Spatial and Temporal Variations of Gaseous and Particulate Pollutants in Six Sites in Tibet, China, during 2016–2017

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ABSTRACT

Long-term air quality data with high temporal and spatial resolutions are necessary to understand some processes influencing air quality and corresponding environmental and health effects. In this study, spatiotemporal variations of PM_{2.5}, PM₁₀, SO₂, NO₂, CO, and O₃ were investigated over a one-year period (June 2016–May 2017) at six sites of the Tibetan Plateau (TP). The annual mean concentrations of PM_{2.5} in all cities except Nagchu were below the Grade II standard (35 µg m⁻³), and the values in Nagri and Nyingchi were even less than the Grade I standard (15 µg m⁻³). PM₁₀ concentrations showed similar distribution pattern with PM_{2.5}. Evident seasonal variations of PM_{2.5}, PM₁₀, SO₂, NO₂, and CO concentrations were observed, with the highest seasonal average value being in winter followed by fall, spring, and summer, in descending order. By contrast, the 8-h O₃ concentration showed an opposite seasonal variation because the O₃ depended on lots of factors such as stratospheric incursions, weather conditions, and intensity of solar radiation. The diurnal trends of PM_{2.5}, PM₁₀, SO₂, NO₂, and CO concentrations in study region generally showed a flat “W” shape with two peaks occurring around noon (10:00–12:00) and midnight (21:00–23:00); these peaks were found to be affected by emission sources and weather conditions. However, the O₃ concentration trends did not significantly differ among the six regions, with the maximum concentration being in the afternoon. In sum, cities on the TP showed slightly higher pollution levels in regions affected by anthropogenic activities such as Lhasa and Nagchu, whereas other cities showed good air quality. Beside long-range transport pollutants from surrounding regions, local emissions (e.g., biomass burning, religious activities) also contributed much to the atmospheric pollutants. This study provides a basis for the formulation of future urban air pollution control measures on the TP.

Keywords: PM_{2.5}; Ozone; Air pollution; Distribution; Tibetan Plateau.

INTRODUCTION

As the world's most populous developing country, China has experienced severe air pollution with considerable increases of air pollutants owing to rapid economic development and increasing urbanization in recent decades (Chan and Yao, 2008; Guo *et al.*, 2014; Du and Li, 2016; Lin *et al.*, 2018; Zhao *et al.*, 2018). The Asian Development Bank reported that 70% of the most polluted cities in the world are situated in China (Bapna, 2012). On the basis of the Global Burden of Disease Study, 4.2 million deaths

have been caused by air pollution in 2015, among which 1.6 million individuals were from China (Hu *et al.*, 2014; Forouzanfar *et al.*, 2016; Landrigan, 2016). One study reported that ambient PM_{2.5} accounts for 15.5% of all the causes of death in China (Song *et al.*, 2017a). The elevated PM_{2.5} and ozone concentration significantly affects human health and threatens sustainable development of China (Liu *et al.*, 2017b; Zhao *et al.*, 2018). Therefore, these air quality data are requisite to understand pollution status and assess the human health risks of China (Wang *et al.*, 2014).

The Chinese Ministry of Environmental Protection started to release hourly averaged concentrations of PM_{2.5}, PM₁₀, SO₂, NO₂, CO, and O₃ recorded from the monitoring stations situated in over hundred cities in China from Jan 2013. The characteristics of these six pollutants and their influence factors have been widely studied in terms of released monitoring data (Hu *et al.*, 2014; Wang *et al.*,

