



Study on sandstorm PM₁₀ exposure assessment in the large-scale region: a case study in Inner Mongolia

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Abstract

The current exposure-effect curves describing sandstorm PM₁₀ exposure and the health effects are drawn roughly by the outdoor concentration (OC), which ignored the exposure levels of people's practical activity sites. The main objective of this work is to develop a novel approach to quantify human PM₁₀ exposure by their socio-categorized micro-environment activities-time weighed (SCMEATW) in strong sandstorm period, which can be used to assess the exposure profiles in the large-scale region. Types of people's SCMEATW were obtained by questionnaire investigation. Different types of representatives were trackly recorded during the big sandstorm. The average exposure levels were estimated by SCMEATW. Furthermore, the geographic information system (GIS) technique was taken not only to simulate the outdoor concentration spatially but also to create human exposure outlines in a visualized map simultaneously, which could help to understand the risk to different types of people. Additionally, exposure-response curves describing the acute outpatient rate odds by sandstorm were formed by SCMEATW, and the differences between SCMEATW and OC were compared. Results indicated that acute outpatient rate odds had relationships with PM₁₀ exposure from SCMEATW, with a level less than that of OC. Some types of people, such as herdsmen and those people walking outdoors during a strong sandstorm, have more risk than office men. Our findings provide more understanding of human practical activities on their exposure levels; they especially provide a tool to understand sandstorm PM₁₀ exposure in large scale spatially, which might help to perform the different categories population's risk assessment regionally.

Keywords Particle matter (PM₁₀) · Socio-categorized micro-environment activities-time weighed (SCMEATW) · Large-scale spatial exposure assessment · Geographic information system (GIS)

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Introduction

In arid and semi-arid areas of Asia, dust storms occur frequently. Sandstorms occur in the Mongolian plateau largely due to overworking of the land, drought, and inadequate watering of crops. The reason that a dust storm arises is regular wind from the west as well as the structure of the mountains in Mongolia (Munkhdorj et al. 2014). Particle matter 10 (PM₁₀) is one of the typical pollutants reflecting the intensity of dust storms. It is reported that the highest PM₁₀ value even exceeds 140 mg/m³ in a sandstorm's most violent interval (Yue et al. 2009).

Chronic exposure to sandstorm PM₁₀ contributes to the risk of developing cardiovascular and respiratory diseases, as well as lung cancer (Downs et al. 2007). There is a close, quantitative relationship between PM₁₀ exposure and increased morbidity, both daily and over time (Chen et al. n.d.). A study of the effects of air pollution in Europe reported that if PM₁₀ were to increase in concentration by 50 µg/m³, the total

mortality in West European cities would rise by 2.1% (Sajani et al. 2011). A 0.65% risk of hospitalization for MI would rise per 10 μg/m³ outdoor PM₁₀ concentration increase (Zanobetti and Schwartz 2013). Though a lot of researches have been done, most of them only take the outdoor concentration (OC) as the human exposure profiles, and health effects induced by PM₁₀ are thus drawn roughly (Ziqiang and Lei 2007; Larrieu et al. 2006; Kim et al. 2004; Macnee and Donaldson 2003; Zhenhua et al. 2015).

Traditionally, the exposure assessment method in particle matter (PM) is shown in the following (Eq. 1).

$$PWEL = \frac{\sum (P_i \times C_i)}{\sum P_i} \tag{1}$$

where PWEL is the population’s average exposure level; population means people’s activities in a certain area of the geography and the area can be divided into *i* means the grid number. *P_i* represents the population inside each grid, and *C_i* indicates the average concentration of air pollutants inside every grid, with every unit being micrograms per cubic meter or milligrams per cubic meter (Hou et al. 2016). Equation (1) has been popularizing for quite a long time in describing the exposure assessment in a large-scale region. Subsequently, its weakness is suspected on reflecting the practical exposure levels of people’s micro-environmental activity patterns.

With insight into exposure assessment, more and more scientists begin to associate the people’s exposure profiles with their activity sites and the micro-environment concentration. Micro-environment concentrations are the pollution levels which people are exposed to in their multi-activity sites. Some researchers have established a more accurate method containing parameter of various micro-environments personally to take place OC (Masih et al. 2017; C. CR, N. C, G. EM, N.-A. A, V. SP, B. D 2017), based on the view that people’s activity exposure amounts were decided by their multi-activity micro-environment and activities-time weighed (MEATW), and peoples’ MEATW are associated with their social factors such as education, occupation, habits, etc. A comparison of MEATW to OC demonstrated that levels of multi-activity sites and weighed stay-times both play an important role on the practical PM amount (Delfino et al. 2004). A primary model, with parameters containing the integrated micro-environment patterns by recording a person’s annual and episode settings, was developed, and its advantage was advocated (Hänninen et al. 2009). Another study reported children’s changes of lung function during childhood may be decided by their micro-environment activity patterns (Wilson et al. 2007). In the later study, methods of MEATW and OC, describing personally micro-environment activities-time weighed and outdoor concentrations, respectively, have been tested for their accuracies. Results indicated that factors of the regional and socio-economic charters may affect the total of exposure levels

(Stroh 2011). Other researchers confirmed that people’s practical activity patterns were associated with their social-categorized factors, for instance, occupation, habit, education, and so on. A similar study was performed in Phoenix, a place where sandstorms occur frequently. The differences of the acute cardiovascular mortality by PM exposure were explored. After long-time observation, scientists speculated the exposure derivation might be impacted by socio-economic status including education and income, all of them playing important roles on people’s protection mode to sandstorm (Macnee and Donaldson 2003). To record the real exposure level, some researchers have explored the portable aethalometers for monitoring personal exposure to air pollutant black carbon, which could keep detailed records on individuals’ time-activity patterns and whereabouts (Dons et al. 2012); this method has been popularized in later research (Piedrahita et al. 2017). However, this method seems unsuitable to the large number of population due to its cost.

Most sandstorms have been occurring with expanded geography scales; however, the available information, neither MEATW nor OC, can describe large-scale pollutant variability and population exposure patterns from geographical epidemiological studies. Inspiringly, for the PM level distribution in a large-scale region, the geographical information system (GIS) has provided such a perfect method to overcome the obstacle (Estarlich et al. 2008), which also helps to understand that the regional-scale varies in exposure assessment by model, rather than the monitoring “dot” data adopted in the past. However, it is insufficient to develop an approach concluding socio-categorized regionally and micro-environment activities-time weighed (SCMEATW), which can figure out the large-scale air pollutants in a precise way, and predict the average exposure levels for the regional population.

