INVESTIGATION OF FINE PARTICULATE POLLUTION IN A COASTAL CITY WITH A MOBILE MONITORING PLATFORM

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ABSTRACT

Spatial and temporal variation of fine particulate pollution in a complex small coastal city, Macau, was investigated by using a mobile air quality monitoring platform. Real-time street level measurements of aerosol size distribution were carried out three times per day by using an on-board wide-range particle spectrometer along a designed route covering the main area of the city for one week. The measured distributions were then transformed into $PM_{2.5}$ mass concentrations for assessment based on an empirical relation estimated from a co-located measurement calibration process. Within this week, the averaged $PM_{2.5}$ mass concentrations of the morning, afternoon, and evening sessions are 51.76 μg m^{-3}, 28.87 μg m^{-3} and 30.77 μg m^{-3}, respectively. By comparing the spatial statistics of the estimated $PM_{2.5}$ concentrations with the US 24-hour primary NAAQS as a reference, a significant probability of exceedance (> 86%) was observed in 1/3 of the monitoring sessions, particularly in the mornings of high traffic volume. Meanwhile, majority of the hotspots were found in the districts of the Macau peninsula. In addition, by performing analysis of the backward trajectories, daily MODIS images, and comparison of the $PM_{2.5}$ patterns of the entire route of three selected measuring sessions during weekdays and weekend, it was observed that long range transport of fine particulates may affect Macau in a larger scale. Therefore, regional land source influence could shadow the local one when the ambient conditions are met.

KEYWORDS: Macau, Mobile monitoring platform, $PM_{2.5}$, Wide-range Particle Spectrometer.

INTRODUCTION

Particulate pollution arising from urbanization is a severe air pollution problem in most megacities and this problem is worth concerning due to its adverse impacts to people and the urban environment (Kan *et al*., 2007; Kim *et al*., 2006; Jacobson and Kaufman, 2006). Therefore, taking actions towards its proper management is necessary and urgent. The process requires many steps. Understanding the current condition of the city is obviously an initial but important one. Usual method of achieving this goal is by reviewing the data collected from the stations of a monitoring network which perform mass concentration measurements of $PM_{2.5}$. However, these stations are normally sparsely distributed. The data recorded at each station can only reveal the situation of its nearby vicinity. This makes it difficult to perform detailed spatial assessment of the particulate pollution for the entire city. Thence, the objective of this study is to conduct an assessment within the Macau Special Administrative Region (SAR), a gaming mecca in the Pearl River Delta (PRD) region of China as a case study by using a mobile monitoring platform (Yao *et al*., 2005; Yao *et al*., 2007; Hu *et al*., 2012; Pirjola *et al*., 2012). Macau is on the western bank of the PRD. It has an area of 29.9 km^2, comprised of the Macau Peninsula 9.3 km^2, the islands of Taipa (7.4 km^2) and Coloane (7.6 km^2) and the reclaimed area COTAI (5.6 km^2) and the reclaimed area COTAI (5.6 km^2). Three bridges connect Macau to Taipa. In previous aerosol studies of Macau, Mok and Hoi (2005) found that the seasonal behaviour of PM_{10} is related

to the Asian monsoons and tropical cyclones can cause PM_{10} episodes during summer. Hoi *et al*. (2008, 2009, 2010) further found through modelling that the daily averaged PM_{10} concentrations in Macau can be varied by its past history, the change of the replenishing air masses, and the rainfall. However, overall assessment of the particulate pollution within this city has not been addressed yet. Therefore, the present study is a timely and important one to fill this gap.

SAMPLING INSTRUMENTS AND METHODOLOGY

The Mobile Air Quality Monitoring Platform (MAP) (Yao *et al*., 2005) leased from the Hong Kong University of Science and Technology was employed to carry out street level measurements of particle size distribution function using a Wide-range Particle Spectrometer (WPS) to cover the main area of Macau in seven consecutive days (Feb.18 to 24, 2009). The WPS used can measure the size-segregated particle number concentrations from 0.01 μm to 10 μm by combining laser light scattering, electrical mobility and condensation particle counting technologies (Liu *et al*., 2010). It is used on MAP instead of a Tapered Element Oscillating Microbalance (TEOM) since the vibration of external sources especially from the moving platform could interfere with the TEOM's operation (Cantrell *et al*., 1996).