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2014; Huang *et al.*, 2015; Ma and Jia, 2016; Zhang *et al.*, 2016; Guan *et al.*, 2017; He *et al.*, 2017; Song *et al.*, 2017b; Yin *et al.*, 2017a; Zhou *et al.*, 2017; Zhao *et al.*, 2018). These researches have revealed that the pollutant concentrations in cold months are much higher than those in summer; this is in contrast to the case of ozone. Some studies suggested that the frequent heavy haze-fog episodes in China are mainly caused by large amount of air pollutant emissions during the cold season (Wang *et al.*, 2013; Tan *et al.*, 2016; Yin *et al.*, 2017a). Other studies have demonstrated that weather conditions also play an important role in affecting the pollutants diffusion. In addition, high mountains like Qinghai-Tibet Plateau are considered to be barrier which can block pollutants transporting from South and East Asia (Cao *et al.*, 2015; Jia *et al.*, 2015; Zheng *et al.*, 2015; Xu *et al.*, 2016; Ding *et al.*, 2017; Yin *et al.*, 2017a). However, most of the previous studies simply analyzed the characteristics of pollutants in central and eastern China (Chai *et al.*, 2014; Hu *et al.*, 2014; Wang *et al.*, 2014; Xie *et al.*, 2015; Zhao *et al.*, 2016; He *et al.*, 2017; Wang *et al.*, 2018), whereas little has been reported in western China especially the Tibetan Plateau (TP) which is located in large-scale complex terrain.

The TP is one of the world's least scientifically studied regions regarding air pollutant concentration, variation, transportation, and health risk assessment. Pollutant emissions from the TP itself are relatively less compared with densely populated and industrialized parts of East of China and South Asia (Chen *et al.*, 2018a). Local residents in most parts of the TP depend on traditional agriculture and animal husbandry for their livelihood, whereas the proportion of industry accounts for only 8% of the GDP of this huge area (<http://www.tibet.stats.gov.cn/>). Therefore, the TP is known as a remote background region worldwide. However, numerous recent researches have pointed out

that air pollutants emitted from South Asia can reach this remote region by long-range transport (Cong *et al.*, 2015; Lüthi *et al.*, 2015; Kang *et al.*, 2016; Li *et al.*, 2016a; Chen *et al.*, 2018b; Wu *et al.*, 2018). In addition, local anthropogenic emissions such as yak dung burning and religious incense burning also contributes significantly to the atmospheric environment (Kang *et al.*, 2009; Gong *et al.*, 2011; Li *et al.*, 2012; Chen *et al.*, 2015; Xiao *et al.*, 2015; Li *et al.*, 2016a; Chen *et al.*, 2018a).

This study presents the results of six criteria air pollutants in Lhasa, Ngari, Qamdo, Nyingchi, Nagchu, and Shigatse during 2016–2017. The main objectives are (1) to investigate the concentrations of the six criteria pollutants in the TP, and (2) to identify their seasonal variations and the relationships among the pollutants.

METHODS AND DATA

Site Information

Six sites, namely, Lhasa, Ngari, Qamdo, Nyingchi, Nagchu, and Shigatse, were chosen in this study (Fig. 1 and Table 1). Ngari, located on the border of China and Kashmir, India, is controlled by the seasonal shifting of atmospheric circulations, with Indian monsoon controlling in summer, whereas the westerlies predominated in other seasons (Gong *et al.*, 2015). The region is covered by bare soil or grassland. The annual average temperature is approximately 2°C and annual precipitation was approximately 90 mm for the period 2010–2013. About 80% of rainfall occurs in the summer (June–September). Qamdo, located in the eastern of the TP, with an average elevation of 3500 m, has a semi-arid monsoon climate, which is dry and cold in winter and moist and moderately hot in summer. The annual average temperature is 7.6°C and precipitation is 400–600 mm. Nyingchi city, located downstream of the

Fig. 1. Geographical map and locations of the cities in the TP.

Table 1. Detailed information of study regions on the TP.