Based on different types of people’s social classification in the large region, combined with the identification factors of their exposure patterns including micro-environmental activity weighed, the method on prediction of the average exposure levels by their practical activity and exposure levels (SCMEATW) is to be developed urgently. SCMEATW, presented in this paper, consists of various micro-environments, the main of the sites will be discussed here, and the detailed information is stated as Eq. (2).

$$PWEL = \frac{\sum (SP_i \times SC_{ij} \times ST_{ij})}{\sum P_i} \tag{2}$$

where PWEL (SCMEATW) is the population’s average exposure levels; here, population means people’ activities in administrative regions and the regions consist of different villages, cities, or other administrative part units. *i* means the administrative unit number. Different types of populations inside the administrative unit can be categorized by their social activities. *P_i* represents the types of populations inside the administrative

units. SP_i means the total of the types of populations. Here, C_i indicates one type of population's micro-environmental concentration in one way, and j means the variable for the number of micro-environmental places or staying time. SC_{ij} means the sum of various micro-environmental levels of all gridded populations. T_{ij} means the activities' time of types of population inside their micro-environments. ST_{ij} represents the sum of activities time of types of population inside their micro-environments. The advantage of Eq. (2) contains the type of people in different administrative regions and their micro-environmental places or staying time during the sandstorm.

The main objective of this work is to develop a novel approach on how to establish the exposure parameters for people's sandstorm PM_{10} exposure assessment, which includes a spatial property information and epidemiology parameter synthetically. It will not only improve the precision of a population's exposure level in large scales but also identify the risk of different types of population.

Materials and methods

Study design

Asian dust storms have a major impact on the air quality of the densely populated areas of China, Korea, and Japan, and are important to the global dust cycle. In extreme cases, they result in the loss of human lives and disruptions of social and economic activities. In recent years, systematic research on Asian dust storms has been carried out (Shao and Dong 2006); it displays Inner Mongolia as one of the main areas suffering from sandstorms. In this study, PM_{10} concentrations were collected from local monitor stations in March 4 to 7, 2016, in Inner Mongolia, People's Republic of China. At the same time, meteorological data illustrated a large dust storm had been occurring simultaneously, with the wind veering from the west to the north, crossing most parts of Inner Mongolia. Inner Mongolia has low-population-density cities and counties, and the number of residents is about 11.15 million in 2014, surveyed from the authority statistical yearbook. The impacted areas included Erlianhaote, Xilinhote, Tongliao, and other places. In this big sandstorm, the total affected area was nearly 428,103.52 km². The monitor stations selected here were not evenly distributed over the areas, but the administrative districts where they were located covered six districts and 40 counties (Table S1).

PM_{10} concentration

1. Outdoor concentration

All environmental PM_{10} levels were monitored hourly by the environmental stations. The simulated data came from

monitor stations in Inner Mongolia originally, and they were used to create the distribution PM levels outdoors in geographical locations. The spatial variation was simulated by kriging of ArcGIS 10.2 software.

2. Indoor PM concentrations

The indoor micro-environment included homes, offices, entertainment places, and the inside of vehicles. Portable particulate monitors PDR-1500 (USA, Thermo) were applied to record the micro-environment levels continuously. Portable particulate monitor PDR-1500 instruments (USA, Thermo) and other Thermo 1405 F series instruments were employed to sample PM_{10} in 24 h continuously. The equipment had been regularly inspected and maintained in a timely manner to ensure its quality assurance.

Questionnaire survey

Questionnaire

Seven hundred and sixty local residents were selected randomly for the questionnaire. All questionnaires were administered on the condition that informed consents were signed; this study was approved by the human ethics committee of Erlianhaote CDC agency.

Questionnaire contents were classified into education, occupation, lifestyle, daily life exposure patterns, the subjective understanding of the storms' risk, etc. Socio-demographic variables designed in this study were age, gender, and ethnicity. The population categorized socio-economically included home-staying people, office men, students, and herdsmen. Questions about protection mode were whether or not the people wear masks during sandstorms. The survey on the working environment included occupational type and protection mode. All participants were questioned face to face, with socio-demographic data self-reported.

Population data and disease odds

Highly accurate population data, precise to the villages, were collected from the annual Inner Mongolia Local Statistical Yearbook. The disease odds discussed here have been collected from the local Disease Prevention and Control Agency in 2016.

Methods of weighing the average exposure levels

PWEL shown in Eq. (1) and SCMEATW presented in Eq. (2) are to be discussed here.

To establish the SCMEATW, the first important thing is to obtain the practical activities behave for the types of population. Different types of people, categorized by their social

attributes, had great differences on the risk recognition on sandstorms. Therefore, factors of education, occupation and ages, etc that resulting, which result in their difference in subjective awareness of protection, were designed here. By sorting the exposure patterns of population, we obtain the factors of social classification. In our study, we use administrative region data to take the place of the gridded map, since it is easy to tell the demographical data.

Statistical analysis

Statistical analyses were performed with SPSS 18.0 software. The correlations between social factors (education, types of occupations, ethnic, etc.) and sandstorm concern index were described by Pearson analysis, with linear correlation coefficients, and *p* values less than 0.05 were considered to indicate the significant differences.

Results

Environmental levels of PWEL

To identify the sandstorm duration and its routines in March 2016, both meteorological information and monitor data were analyzed together. Meteorological data indicated that the wind moved from the west to the east since five

o'clock in March 5, with the direction displayed as Erlianhaote→Xilinhot→Chifeng→Tongliao (Fig. 1). Environmental station data demonstrated that with the wind increasing, the hourly average PM₁₀ concentration of Erlianhaote outdoors became higher and higher and once reached 4.47 mg/m³ in March 4. Obviously, a big sandstorm took place at that time. After simulating the environmental station data to spatial distribution, the map of integrated outdoor levels of the affected area was created (Fig. 2). In Fig. 2, the degree of shallow dark represents PM₁₀ levels. The darker it is, the stronger PM₁₀ it has. The map outlined the trend of dark background from the strong to the weak to the wind direction. It means that the outdoor PM concentration decreased from Erlianhaote to Xilinhaote gradually from the east to the west. Population density and pollution concentrations are unevenly exhibited geographically.

