CAPABILITIES AND LIMITATIONS OF URBAN NEAR-SURFACE PARTICULATE MATTER MONITORING NETWORKS – EVIDENCE FROM WUHAN

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ABSTRACT:

Recent years have seen the emergence of local air pollutant monitoring networks that feature close proximity to urban activities, higher requirement for temporal granularity, and improvisions in equipment hardware and installation conditions. These networks are intended for the pertinent monitoring and improvement of urban air quality, but potential technical issues may undermine their ability to serve such purposes. This study utilizes a minute-granularity network in a university campus, and designs and conducts a series of experiments on how it performs under practical scenarios, including response to sudden environment change, reflection of multi-scale influencing factors, usability of different baseline stations, and ability to detect local emission events. Statistical and signal-processing technics are applied for understanding these experiments. The results indicate the source of complexity in such networks, the preferred temporal granularity for capturing different temporal patterns, the necessary reserved time for mobile stations, and the sensor location requirement for monitoring local emission events etc. In practical terms, these results provide a large amount of information on the specific capabilities and limitations of a near-surface, high-granularity monitoring network in the urban environment, and what to consider and to expect as a designer or user of such a network. In scientific terms, it is a strong reminder of the significance of numerous uncertainty issues in similar empirical studies.

1. INTRODUCTION

Fine particulate matter (PM) is the main air pollutant in the majority of Chinese cities, which have caused heavy losses to resident health and economic activities (C.N.E.M Centre, 2020; Mehta et al., 2013; Seposo et al., 2019). Motivated by air quality improvement objectives, local authorities have grown eager to analysis PM distribution in their jurisdiction, locate the sources of emission, assess the damage and influence of each source, and seek effective and cost-efficient countermeasures (Shafran-Nathan et al., 2019). Large investments are thereafter put into the construction of local or mobile near-surface urban PM monitoring networks in cities such as Beijing, Wuhan, Fuzhou, Chongqing and Xiangyang (Huang et al., 2019; Yu er at., 2019; Xue et al., 2020). Some very innovative attempts are also noticed, such as 3-dimensional monitoring with UAVs (Unmanned Aerial Vehicle) or mobile monitoring with cycle-mounted stations (Al-Ali et al., 2010; Joris et al., 2016; Peng et al., 2015; Li et al., 2017).

The location and allocation, sensor selection, and equipment installation in these networks are quite different from old-fashioned ones in National Ambient Air Quality Monitoring Network or administrated by municipal environment protection authorities:

First, earlier monitoring stations are mostly either located in rural areas to record background concentration variations, sparsely located in city parks or suburban to profile the pollution distribution of the whole city, or at industrial exhaust to directly monitor the quantity of emission. Respectively, they are classified as Regional/Background Stations, Urban Stations and Pollution Control Stations in the national standards (M.E.E of PRC, 2013). New, local networks are mostly focused on residential and commercial districts in urban centre to monitor local sources and assess the impact on residents and urban activities.

Second, old urban networks often cover a whole metropolis with around 10 stations, a result of their focus on background pollution; new networks often consist of more stations but cover a much smaller area. Also, local governments often ask for new features to pertinently serve their purposes: higher temporal granularity to detect transient events; multi-sensor system for multiple pollution control objectives and for discovering potential connections; and integrated internet communications for access to urban management platforms. Limited investment and these extra requirements tighten their budget to lower-cost sensors.

Third, earlier, standardized stations are preferably mounted on elevated towers in open ground to ensure minimum interferences from ambient environment; but in local, urban networks, the sensors are usually installed on walls, roofs or wire poles, about 2 to 4 meters above ground. Three reasons are behind this difference: (a) There is very limited possibility in dense urban areas to establish multiple stations at ideal locations; (b) The networks themselves are designed to reflect the air quality of the actual ambient environment of local residents. (c) Some stations are specifically aimed at the monitoring of known or potential local sources.