City	Latitude/degree	Longitude/degree	Population/million	GDP/Billion
Lhasa	29°39.16'	91°10.32'	0.90	42.50
Ngari	32°30.09'	80°06.34'	0.09	2.89
Qamdo	31°08.46'	97°10.33'	0.73	5.49
Nyingchi	29°38.96'	94°21.72'	0.23	7.24
Nagchu	31°28.58'	92°03.08'	0.50	10.62
Shigatse	29°16.03'	88°52.83'	0.75	12.45

YarlungZangbo River, with an average elevation of 3100 m, has an annual average temperature of 8.7°C and precipitation of 650 mm. Lhasa is the capital of Tibet autonomous region. It is a famous historic tourist city and currently undergoing rapid urbanization and tourism development (Li and Wang, 2014; Li *et al.*, 2016b; Li *et al.*, 2018). The temperature ranges from −5.7 to 21.2°C (average: 9.0°C), and the relative humidity range 7%–75% with an average of 38.7% (Wan *et al.*, 2016). The annual average precipitation is approximately 400 mm with most occurring during summer due to influence of Indian monsoon. Nagchu, located in the central of the TP, has an average temperature of −2°C and an annual mean precipitation of approximately 420 mm. Shigatse, known as the Tibet's barn, is the second largest city in the TP. It has an elevation of approximately 3800 m and a population of about 720,000. Shigatse contributes approximately half of the total agricultural output of the Tibet Autonomous Region (Yang *et al.*, 2016). The annual mean precipitation is approximately 433 mm, and the average temperature and wind speed are 2.5°C and 1.43 m s^{−1} in dry season and 14.3°C and 1.74 m s^{−1} in wet season, respectively (Yang *et al.*, 2016).

Air Quality Data

In order to understand the characteristics of these six pollutants in cities of the TP, real-time hourly averaged monitoring data of PM_{2.5}, PM₁₀, SO₂, NO₂, CO, and O₃ from June 2016 to May 2017 were obtained from the China National Environmental Monitoring Center (CNEMC) (<http://113.108.142.147:20035/emcpublish/>). Detailed information about the data obtaining were described by previous researches (Hu *et al.*, 2014; Wang *et al.*, 2014; Zhao *et al.*, 2018). Briefly, automated monitoring systems were set at each site to monitor the ambient concentration of these six criteria pollutants according to the China Environmental Protection Standards HJ 193-2013 (<http://www.es.org.cn/download/2013/7-12/2627-1.pdf>) and HJ 655-2013 (<http://www.es.org.cn/download/2013/7-12/2626-1.pdf>). Two methods including micro-oscillating balance and β-absorption are used for measuring particulate matter (PM_{2.5} and PM₁₀) concentrations; and chemiluminescence method, ultra-violet (UV) fluorescence method, and UV-spectrophotometry method are used for NO₂, SO₂, and O₃ concentrations, respectively. For CO, both the nondispersive infrared absorption method and the gas filter correlation-infrared absorption method are used. Before publish these hourly averaged data, a sanity check was conducted at each station to remove problematic data

points. The 8-h O₃ concentrations were calculated when there were valid data for at least 6 h for every 8 h during that day, whereas the mean daily concentrations for other five pollutants were calculated only when there were valid data for more than 20 h (Hu *et al.*, 2014; Wang *et al.*, 2014; Zhao *et al.*, 2018).

RESULTS AND DISCUSSION

Overview of Air Pollutants

The annual average concentrations of the six criteria pollutants in six cities of the TP were given in Table 2 and Fig. 1. The PM_{2.5} concentrations ranged 13.4–48.7 µg m^{−3}, with Nagchu and Nyingchi having the highest and lowest concentrations, respectively. Lhasa, Shigatse, and Qamdo showed medium values of approximately 25 µg m^{−3}. PM_{2.5} concentrations in all cities except Nagchu were below the Grade II standard (35 µg m^{−3}), and the values in Nagri and Nyingchi were even less than the Grade I standard (15 µg m^{−3}). PM₁₀ concentrations exhibited a similar distribution pattern, with high values occurring in Nagchu and Lhasa, which exceeded the Grade II standard (70 µg m^{−3}) and low values in Nagri and Nyingchi, which were below the Grade I standard (40 µg m^{−3}). Nagchu had the highest SO₂ concentrations (34.9 ± 10.8 ppb), which exceeded the Grade II standard (21 ppb), whereas other five cities had similar SO₂ concentrations of approximately 10 ppb. Lhasa had the highest NO₂ concentrations, followed by Nagchu, both exceeding the Grade II standard (20 ppb), whereas Shigatse, Qamdo, and Nagri had similar values of approximately 16 ppb and Nyingchi had the lowest concentration (8.31 ppb). The annual average CO concentrations ranged from 408 ppb (Nyingchi) to 1283 ppb (Nagchu). Nagchu, Lhasa, and Qamdo had higher values than those of the other three cities. The annual average 8-h O₃ concentrations showed similar values in all cities except Nagchu. Spatial distributions of these six pollutants indicated that regional high concentrations were mainly concentrated on densely populated cities of the TP with higher GDP (Table 1).

