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A Study of the Relationship between Air Pollutants and Inversion in the ABL over the City of Lanzhou

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ABSTRACT

By analyzing the pollutant concentrations over the urban area and over the rural area of the city of Lanzhou, Gansu Province, China, the relationships between the daytime inversion intensity and the pollutant concentration in the atmospheric boundary layer (ABL) are studied with the consideration of wind speed and direction, potential temperature, specific humidity profiles, pollutant concentration in the ABL, the surface temperature, and global radiation on the ground. It was shown that the daytime inversion is a key factor in controlling air pollution concentration. A clear and positive feedback process between the daytime inversion intensity and the air pollutants over the city was found through the analysis of influences of climatic and environmental factors. The mechanisms by which the terrain and air pollutants affect the formation of the daytime inversion are discussed. The solar radiation as the essential energy source to maintain the inversion is analyzed, as are various out-forcing factors affecting the inversion and air pollutants. At last, a physical frame of relationships of air pollution with daytime inversion and the local and out-forcing factors over Lanzhou is built.

Key words: relationship, Lanzhou City, inversion, pollutant, out-forcing factors

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1. Introduction

As a typical city in an arid area, Lanzhou which is located in a long valley runs mainly from the east to the west with a length of about 30 km, maximum width of 8 km, and depth of 200–600 m. Its urban area lies mainly in the valley. Because of its specific valley terrain and resulting climate, the diffusion process of air pollutants over it is more complicated than those over other cities (Zhang and Hu, 1998). Thus, the interaction processes between different factors related to the air pollution are of interest. However, more factors need to be considered to better analyze trends in the air pollution of the city and improve the countermeasures (Hu and Zhang, 1999).

The diffusion and transfer of air pollution in Lanzhou City have been a focus for around two decades. Some important progress has been made, such as the discovery that a temperature inversion is maintained not only at night, but also in the daytime (Yuan, 1985; Wang and Zhang, 1999; Zhang, 2001; Xi et al., 2002). However, most studies have resulted in qualitative discussions and inferences while quantitative analyses and experimental investigations are lacking. For example, it is not clear how much the daytime inversion contributes to the increase in air pollutant concentration, and it is also not clear how strong the feedback of increase in air pollutant concentration to the daytime inversion is. On the other hand, in some studies, the explanations given on inver-

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sion are not satisfactory. For example, it was proposed that effects of hill peak heating and uphill wind partly contribute to the formation of the inversion (Hu et al., 1989; Zhang and Hu, 1992; Zhang and Hu, 1998; An et al., 2008). Some studies went further claiming that hill peak heating and uphill wind are two key factors causing the inversion. According to these viewpoints, the inversion should be stronger in summer than in winter. In fact, the daytime inversion in summer is weaker than that in winter, which shows that hill peak heating and hill breeze are not major factors for the formation of winter inversions.

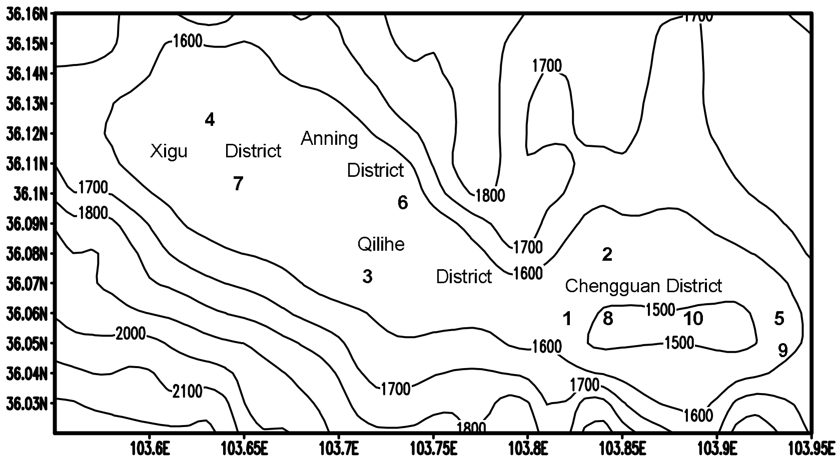
Multiple local factors cause specific air pollution in Lanzhou City. First, the specific terrain of the city weakens the wind speed in Lanzhou, making it difficult to blow air over its hills (Kaimal and Finnigan, 1994). Therefore, the capability to diffuse and transfer air pollutants over the city is congenitally deficient. Second, the daytime inversion worsens the dispersion of air pollution. Third, the feedback between the daytime inversion and air pollutants further complicates the diffusion of air pollution. It can be seen that the valley terrain, weak wind velocity, temperature inversion, feedback between the daytime inversion and the air pollutants, and arid climate are five important local factors that interact with one another and affect air pollution in Lanzhou City. In addition, the Froude number and the bulk stability of the ABL are two parameters that can be used to better synthesize several of the local factors mentioned above and approximately indicate the capabilities of airflow transfer over hills and turbulent diffusion, respectively (Zhang, 2001; Zhang and Lü, 2001; Gao and Bian, 2004). Thus, in order to determine the correct countermeasure for the air pollution of Lanzhou City, it is very important to investigate complicated atmospheric diffusion and transfer processes formed under the influence of these factors.

