Reducing air pollution increases the local diurnal temperature range: A case study of Lanzhou, China

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Abstract

Lanzhou is one of the largest heavy industry cities in northwestern China. The city has carried out massive air pollution-control programmes since 2012. As a result, the concentrations of air pollutants in Lanzhou have decreased. In order to examine the effects of air pollution-control programmes on air temperature, the differences in air temperatures between Lanzhou and Yuzhong (a small county adjacent to Lanzhou) and their change between 2009–2011 (P1) and 2013–2015 (P2) were calculated. The results showed that the maximum (minimum) temperature difference significantly increased (decreased) by 0.32°C (0.40°C) in winter (summer) between P1 and P2, indicating an increase (decrease) of the maximum (minimum) temperature in winter (summer) in Lanzhou caused by the reduction in air pollution. Therefore, the diurnal temperature range in Lanzhou increased by 0.50°C in summer and 0.22°C in winter during P2 compared with P1. The increase in the maximum temperature in winter and the decrease in the minimum temperature in summer are supported by a decrease in mean air temperature at night and by an increase of mean air temperature in daytime in winter and summer during P2 compared with P1. The increase in temperature in daytime may be ascribed to more absorption of solar radiation at the surface. The decrease in temperature at night in winter is caused by increasing light rainfall. The decrease in temperature at night during winter may be related to more loss of surface heat through long wave radiation.

KEYWORDS

aerosols, air pollution control, diurnal temperature range, maximum temperature, mean temperature, minimum temperature

1 | INTRODUCTION

Air pollution mainly refers to emissions of particulate matters, sulfur oxides, nitrogen oxides and volatile organic compounds caused by natural factors and human activities (Zheng et al., 2015; He et al., 2017). Air pollution not only harms human health severely (Song et al., 2019) but also causes changes in local meteorological...
factors such as air temperature and light rainfall through aerosols (Qian et al., 2009, 2011; Yang et al., 2013). The aerosols produced by air pollution affect surface air temperature directly by reflecting solar and long wave radiation (direct effect) (Coakley et al., 1983; Charlson and Heintzenberg, 1995). In the meantime, as a kind of cloud condensation nuclei (CCN), aerosols can change the albedo of clouds (the first indirect effect) (Twomey, 1977; Penner et al., 2004) and suppress precipitation through a positive feedback loop via the aerosol–cloud–precipitation interaction (the second indirect effect) (Albrecht, 1989; Rosenfeld et al., 2008).

Many studies have examined the influence of air pollution caused by human beings on meteorological factors (e.g. Twomey, 1977; Givati and Rosenfeld, 2004; Qian et al., 2009, 2011; Bollasina et al., 2011; Li et al., 2011; Yang et al., 2013). Some examined the influence of human-induced aerosols on meteorological factors with modeling approaches (Chen et al., 2013, 2018, 2019; Dong and Zhou, 2014; Chen and Dong, 2019; Zhang et al., 2019). What is more, there are relatively fewer studies on the influence of air pollution through observation data. The latest research based on observation indicate that air pollution modulates urban heat island intensity through a cooling effect in daytime and by a weak warming effect at night, and thus reduces the diurnal temperature range (DTR) (Zheng et al., 2018; Yang et al., 2020a, 2020b). However, air pollution has different effects on daytime urban heat island intensity in different seasons, reducing (increasing) the urban heat island intensity in summer (winter) (Han et al., 2020). The challenge of these studies through observation data is to detect air pollution effect from substantial natural climate variability. Travis et al. (2002) studied the effects of the disappearance of condensation trails on the DTR when all US commercial aircraft had been grounded for three days after September 11, 2001. They analysed the difference between the DTR during the three days and the average DTR over the past 30 years (1971–2000) and found an increase of 1.1°C in the DTR during the three days, indicating a possible influence of air pollution emissions on the DTR. It is obvious that observational analysis is helpful to learn the influence of air pollution on local meteorological factors and supports the conclusion of modeling results.

The present paper studies the possible influence of air pollution on local air temperature based on in-situ air temperature at meteorological stations. Lanzhou is one of the largest heavy industry cities in northwest China, with massive pollutant emissions during recent decades (Gong et al., 2017). Since 2012, however, Lanzhou has carried out a series of huge air pollution-control programmes (Lanzhou Ecology and Environment Bureau, 2012a, 2012b, 2012c). As a result, air pollution in Lanzhou has been significantly decreased, which is a typical event regarding the effect of human activities on the atmosphere. Therefore, whether there is a possible influence of air pollution reduction on local temperature such as maximum air temperature ($T_{\text{max}}$), minimum air temperature ($T_{\text{min}}$), diurnal temperature range (DTR) and mean temperature ($T_{\text{mean}}$) was examined. Besides, there have been many studies carried out in eastern China (Wu et al., 2017; Chen et al., 2018; Yang et al., 2020b), yet studies in western China are limited. Thus, the present study can serve as a typical supplement for the influence of air pollution on meteorological factors in western China using observation data.