Within these seven consecutive days, three times of continuous street level measurements per day (local time: 08:00 AM-10:00 AM, 16:00 PM-18:00 PM, 21:00 PM-23:00 PM) were carried out with MAP along a designed route (length: 45 km) that covers the main areas of Macau as shown in figure 1. Given the small size of Macau, travelling along this route requires about one hour and twenty two minutes on average at an average speed of 32.5 km hr^{-1}. With the sampling interval for the WPS set at 38 seconds, each WPS reading covers about 343 meters of road length on average; i.e. about 1/131 of the total route length. Therefore, this study is the first of its kind that could give a snapshot of the fine particulate pollution for the entire city within a short period of time for systematic comparison. Besides assessing the pollution condition of the whole route, the route is also divided into eight segments (M1 to M8) according to the official district classification of the Macau SAR Government, so that district based assessment could be performed later.
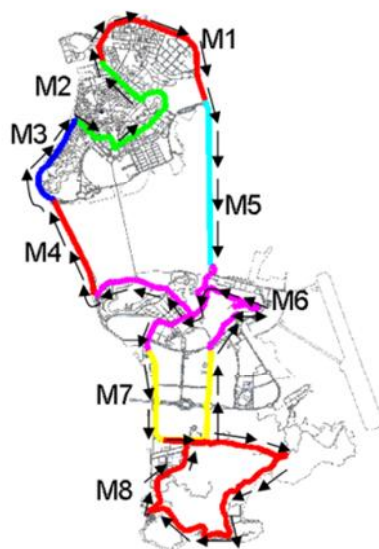

Figure 1. Route and its district classification travelled by MAP

Although using MAP is a good approach for assessing the particulate pollution over the city of Macau within a short period, the aerosol size distributions obtained by the on-board WPS cannot be compared directly with known references for assessment. Since the target values set by the international air quality standards for fine particulate pollution assessment are based on the total mass concentrations of $PM_{2.5}$, transforming the measured aerosol size distribution function into $PM_{2.5}$ mass concentrations for analysis is necessary. This is done with an empirical relationship derived from the co-located measurements of the WPS on MAP and the TEOM at a fixed ambient (Taipa) air quality monitoring station during each overnight period (local time: 11:30 PM – 07:30 AM tomorrow) of the seven studied days. This fixed ambient station is located at the top of the Taipa Grande Hill with an altitude of 159.3 m. It is believed that the aerosol spectrum sampled at this

location is representative of the general ambient condition of the city. Meanwhile, the overnight sampling period is between the evening and the following morning street-level-measurement periods. The record may capture the diurnal variability of the relative humidity as well as the different chemical composition in PM$_{2.5}$ (background value vs. local emissions). Furthermore, the overnight measurements were made daily. The results can also reflect the daily variability of the two mentioned factors due to different replenishing air masses caused by the variation of synoptic scale weather system within the studied period. Procedures of the transformation are explained in the following section.

TRANSFORMATION OF WPS MEASUREMENTS

The WPS can divide the entire size range from 0.01 μm to 10 μm into 67 diameter segments and measure the corresponding particle number concentrations. The discretized aerosol size distribution function n_i is given by:

$$n_i \equiv n(i\Delta \log D) = \frac{N_i}{\Delta \log D}, \; i = 1,...,67 \; (\text{cm}^{-3}) \tag{1}$$

where D and N_i denote the particle diameter and the total particle number concentration of the ith logarithmic diameter segment [$\log D_{i-1}, \log D_i$], respectively. To perform the transformation, it is necessary to estimate the empirical relation between the volume concentrations $V_{t,PM2.5}$ deduced from the WPS measurements and the measured PM$_{2.5}$ mass concentrations $[PM_{2.5}]$. By assuming that all particles are spherical, the total particle volume concentration of the ith diameter segment is given by:

$$V_i \equiv \frac{\pi}{6}D^3_{m,i}N_i = \frac{\pi}{6}D^3_{m,i}n_i\Delta \log D, \; i = 1,...,67 \; (\mu\text{m}^3\,\text{cm}^{-3}) \tag{2}$$

where $D_{m,i}$ denotes the ith mean particle diameter given by $(D_{i-1}+D_i)/2$. Among the 67 segments, segments from 1 to 58 refer to the fine fraction of the respirable particulates (PM$_{2.5}$) and the rest represents the coarse fraction (PM$_{2.5-10}$). The total volume concentration of PM$_{2.5}$ is obtained by summing up the volume concentrations of the first 58 segments:

$$V_{t,PM2.5} = \sum_{i=1}^{58} V_i \; (\mu\text{m}^3\,\text{cm}^{-3}) \tag{3}$$

The ordinary least squares (OLS) linear regression between the measured PM$_{2.5}$ mass concentrations by TEOM and the derived volume concentrations from WPS yields the following equation:

$$[PM_{2.5}] = 1.12V_{t,PM2.5} + 1.75 \tag{4}$$

The slope of 1.12 g cc^{-1} represents the apparent density of PM$_{2.5}$ with the assumption that the density is constant in all diameter segments associated with PM$_{2.5}$. The estimated apparent density is comparable to the range of 1.05 g cc^{-1} to 2.36 g cc^{-1} found from the study of the urban PM$_{2.5}$ at Augsburg, Germany (Pitz *et al.*, 2008). The regression line has an r^2 value of 0.78 and a root-mean-square error (*RMSE*) of 9.08 μg m^{-3}. The uncertainty of the regression may be due to the measurement errors of both instruments, and the significant hygroscopic growth of aerosols during days of high relative humidity (> 80%) (Eichler *et al.*, 2008) as well as the diurnal or daily variation in the chemical composition of PM$_{2.5}$. Since the OLS regression assumes that the modelling error follows a Gaussian distribution with zero mean and its variance is the *RMSE*^{2} according to the central limit theorem, error of the subsequent transformation of the route measurements by Eqn. (4) is assumed to follow the same distribution and variance. This will help to quantify the uncertainty associated with Eqn. (4) in the following discussion.

RESULTS

District-based assessment

To evaluate the severity of the fine particulate pollution of Macau within the seven consecutive days, the rational approach is to compare the estimated PM$_{2.5}$ mass concentrations from the WPS measurements along the route with a target value adopted from a well-known air quality standard. Since there is currently no standard target value of PM$_{2.5}$ designated for real-time or hourly measurements, the value of 35 μg m^{-3} which is the 24-hour primary National Ambient Air Quality Standards (NAAQS) set by the Environmental Protection Agency of the United States (USEPA) for PM$_{2.5}$ is adopted. It is noted that the value chosen here is used mainly for reference, but not for the

actual decision of the standard attainment as the duration of average used for analysing the measurements is no more than two hours even all data of the entire route in each run are considered.

Spatial statistics of the entire route and its eight segments (M1-M8) are studied first to assess the overall condition of the city as well as its district based distribution within the studied period. Table 1 shows their spatial averages of the estimated $PM_{2.5}$ mass concentrations in the morning (Mm) session, the afternoon (Ma) session and the evening (Me) session during Feb. 18 and 24, 2009. Hot spot and clean zone among the eight segments for a given session are identified by the maximum (orange) and the minimum (green) of the segment averages. For the spatial statistics of the entire route, exceedance of the target value 35 µg m^{-3} highlighted in red is observed in about one third of the monitoring sessions. To confirm these exceedances are not due to the statistical uncertainty of transforming the measured aerosol size distribution function into $PM_{2.5}$ mass concentrations by Eqn. (4), the probability of exceedance (PE) defined as the probability that the estimated concentration by Eqn. (4) is higher than 35 µg m^{-3} (the target value) is calculated and shown in Table 1. It was found that all monitoring sessions with exceedance have their PEs higher than 86%. This means that the observed exceedances are very likely to happen. Hence, the fine particulate pollution of Macau was severe during the studied period. Within the sessions of exceedance, 57.1% occurred in the morning. It is believed that this is mainly caused by the morning traffic during the rush hour (08:00AM-09:30AM).

For the district based spatial averages, the $PM_{2.5}$ mass concentration exhibits high spatial variability among districts. Major hotspots are in the Macau peninsula at M1, M2 and M3 taking up about 85.7% of the maximum values among the monitoring sessions. As the Macau peninsula is the older part of the city with a higher population compared to the other two recently developed islands, it has a higher traffic volume, severer traffic congestion, narrower old streets surrounded by dense array of buildings, and more traffic lights that introduce frequent stop-and-go driving patterns. These factors are expected to induce more traffic emissions and adverse dispersion conditions in the Macau peninsula leading to severer pollution condition. On the contrary, most of the clean zones (~90.7% of the monitoring sessions) are in the bridges connecting the Macau peninsula and the Taipa island (M4 and M5), the main roads connecting the Taipa island and the Coloane island (M7), and the Coloane island (M8). This is due to the much lower traffic volumes in M7 and M8 as well as the better dispersion conditions exhibit in all of these districts.

Although the local traffic emission is a plausible leading cause for the observed high $PM_{2.5}$ concentrations, its daily emission pattern should not vary significantly within these seven days; hence this factor alone is not sufficient to explain the observed larger fluctuations of $PM_{2.5}$ mass concentrations between the measurement sessions shown in Table 1. Therefore, another important factor to be considered is the ambient wind condition as it controls the dispersion condition as well as the type of the replenishing air masses being brought to Macau within the studied period. To examine this effect, a whole area assessment is performed next.