2. Observational data

The joint research project of Gansu province and the Chinese Academy of Sciences named "Study on Atmosphere Pollution and its Countermeasure of Lanzhou City" started in 2000. Several sets of data were collected in this project, including the wind speed and direction, temperature and humidity in the ABL, the pollutant concentration, the surface temperature, and global radiation. Lanzhou topography and the distribution of urban pollutant monitoring and meteorological observation sites are shown in Fig. 1.

Seven sites (St-1 to St-7 in Fig. 1) in the urban area of Lanzhou selected to monitor long-term air pollution are as follows: Railway Bureau, Institute of Biological Products, Gansu Provincial Construction Workers' Hospital, Lanlian Hotel, Langang Welfare Area, Anning Environmental Protection Bureau, and Lanlian Cultural Palace. The pollution sources and the whole terrain were fully taken into account. A background site in Yuzhong County, located at 36°21′N, 103°56′E, and about 50 km southeast in the downwind direction of Lanzhou City, was used to compare air pollution over the urban area with that over the rural area.

Meteorological data was collected at other sites



St-1---- St-7 urban pollutant monitoring sites

St-8---- St-10 meteorological observation sites

Fig. 1. Lanzhou topography and distribution of urban pollutant monitoring and meteorological observation sites.

(St-8 to St-10 in Fig. 1). A tethered balloon profiler was used to observe the ABL times per day at 0200–2400 LST every two hours. The ABL observation was related to measurements of air pressure, air temperature, wind speed, wind direction and air relative humidity, whose accuracies were 0.1 hPa, 0.2°C, 0.5 m s^{-1}, 0.6°and 3% respectively. The launch site was at the open sports ground of Lanzhou University (St-8, 36°03′N, 103°51′E, altitude of 1520 m) located in the center of the city (Zhang, 2003). The data was recorded about every 10 s. The maximum observational height was about 800 m, the minimum 450 m, mostly, higher than 650 m. Surface temperature and global radiation with sensor accuracies of 0.1°C and 5% respectively were observed in the regular meteorological station of Gansu Meteorological Bureau (St-9) located near the observational site of the tethered balloon profiler. Some other micrometeorological observations were conducted at the automatic weather station (AWS) of Daqing Mountain (St-10, 36°01′N, 103°57′E, altitude of 1700 m), located on the east side of the urban area and 200-m higher than the bottom of the valley. Data were recorded every hour at both the AWS and the regular meteorological station. Table 1 shows observational items at the three meteorological observation sites.

In order to simplify data analyses, the overall pollutant concentration of the urban area was represented by the average of observed values at the seven sites. In addition, the original temperature of the ABL collected by the tethered balloon profiler was incorporated into the new data consisting of a set of records every 20 m. The analyzed ABL data was mainly observed below 650 m. The relationship between the air potential temperature. θ (°C) and the air temperature T (°C) is as follows:

$$\theta = T\left[1 + 0.098 \times (h_0 + z)\right], \qquad (1)$$

where h_0 is altitude of the surface (m), z is height (m). The average of data observed at 0200, 0400, 0600, 2000, 2200 and 2400 LST was taken as the mean value at night, and the average of data observed at 1200, 1400 and 1600 LST was used as the mean value during daytime.