The paper is organized as follows. Section 2 describes the data used and method employed. Section 3 measures changes in the $T_{\text{max}}$, $T_{\text{min}}$, DTR and $T_{\text{mean}}$ caused by air pollution reduction for the four seasons. Section 4 discusses possible mechanisms for the variations in temperature caused by the air pollution reduction. Finally, a summary is provided in Section 5.

2 | DATA AND METHOD

2.1 | Study area

Lanzhou, the capital city of Gansu province, is located in northwest China (Figure 1), with an average elevation of 1,520 masl. It is located in a semi-arid region with limited annual precipitation (327 mm), and its annual mean temperature is 10.3°C. Lanzhou is located in an east–west narrow river valley, where is more prone to static weather because of the blocking effects of the southern and northern hills surrounding it (Gong et al., 2017). The frequency of static weather is up to about 81% for all days of the year (Lei et al., 2000). Therefore, temperature inversion occurs frequently, which is not helpful for the dispersion of air pollution. What is worse, pollutant emissions in the air from heavy industry is a serious concern in Lanzhou. High atmospheric stability and massive pollutant emissions jointly lead to serious air pollution problem in the city.

To highlight the changes in air temperature in Lanzhou caused by pollution reduction, Yuzhong county, which is about 35.4 km from Lanzhou, was analysed as a reference (Figure 1). It is located in the southeast of Lanzhou, with an average elevation of 1874.4 masl. The permanent populations of Lanzhou and Yuzhong are 2.68 million and 0.44 million in 2018, respectively (Lanzhou Municipal Bureau of Statistics, 2018). The concentration of air pollution is much lower in Yuzhong because it has fewer industries and a smaller population. Therefore, there is a large gap in the social and economic levels between the two places.
2.2 | Data and method

The air pollution data in Lanzhou were obtained from the Air Quality Bulletin (Lanzhou Ecology and Environment Bureau, 2015), including dust fall quantity, inhalable particulate matter, concentration of sulfur dioxide (SO_2) and nitrogen dioxide (NO_2), from 2002 to 2016. The meteorological data in Lanzhou and Yuzhong were provided by the Gansu Meteorological Agency for the period 2009–2015, and both stations did not relocate during the study period. Hourly air temperatures at 2 masl were used in annual and diurnal analyses. Hourly near-surface air pressure and dewpoint temperature were used to calculate hourly specific humidity. Daily precipitation, hourly precipitation, 6 hourly low cloud cover and hourly specific humidity are analysed below. Hourly precipitation is only available for Lanzhou, and low cloud cover only has records at 08:00, 1400 and 2000 hr (Beijing time) during the period 2009–2013. The analysis filtered out a few records (< 1%), so that only records for Lanzhou and Yuzhong simultaneously were retained (> 99%). The \( T_{\text{max}} \), \( T_{\text{mean}} \), DTR and \( T_{\text{min}} \) were analysed. The \( T_{\text{max}} \) (\( T_{\text{min}} \)) is the highest (lowest) temperature of 24 observed records every day. The DTR is calculated as: \( T_{\text{max}} - T_{\text{min}} \). The \( T_{\text{mean}} \) is the average of \( T_{\text{max}} + T_{\text{min}} \) in a day. Moreover, in order to describe atmospheric humidity change, specific humidities at both Lanzhou and Yuzhong stations were calculated according to the formulas in WMO (2006).

Lanzhou began air pollution-control programmes in 2012 (Lanzhou Ecology and Environment Bureau, 2012a, 2012b, 2012c). Therefore, the periods 2009–2011 (P1) and 2013–2015 (P2) are defined as high and low pollution, respectively. Air temperature differences between Lanzhou and Yuzhong stations during P1 and P2, respectively, were first calculated. By using temperature difference between the two stations, the influence of background climate change on air temperature fluctuation at Lanzhou station was minimized. It was hypothesized that the influences of large-scale atmospheric circulation on Lanzhou and Yuzhong are similar because of the short distance between them (around 35.4 km). The air temperature difference between P1 and P2 was then compared. The change in the air temperature differences during two periods may reveal the influence of air pollution-control programmes on air temperature in Lanzhou. During this calculation, it was assumed that systematic bias, such as topographical condition, elevation and urbanization, changed weakly over the period 2009–2015 and could be removed by a comparison of air temperature difference between the two periods. Following this method, the differences in \( T_{\text{mean}} \), \( T_{\text{max}} \), \( T_{\text{min}} \) and DTR of the two places were first calculated for two periods, and then the change in the difference in these temperature variables between the two periods was obtained. Moreover, for the purpose of removing the influence of precipitation on air temperature change, the air temperature difference between the two places was calculated by using data for non-rainy days and then the difference between P1 and P2 was then compared.