Whole area assessment
In order to investigate the influence of the wind condition on the fine particulate pollution of Macau, assessment of the instantaneous $PM_{2.5}$ mass concentrations along the route is performed for three selected cases during weekdays (Feb. 19 and 20) and weekend (Feb. 22), respectively. The wind conditions in Macau are reviewed first. Figure 2 shows the hourly wind velocity vectors recorded at the ambient (Taipa) station over the studied period. It is noted that Macau was prevailed by south-easterly and southerly winds except for Feb. 20. On Feb. 20, there was the passage of a cold front moving south from the mainland to the PRD, which led to the transition of wind directions from southerly in the night-time of Feb. 19 to northerly in the early morning of Feb. 20. Checking the route averaged $PM_{2.5}$ concentration of this period in Table 1, the value increases significantly from 25.82 µg m^{-3} (evening session, Feb. 19) to 74.82 µg m^{-3} (morning session, Feb. 20). To investigate the underlying mechanism, four-day backward trajectories associated with these two periods are generated by the Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPLIT) of the NOAA Air Resources Laboratory (Draxler and Rolph, 2013; Rolph, 2013) to check the possible types of air masses brought to Macau.

Table 1. Spatial averages of the estimated $PM_{2.5}$ mass concentrations (µg m^{-3}) of the entire route and its eight segments during Feb. 18 and 24, 2009; (S = session of measurement; R = route segment where average is taken)

| Date	18/2 Wed			19/2 Thurs			20/2 Fri			21/2 Sat		
S R	Mm	Ma	Me	Mm	Ma	Me	Mm	Ma	Me	Mm	Ma	Me
Entire	34.40	18.71	21.48	22.68	15.49	25.82	74.82	34.93	28.99	30.76	47.11	45.15
PE	47.37	3.64	6.82	8.74	1.58	15.60	100	49.69	25.40	32.03	90.88	86.82
M1	34.38	22.84	15.22	16.77	26.23	24.33	63.02	34.88	28.73	28.06	44.42	47.87
M2	48.13	22.01	32.16	26.69	16.88	44.94	96.93	38.24	34.14	31.46	53.00	59.07
M3	65.22	14.89	31.18	58.62	14.38	46.79		35.18	31.90	42.82	57.01	56.49
M4	31.24	15.22	21.31	18.72	38.47	28.47		34.65	28.49	33.29	34.45	33.14
M5	34.22	18.88	13.28	13.76	15.74	19.38	71.64	34.97	27.40	22.94	39.47	38.21
M6	27.27	17.15	21.49	22.80	13.43	22.23	65.83	33.94	29.37	29.81	41.82	36.00
M7	25.58	17.52	15.86	12.73	11.05	13.27	70.99	32.44	25.04	30.44	42.48	42.23
M8	26.47	15.83	14.80	11.73	10.00	11.47	69.07	31.42	24.56	30.43	52.19	38.54
Date	22/2 Sun			23/2 Mon			24/2 Tue					
S R	Mm	Ma	Me	Mm	Ma	Me	Mm	Ma	Me			
Entire	65.31	27.15	48.00	74.89	26.09	18.44	59.48	32.58	27.48			
PE	99.96	19.36	92.39	100	16.32	3.41	99.65	39.49	20.38			
M1	71.64	40.92	51.53	78.34	48.23	26.77	66.34	34.33	25.81			
M2	62.36	43.10	52.86	82.62	44.73	26.99	74.03	35.65	30.58			
M3	81.66	26.16	55.31	132.34	18.81	17.80	97.81	33.13	27.70			
M4	52.86	16.21	44.78	103.18	12.68	12.37	44.71	36.69	25.08			
M5	59.15	34.08	44.63	62.44	23.80	15.36	77.27	26.32	24.21			
M6	63.42	23.30	46.67	69.90	18.43	18.29	48.34	31.68	24.24			
M7	70.07	21.46	45.06	51.52	9.96	12.52	23.20	34.33	38.54			
M8	64.04	15.48	44.43	51.79	17.36	12.63	45.44	27.64	21.76			
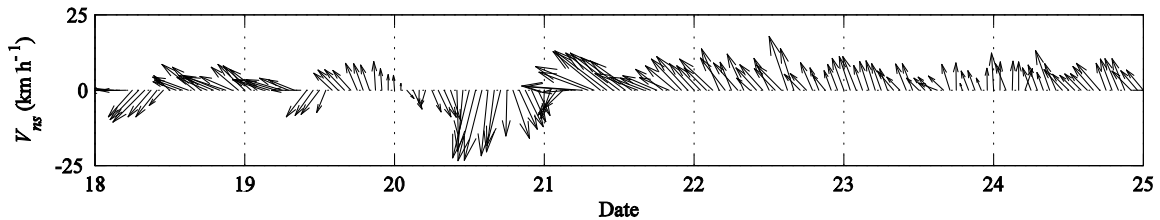
Figure 2. Hourly wind velocity recorded at the ambient (Taipa) station during Feb. 18 and 24, 2009; V_{ns} is the north-south component of the wind velocity vector (↓Northerly wind, ↑Southerly wind, ←Easterly wind, →Westerly wind)