3. Mechanism of forming air pollution over Lanzhou City

3.1 *Comparison of urban and rural air pollutant concentrations*

Large quantities of industrial pollutants are released into the atmosphere in Lanzhou, which is a typical heavy industry city. Additionally, dust storms occurring over the arid area may extend to Lanzhou and bring a lot of particulate aerosol to it (Chu et al., 2008). Thus, both the local industrial sources and remote preconditions can cause air pollution. The main components of air pollutants over the urban area are particulate loading and industrial gas pollutants including sulfur dioxide and nitrogen oxides. Figures 2a and b respectively show the variations of gas pollutant and particulate loading concentrations over the urban area of Lanzhou and its rural area Yuzhong County from 8 to 22 December 2000. From the figures, the following conclusions are drawn: (1) If the daily mean emission of pollution sources is thought to be nearly stable, the variation of the pollutant concentration with time in the urban area can be attributed to atmospheric diffusion and transfer. (2) Both the gas pollutant concentration and the particulate loading concentration over the urban area have the same trends: increasing evidently from 11 to 16 December 2000, then dropping sharply from 17 to 19 December, and going up again after 19 December. This indicates that air diffusion and transfer abilities gradually decreased during 11–16 December and after 19 December and increased from 17 to 19.

As shown in Fig. 2a, the gas pollutant concentration over the urban area was generally much higher than that over the rural area, and its change with time was also much faster than that over the rural area. This is accounted for by more industrial gas pollution sources in this industrial city. As shown in Fig. 2b, the average particulate loading concentration over the urban area was clearly higher than that over the rural area during the observational days. Even so, the

Table 1. Observational items in three meteorological observation sites.

Site	Item						
	A	B	C	D	E	F	G
St-8 Sports ground of Lanzhou Univ.	√	√	√	√	√	×	×
St-9 Daqing Mountain	×	×	×	×	×	√	×
St-10 Gansu Meteorological Bureau	×	×	×	×	×	√	√

Note: A—air pressure in the ABL, B—air temperature in the ABL, C—wind speed in the ABL, D—wind direction in the ABL, E—air relative humidity in the ABL, F—ground surface temperature, G—shortwave radiation

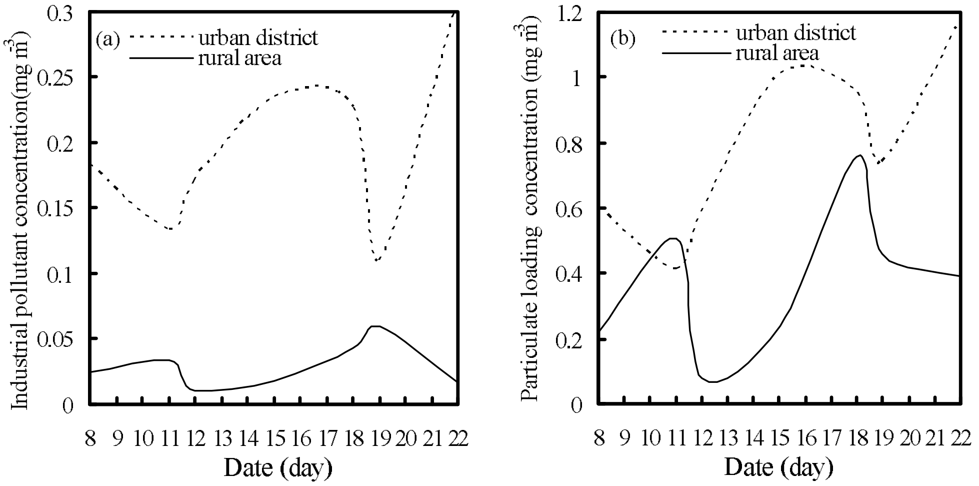


Fig. 2. Variations of (a) the industrial gas pollutant and (b) particulate loading concentrations over the urban area of Lanzhou City and rural Yuzhong County, from 8 to 22 December 2000.