Exposure parameters of SCMEATW

People’s activity sites and time weighed factor are the most important factors to the total exposure amount, since people stay indoors more than 90% of the time in the period of the strong sandstorm. Related parameters of SCMEATW are discussed here.

PM concentrations of two hotels, two hospitals, two schools, and seven office workplaces were monitored during the sandstorm, as well as 31 residents’ homes. In the period of the sandstorm, the daily average indoor level was calculated only as

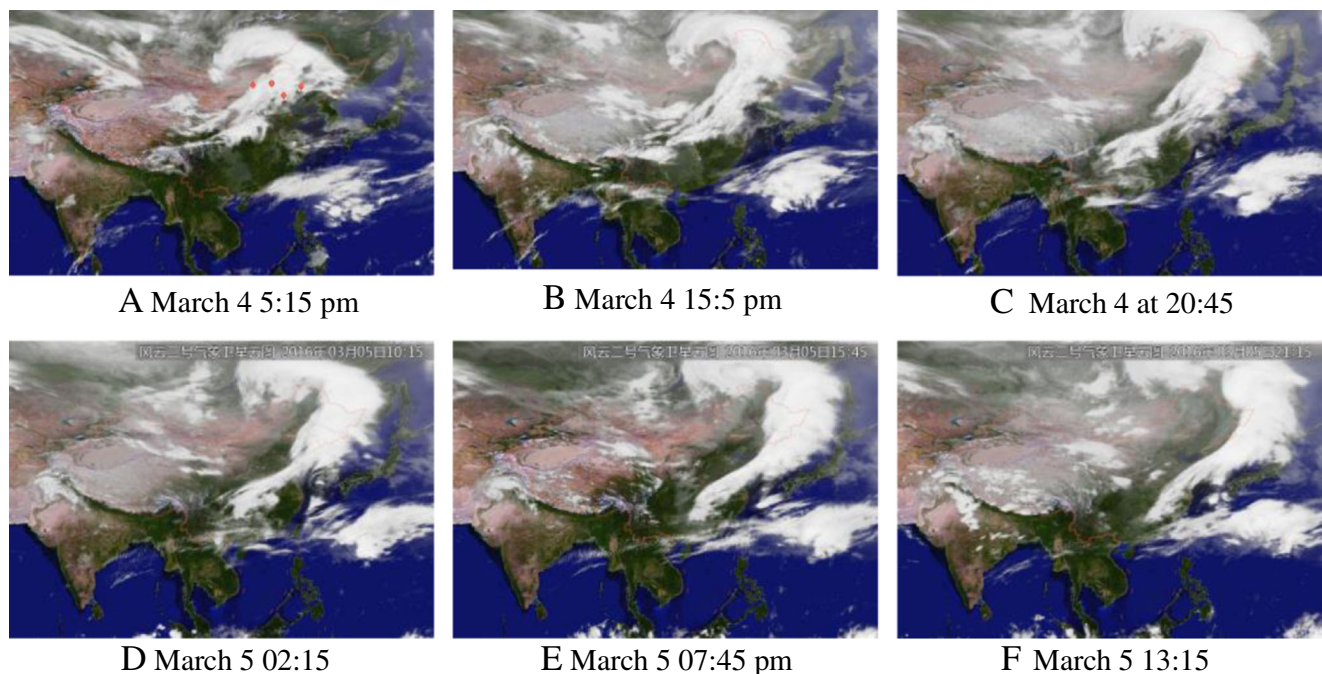


Fig. 1 Meteorological data during the big sandstorm in Inner Mongolia, March 4 to March 5. **a** March 4, 5:15 p.m. **b** March 4, 15:5 p.m. **c** March 4 at 20:45. **d** March 5, 02:15. **e** March 5, 07:45 p.m. **f** March 5, 13:15. **a–f** represented the cloud map in different times from March 4 to March 5, 2016. Four red spots from left to right in **a** indicated Erlianhaote,

Xilinhot, Chifeng, and Tongliao, respectively. The brown part of the cloud image from meteorological data illustrated that a big sandstorm had taken place during this period. The wind moved from the west to the east since five o'clock March 5, and its direction was shown as Erlianhaote→Xilinhot→Chifeng →Tongliao

Daily average levels of ambient and population exposure in March 4 ($\mu\text{g}/\text{m}^3$).