Figure 3a shows two four-day backward trajectories arriving Macau with UTC starting time of 13:00 (local time: 21:00) on Feb. 19. The two trajectories are with starting height of 500 m (line color: red) and 1000 m (line color: blue), respectively. According to the nearby vertical profile of the potential temperature recorded at the King's Park of Hong Kong (about 60 km from the Taipa station in Macau) as well as the time histories of the normalized backscattering signal of LIDAR at Yuen Long and Sha Tau Kok of Hong Kong, the boundary layer thickness at UTC 12:00 (local time 20:00) on Feb. 19 was between 400 m and 500 m. Therefore, the lower level trajectory (500 m) serves to reveal the transport of the boundary layer, while the upper one (1000 m) represents the movement of the residual layer. Results show that the 1000 m trajectory originated at the west end of the northern Pacific Ocean. Hence, clean and humid air masses could be transported to Macau at the upper level. On the other hand, the 500 m trajectory originated from Northern China. It passed through Korea,
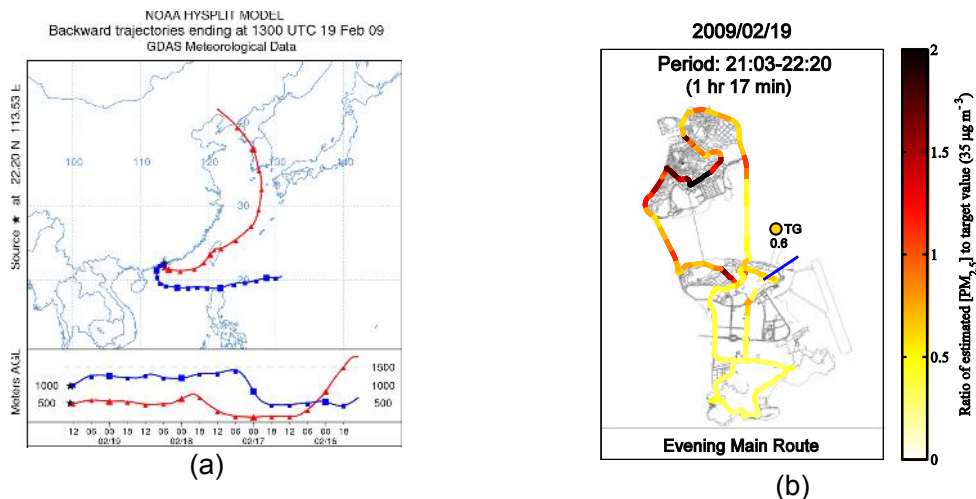
Figure 3. (a) Four-day backward trajectories arriving Macau at 13:00 UTC (local time: 21:00) Feb.19, 2009, (b) Spatial plot of the ratios of estimated PM$_{2.5}$ mass concentrations to the target value of NAAQS in the evening session of Feb.19, 2009

the East China Sea, Taiwan and entered the South China Sea before it was bent towards Macau by the south-easterly and southerly winds. When the air masses passed southern Taiwan at 00:00 UTC (local time: 08:00) on Feb. 18, the PM$_{2.5}$ mass concentration recorded at the Sinying station of Yun-Chia-Nan there was 16 μg m^{-3}. It implies that the PM$_{2.5}$ concentration in the replenishing air masses before reaching Macau should be low. Figure 3b shows the spatial plot of the ratio of estimated PM$_{2.5}$ concentration to the target value (35 μg m^{-3}) for the evening session of Feb. 19. The ratio at the ambient Taipa station (TG) is also shown in the figure for reference. Since there are some outliers of abnormally high PM$_{2.5}$ mass concentrations recorded in the route, they would distort the contrast of the spatial distribution if plotted to scale. An upper limit of 2 is set for the color bar. Any ratio that is larger than 2 is plotted with the same color as the upper limit. Initial observation is that the ambient Taipa station and its vicinity have consistent colors, meaning that the estimated PM$_{2.5}$ mass concentrations from the WPS measurements are close to those recorded by TEOM. This further validates the performance of the empirical relation estimated by Eqn. (4). Examining the color distribution of the route in Figure 3b, clear differences between districts are seen. The hot spots (M2 and M3) are at the center of the Macau peninsula up north, while the clean districts are at the COTAI reclaimed area (M7) and the rural Coloane Island (M8) down south. Because the replenishing air masses brought to Macau then were relatively clean as indicated by the backward trajectories shown in Figure 3a, these differences are believed due mainly to the distributions of the local traffics at the time; i.e. busy in the city center and quiet in the rural areas at night.