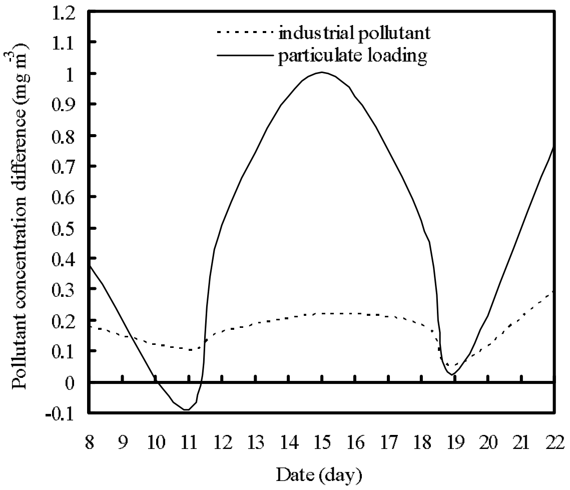


Fig. 3. The difference between the urban and rural pollutant concentrations from 8 to 22 December 2000.

trends with time are similar, although the trend for the rural areas is a little steeper.

Meanwhile, Figs. 2a and b also clearly indicate that change in the urban pollution is always anticorrelated with that in the rural pollution. Passing air pollutants are easily captured by the urban valley, and the locally produced pollutants are difficult to diffuse and transfer freely in all directions. Also, because the urban area is in the upwind direction of the rural area (Yuzhong County), rural air pollution is easily influenced by urban pollution, but not vice versa. Comparing Fig. 2b with Fig. 2a, it is found that the influence of particulate loading over the urban area on the city is stronger than that of gas pollutants. In other words, poor air diffusion and transfer in Lanzhou inhibit gas pollutant spreading more than particulate loading. Thus, the change in particulate loading over the urban area is more dramatic than the gas pollutants.

Figure 3 shows the difference between the urban and rural pollutant concentrations with time from 8 to 22 December 2000. In the weather records, passing cold air was found twice, on days 11 and 19. From the figure it is clear that the difference decreased a few days before the cold air arrived at Lanzhou and reached a minimum of 0 when the cold air passed on days 11 and 19.

A few days before the cold air arrived, the restrictive effect on the diffusion and transfer of air pollutant began to decrease. Consequently, more pollutants were released from the urban area to the rural area, causing the difference between the pollutant concentrations in two areas to gradually decrease. The local particulate loading and gas pollutants frequently spread to the rural area, so the pollution level in the rural area was enhanced following a reduction in pollution in the urban area. When the cold air passed on days 11 and 19, the restrictive effect on the diffusion and transfer dropped to the lowest level and even disappeared, leading to the difference between the urban pollutant concentration and the rural one reaching the minimum as shown in Fig. 3. After the cold air passed, the ability to restrict air diffusion and transfer recovered , so spreading of the pollutants from the urban area to the rural area decreased, causing the difference to increase again.

In short, the time-related ability to limit air diffusion and transfer over Lanzhou has a significant influence on the degree of industrial gas and particulate

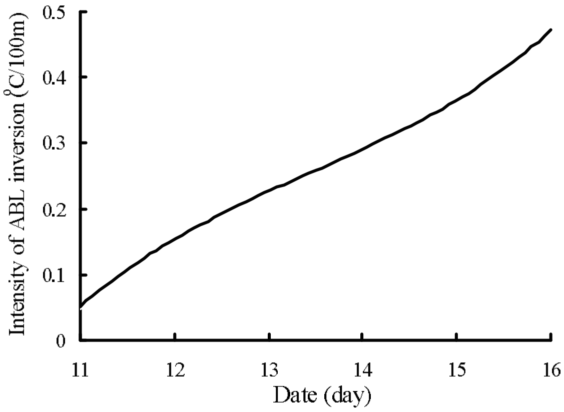


Fig. 4. The daytime inversion in ABL over Lanzhou City from 11 to 16 December 2000.

loading pollutants over the urban and rural areas. The above analyses indicate that the ability grew during the periods from 11 to 16 December and after 19 December, and dropped during the periods from 17 to 19 December and before 11 December.

3.2 *Inversion and its relationship with air pollution*

The daytime inversion in the ABL over Lanzhou City from 11 to 16 December 2000 is shown in Fig. 4. The daytime inversion intensity was very weak on 11 December. A strengthening process increased the inversion intensity in the following days. In addition, the trend of the daytime inversion is similar to that of the urban pollutant concentration shown in Fig. 2, revealing that the inversion is a key factor controlling air pollutant diffusion and transfer during the daytime.