In the study, a \( t \)-test was applied to judge the significance of the changes in temperature and specific humidity between P1 and P2. A Chi-square test and Wilcoxon's rank test were used for precipitation and low cloud, respectively. The studies were conducted for four seasons, that is, spring (March–May), summer (June–August),
autumn (September–November) and winter (December–February of the following year) and for four times per day, that is, 2:00, 8:00, 14:00 and 20:00 hr (Beijing time).

3 | RESULTS

3.1 | Changes in the concentrations of pollutants

Figure 2 shows the variations of the concentrations of SO$_2$, NO$_2$, inhalable particles and dust deposition quantity in Lanzhou for the period 2002–2016. Except for NO$_2$ concentration, all pollutants had decreasing trends during 2002–2016. Because Lanzhou has experienced since 2012 a massive air pollution-control programme to reduce pollutant emissions (Lanzhou Ecology and Environment Bureau, 2012a, 2012b, 2012c), the concentration of pollutants between the periods 2002–2011 and 2013–2016 was compared. Compared with 2002–2011, the average concentration of SO$_2$, inhalable particles and dust fall quantity decreased by 60.43% (0.026 mg·m$^{-3}$), 16.93% (0.027 mg·m$^{-3}$) and 18.78% (3.9475 t·km$^{-2}$) in 2013–2016, respectively. The results show that the pollutant concentrations in Lanzhou reduced obviously after 2012 because of the massive air pollution-control programmes.

3.2 | Changes in the air temperature difference between the two periods

3.2.1 | Annual and seasonal changes in the differences in air temperature

Seasonal changes in air temperature difference between the two periods were first analysed (Figure 3). Compared with the P1 period, the $T_{\text{max}}$ difference increased in autumn (0.28°C) and winter (0.32°C) during P2, significant at the 99% confidence level. The $T_{\text{min}}$ difference decreased largely in summer by > 0.40°C in P2 compared with P1, also significant at the 99% confidence level. As a result, the DTR difference increased in summer (0.50°C) and autumn (0.40°C), significantly at the 99% confidence level. In the meantime, the $T_{\text{mean}}$ difference showed a decrease of 0.16°C in summer and an increase by 0.20°C in winter, both of which were significant at the 95% and 99% significant confidence levels, respectively. The significant changes in seasonal air temperature difference determine the annual changes in air temperature difference. At an annual timescale, the $T_{\text{max}}$ difference increased by 0.16°C (significant at the 99% confidence level) and the $T_{\text{min}}$ difference decreased by 0.10°C in P2 compared with P1. Accordingly, the annual DTR difference increased by 0.25°C in P2 compared with P1, significantly at the 99% confidence level. However, the annual $T_{\text{mean}}$ difference changed weakly from P1 to P2.

In order to remove the effects of precipitation change on air temperature difference, the changes in air temperature difference for non-rainy days between the two periods was studied (Supporting Information Figure S1). The results from non-rainy data resemble those from data including rainy data. The $T_{\text{max}}$ difference increased in autumn (0.31°C) and winter (0.35°C) and the $T_{\text{min}}$ difference decreased in summer (0.32°C), both of which were significant at the 95% confidence level. The DTR difference increased in summer (0.50°C), autumn (0.33°C) and winter (0.30°C). The results of the DTR difference in summer and autumn were significant at the 95% confidence level. Because of opposite changes in the $T_{\text{max}}$ difference and the $T_{\text{min}}$ difference in summer and autumn, the $T_{\text{mean}}$ difference weakly changed in summer and autumn. However, due to consistent changes in the $T_{\text{max}}$ difference and the $T_{\text{min}}$ difference in winter, the $T_{\text{mean}}$ difference in winter increased by 0.20°C, significantly at
the 99% confidence level. At the annual time scale, the annual $T_{\text{max}}$ difference increased by 0.17°C and the annual $T_{\text{min}}$ difference decreased by 0.08°C. Therefore, the annual $T_{\text{mean}}$ difference increased by 0.24°C, significantly at the 95% confidence level. However, the annual $T_{\text{mean}}$ difference weakly changed because of opposite changes in both the annual $T_{\text{max}}$ difference and annual $T_{\text{min}}$ difference. In general, whether or not precipitation effects are considered for air temperature difference, there is an increase in the $T_{\text{max}}$ in autumn and winter, with a peak in winter and a decrease in the $T_{\text{min}}$ in summer. The air temperature differences in summer and winter is discussed in detail at a diurnal time scale in the following sections.