The PM_{2.5}/PM₁₀ ratios were different among these six sites with the highest and the lowest values observed in Nagchu and Lhasa, respectively (Table 2). Shigatse was also found to have higher PM_{2.5}/PM₁₀ ratio than 52% which are comparable with those in some other regions such as North China Plain, west of Sichuan and Xi'an (Wang *et al.*, 2014; Song *et al.*, 2017b; Zhao *et al.*, 2018). However, the values in other three cities were significantly lower than those obtained in urban cities such as Beijing, Shanghai,

Table 2. Annual average concentrations of the six criteria pollutants in six cities of the TP.

	PM _{2.5} μg m ⁻³	PM ₁₀ μg m ⁻³	SO ₂ ppb	NO ₂ ppb	CO ppb	8hO ₃ ppb	PM _{2.5} /PM ₁₀ %
Lhasa	33.1 ± 20.2	87.3 ± 69.4	11.8 ± 5.7	31.2 ± 21.6	985 ± 734	65.9 ± 30.7	37.9
Shigatse	26.3 ± 20.3	50.2 ± 39.8	16.6 ± 5.3	16.6 ± 13.3	484 ± 218	68.8 ± 24.9	52.4
Ngari	13.9 ± 11.8	33.6 ± 30.3	14.7 ± 9.32	16.6 ± 13.6	565 ± 201	54.9 ± 17.5	41.5
Nagchu	48.7 ± 46.4	89.8 ± 72.4	34.9 ± 10.8	24.1 ± 16.9	1283 ± 763	38.7 ± 15.3	54.3
Qamdo	20.9 ± 16.9	47.9 ± 41.2	10.1 ± 2.87	17.9 ± 18.3	888 ± 391	62.1 ± 30.0	43.8
Nyingchi	13.4 ± 7.7	28.6 ± 20.8	9.2 ± 2.4	8.31 ± 5.9	408 ± 139	66.7 ± 22.9	46.7
North China Plain ^a	84.5 ± 9.6	138.9 ± 16.8	39.0 ± 8.5	49.7 ± 1.6	1330	54.9 ± 0.3	56
YRD ^a	53.7 ± 5.6	83.9 ± 7.1	20.9 ± 2.7	39.5 ± 1.1	900	63.2 ± 1.3	63
West of Sichuan ^b	24.3 ± 5.5	45.0 ± 12.7	23.6 ± 10	23.7 ± 8.7	1000 ± 400	76.0 ± 16.1	54
Beijing ^c	87 ± 67	109 ± 62	9 ± 8	25 ± 11	1068 ± 668	45 ± 27	79.8
Shanghai ^c	56 ± 41	80 ± 47	7 ± 5	20 ± 9	704 ± 256	48 ± 21	70
Guangzhou ^c	52 ± 28	72 ± 35	7 ± 3	24 ± 10	821 ± 185	45 ± 24	72.2
Xi'an ^c	97 ± 83	181 ± 127	14 ± 10	25 ± 9	1569 ± 752	37 ± 20	53.6

Note YRD: Yangtze River Delta; ^a reported data from Jan 2014 to Dec 2016 (Song *et al.*, 2017b); ^b reported data from Jan 2015 to Feb 2017 (Zhao *et al.*, 2018); ^c reported data from Mar 2013 to Feb 2014 (Wang *et al.*, 2014).