To understand how the daytime inversion forms, the daytime air temperature at the heights of 10 m and 600 m, and their contributions to the daytime inversion from 11 to 16 December 2000 are plotted in Fig. 5. As shown in Fig. 5a, the air temperature at 600 m increased from 11 to 16 December, while it decreased at 10 m during the same period. This indicates the formation and continuous development of the daytime inversion. Pollutant aerosol in the atmosphere can absorb and scatter solar radiation, consequently heating the atmospheric layer in which the particles reside and changing the radiative heating of the atmosphere and surface (Peter, 2007). These effects may alter the dynamical and hydrological processes governing cloud formation (William et al., 2002; Yoram et al., 2008). Therefore, the air temperature of the high layer in which the particles reside goes up with aerosol absorption of solar radiation. Although aerosol absorption also influences the air temperature at low levels, its effect is much less than that of the sun's heat on the ground surface. Therefore, when the surface solar radiation decreases, air temperature at low levels also decrease. Similar studies (Dinar et al., 2008) have also found that atmospheric aerosols absorb and reflect solar radiation causing surface cooling and heating of the atmosphere. Thus, the relation between the daytime inversion and air pollutants is feedback-positive. If no other factor interrupted the process, both daytime inversion intensity and pollutant concentration would become higher and higher.

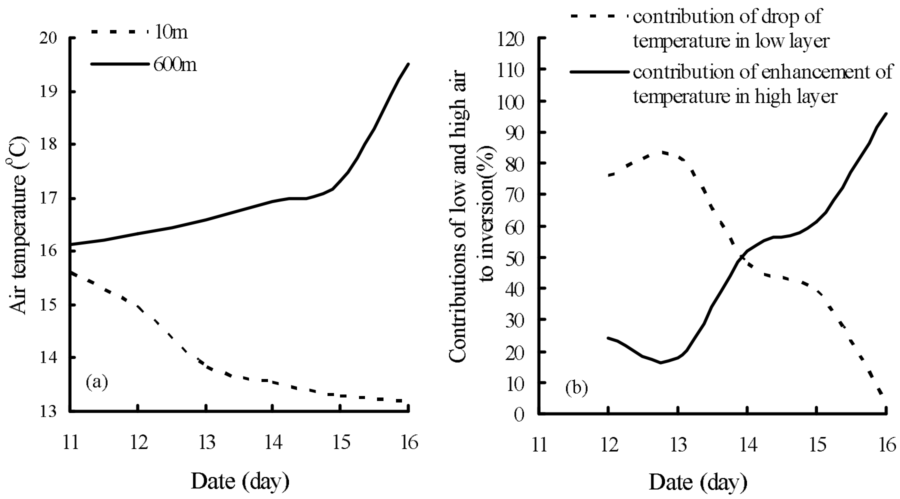


Fig. 5. (a) The daytime air temperature at the heights of 10 m and 600 m during 11 to 16 December 2000, and (b) their contributions to the daytime inversion over Lanzhou City.

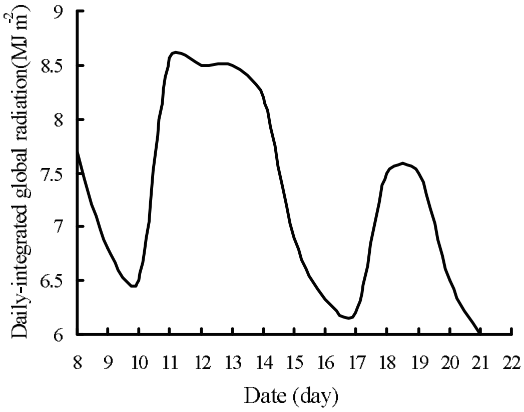


Fig. 6. The integrated flux of daily surface global radiation in Lanzhou City from 8 to 22 December 2000.

Figure 5b shows the contribution of the absorption of solar radiation and the reduction of surface solar radiation to the daytime inversion intensity from 11 to 16 December 2000. The contribution of the absorption of solar radiation to the daytime inversion gradually increases with time from 11 to 16 December. The opposite is true for the reduction of surface solar radiation.