As we can see, these new near-surface urban monitoring networks, in general, are thus designed to serve their new purposes. However, while establishing and testing our own network, we realized that there are potential technical risks in such characteristics: Will low-cost sensors undermine the accuracy of concentration measurement? Is higher temporal granularity really practical in detecting local pollution events? Are urban stations too much more subject to proximate sources and small-scale wind field than suburban ones? And, will

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substandard installation bring unexpected interference to the monitoring results?

To facilitate our own further studies, and to provide for other researchers and local governments first-hand practical experience on these issues, we designed and conducted a series of exploratory experiments on the performance of the network under various practical scenarios. These experiments produce rich implications regarding what to expect from such a network, how to properly design the network, and how its records can be appropriately processed and interpreted.

2. MATERIALS

2.1 Equipment

The equipment we use is CityGrid G3.2, a multi-sensor, AC-powered outdoor monitoring station developed by Beijing Phase Number Technology Co., Ltd. It measures meteorological parameters, vehicle and pedestrian count and concentration of major air pollutants every minute, and transmit the data to the server in real time. Sensor maximum deviation for fine particulate matter is 10% under common meteorological conditions in Wuhan. In every six months, sensors are recalibrated for consistency in identical environment. The specifics of the equipment are demonstrated in Fig. 1 and Table 1.

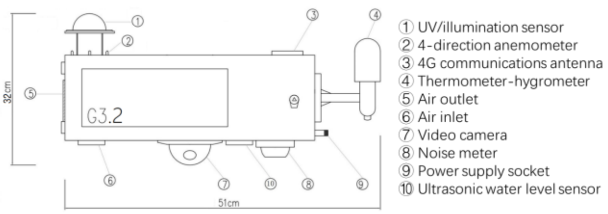

Figure 1. Equipment diagram

No.	Sensor	Range	Interval
1	PM2.5	0-1000 μg/m3	1μg
2	PM10	0-2000 μg/m3	1μg
3	SO2	0-20 ppm	1 ppm
4	NO2	0-20 ppm	1 ppm
5	O3	0-20 ppm	1 ppm
6	Pressure	300-1100 hpa	1 hpa
7	Wind velocity	0-45 m/s	1 m/s
8	Wind direction	0-360°	1°
9	Illumination	0-200000 lux	1 lux
10	Air temperature	-20-60 ℃	1 ℃
11	Air humidity	0-100%	1%

Table 1. Sensor configuration

2.2 Location

The network is located in the campus area of Wuhan University. To the north and the east of the campus is Donghu, a 32 km2 lake, and across the lake is a major coal and steel industrial area; to the west are residential communities and an elevated trunk road; to the south is another trunk road, another university and a major commercial centre.

The campus itself is divided into 5 natural areas by hills and ridges. Respectively, they are: The lakeside area between Donghu Lake and Shizishan Hill; The shallow valley between Shizishan Hill and Luojiashan Hill; The northern and southern slope of Luojiashan Hill; and the southern campus surrounded by urban areas. These 5 areas are demonstrated in Fig 2.

In general, the atmospheric environment in Wuhan University is under the influence of multiple exterior emission sources, and both external and interior natural features. Therefore, we believe it is a suitable site for explorative studies.

2.3 Network

A total of 28 monitoring stations are purchased; 25 of them are installed on walls or wire poles as fixed stations in the monitoring network, and the other 3 are reserved as mobile stations. Fixed stations are installed 2.5 to 3 meters above ground to best reflect the interaction between pollutants and human activities while reducing accidental interferences.

The site locations are determined by the following principles: (a) Relative balance among the five areas; (b) Accordance to implicit spatial structures, such as major axis; (c) Coverage of different functional areas, including transportation, accommodation, teaching, and catering etc. (d) Coverage of different spatial forms, such as street valleys, open yards etc. The location of each site is demonstrated in Fig 2.