and Guangzhou (Wang *et al.*, 2014). In general, the average PM_{2.5}/PM₁₀ ratio was approximately 46.1% in the six sites, which is significantly lower than the ratios obtained from the literature, namely, 65% in China before 2012 (Zhou *et al.*, 2016; Xu *et al.*, 2017), 58% in 31 Chinese provincial capital cities during 2014–2015 (He *et al.*, 2017), and 56% in 190 Chinese cities during 2013–2014 (Zhang and Cao, 2015). The case may be in connection with the fact that Tibetan cities are easily affected by dust events such as floating dust, dust storms, and blowing dust, leading to a obvious increase in PM_{2.5–10} (particle size: 2.5–10 μm) mass concentrations. Previous studies has proved that mineral dust is one of the main aerosol compositions in some regions of the TP (Decesari *et al.*, 2010; Zhang *et al.*, 2001; Kang *et al.*, 2016). And analysis of dust conducted at surrounding deserts (e.g., the Taklimakan, Gobi, and southwest Asian deserts) has also provided evidence for atmospheric particulates transporting on the TP (Huang *et al.*, 2007; Liu *et al.*, 2008; Xia *et al.*, 2008).

As shown in Table 2, the concentrations of six pollutants on the TP are compared with those in other regions in China. The annual average PM_{2.5} concentrations were only close to those in the Sichuan Basin (Zhao *et al.*, 2018) and considerably lower than those in the NCP, YRD, and in cities of other typically heavily polluted regions (Wang *et al.*, 2014; Song *et al.*, 2017a, b). However, the mean PM₁₀ concentrations of Lhasa and Nagchu were comparable to those of cities such as Shanghai and Guangzhou. Moreover, the annual SO₂ concentrations of all cities except Nagchu were lower than those in the NCP and were close to those of the YRD and Sichuan Basin. In addition, concentrations of NO₂ and CO in Lhasa and Nagchu were comparable to those in typical polluted cities. The annual mean O₃ concentrations in all six cities were slightly higher than those in other regions of China. These analyses indicate that the air in Lhasa and Nagchu is affected by anthropogenic activities to some extent, whereas other sites show background values.

Temporal Variations

To better understand the air pollution status on the TP, the monthly averaged pollutant concentrations are shown in Fig. 2. PM_{2.5} concentrations in the study region exhibited considerable temporal variability, with the highest being in November and December and the lowest during June to August. The concentrations in other months were approximately the same. The elevated PM_{2.5} concentration in cold season might due to increased fuel burning for residential heating and cooking. In addition, unfavorable weather condition such as few precipitation and slow winds is unfit for air pollutants dilution and dispersion (Chai *et al.*, 2014; Wang *et al.*, 2014). Usually, industrial and vehicle emissions play an important part in some cities for high PM_{2.5} concentrations. For example, two previous studies reported that iron and steel manufacturing contributed 11% to PM_{2.5} concentration in Chengdu during 2011 (Tao *et al.*, 2014) and industrial emissions account for 27% in Wuhan during 2011–2012 (Cheng *et al.*, 2012). However, the proportion of industry accounts for only 8% of the GDP of the TP, thus biomass burning and religious activities as well as weather condition might be the main reason for PM_{2.5} variation.

PM₁₀ concentrations in Lhasa, Shigatse, and Qamdo showed similar seasonal variations as those of PM_{2.5} concentrations. However, PM₁₀ concentrations were found to be the highest in fall in Nagchu and were did not differ significantly among the four seasons in Ngari and Nyingchi (Fig. 2). SO₂, NO₂, and CO also showed similar seasonal variations, with the highest and lowest values occurred in winter and summer, respectively. The seasonal pattern was found to be a typical feature in East Asia (Wang *et al.*, 2014; Zhao *et al.*, 2018). These seasonal variations were mainly affected by the meteorological conditions and emission sources. Usually, stagnant weather conditions occurred more frequently in winter which characterized by shallow mixing layers, few precipitation and slow winds. This can trap the pollutants emitted by local emissions or transported from other regions and elevating their concentrations near