3.2.2 Diurnal changes in the difference in air temperature

Figure 4 shows the diurnal changes in air temperature difference in summer and winter. In summer, the $T_{\text{mean}}$ difference decreased significantly at 2:00 and 20:00 hr by 0.43°C and 0.49°C, respectively, and increased significantly at 8:00 hr by 0.19°C and insignificantly at 14:00 hr by 0.12°C (Figure 4a). When data in rainy days were excluded (Supporting Information Figure S2a), the $T_{\text{mean}}$ difference showed an increase in daytime by 0.17–0.33°C and a decrease of 0.65–0.71°C at night (significant at the 99% confidence level except at 14:00 hr). The decrease in the $T_{\text{mean}}$ difference at night (2:00 and 20:00 hr) and the increase in the $T_{\text{mean}}$ difference in daytime (8:00 and 14:00 hr) were consistent with the decrease in the $T_{\text{min}}$ difference and the increase in the $T_{\text{max}}$ difference in summer, respectively. As depicted in Figure 4b, the $T_{\text{mean}}$ difference in winter showed an increase by 0.31°C at 14:00 hr (significant at the 95% confidence level) and a decrease of 0.15°C at 20:00 hr. The results derived from non-rainy data showed an increase of 0.31°C at 14:00 hr and a decrease of 0.28°C at 20:00 hr, both of which were significant at the 95% confidence level (Supporting Information Figure S2b). In sum, whatever in summer or winter, precipitation may dampen the increase in the $T_{\text{mean}}$ difference in daytime and strengthen the decrease in the $T_{\text{mean}}$ difference at night.

The study indicates that the air temperature difference between Lanzhou and Yuzhong increased in daytime (8:00 and 14:00 hr) and decreased at night (2:00 and 20:00 hr), especially in summer during P2 compared with P1, implying both a warming and a cooling effect of air pollution reduction on air temperature in daytime and at night, respectively. The increase in air temperature in daytime may be related to the direct effect (Coakley...
et al., 1983; Charlson and Heintzenberg, 1995) of atmospheric aerosols. The decrease in aerosol concentration caused by air pollution reduction could decrease the scattering and increase the absorption of solar radiation at the surface. Hence, increasing short wave radiation received by the ground during the day warms the atmosphere (Solomon et al., 2007). But the cooling effect of air pollution reduction at night might be more complex since the main heat source is not the short wave radiation, and the possible mechanism is discussed in the following section.

4 | POSSIBLE MECHANISM FOR A DECREASE IN AIR TEMPERATURE AT NIGHT

Precipitation amount and frequency

Change in air temperature at night is partly influenced by precipitation (Gong et al., 2017). Figure 5 shows changes in the hourly amount and frequency of precipitation in Lanzhou in summer during P1 and P2. There is a large difference in the diurnal variation of precipitation amount and frequency between P1 and P2. The precipitation amount and frequency were higher from early morning to noon during P1, with a peak at 8:00 and 12:00 hr for precipitation frequency (7.97%) and at 10:00 hr for precipitation amount (0.13 mm), respectively. However, the higher amount and frequency of precipitation during P2 moved toward the night, with a peak at 18:00 hr for precipitation frequency (9.78%) and at 21:00 hr for precipitation amount (0.26 mm). This implies that the increase in precipitation and frequency at night may play a role in the cooling effect of air pollution reduction at night in summer.

Precipitation frequency according to grades of rain between P1 and P2 was further compared (Figure 6). It showed increases at all grades in Lanzhou during P2 compared with P1, of which light rainfall frequency (0.1–0.9 mm day⁻¹⁻¹) increased significantly by 7.25% in P2 compared with P1 (Figure 6a). As for Yuzhong, however,
a change of precipitation frequencies at each grade is not significant (Figure 6b). Figure 7 shows the hourly frequency of light rainfall (0.1–0.9 mm) during the summer in Lanzhou. The frequency of light rainfall increased from 16:00 to 5:00 hr during P2 compared with P1, with a peak at 1:00 hr (6.88%). To sum up, the increase of precipitation at night in Lanzhou is mainly due to the increase of light rainfall during P2, resulting in a cooler air temperature at the surface. In the circumstance of low water vapour content in the atmosphere of Lanzhou, the decrease in aerosols caused by air pollution reduction may increase cloud droplet size, resulting in the effective participation of small raindrops in the process of collision, and hence causing the increase in precipitation amount and frequency, especially light rainfall (the “Albrecht effect”) (Albrecht, 1989; Ding et al., 2009; Qian et al., 2009; Li et al., 2011; Zhou et al., 2018).