Although the observational period of the ABL is too short to be used to analyze the correlation between the daytime inversion and the air pollutant concentration in the long term, the change in daily integrated surface radiation flux on the urban area of Lanzhou from 8 to 22 December 2000 can indirectly verify the above results, as shown in Fig. 6. From the figure, it is clear that the change in daily integrated surface radiation flux is anticorrelated with the trend of the pollutant concentration in Fig. 2, indicating that the increase in the air pollutant concentration can attenuate the surface solar radiation flux in the urban area and vice versa. This result is consistent with previous studies (Shen et al., 1982; Chen et al., 1993).

The above discussion suggests that the pollutant radiation effect plays an irreplaceable role in the formation and development of daytime inversions. Some studies (Stull, 1988; Zhang and Hu, 1998; Hu and Zhang, 1999) have shown that the peak heating and uphill wind caused by the valley terrain and arid surface can also form a daytime inversion. The gas pollutant and particulate loading concentrations over the urban area reached the lowest levels when cold air passed on 11 December. Because of such low pollutant concentrations, the peak heating and uphill wind caused by the valley terrain had greater advantages than pollutants in the formation of the daytime inversion. In Fig. 5, the difference between the daytime air temperature at a height of 600 m and that at a height of 10 m was about 0.7°C, which can be primarily taken as the contribution of the valley terrain to the ABL inversion. However, when pollutant aerosol over the valley took part in the formation of an urban daytime inversion, the inversion became stronger and lasted longer following enhancement of the pollution level. The difference between the temperature values at the two heights grew rapidly and on 16 December reached the maximum value of 6°C, about eight times higher than 0.7°C. According to the above discussion, we can see that when the previous inversion state is ruined by the passing cold air, the formation of a new inversion state is mainly attributed to the effect of the valley terrain just as it acts on 11 December. In promoting the development of an inversion, pollutants play a more important role than the valley terrain, which is just regarded as a factor to start the new inversion state.

Both the valley terrain and pollutants affect the daytime inversion through solar radiative forcing. Therefore, the solar radiation flux is the essential energy source for maintenance of the daytime inversion. Other out-forcing factors also have significant impacts on the daytime inversion and air pollution. Especially, the daytime inversion is reduced by the passing of cold air and increased by the passing of warm air over the valley. During the two cold air processes occurring on 11 and 19 December, the restriction on air diffusion and transfer was eliminated, causing the pollutant concentration to drop sharply (see Fig. 2) and the daytime inversion to weaken. Thus, cold airflow can interrupt the positive feedback process between inversions in daytime and pollutants.

Precipitation can also wash out air pollutants and sharply reduce the pollutant concentration, so it can also interrupt the positive feedback process. However, the precipitation is especially limited in winter because of the arid climate of Lanzhou, so it is not enough to wash out the pollutants and clear them away. Synoptic processes are known to have a certain periodicity. Following periodical synoptic processes, the feedback process can be interrupted or strengthened, changing the pollutant concentration regularly.

Overall, there are relatively complex relationships between daytime inversions and the local and out-forcing factors including valley terrain, weak wind speed, sources of particulate, and the arid climate in Lanzhou City. A rough physical frame of these relationships can be given out through a combination of the above facts and inferences, as shown in Fig. 7.

4. Discussion

Change in the pollutant concentration over Lanzhou City with time results from change in the