As for the sudden increase of the route averaged PM$_{2.5}$ concentration in the morning session of Feb. 20 from the lower value in the evening session of Feb. 19 mentioned earlier, the four-day backward trajectories arriving Macau with starting time of 00:00 UTC (local time 08:00) on Feb. 20 and the spatial plot of the ratio of estimated PM$_{2.5}$ concentration to the target value (35 μg m^{-3}) for the morning session of Feb. 20 in Figure 4 provide some explanations.

The two four-day backward trajectories in Figure 4a use the same starting heights of 500 m (line color: red) and 1000 m (line color: blue) as those in Figure 3a due to similar boundary layer thickness. These two trajectories originated from similar locations with the 1000 m one at Korea and the 500 m one at the north end of the East China Sea. Their earlier passages were similar passing through the central part of the East China Sea and reaching the south-eastern coast of China and the South China Sea at 00:00 UTC 18 Feb 2009, respectively. Their last two day passages before reaching Macau were more complicated especially for the 500 m trajectory. The lower trajectory stayed close to the coastline of China. It was bent north to enter the inland of Guangdong province when it was near Macau but only to make a sharp southerly turn shortly after to reach Macau at 00:00 UTC (local time 08:00) 20 Feb 2009. Spatial plot of the ratio of estimated PM$_{2.5}$ concentration to the target value for the morning session on Feb. 20 in Figure 4b shows exceedance of the target value over the entire route with weak spatial variability. (Note that the data of segments M3 and M4
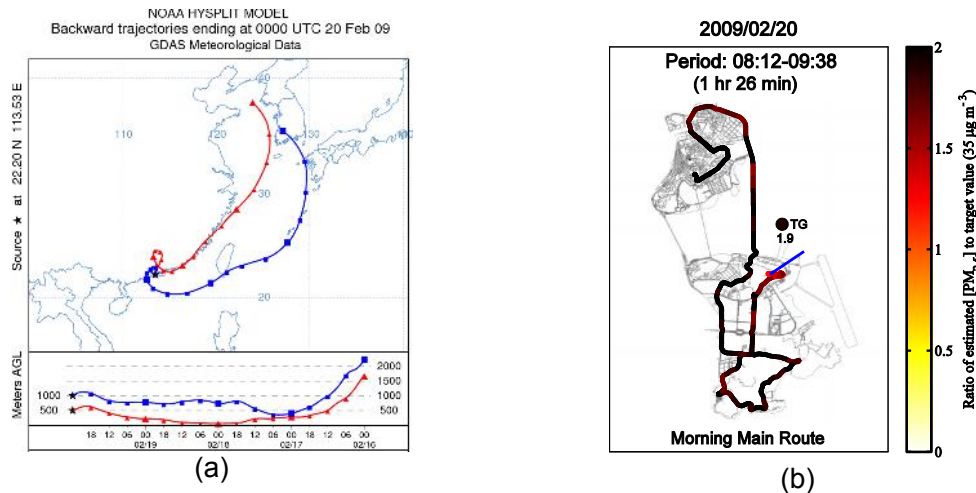
(a)   (b)

Figure 4. (a) Four-day backward trajectories arriving Macau at 00:00 UTC (local time: 08:00) Feb. 20, 2009, (b) Spatial plot of the ratios of estimated $PM_{2.5}$ mass concentrations to the target value of NAAQS in the morning session of Feb. 20, 2009

are missing due to malfunction of the equipment in that morning session.) Therefore, it is obvious that this rapid rise over the whole area of Macau could not be caused by local traffic emissions alone. It must be from the effect of a larger scale phenomenon. Examination of the complicated backward trajectories coupled with the aerosol patterns in the air masses of the region up to the time of the day and the day before is needed.