Figure 2. Network layout

3. EXPERIMENTS AND RESULTS

3.1 Response to Environment Change

In late October, 2020, we created two pairs of contrasting environments to test how the equipment responses to change of ambient environment: (a) Inside a sealed, foam-filled equipment box; outside the box on the pavement of a campus street. (b) On the table in the air-conditioned laboratory; mounted on the tripod on the rooftop of the 5-floor laboratory building. In either case, the equipment can be transformed from one environment to the other in less than 2 minutes. We found that:

1) Once locked in the box, the $PM_{2.5}$, PM_{10}, O_3, NO_2 readings reduce to 0 in 5 to 15 minutes. Once taken out of the box or taken from indoor to outdoor environment, $PM_{2.5}$ and PM_{10}

readings climbs up and stabilizes in 15 to 30 minutes (Fig. 3); and for NO_2 and O_3, it is about 10 minutes. During the delay, the readings increase or decrease at nearly stable rates.

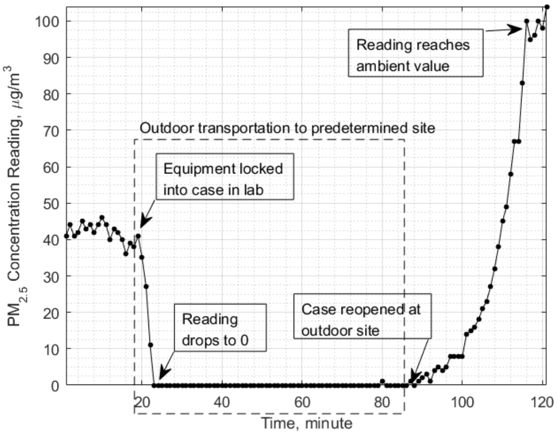

Figure 3. $PM_{2.5}$ readings through environment change

2) The reaction of temperature readings to environment change takes even longer. When transported from outdoor (cold) to indoor (warm) environment, it takes about 1 hour for its temperature reading to catch up with another equipment already indoor; as for the other way around, the drop takes 3 to 4 hours.

We speculate two possible reasons behind this astonishingly long reaction time: (a) When the equipment is moved around, it disturbs the air closely surrounding it; then, after some time it eventually full mixes with background air, and thus the readings are correspondent to its ambient environment. (b) Due to efficiency issues with the air inlet, equipment readings do not reflect the air closely surrounding it in time. To find out the cause, a controlled experiment is designed, where a cigarette is lit and put out 20 centimetres beneath the inlet. The $PM_{2.5}$ readings peaks within the 2nd minute, and drops to baseline in 3 minutes; the long delay is not observed. This and the results of the muck truck experiment in Section 3.4 convince us that (a) the equipment being moved is the reason behind the delayed reflection of changing environment. Therefore, caution should be used when utilizing mobile stations; ample time should be reserved after each time the equipment is relocated.

3.2 Multi-scale Influencing Factors

In analysing meteorological and air pollutant records of the network, we noticed ample implications of the coexisting impact from proximate, local, and large-scale processes. These processes are reflected by both the spatial distribution and the temporal variations of sensor records. We applied wavelet decomposition and other temporal analytics (Mallat, 1989; Ba et al., 2016; Liu et al., 2021) on the PM records of each station to study the specific influence of multiple processes. Results show that:

1) Strong temporal locality. In studies based on hourly records from background or urban stations, strong daily and weekly periodicity due to urban commute, industrial production and changes in atmosphere boundary layer is commonly mentioned. In our network, more than 40% of PM variations cannot be explained by daily cycles; and nearly 85% cannot be explained by weekly cycles, even within the same season (Fig. 4). Strong local surges can be identified from wavelet components of PM variations, with various amplitudes and durations. We believe that temporally local influences are introduced by the complex ambient environment, and that the high temporal granularity reflects short-term variations which would be hidden in hourly records.