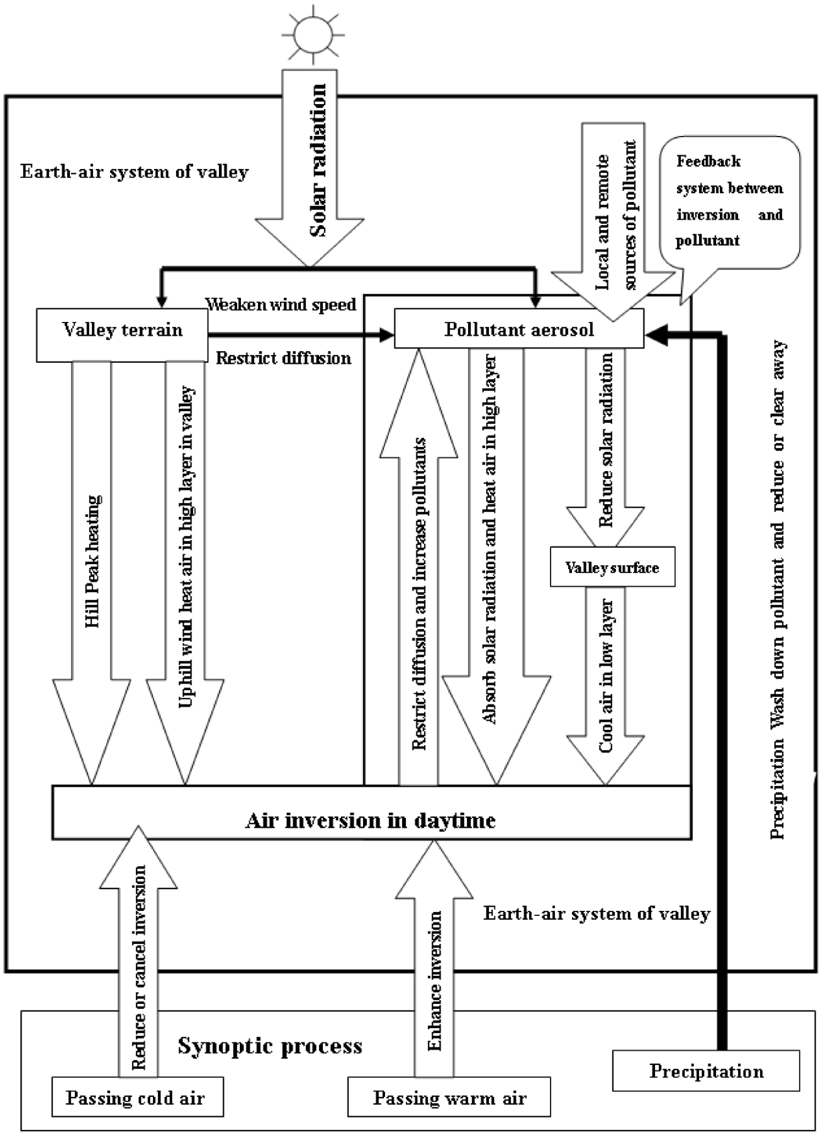


Fig. 7. Physical frame of the relationships between daytime inversion and the local and out-forcing factors in Lanzhou City.

specific capability of diffusion and transfer. The events in which the pollutant concentration went up sharply during 11 to 16 December and after 19 December mean the capability became lower, while the event in which the pollutant concentration decreased on days 17 to 19 shows that the capability became stronger. Compared with the rural area, the air pollution over the urban area is much more serious due to more pollutant sources. Due to the urban area being in the upwind direction of the rural area, the pollutants over the urban area can be transferred to the rural area by wind. Thus, the air pollution over the rural area is seriously influenced by that over the urban area. When cold air passes, the difference between the concentrations over two areas reaches a minimum value.

The daytime inversion intensity increases gradually along with the increase of pollutant concentration, indicating it is a key factor in controlling the air pollutant diffusion and transfer. The pollutant aerosol not only absorbs solar radiation, but also weakens the surface solar radiation flux on the ground. As to air temperature, the heating effect is dominant at a high height, and the cooling effect is dominant at a low height. Both of them contribute to daytime inversion formation. Therefore, the interaction between daytime inversions and air pollutants is actually a positive feedback process. If no out-forcing factor interrupted the feedback process, both daytime inversions and pollutant concentrations would become higher and higher.

The solar radiation flux is the essential energy source needed to maintain a daytime inversion. Synoptic processes are also important out-forcing factors in changing the inversion and restricting air diffusion and transfer. Cold airflow can reduce or eliminate a daytime inversion, while warm airflow can enhance it. Additionally, precipitation can wash away air pollutants and, consequently, interrupt the feedback process between the inversion and the pollutants. It is not difficult to understand that the pollutant concentration changes regularly, following periodical synoptic processes.

In all, feedback between air pollutants and daytime inversions makes a large contribution to air pollution, while the specific factors including valley terrain, weak wind speed, remote sources of particulate, and the arid climate lead to the special mechanism of forming air pollution that is different from other cities.