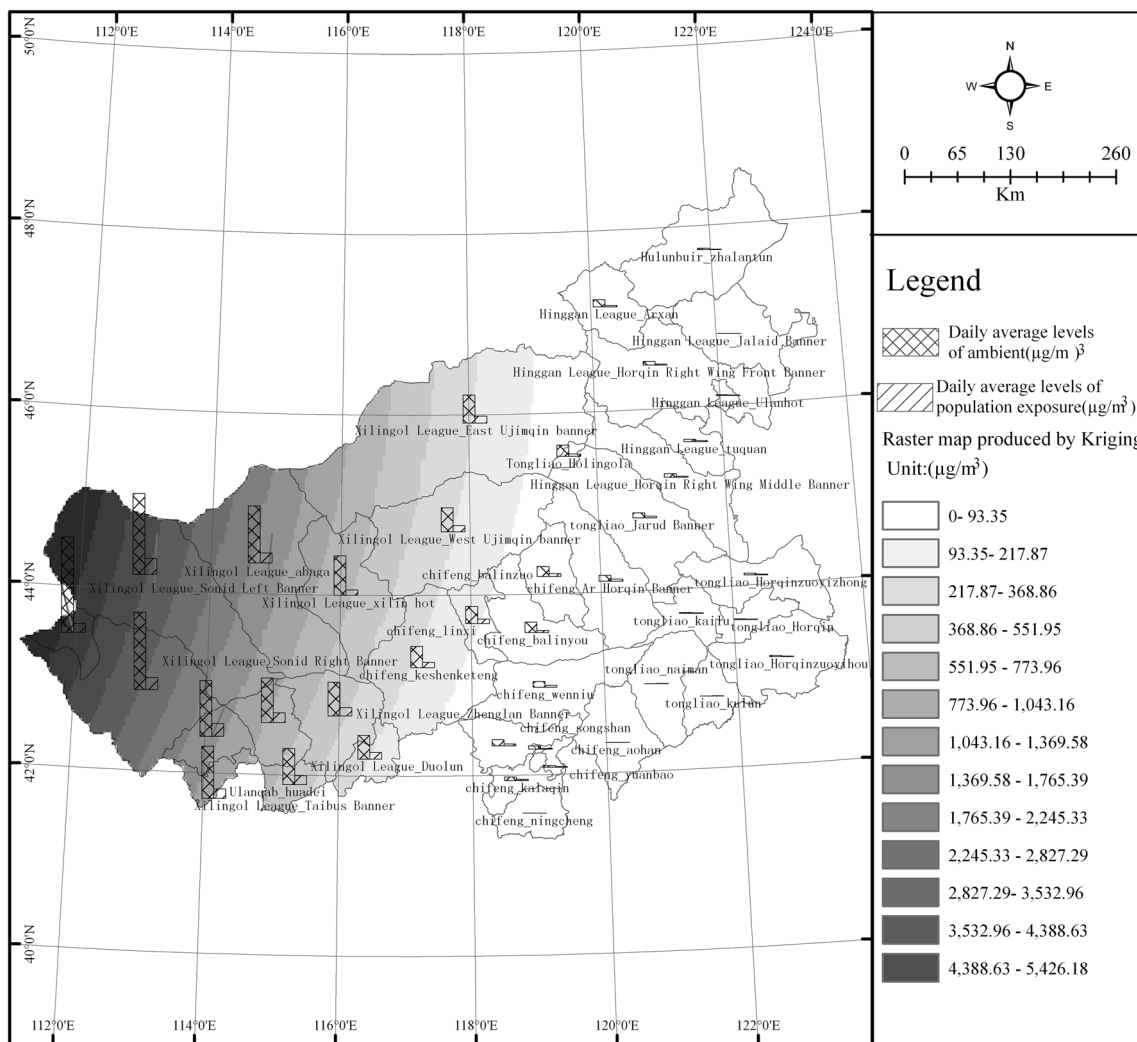


Fig. 2 Daily average levels of ambient and population exposure in March 4 ($\mu\text{g}/\text{m}^3$)

154.61 $\mu\text{g}/\text{m}^3$ in March 4, the value far less than that of the outdoors (4.47 mg/m^3). The previous study pointed out that the outdoor air pollution levels may contribute to the indoor levels (Jensen 1999). However, the difference between outdoor and indoor levels was found as a gap in our study. Here, the outdoor level was very high (4472.88 $\mu\text{g}/\text{m}^3$) during the big sandstorm. Different from the terribly high levels of outdoor PM_{10} , there

were relatively lower concentrations (149.55 $\mu\text{g}/\text{m}^3$) indoors and inside vehicles (72.1 $\mu\text{g}/\text{m}^3$) (Fig. 3).

Times of staying in micro-environments were important factors we have taken into account. In our investigation, the micro-

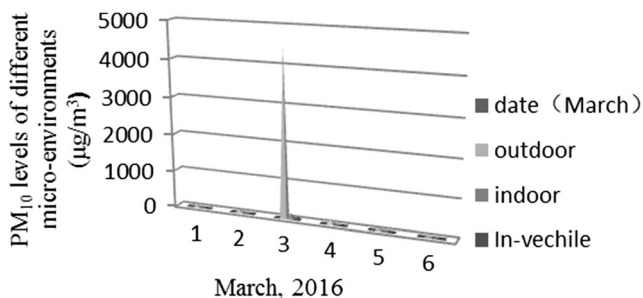


Fig. 3 PM_{10} levels of different micro-environments

Table 1 Percentage attention on sandstorm's index

Sandstorm's attention index	Ages				
	0–20	20–40	40–60	60–80	> 80
I	21.95%	27.46%	25.32%	15.94%	50%
II	48.24%	37.32%	31.17%	15.94%	25%
III	12.74%	19.01%	23.38%	24.64%	0%
IV	17.07%	16.20%	18.83%	36.23%	0%
V	0.00%	0.00%	1.30%	7.25%	25%

Sandstorm's attention index means the degree of attention to sandstorm paid by people. I, very much concerned; II, general concern; III, occasional attention; IV, does not care; V, knows nothing about sandstorms

Table 2 Unstandardized regression coefficients reflecting the relationship between social factors and sandstorm’s attention

	Unstandardized coefficients nts		<i>p</i> value
	<i>B</i>	Std. error	
1 (Constant)	1.530	0.691	0.028
Education degree	−0.006	0.070	0.931
Type of occupation	0.626	0.187	0.001
Nationality	−0.337	0.227	0.139
Age	0.006	0.006	0.343

Dependent variable: sandstorm’s attention index. Each of the social factors was used as a predictor in a separate linear regression model

B unstandardized regression coefficient, *S.E.* standard error, *p* significance value

environment activity times of adults whose workplaces were in offices had slight difference from that of the students ($p < 0.05$), and the adults spent less time in libraries and sports places. For herdsmen, they have to experience higher PM exposure because most of their tent accommodation was easily penetrated by PM during the dusty weather. In our surveys, their work time was assumed as 8 h in the dust day. Most of the old men, the retired, or the unemployed preferred staying home during the big sandstorm; their average outdoor time was estimated to be 1 h. Our research supported that people’s activity modes had tight correlations with their social characters.

The exposure protection modes were further surveyed here. Besides this, the concern index was designed in our investigation, which was affected by social factors and associated tightly with the individual protection mode. We administered the questionnaire to the local residents randomly, and their recognitions to sandstorm risk appeared differently by age

Table 3 A survey of transportation mode chosen during the sandstorm

	Ages			
	0–20	20–40	40–60	60–80
Walk by foot	29.65%	17.46%	12.06%	9.09%
Ride bicycle	15.90%	30.16%	7.80%	1.52%
Take bus	10.24%	16.67%	16.31%	16.67%
Other vehicles	43.67%	35.71%	63.12%	71.21%
Others	0.54%	0.00%	0.71%	1.52%

Most of the residents preferred to take vehicles than walk in the period of the sandstorm (Table 3); the number of young people walking by foot (29.65%) during the sandstorm was validated than that of the old men (9.09%). Those people who were older than 40 took little bicycles. The recognition of dust storm risks decided the choice of transportation to some extent. A survey of investigation revealed that most of the people living in the cities stayed home or in their workplaces; they would not go outdoors during the big sandstorm. Even if the local residents have to go out, their outdoor time was very short, usually less than an hour. It further pointed out that the more education people owned, the better airtight traffic they would choose

(Table 1). Most of the young people cared about sandstorm prediction than the old men. For those people whose ages were below 40 years, their concern index was nearly 64.78%, while the middle aged of the population whose ages varied from 40 to 60 years had concern indexes decreased to 56.49%; a more decreased trend in concern was found in the ages between 60 and 80 years.