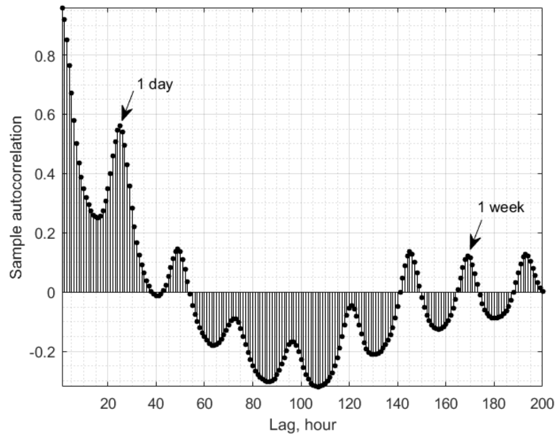

Figure 4. Autocorrelation of $PM_{2.5}$ temporal variation

2) Long-term consistency and short-term differences among different stations. Shape distances and piecewise linear representation results show that, among all stations in the network, wavelet components of PM variations at 7-day or longer periods are identical in terms of overall temporal patterns; those at 4-hour or shorter periods are different from each other. This indicates the dominance of background factors in long-term changes, and of local factors in short-term changes.

3) Temporal stationarity in long samples of high-frequency components. As is shown in Fig. 5, More than 80% of hour-period components or components on lower frequencies are non-stationary, indicating that hourly oscillations are ubiquitous within the tested environment; this is consistent with the common practice of using hourly records in most networks. On the other hand, the overwhelming majority of components on 1-minute or 2-minute periods are stationary. They are therefore more probably equipment noise rather than the consequences of effective, observable factors. For components on intermediate frequencies, the proportion of non-stationary samples decreases with the increase of sample length, confirming that actual short-term oscillations can be represented in 8-minute to half-hour records.

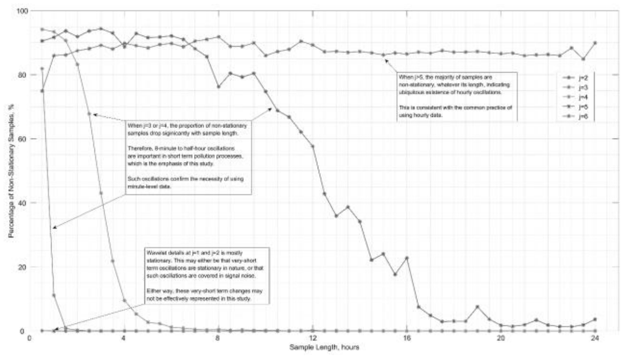

Figure 5. Sample stationarity distribution on different frequencies (Fan et al., 2021)

4) Inter-station asynchrony due to complex near-surface wind field. When dominated by the influence of background factors or large-scale pollution events, the PM variations at different

stations abide to similar general patterns. However, short, but very random asynchrony can be observed among different stations. The direction and length of such asynchrony changes wildly over time, and vary among different station pairs. Wind records from the network show violently changing near-surface wind field, which we believe is the reason behind such asynchrony (Fig. 6).