Using the Giovanni (Acker and Leptoukh, 2007) online data system developed and maintained by the NASA GES DISC, two daily MODIS images of the aerosol optical depth (AOD) at 550 nm in Asia from Terra between 00:00 UTC 18 Feb. 2009 and 00:00 UTC 20 Feb. 2009 were produced in Figure 5. Figure 5a shows that the AODs of the region passed by both trajectories (Figure 4a) on Feb. 18 were low (< 0.5), meaning that the $PM_{2.5}$ mass concentrations in the replenishing air masses may still be low till 00:00 UTC (local time: 08:00) Feb. 19. Figure 5b shows that the south-eastern China including the PRD region was covered by an aerosol plume with the AOD near the upper scale of the color bar between 00:00 UTC 19 Feb. and 00:00 UTC 20 Feb. Referencing to the boomerang-like segment of the 500 m backward trajectory closing in to Macau in Figure 4a, the return path indicated that air masses originally left Macau moving north started to be brought back by the northerly wind due to the arrival of a cold front at the north end of the Guangdong province at 06:00 UTC 19 Feb. Therefore, the large aerosol plume shown in Figure 5b would be brought to Macau leading to the up surge of the $PM_{2.5}$ concentrations over the whole city that shadowed the effect of the local traffic emissions as shown in Figure 4b.
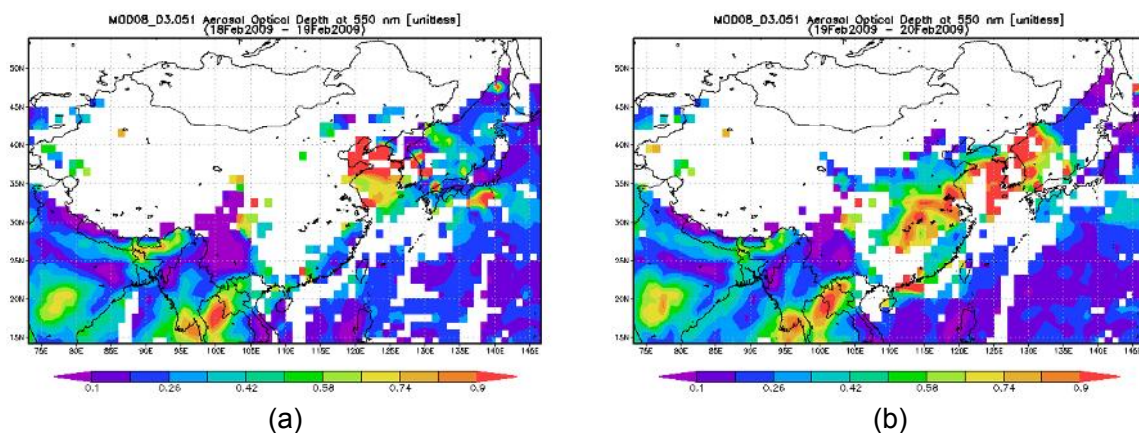

(a)   (b)

Figure 5. MODIS images of aerosol optical depth at 550 nm in Asia from Terra (a) 00:00 UTC (local time: 08:00) Feb. 18, 2009 – 00:00 UTC Feb. 19, 2009, (b) 00:00 UTC (local time: 08:00) Feb. 19, 2009 – 00:00 UTC Feb. 20, 2009