Fig. 2. Mean annual variations of the monthly averages for six criteria air pollutant concentrations in cities of the TP.

the surface (Tai *et al.*, 2010; Wang *et al.*, 2014). Emission source is another important factor influencing the seasonal distributions of pollutants. Previous studies have reported that pollutants emitted from IGP can be transported to the TP (Ji *et al.*, 2015; Li *et al.*, 2016a; Chen *et al.*, 2017; Yang *et al.*, 2018). For example, Yang *et al.* (2018) simulated the origin of anthropogenic black carbon transported to the TP, which showed that South Asia contributed 40–80% and 10–50% of surface black carbon in the non-monsoon and monsoon seasons, respectively. Whereas anthropogenic black carbon from eastern China accounted for less than 10% in the non-monsoon season but can be up to 50% in the monsoon season for the northeastern TP. Besides long-range transport pollutants, local emissions such as yak dung combustion also contributed part of pollutants throughout the TP (Chen *et al.*, 2015; Li *et al.*, 2016a). Along with fast development of China during last decades and the setup of Qinghai-Tibet Railway at 2006, the Tibetan Autonomous Region experienced intensively urbanization process, so

that fossil combustion had intensively influenced the atmosphere of its urban area (Li *et al.*, 2018). Research based on carbon isotope also provided direct evidence that local biomass burning are important to atmospheric pollution on the TP (Li *et al.*, 2016a). This is further supported by previous researches based on regional climate-atmospheric chemistry model and positive matrix factorization receptor model. For example, Yang *et al.* (2019) reported the contribution proportions of various emission sources to $PM_{2.5}$ in western China. The results showed that residential sector was the largest contributor to the $PM_{2.5}$ concentrations with a contributions ratio of 56.2%, while the transportation and industrial sectors contributed 14.3% and 17.6%, respectively, in cities of the TP. In addition, the particle phase PAHs sources were quantified using the PMF model in Lhasa city and the results also revealed that biomass burning from local residents was the main source (48.4%) followed by vehicle emissions and coal combustion (Chen *et al.*, 2018a).

Ozone concentration in urban regions is largely affected by local weather condition, large-scale circulation, and various emission sources (Shu *et al.*, 2016; Li *et al.*, 2017; Kim *et al.*, 2018). Using the factor separation approach, Li *et al.* (2017) suggested that fossil fuel consumption contributed most in O₃ formation and is the major causes of severe O₃ pollution in eastern China. Furthermore, complex topography also significantly impacts O₃ distributions (Kang *et al.*, 2012). However, the effects of emissions and weather condition on O₃ concentration have not been sufficiently studied in cities of the TP (Zheng *et al.*, 1998; Cui *et al.*, 2015). The seasonal variation of surface O₃ is influenced by many factors including stratospheric intrusion, long-range transport air masses, local vertical mixing, and even deposition (Li *et al.*, 2016c; Wang *et al.*, 2017; Yin *et al.*, 2017b; Zhao *et al.*, 2018). In this study, the 8-h O₃ concentration showed an opposite seasonal variation to

other pollutants with the highest and the lowest values occurred in late spring-early summer and winter, respectively (Fig. 2). On the TP, the largest stratospheric incursions usually occurred in spring and the planetary boundary layer height is higher at same period which facilitated the impact of downward transport from the stratosphere to surface of these sites. In addition, the late spring to early summer period has more intense solar radiation because the monsoon leads to increased cloudiness in summer. The increased solar radiation promotes the photochemical production of surface O₃ in such periods. In winter and fall, the shortwave radiation is weaker than that in other seasons, thus cause relatively low level of O₃.