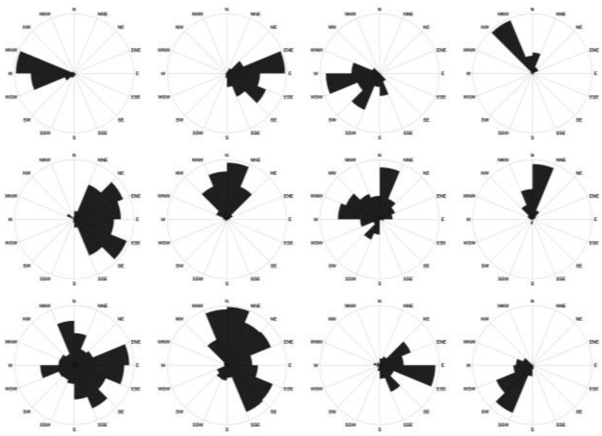

Figure 6. Per-minute wind-rose of 12 stations in January, 2020

To summarize, high-granularity temporal variations of PM concentrations in fixed near-surface stations are the mixed result of meteorological factors, local terrain, emission processes at various distances and with various durations, and equipment errors and other unobservable factors. To analyse or assess specific factors using such networks would therefore require deep understanding of mechanisms, and powerful mathematical tools to separate the features of interest. A detailed report on the above issues and the technics developed to deal with them can be found in our previous publication (Fan et al., 2021).

3.3 Establishment of Baseline Stations

In attempts of local monitoring networks, baseline stations are often installed away from roads, residents, and other potential local sources, so that the consequence of such local sources could be easily identified.

In our study, Station 6 is mounted on a wire pole at the middle-top of the Luojiashan Ridge, approximately 110 meters above campus ground, to serve this purpose. Later time-series and frequency-power analysis indicates that:

1) The different atmospheric movements in the near-surface layer and the Ekman layer may have affected the background concentration variations on the ridge top, which is difficult to remove. The temporal pattern of particulate matter concentration at Station 6 is, in general, consistent with stations in lakeside area, valley area or southern area; however, in the night (between about 21:00 and 8:00) it significantly exceeds other stations on most days, but with a few exceptions on windy days. This is most probably the result of the near-periodic change of atmospheric boundary layer. However, despite being roughly periodic, such discrepancies largely vary over time, and the introduction of meso-scale observation is probably necessary for its calibration. Also, the duration of such inconsistency overlaps with the morning commute and the midnight barbecue time, directly bringing complexity in the analysis of these sources.

2) The high-frequency disturbances at the ridgetop station are not significantly less than the other stations, but are under the influences of different factors. We assumed that, with less proximate particulate emissions and less vehicular or pedestrian activities, the temporal variation of particulate concentration would demonstrate a more stable pattern and contain less high-frequency components. However, we observe no significant difference between the amplitude or power of 1-minute to 8-minute components of Station 6 and other stations. Moreover, strong locality can also be found in its high-frequency components, indicating that there are more causes than observation errors. In 1-minute components, such locality is in general consistent with all other stations, which is probably the result of equipment error due to change in ambient humidity; but in 2-minute and 4-minute components, surges at Station 6 are observed at different times from other stations. We speculate the complex terrain and the heavy vegetation on the ridge may have contributed to this result, but we do not have the necessary conditions to conduct a control experiment.

Another station, Station 14, is mounted on the rooftop of a 2-floor astronomic observatory surrounded by a 100×100 m^2 grassland. As we can expect, there is no evidence that this station is interfered by atmospheric boundary layer; however, the time-series similarity between Station 14 and Stations 5 and 11 in its proximity indicate strong influence from ambient environment. Therefore, it is not suitable as the baseline station of the whole network.

To summarize, in a local network in urban environment, strong influence form both background and ambient factors makes it difficult to locate a baseline position. In our case, neither Station 6 nor Station 14 is not able to provide the quantitative baseline for our network in the way we expected it to. A proper baseline station would require cleaner surroundings and moderate altitude; for example, elevated by a frame-type tower in open space like a standard weather station. This is unachievable in our study area – and, most probably, in many other areas of interest. This conclusion led to our later development of a signal-processing framework for the estimation of baseline variations of a small-scale near-surface network.

3.4 Detection of Local Emission Events

One of the main objectives of local authorities to establish small-scale air pollution monitoring networks is to identify, assess, and administrate local emission sources. Most commonly, they are installed to monitor construction sites, road intersections, catering emissions etc. To achieve similar ends, we installed the equipment both at busy crossroads or school gates (Stations 3, 7, 9, 13, 19, and 24), in dense residential blocks (Stations 4 and 10), and in gardens and playgrounds (Stations 14, 16, and 18). Analysis of roadside stations and on-site observations show that:

1) In street valleys with a relatively closed spatial forms, typically Station 13, peaks that last about 1 to 2 hours can be observed at noon or in the afternoon, when there is much traffic on the road. We speculate that, with unfavourable diffusion conditions within a street valley, continuous traffic loads exceed the capacity of outlet wind, and result in progressive accumulation of local PM concentration.