In our investigation, social charters were classified as types of occupations. The younger people paid more attention to sandstorm prediction and its hazardous materials, because they experienced better education and internet media than the old men. Office men preferred to spend less time in libraries and entertainment places than students. Herdsmen had to stay outdoors or in tents that are easily penetrated by PM (Tables 1, 2, and 3). Therefore, they will suffer more from PM. Most of the old men preferred staying home during the big dust storms, with windows closed. The types of occupations were confirmed as the only one of the social factors affecting the sandstorm’s attention ($p = 0.001$) (Table 2). Meanwhile, the factor of education degree had been found the significance with the crowds types’ understands of st storms constitutes ($p = 0.008$) (not shown). It suggested that the higher the education degree the people had, the more protection they might take. Besides, as far as the people’s ethnicity was concerned, their languages might be the “barrier” to learning about the sandstorm hazard, especially among herdsmen, most of whom were Mongol. Meanwhile, our surveys revealed that most of the people living in the cities preferred staying home or in their workplaces, rather than go out during the big sandstorm. Even if the residents had to go out, their outdoor time was very short, usually less than an hour. The selected transportation mode was the key factor to the outdoor exposure profiles. Most of the residents preferred taking vehicles than walking in the big sandstorm (Table 3). The number of young people walking by foot (29.65%) during the sandstorm was confirmed more than that of the old men (9.09%). Furthermore, different socio-classification people were sorted. The parameters of SCMEATW were proved rather different for types of populations. The parameters of students were given as an example here (Tables 4, 5, 6, and 7), which differed from those of the herdsmen. To better understand the exposure levels by SCMEATW and OC, we employed ArcGIS software to map the people’s average exposure levels in large scales (Fig. 2).

Both exposure levels of PWEL and SCMEATW

Results pictured out the decreased exposure levels of OC trend gradually from the west to the east. It was easy to tell the stronger of PM₁₀ in Erlanhaote than Xilinhaote, similar to the exposure level of SCMEATW. It implies that the outdoor levels may influence the levels of SCMEATW regionally. Further analysis illustrated that though high OC levels were

Table 4 A survey of students' exposure patterns

		Micro-environment time-activities (h)					
		Nighttime (from 22 o'clock to 7 o'clock the next morning)	Average time of round way between home and school	Classroom time	Intermittent time between classes	Entertainment, indoor sport, library, or other places	Percentage (%)
Student	Taking vehicles and other transportations	9	0.5	7.5	1.75	5.25	
	Walking	9	1	7.5	1.75	4.75	

exited outdoors, the relatively lower average exposure of SCMEATW was identified (Fig. 2). It confirms that the method of OC will rather bring bias to average population exposure estimation practically, compared to people's SCMEATW. To ascertain the exposure levels of people sorted by the social factors mentioned above, we continued to map them based on SCMEATW by ArcGIS (Fig. 4). It can provide the better elucidation for the difference of people's activities and time weighed. The exposure level of herdsmen in the pasture area, such as Xilinhaote and Erlianhaote, could be found higher than that of other types of population. Differences of total exposure profiles are determined by people's socio-features.

All results of the exposure level of PWEL and SCMEATW are available in the supplementary material (Table S2).

Comparison of dose-effect by both methods

Based on the method SCMEATW, the health effects of sandstorm PM₁₀ exposure are further discussed here. The disease numbers counted from the big sandstorm day to the lagged 2 days were collected in 24 counties, which were affected by this big sandstorm, and the disease odds affected by OC and SCMEATW were illustrated (Fig. 5), respectively. Figure 5 I and II represents the exposure-effect curves representing respiratory outpatient odds and the exposure level of OC and SCMEATW, respectively. Figure 5 III and IV represents the relationship between cardiovascular clinic odds and OC and SCMEATW, respectively.

It displayed rather lower respiratory outpatient odds when the exposure levels of OC were below 300 µg/m³ (Fig. 5I) and

relatively higher odds when the OC levels were higher than 1000 µg/m³. At the same time, when the levels of SCMEATW were higher than 250 µg/m³, respiratory outpatient odds started to rise sharply, which was quite different from the OC exposure level. The relationship between cardiovascular clinic odds and the exposure levels of OC and SCMEATW are also shown the analogous conclusion (Fig. 5 III, II, and IV). Our results suggest disease odds by exposure level of SCMEATW are far lower than those of OC, which differ from the previous results only based on OC (Bell et al. 2008). Because the parameter of SCMEATW was designed to reflect the people's practical site exposure levels, staying time, and prevention modes, it may therefore reflect the real exposure to PM₁₀ than OC. By further fitting the four curves of Fig. 5, equations were obtained, which proved a multivariate function relationship rather than a simple linear relationship ($R^2 > 0.90$), which showed greater difference compared to the previous study; most of them presented the exposure-response linearly (Hänninen et al. 2007; Dominici et al. 2002). Our finding suggests that there would be non-linear relationships between the high PM₁₀ exposure and the disease odds (Table 5), which implied that the method of OC might bring "less estimation" of big sandstorm PM₁₀ risk.

Discussions

PM₁₀ is one of the typical pollutants involved with sandstorms; usually, its level is related to the intensity of the sandstorm (Liu et al. 2012). Estimation of PM₁₀ exposure profiles

Table 5 A survey of office men's exposure patterns

		Micro-environment time-activities (h)				
		Nighttime (from 22 o'clock to 7 o'clock the next morning)	Average time of round way between home and workplace	Inside the office	Inside the vehicles	Entertainment, indoor sport, library, or other places
Office men including people working in government, school, etc.	Taking vehicles and other transportation	9	1	8	0.5	5.5
	Walking	9	1.5	8	0	5.5

Table 6 A survey of herbmen’s exposure patterns

Herbmen	Micro-environment time-activities (h)		
	Nighttime (from 22 o’clock to 7 o’clock the next morning)	Working place	Entertainment, indoor sport, library, or other places
	9	8	7

in a precise way has become the priority research area when assessing its health effects. Numerous epidemiological studies indicated that both long- and short-term exposures to atmospheric PM had associations with increases in mortality and morbidity (Zhang et al. 2015; Wong et al. 2016). In the past, fixed stationary monitors’ data were employed as the general spatial distribution and used to reflect the average population exposure level. With the insight into the exposure profiles, data from the fixed monitor stations were thought as poor indicators to average personal exposure as they just reflected the limited spatial levels, whereas population distributed in large-scale geography.