Fig. 3 showed the hourly average concentrations of six pollutants. The trends of PM_{2.5}, PM₁₀, SO₂, NO₂, and CO concentrations generally showed a flat “W” shape on the TP with two valleys occurred approximately in the early

Fig. 3. Mean diurnal variations of the hourly averages of six criteria air pollutants in cities of the TP.

morning and the late afternoon (~16:00), respectively. In the early morning, reduced anthropogenic activities and pollutant deposition might be the main reason for low pollutant concentrations; whereas relatively high planetary boundary layer height is conducive to the dispersion and dilution of air pollutants in the late afternoon (Tie *et al.*, 2007; Zhao *et al.*, 2018). Correspondingly, two peaks occurred at noon (10:00–12:00) and night (21:00–23:00), respectively, when the planetary boundary layer height was low and human activity was high, which are conducive to the formation and concentration of pollutants. This pattern differs from those in eastern cities (e.g., Beijing), where have peak pollutant concentrations at 20:00 pm. The time difference between eastern cities and the study region might be the reason for two variation patterns. Notably, the daytime PM_{2.5} concentrations were somewhat lower than those during nighttime. It seems that substantially enhanced local emissions (e.g., religious activities, biomass burning for heating and cooking) after sunset cause this diurnal variation of PM_{2.5} concentrations on the TP (Li *et al.*, 2018).

In the present study, it was observed that the O₃ concentrations did not show considerable differences among the six regions; the maximum concentration was in the afternoon (Fig. 3). Wind speed and planetary boundary layer height are generally regarded as the main factors influencing the diurnal cycle of surface O₃. Previous studies have reported that high levels of surface O₃ were associated with high wind speeds and high mixing heights on the TP. In addition, local photochemical production may also contribute to the higher concentration of O₃ in the daytime (Tang *et al.*, 2002; Yin *et al.*, 2017b). Furthermore, Temperature can influence O₃ production by accelerating the chemical reaction rate and increasing the VOCs (e.g., isoprene) emission (Coates *et al.*, 2016), thus O₃ increases with temperature (Abeleira and Farmer, 2017). On the TP, O₃ concentration showed same diurnal variation with other studies conducted at Nam Co, Dangxiong, and Lhasa (Ran

et al., 2014; Lin *et al.*, 2015; Yin *et al.*, 2017b). However, surface O₃ at NCO-P and Waliguan showed different patterns because thermal circulation and mountain-valley breeze were the most influential factors in two regions respectively (Cristofanelli *et al.*, 2010; Xue *et al.*, 2011).

Correlations between Air Pollutants

The Pearson correlation coefficients (R) between pollutants were calculated for each of the six cities (Table 3). Over the 1-year period, PM_{2.5} was positively correlated with PM₁₀, CO, SO₂, and NO₂ in all six cities, especially in Lhasa and Nyingchi ($R > 0.5$), thus suggesting their common sources from biomass (e.g., yak dung, woods, crop straw) burning and fossil fuel combustion such as vehicle emission. For Lhasa city, high mountains situate at its south and north sides making difficult for pollutants to diffuse when atmosphere is relatively stable, thus causing high correlations among PM_{2.5} and other pollutants (Li *et al.*, 2018). Nyingchi covered mainly by alpine forest, therefore, biogenic emissions, local woods burning for cooking and heating, and vehicle consumption may be essential sources of PM and gas pollutants. Positive correlations with slightly weaker R values between PM_{2.5} and other pollutants were observed in other cities, which might imply influence of dust or weather condition. For example, Ngari is located in a place with relatively open geomorphological setting and was classified as barren region according to MODIS land cover classification (Liu *et al.*, 2017a). Relatively weak correlations among these pollutants implied a disturbance of PM masses from dust impact (Liu *et al.*, 2017a). Previous studies have reported frequent dust plumes in the lower atmosphere in the western TP which can possibly impact the distribution of aerosol masses of TP (Huang *et al.*, 2007).

In this study, O₃ was negatively correlated with the other pollutants with low ($-0.25 < R < 0$) to moderate ($-0.5 \leq R \leq -0.25$) correlation coefficients. O₃ can be affected by lots

Table 3. Correlations of pollutants in six cities of the TP based on annual data during 2016–2017.