2) At crossroads, no significant surge can be identified, even at extremely busy hours (Fig. 8 Left). Station 19, installed outside an affiliated school, is a typical example: there is heavy traffic

in the morning, at noon and in the afternoon, where parents would drive and fetch their children; but no corresponding change could be found on PM concentration records. Relatively more complicated near-surface wind field and better diffusion conditions probably led to this result: the particulate matter from ground dust and automobile exhaust quickly diffuses to multiple directions, causing little influence to the specific location of the station. Similar experiments near canteens and in residential blocks led to the same conclusion: there is no detectable sign of extra influence from these potential sources, during dinner hours or not.

3) In either case, we are unable to connect short-time changes in traffic load with PM concentrations. We formulated 1-minute, 5-minute, quarter-hour and half-hour summaries of both PM concentration and traffic load records. There is no significant statistical relationship between the two variables in any case, and there is no apparent connection between transient PM concentration surges and traffic load surges.

To further explore this issue, we established a temporary station at a sloping road intersection near the No.2 south campus gate of the Southern Area (Fig. 7). The intersection is a passing point from a construction site to a temporary stockyard. Every afternoon, earthwork is transported by muck trucks from the construction site to the stockyard, and every evening from the stockyard to outside the campus though No.2 south campus gate. The containers of the muck trucks are covered in canvas, but there is still heavy dust as it rushes down or up the slope.

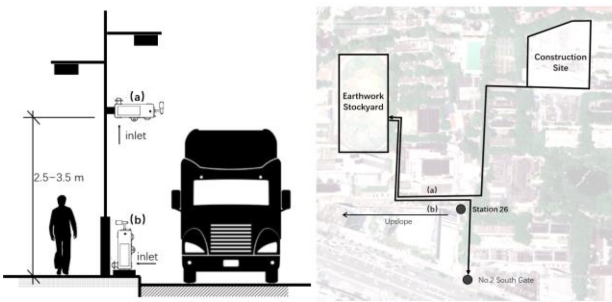

Figure 7. Left: The installation of (a) a typical road side station, and (b) Station 26 in the muck truck experiment. Right: Surrounding environment of the much truck experiment. (a) Truck path from construction site to the stockyard; (b) Truck path from the stockyard to outside the campus.

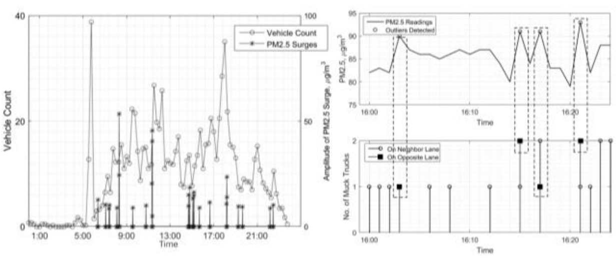

Figure 8. Left: Vehicle count records at a crossroad and identified $PM_{2.5}$ surges of a station nearby; Right: Muck truck records and $PM_{2.5}$ records of Station 26. (Fan et al., 2021)

On October 29th, 2020, we mounted Station 26 upon a suitcase 0.5 meters above the pavement, with its inlet toward the road. Two video cameras are placed nearby to record any vehicular and pedestrian activities in the vicinity. By cross-comparison between the PM concentration records and the camera records, we found that (Fig.8 Right):

1) Proximity to muck truck passage does increase local PM concentration. By average, Station 26 records were 8 to 12 μg/m^3 higher than Station 5, 11, and 14 nearby. This is much higher than inter-station differences in the whole Southern Area.