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REFERENCES

An, X., Y. Hu, S. Lü, and H. Zuo, 2008: Numerical Simulation of Heating Effect of Mountain Peak. *Plateau Meteorology*, **27**(2), 286–292. (in Chinese)

Chen, C., J. Huang, and L. Cheng, 1993: *The Research on the Atmospheric Boundary Layer and Regularity of Atmospheric Diffusion over Complex Terrain*. China Meteorological Press, Beijing, 213pp. (in Chinese)

Chu, P. C., Y. Chen, S. Lü, Z. Li, and Y. Lu, 2008: Particulate air pollution in Lanzhou China. *Environment International*, **34**, 698–713.

Dinar, E., and Coauthors, 2008: The complex refractive index of atmospheric and model umic-like substances (HULIS) retrieved by a cavity ring down aerosolspectrometer (CRD-AS). *The Royal Society of Chemistry*, **137**, 279–295.

Gao, Z., and L. Bian, 2004: Estimation of aerodynamic roughness length and displacement height of an urban surface from single-level sonic anemometer data. *Australian Meteorological Magazine*, **53**, 21–28.

Hu, Y., and Q. Zhang, 1999: Atmosphere pollution mechanism along with prevention cure countermeasure of the Lanzhou hollow basin. *China Environmental Science*, **19**(2), 119–122. (in Chinese)

Hu, Y., Z. Ge, and J. Liu, 1989: An observational experiment of surface layer over Lanzhou mountainous region in the early winter. *Chinese J. Atmos. Sci.*, **13**(4), 452–459. (in Chinese)

Kaimal, J. C., and J. J. Finnigan, 1994: *Atmospheric Boundary Layer Flows*. Oxford University Press, New York, 304pp.

Peter, P., 2007: Aerosols heat up. *Nature*, **448**, 541–542.

Shen, Z., Y. Wang, and G. Ji, 1982: Weakening of solar radiation crossing polluted atmosphere layer in Lanzhou hollow. *Plateau Meteorology*, **10**(1), 74–83. (in Chinese)

Stull, R. B., 1988: *An Introduction to Boundary Layer Meteorology*. Kluwer Academic Publisher, Dordrecht, 671pp.

Wang, S., and L. Zhang, 1999: Retrospect and prospect for the studies of atmospheric environment in the Lanzhou area. *Journal of Lanzhou University* (*Natural Sciences*), **35**(3), 189–201. (in Chinese)

William, C. C., N. Athanasios, and H. S. John, 2002. Black carbon radiative heating effects on cloud microphysics and implications for the aerosol indirect forcing: 1. Extended Köhler theory. *J. Geophys. Res.*, **107**(D21), 4604, doi: 10.1029/2002JD002094.

Xi, X., J. Quan, C. Chen, and X. Zhao, 2002: Monitoring analysis of winter TSP over Chengguan District of Lanzhou and their effects on radiation. *Plateau Meteorology*, **21**(4), 427-431. (in Chinese)

Yoram, J. K., I. Koren, L. A. Remer, D. Rosenfeld, and Y. Rudich, 2008: The effect of smoke, dust, and pollution aerosol on shallow cloud development over the Atlantic Ocean. *Proceedings of the National Academy of Sciences of the U.S.A*, **102**(32), 11207–11212.

Yuan, J., 1985: The characteristics of lidar echo of inversion layer Lanzhou in the winter. *Environmental Study and Monitoring*, **2**(1), 20–26. (in Chinese)

Zhang, Q., 2001: The influence of terrain and inversion layer on pollutant transfer over Lanzhou City. *China Environmental Science*, **19**(3), 230–235. (in Chinese)

Zhang, Q., 2003: A study of the interaction between concentration of pollutants and climatic and environmental factors of Lanzhou. *Journal of Lanzhou University* (*Natural Sciences*), **30**(1), 99–106. (in Chinese)

Zhang, Q., and Y. Hu, 1992: A research about turbulent transport and intensity over complex terrain of Lanzhou. *Plateau Meteorology*, **11**(2), 126–132. (in Chinese)

Zhang, Q., and Y. Hu, 1998: Shallow discussion on some problems of pollution and its controlling of atmospheric environment over the Lanzhou City. *Plateau Meteorology*, **17**(2), 202–210. (in Chinese)

Zhang, Q., and S. Lü, 2001: The relationship between the pollutant transfer and terrain, and micrometeorology over Lanzhou city. *Plateau Meteorology*, **20**(Suppl.), 118–125. (in Chinese)