	PM ₁₀	SO ₂	NO ₂	CO	8hO ₃	PM ₁₀	SO ₂	NO ₂	CO	8hO ₃
Nagchu						Lhasa				
PM _{2.5}	0.45	0.52	0.62	0.76	−0.25	0.85	0.71	0.76	0.78	−0.49
PM ₁₀		0.48	0.53	0.51	−0.33		0.69	0.84	0.80	−0.45
SO ₂			0.43	0.51	−0.24			0.65	0.81	−0.46
NO ₂				0.54	−0.28				0.79	−0.49
CO					−0.21					−0.45
Shigatse						Qamdo				
PM _{2.5}	0.78	0.37	0.49	0.54	−0.41	0.65	0.40	0.47	0.42	−0.33
PM ₁₀		0.34	0.44	0.52	−0.46		0.36	0.39	0.49	−0.22
SO ₂			0.34	0.45	−0.27			0.27	0.39	−0.32
NO ₂				0.44	−0.32				0.57	−0.30
CO					−0.34					−0.34
Ngari						Nyingchi				
PM _{2.5}	0.55	0.47	0.41	0.56	−0.22	0.53	0.58	0.67	0.65	−0.11
PM ₁₀		0.39	0.30	0.36	−0.15		0.44	0.46	0.50	−0.14
SO ₂			0.23	0.53	−0.11			0.40	0.46	−0.21
NO ₂				0.37	−0.26				0.40	−0.11
CO					−0.23					−0.18

of factors (Zhang *et al.*, 2015; Derwent *et al.*, 2016; Yin *et al.*, 2017b; Gong *et al.*, 2018), thus it is difficult to identify the exact impact factor here. However, previous studies reported that in the northern TP, horizontal and vertical wind transports were considered as major contributors to surface O_3 (Shen *et al.*, 2014). Whereas titration of O_3 by NO_x as well as the differences in altitude and meteorology such as photochemistry are main factors affecting surface O_3 in the central TP (Ran *et al.*, 2014). In addition, frequent stratospheric intrusions were recorded in all seasons except spring along the southern ridge of the Himalaya, which might be the major factors (Cristofanelli *et al.*, 2010). Therefore, surface O_3 on TP may dominate by mixed processes involving photochemical reactions, vertical mixing and downward transport of stratospheric air mass which caused different correlations with other pollutants.

CONCLUSION

This study analyzed the spatial and temporal variations of $PM_{2.5}$, PM_{10} , SO_2 , NO_2 , CO, and O_3 observed in six cities on the TP from June 2016 to May 2017. This was done to gain a deep understanding of the pollution levels of different pollutants, evaluate the attainment of air quality standards in various cities, and mark the seasonal variation of major pollutants. High concentrations of $PM_{2.5}$, PM_{10} , SO_2 , NO_2 , and CO were observed in Nagchu and Lhasa, especially during winter, indicating a strong contribution of anthropogenic activities. Beside long-range transport pollutants from surrounding regions, local emissions (e.g., biomass burning, religious activities) also contributed much to the atmospheric pollutants in the study region. However, pollutants in other cities, especially in Nagri and Nyingchi, met the newly revised ambient air quality standards (Grade I), indicating that even though some cities were affected by anthropogenic emissions, the air conditions in most regions were good and still can be looked as background sites. Seasonal variations of all pollutants except O_3 were observed, with the highest concentrations in winter followed by fall, spring, and summer, in descending order. Weather conditions and emission sources are main factors influencing the seasonal variation of these pollutants. However, opposite O_3 variation was observation with other pollutants due to the combined influence of stratospheric intrusion, solar radiation and weather conditions. The diurnal trends of $PM_{2.5}$, PM_{10} , SO_2 , NO_2 , and CO concentrations in the TP generally exhibited two peaks around noon and midnight, whereas O_3 concentrations were similar among the six regions, with the maximum in the afternoon. Positive correlations were observed between $PM_{2.5}$ and other pollutants (e.g., PM_{10} , SO_2 , NO_2 , and CO), indicating that these pollutants might have common sources or experience similar chemical process. However, surface O_3 exhibited negative correlations with other pollutants because of combined influences on it.

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