During winter, precipitation is sparse in Lanzhou and Yuzhong. Moreover, precipitation frequency changes weakly in both places during P1 and P2. There were only 21 (28) and 19 (24) records of precipitation during P1 and P2 in Lanzhou (Yuzhong), respectively. Therefore, the cooling effect of air pollution reduction at night may not be realized through the precipitation process in winter. According to the weak contribution of cloud cover to surface air temperature at night in winter, the $T_{\text{mean}}$ at night may be largely controlled by the loss of surface heat. Aerosols in the semiarid region such as dust aerosol can effectively reduce land surface long wave emission, and therefore contribute to the warming effects on surface air temperature (Zhao et al., 2015; Wang et al., 2017). When dust fall quantity and other aerosols decline due to air pollution-control programmes, the long wave radiation emitted from the surface increases, which might be the main cause of the air temperature drop at the surface at night in winter.

### 4.1 Specific humidity and low cloud cover

The diurnal changes in specific humidity (Figure 8) and low cloud cover (Supporting Information Figure S3) in summer between Lanzhou and Yuzhong during P1 and P2 were compared. There was a significant increase from $-1.27 \text{ to } -0.80 \text{ g}\cdot\text{kg}^{-1}$ in specific humidity difference at 20:00 hr, significantly at the 95% confidence level (Figure 8). Even after excluding data for rainy days, the specific humidity difference still increased from $-1.31 \text{ to } -0.82 \text{ g}\cdot\text{kg}^{-1}$ at 20:00 hr, significantly at the 95% confidence level.
Compared with Yuzhong, the atmospheric moisture in Lanzhou increased significantly at night in summer. In addition, low cloud cover increased by 5.51% (11.09%) in Lanzhou (Yuzhong) at 20:00 hr during P2 compared with P1 (Supporting Information Figure S3). Those derived from data for non-rainy days insignificantly increased by 5.64% (6.94%) in Lanzhou (Yuzhong) at 20:00 hr as well (Supporting Information Figure S5). The increase of low cloud cover and atmospheric humidity in summer during P2 is helpful for a greater occurrence of precipitation in association with air pollution reduction programmes. Therefore, there was an increase in the maximum temperature and a decrease in the minimum temperature during P2 in Lanzhou. Moreover, the diurnal temperature range (DTR) significantly increased during summer and significantly increased during winter in Lanzhou during P2. The increase (decrease) in the maximum (minimum) temperature caused by air pollution-control programmes was more significant in summer and winter when the influence of precipitation was excluded.

The increase in air temperature in daytime may be related to a decrease in aerosol concentration caused by air pollution reduction, which could be ascribed to the decrease of scattering and the reflection of solar radiation in the atmosphere, and hence the increase of absorption of solar radiation at the surface. During summer, the decrease in air temperature at night caused by air pollution reduction is related to the increase in light rainfall frequency during P2. Since water vapour content in the atmosphere is limited in Lanzhou, the decrease in aerosols caused by air pollution reduction may increase cloud droplet size, resulting in the more effective collisions of small raindrops, and hence increasing light rain frequency. During this process, more low cloud cover and atmospheric humidity in P2 than P1 are helpful for a greater occurrence of precipitation in association with air pollution reduction programmes. In contrast to summer, the decrease in air temperature at night during winter may be more related to the loss of surface heat through long wave radiation at night during P2 compared with P1.

5 | CONCLUSIONS

Lanzhou is one of the largest heavy industry cities in northwest China. The city has carried out massive air pollution-control programmes since 2012. Thus, the concentrations of air pollutants in Lanzhou have decreased after 2012. In order to discover the effects of the air pollution-control programmes on local air temperature, the air temperature difference between Lanzhou and Yuzhong (a county adjacent to Lanzhou) was calculated to minimize the influence of background climate change on air temperature in Lanzhou. Changes in air temperature difference between the periods 2009–2011 (P1) and 2013–2015 (P2) were then examined to reveal the influence of air pollution-control programmes on air temperature in Lanzhou. The results showed that the air temperature difference increased significantly in daytime in both summer and winter and decreased significantly at night in summer during P2 compared with P1, indicating an increase in air temperature in daytime and a decrease in air temperature at night during P2 in Lanzhou in association with mass pollution reduction programmes.
undergraduate research fund project of Beijing Normal University. The study was also supported by the Data Center of Gansu Meteorological Agency.

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