From Table 1, it is noted that four out of the six measurement sessions in the weekend of Feb. 21 and 22 have their route PM$_{2.5}$ concentration averages exceeding the target value with the morning session of Feb. 22 being the highest. Prevailing wind condition during that period shown in Figure 2 indicates mainly south-easterly to southerly blowing from the sea. Therefore, it is interesting to investigate why the sea breeze could cause the observed high PM$_{2.5}$ concentration. Figure 6a shows two four-day backward trajectories arriving Macau with UTC starting time of 00:00 (local time: 08:00) on Feb. 22. As the estimated mixing height was within 250 and 500 m then, the same starting heights as the two previous cases are adopted here. The 1000 m trajectory is found originated at the region of the South China Sea, west of the Philippines, where the observed AODs (< 0.26) on Feb. 18 was low (see Figure 5a). Therefore, clean and humid air masses may be transported to Macau at the upper level. On the other hand, the 500 m trajectory originated at the north end of the East China Sea and circulated around there for some time before moving south. The observed AODs (>0.9) of that area on Feb. 18 to Feb. 19 was high (See Figure 5a,b), so that the replenishing air masses coming from there in the boundary layer may be particle-enriched. As these polluted air masses headed south and reached the east side of Taiwan at 18:00 UTC Feb. 20, the AODs observed there were between 0.58 and 0.82 as shown in Figure 7, indicating the presence of moderately polluted plumes. When these air masses continued to move south into the South China Sea and then turned north to reach Macau in the morning of Feb. 22, they may bring some of the particulates picked up along their journey to Macau.
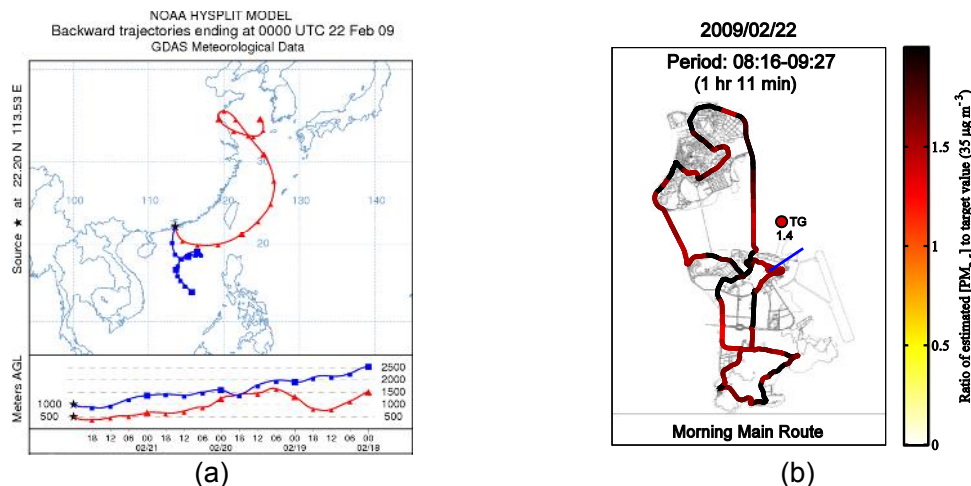

(a)   (b)

Figure 6. (a) Four-day backward trajectories arriving Macau at 00:00 UTC (local time: 08:00) Feb. 22, 2009, (b) Spatial plot of the ratios of estimated PM$_{2.5}$ mass concentrations to the target value of NAAQS in the morning session of Feb. 22, 2009
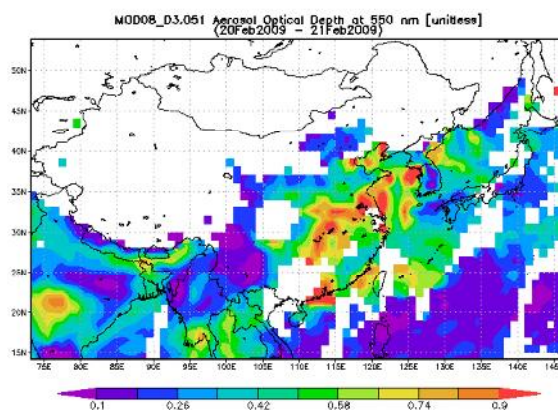

Figure 7. MODIS images of aerosol optical depth at 550 nm in Asia from Terra 00:00 UTC (local time: 08:00) Feb. 20, 2009 – 00:00 UTC Feb. 21, 2009

If they did, the effect would be in larger scale. Figure 6b shows the spatial plot of the ratio of estimated PM$_{2.5}$ mass concentration to the target value in the morning session of Feb. 22. The PM$_{2.5}$ concentrations along the whole route were high with some spatial variability. This confirms that the main contribution to the pollution should be from the regional sources rather than the local ones. In addition, the increase in the averaged PM$_{2.5}$ mass concentration of the entire route from the evening session of Feb. 21 to the morning session of Feb. 22 shown in Table 1 is only 20.16 μg m^{-3}. It suggests that the increase could be caused by the moderately polluted plumes that the air masses passed by the region near Taiwan earlier.

CONCLUSIONS

In this study, the Mobile Air Quality Monitoring Platform was used to perform assessment of the street-level fine particulate pollution along a route designed to cover the main area of Macau during Feb. 18 to 24 of 2009. Based on the district based assessment of the estimated PM$_{2.5}$ mass concentrations within seven consecutive days, it was found that Macau had a significant probability of exceedance (> 86%) of the target value (primary standard of NAAQS) within 1/3 of the studied period; hence concluding the severity of fine particulate pollution. In addition, the spatial variability of the local traffic emissions and the dispersion conditions were concluded to be the plausible causes of the hot spots and clean zones of PM$_{2.5}$ observed along the route. Based on the analysis of the backward trajectories, the daily MODIS images and the whole area assessment of the instantaneous PM$_{2.5}$ mass concentrations, it was concluded that the long-range transport of aerosols from mainland may lead to the rapid rise in the background concentrations over the entire area which shadow the pollution from local sources.

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