2) Transient surges can be connected only to muck trucks passing on the neighbouring lane, but not on the opposite lane. As the transportation is conducted opposite ways during the day and in the evening, this cannot be the result of slope direction; the different distance is the decisive factor.

3) PM concentration reacts within the exact minute of the passing truck, and lasts 1 to 5 minutes afterwards. However, wo do not know whether the surge actually lasts this long, or the equipment took the time to react: in 3.1 General Performance, experiments show that instant removal of ambient PM would take as long to be reflected in the equipment readings.

4) No connection can be found between (a) the number of trucks passing in succession and (b) the intensity or the duration of the transient surge. In fact, there is no observable explanation to us of the varying forms of concentration surges.

To summarize, a monitoring station close to a busy road can generally reflect the influence of heavy traffic on local atmospheric environment; however, such reflection is limited to cumulative effects. Despite high temporal resolution of the sensor itself, the diffusion process of vehicle exhaust or road dust obscures its temporal characteristics at the distance of a typical monitoring station. Stations in close proximity (~1 meter) to sources like muck trucks can detect the transient consequences they bring to local PM concentration; yet the specific properties of these transient surges are difficult to comprehend.

4. DISCUSSION

In general, our experiments affirms that it is not easy to achieve the original purposes of urban near-surface monitoring networks, as they are under strong influence from very complicated environments and seek more meticulous objectives than conventional networks. For future establishment and application of such networks, we suggest:

1) Most importantly, adopt a comprehensive perspective on the emission, diffusion and transportation process of the target air pollutant. Insufficient investigation of the concentration records, especially if using only statistical approaches, will easily lead to unfounded conclusions. For example, these networks are typically intended to explore the influence of local emission sources; but much of inter-station differences are actually caused by the synergy of meteorological and terrain factors. The actual influence of local sources, on the other hand, are often concealed in the influence of other factors. To study the effect of a specific element, an onion-peeling approach would be necessary to control and successively eliminate background, stochastic or irrelevant influences.

2) Conduct pilot experiments before establishment of fixed-station networks or execution of massive measurements. Pilot experiments are necessary in learning about the equipment, the study area, and the target phenomenon, so as to formulate appropriate objectives and network design. (a) The accuracy and spread of the equipment measurement result in different

intensity threshold of practically observable phenomenon. With high equipment noise, the monitoring of weak local sources would be difficult. (b) At specific locations, local interferences may be strong enough to overwhelm background changes, or may be relatively insignificant. More commonly, they are equivalent in magnitude and entangled in the concentration records. The feasible role and objectives of a specific station is therefore highly dependent on its location. (c) For some particular experiment designs, such as baseline stations or mobile monitoring, are very vulnerable to equipment performance or local terrain etc., and therefore must be validated in advance.

3) Develop pertinent mathematical tool for the analysis and interpretation of monitoring records. With the aforementioned factors influencing near-surface atmosphere, the high-granularity concentration variation records feature weak periodicity, high locality, temporal non-stationarity and inter-station asynchrony. Statistical approaches and most time-series analytics are not designed to tackle such problems. Our further studies show that wavelet-based approaches and dynamic time warping can effectively extract background variations, capture local patterns and realign and compare proximate stations.

5. CONCLUSION

In this study, a series of experiments are conducted to test the capabilities and limitations of a local-scale, near-surface, multi-sensor monitoring network of urban particulate matter. Detailed reports are given on the intention, conduction and results of these experiments. Practical recommendations are implied from these results, which we believe are useful for designers and users of such networks both in local governments and in the academia. For researchers, this is also a strong reminder on the significance of uncertainty issues in the empirical studies of complex near-surface urban environment. With this, we call for interdisciplinary efforts in the future, to establish a more systematic framework for ensuring the demanded capabilities of urban environment monitoring networks.

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