To overcome the limitation, a study came up with a method of weighing the average exposure levels by Eq. (1), which weakness is suspected on reflecting the practical exposure levels of people’s micro-environmental activity patterns.

More and more researches focus on the factors to the total exposure levels, which are decided by people’ activities micro-environmental and time weighed (MEATW). A study reported sorted population by type such as children, the elderly, and individuals with predisposed diseases; cardiovascular and pulmonary diseases had been confirmed different risks to PM, due to exposure patterns’ difference (Chen and Kan 2008; Zeka et al. 2005). To characterize the people’s activity patterns, land-use regression (LUR) models were developed; they can provide long-term air pollution exposure assessment, including various contributing sources, such as diesel generator sets and plant emission. In this model, many related emission sources were taken into account, and were quantified towards prevailing outdoor PM concentrations at different land-use categories regionally. Lately, a separate set of models using “traditional” land use and traffic indicators (e.g., distance from road, area of housing within circular buffers) has been developed to enhance the models (Tang et al. 2013; Sharma 2013). Regretfully, LUR models cannot predict the prevailing

Table 7 A survey of exposure patterns of old men (age > 60) and infants (age < 6)

Old men (age > 60) and infants	Micro-environment time-activities (h)
	Indoors
	24

nature PM originated by strong dust in a large-scale area geographically, because the PM level involved with the dust far beyond the levels of emission sources. In our study, a big sandstorm took place in March 4, 2016, in Inner Mongolia, which could be verified by meteorological data. With the strong wind brewing from the west to the east, the PM₁₀ concentration decayed to the wind’s direction (Fig. 1). ArcGIS was used to construct regional shape files from the originally “dot” data of fixed environmental monitors by kriging. During this strong dust storm, PM levels of the impacted area were found very high (Fig. 2). The PM₁₀ mean concentration distribution map showed outdoor levels ranged from Erliahaote (4387.82 μg/m³) to Xinganmeng (0 μg/m³) spatially (Fig. 2), which was much higher than the previous conclusion reported (Canagaratna et al. 2004).

With the insight into exposure profiles, more and more people paid attention to the practical exposure amount by people’s activity sites and weighed time, since most of the people spend more than 90% of their time indoors. Some modern technique, using a portable PM2.5 analyzer, was equipped with a person to record the detailed PM exposure levels (Long et al. 2010). However, this method is unsuitable to the various types of population in a large-scale region because of its cost. It is urgent to establish a method with better prediction than Eq. (1), which can be used to predict the population’s average exposure level in a big sandstorm spatially. And, it can reflect the people’s daily time-activity patterns and possible exposure behavior comprehensively. Hence, a new equation, Eq. (2), is created in our study by the method of SCMEATW.

Equation (2) is established by two superimposed factors; one is the large-scale PM spatially, and the other is a number of the population’s micro-environmental activity factors reflecting their categorized social features. Compared to Eq. (1), Eq. (2) appears more accurate on evaluating the people’s exposure level, especially in calculating the exposure levels in larger-scale geography.

Our investigation revealed that different to the reference applied in LUR models, people’s exposure activities could be altered by their cognitions in the period of dust storms. Most urban residents tended to spend a majority of their time indoors throughout the strong dust storm. Hence, the PM levels indoors played a significant role on their micro-environmental activity levels. To better understand the different micro-environmental and activities weighed time, we listed the student’s micro-environment activities-time weighed here (Table 4), which suggested that people’s activities time-weighed and the counterpart micro-environments become the key factors to their total exposure amount. In our studies, the outdoor concentration of PM₁₀ reached 4472.88 μg/m³, far beyond that indoors (149.55 μg/m³) or inside vehicles (72.10 μg/m³) (Fig. 3). The difference between Eqs. (1) and (2) was evaluated here. After calculating the

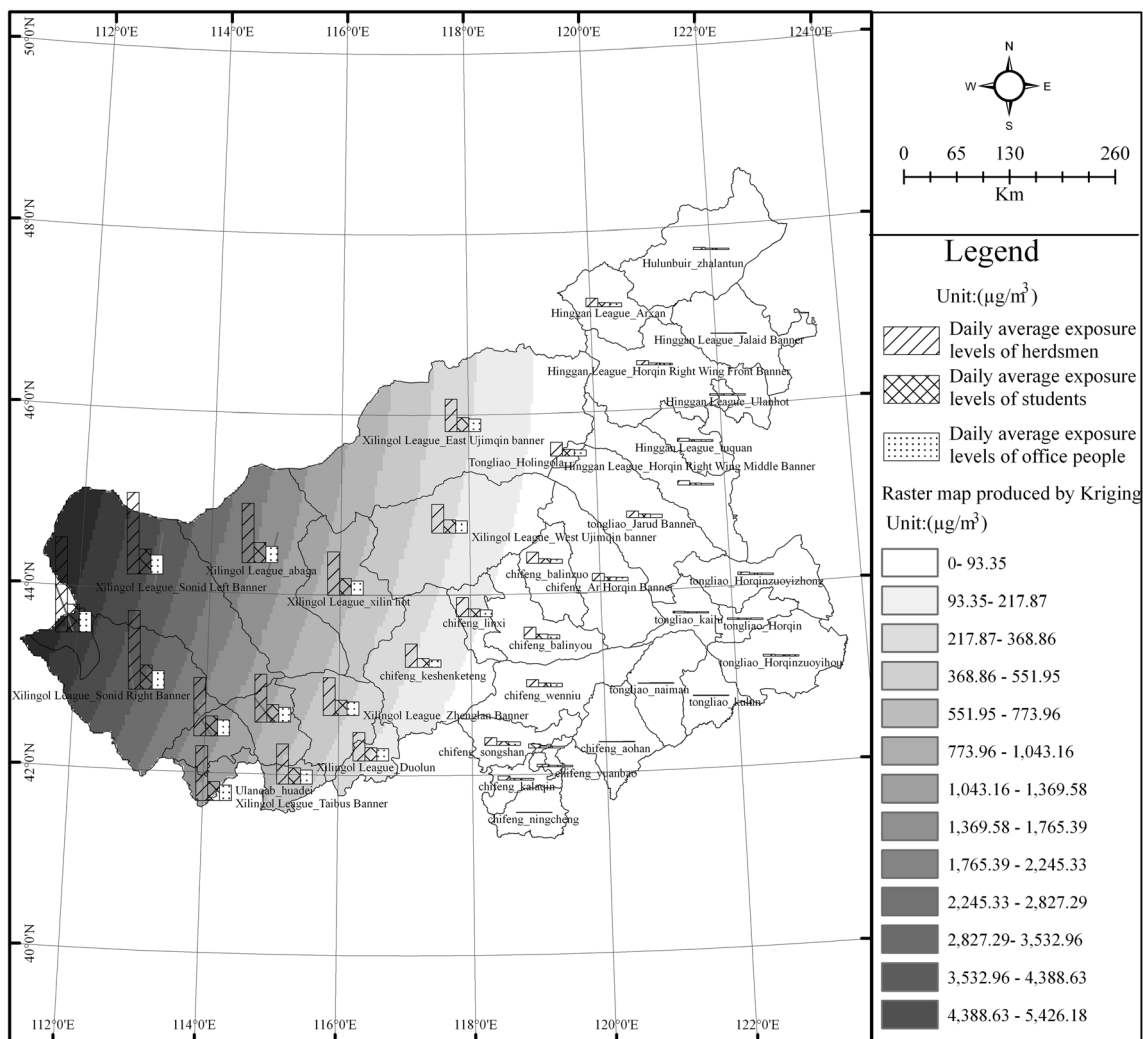
Daily average exposure levels of different population in March 4 ($\mu\text{g}/\text{m}^3$).

