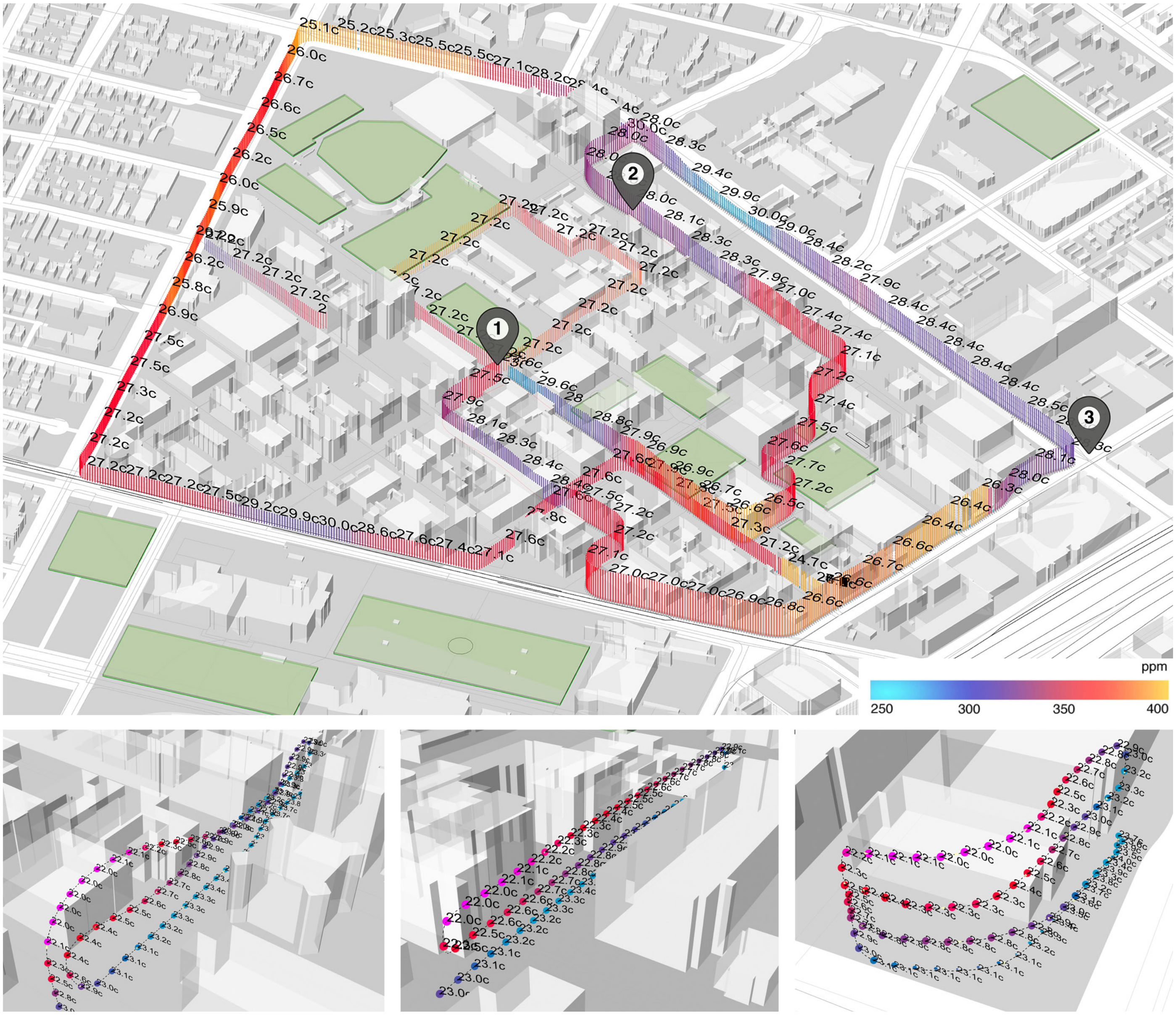


Figure 3: GIS based urban parameterizations displaying i) green topography, ii) temperature, and iii) CO_2 .

2.4 VIDEO FILTERING ANALYSIS

Site documentation in both arts and sciences have mostly been associated with the practice of static or dynamic image capturing. Therefore, with the assertion that image capturing capabilities have become an integral part of our readily available mobile devices, we focus part of our data visualization investigations into data overlay practices on moving images.

In the process of data collection, we also record videos with cameras coupled with the sensing kits. Hence, the recorded data always matches the captured image sequences. We then parameterize the acquired data to correspond to two main filters on the videos. The color gradient filter depicts temperature differences (the blue being cooler and red being warmer). The pixilation on the other hand, shows CO_2 concentration measurements. The larger the pixel the higher the CO_2 concentration (see Figure 5).



1) 2) 3)

Figure 4: 3-dimensional plot of the University of Southern California Temperature, humidity and CO_2 reading using bikes (aerial view) and UAVs. The temperature is represented with numbers as well as through the colour gradient.

a) #1 Watt Way and Childs Way Intersection on USC Campus, b) #2 Along W 34th St on USC Campus, c) #3 Figueroa St and Jefferson Blvd Intersection (North East Corner of USC Campus).

3 CONCLUSION

Due to the lack of availability of high spatial resolution environmental data of our cities, a collective mobile urban sensing methodology has been proposed. The proposed methodology has emphasized the importance of spatial resolution to enable the rationalization of environmental data against urban parameters at the neighborhood and building scales. The need to devise visualization strategies to rationalize the collected environmental data in relation to urban parameters has also been addressed and three visualization strategies have been proposed to analyze the data: i) GIS analysis ii) 3D spatio-temporal analysis and iii) video filtering analysis.

A case study has been presented where bikes for horizontal data recordings, and UAV technologies for vertical data collection have been deployed. The collected results have been displayed following the 3 proposed visualization strategies. 3D spatio-temporal analysis have enabled a qualitative understating of the relationship between urban structures together with a multivariable environmental dataset. Video filtering on the other hand, has proved to be an intuitive first person visualization strategy which appears to be most effective for the engagement of the general citizen in the understanding of the collected data. The proposed visualization strategies have facilitated the qualitative analysis of the collected data for an easier translation to strategies where urban sustainability is promoted.

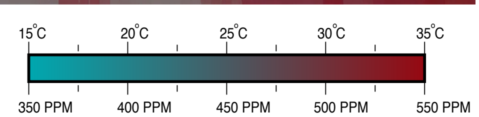


Figure 5: Video filtering analysis using pixel size for CO_2 variation and color gradient for temperature variation. Left sequence, camera view of a biker. Right sequence, camera vide of a UAV.

The proposed working methodology has emphasized the importance of spatial resolution of urban microclimatic data acquisition for both scientific research as well as for elevating public's health consciousness and climate change literacy through active participation. The proposed visualization strategies have shown to enable an easier correlation between the collected data and further urban parameters, proving potentially useful for not only increasing sensitivity towards the built environment, but also motivating the formulation of locally informed urban policies.

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