Fig. 4 Daily average exposure levels of different types of population in March 4 ($\mu\text{g}/\text{m}^3$)

PM_{10} value of March 4, Erlianhaote, we confirmed the average individual exposure level was $2076.18 \mu\text{g}/\text{m}^3$ by Eq. (1), whereas it was $359.26 \mu\text{g}/\text{m}^3$ by Eq. (2). It suggested that the population's average exposure level of SCMEATW was far below that of the OC. In other words, the risk of PM_{10} exposure reported may be far "less estimated" by previous studies (Vinceti et al. 2012; Gupta et al. 2012).

To support our view, the types of people, including herdsmen, students, and old men, were selected randomly and equipped with the portable real-time monitoring apparatus. The micro-environmental concentration was recorded by a real-time PM recorder, and the results were calculated by Eq. (2). Our finding further provided the quantifiable evidence that the PM_{10} exposure level of each type of population was lower by the method of SCMEATW compared to OC.

An integrated map to account for the population average exposure levels by SCMEATW is drawn here (Fig. 2), which mapped mark levels of OC and SCMEATW simultaneously. It

provided a more detailed picture of the difference of both exposure levels. The degree of shallow dark in Fig. 2 represented the strength of PM_{10} , and the columns mean the population's exposure level from SCMEATW (Fig. 2). It can be seen that the levels of OC are far more than that of SCMEATW in Erlianhaote. The explanation might be that Erlianhaote was a typical city for trading, whereas Xilinhaote was a pasture area where more herdsmen lived who spend much more activity times outdoors during the big sandstorm, which contributed more exposure amount to the average exposure level. Another map was drawn to further ascertain the daily average exposure levels of different types of population (Fig. 4) by SCMEATW. It figured out that within the high PM_{10} outdoor area, the daily average exposure levels of herdsmen appeared far more than that of the students and the office men, all of them marked in Erlianhaote and Xilinhaote. By mapping types of population average exposure levels from SCMEATW (Fig. 4), we could comprehensively

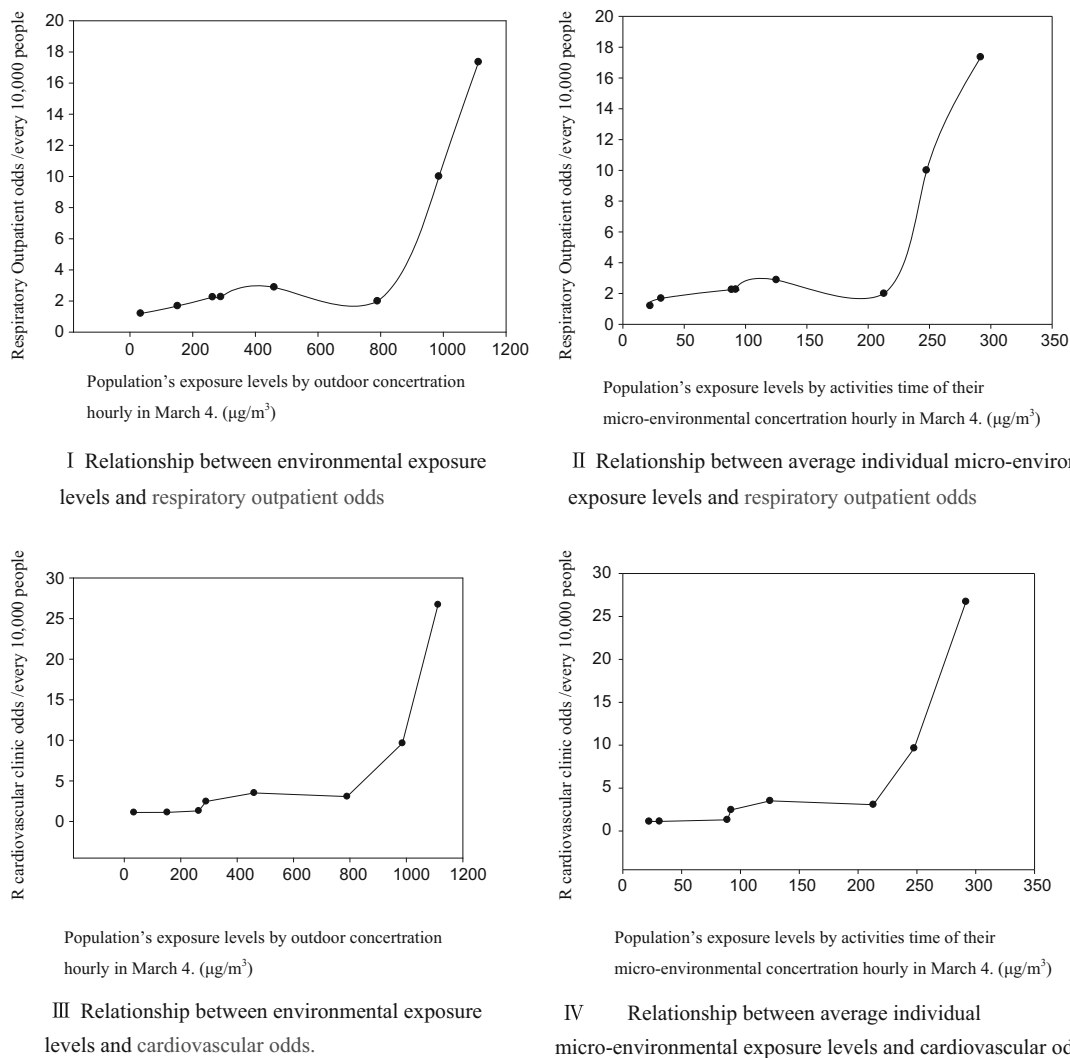


Fig. 5 Relationships between people’s exposure levels and outpatient odds

assess the integrated environmental exposure levels and the individual’s exposure levels in a large-scale region.

Evaluation of the adverse health effects of PM_{10} was very important for protecting human health and establishing pollution control policy. However, the current exposure-effects curves were deduced only by OC (Hänninen et al. 2007; Ziqiang et al. 2007). It would bring “over” estimation or “less” estimation to exposure assessment. In the current study, relationships between respiratory outpatient odds and cardiovascular clinic odds were analyzed with the OC and SCMEATW (hourly average concentration), respectively.

Moreover, the plots in Fig. 5 have the same trend. This seems to indicate that both PCWEL and SCMEATW describe the link between exposure and effect following the same empirical law; there is just a different threshold level, that is, a simple scaling factor. What we can deduce by PWEL is the same as what we can deduce by SCMEATW, and it seems not true that the first is less accurate than the latter (in addition, in statistics, the term “accuracy” has a specific meaning and here it is used improperly).

In our study, both OC and SCMEATW have similar trends to the disease mentioned above (Fig. 5). It showed rather low respiratory outpatient odds in the scope of OC from 100 to $300 \mu\text{g}/\text{m}^3$ (Fig. 5 I), which means the respiratory outpatient odds were less than three every 10,000 people when the outdoor levels were below $300 \mu\text{g}/\text{m}^3$. It also revealed that when the OC concentration was higher than $1000 \mu\text{g}/\text{m}^3$, respiratory outpatient odds appeared to sharply increase. The relationship between cardiovascular clinic odds and OC levels is illustrated as the analogous shape (Fig. 5 III), similar to Fig. 5 II and IV. The increasing relative risk between dust storm and daily respiratory disease has been confirmed by the previous study (Jian 2007). In our study, we did not find the correlation between the risk and the OC within the scope of $300 \mu\text{g}/\text{m}^3$. The explanation was that people would take prevention methods, such as wearing a mask or staying home when the outdoor PM_{10} concentration was higher than $300 \mu\text{g}/\text{m}^3$. When OC was higher than $1000 \mu\text{g}/\text{m}^3$, the people would be exposed to more and more PM even if they had chosen to stay in the

micro-environment buildings. Further analysis revealed that when the average exposure levels of SCMEATW were higher than $250 \mu\text{g}/\text{m}^3$, respiratory outpatient and cardiovascular clinic odds would become sharp. It suggested that the real PM_{10} exposure level exceeding $250 \mu\text{g}/\text{m}^3$ might bring the risk of acute respiratory and cardiovascular clinic odds. The odds by SCMEATW ($250 \mu\text{g}/\text{m}^3$) were far below that of OC ($1000 \mu\text{g}/\text{m}^3$). Our results suggested that less PM_{10} exposure might bring the risk, rather than the exposure of OC.

Conclusions

Examining the validity of exposure metrics used in PM_{10} epidemiologic models had been a key focus of recent exposure assessment. We sought to develop an approach to predict PM_{10} exposure by creating comprehensive factors which include socio-classification exposure, type of personal micro-environmental time-weighted, and regional local-scale outdoor pollution variation. In the current study, a GIS-based PM_{10} environmental dispersion simulation was developed, and socio-categories exposure were probed, combined with the individual micro-environmental activities time-weighted methods, and then, comprehensive individual average exposure levels were obtained in a large spatial region. The method was named as SCMEATW here.

The exposure parameter of this study, which clearly highlights the variety of socio-exposure classification, could be easily accessed by statistical information. This approach might be largely to determine what a given exposure metric represents and to quantify and reduce any potential errors resulting from using these metrics in lieu of Eq. (1). The priority of it includes (1) creating variables for use in GIS modeling of neighborhood levels of outdoor air pollution, (2) enhancing micro-environment time-weighted exposure method by classifying social role, and (3) using social-categorized data available on individual building characteristics to evaluate the regional air pollution individual average exposure level. (4) The estimation of PM_{10} exposure amount by OC might bring less estimation than the SCMEATW. Also, the methodology presented by SCMEATW could be replicated to understand and control the sandstorm risk of different populations in a large-scale area.

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Authors' contributions Hongmei Wang carried out the questionnaire studies and PM exposure assessment, and participated in the drafting of the manuscript. Shihai Lv conceived of the study and contributed ideas in geographical exposure. Zhaoyan Diao participated in the GIS analysis. Baolu Wang carried out the spatial analysis. Caihong Yu helped in the

drafting of the manuscript. All the authors read and approved the final manuscript.

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Compliance with ethical standards

Ethics approval and consent to participate This study has been approved by Erliahaote CDC agency, with the number 201601. All volunteers were administered on the condition that informed consents were signed.

Availability of data and supporting materials section All detail materials were provided in supplement materials. If there is a query, please contact the author for data requests.

Consent for publication Not applicable.

Competing interests The authors declare that they have no competing interests.

Abbreviations GIS, geographic information system; MEATW, micro-environment and activities-time weighed; OC, outdoor concentration; PM_{10} , particle matter 10; SCMEATW, socio-categorized micro-environment activities-time weighed

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