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# Effect of large topography on atmospheric environment in Sichuan Basin: A climate analysis based on changes in atmospheric visibility

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Using 51 years (1960–2010) of observations from meteorological stations in the Sichuan-Chongqing region, including atmospheric visibility as a proxy for aerosol concentration, relative humidity, air temperature, wind speed and FNL reanalysis data (1°×1°) of air temperature, pressure and wind, and the altitude of each station, a linear trend and multivariate fitting approach was used to explore the effects of the large topography on the atmospheric environment in the Sichuan-Chongqing region. The region mainly consists of two areas: Sichuan Basin (SCB) and Western Sichuan Plateau (WSP; eastern part of the Tibetan Plateau). Visibility was relatively low in the SCB and high in the WSP, indicating the high and low levels of aerosols respectively in the SCB and the WSP. Additionally, visibility and wind speed were positively correlated within the basin (altitude below 750 m), while negatively correlated at stations above 1,500 m, such as on the WSP, indicating that the topography had an influence on the atmospheric environment of the basin. On the one hand, the vertical structures of the wind fields and the vertical profiles of latitudinal deviations in wind speed and air temperature in the basin show that the unique large topography causes a “harbour” effect on the leeward-slope of the WSP, with the SCB being a weak wind region, while the descending air currents in the upper westerlies of the basin form a huge “vault” of air. On the other hand, topographic effects can make the basin more susceptible to the formation of inversion structures near the surface and at high altitudes, thus stabilising the atmosphere. The topographic effects, which is not conducive to horizontal diffusion and convective transport of pollutants, were the most significant in winter, followed by autumn and spring.

## KEYWORDS

Sichuan Basin, atmospheric environment, visibility, climate, topographic effects

## 1 Introduction

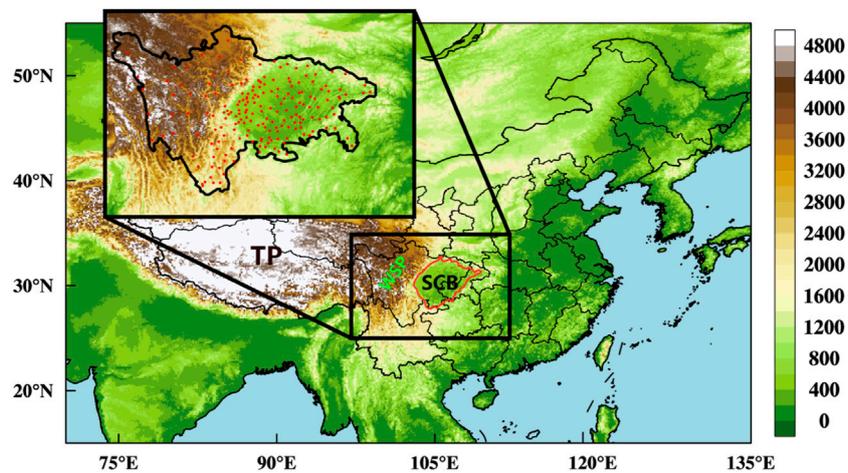
The industrialization and urbanization of China over the past few decades have caused serious air pollution problems (Sun et al., 2016; Gui et al., 2020; Zheng et al., 2021), characterized of high loading of fine particulate matter  $PM_{2.5}$  (particulate matter with an aerodynamic diameter equal to or less than  $2.5\ \mu\text{m}$ ) in ambient air and low horizontal visibility (Che et al., 2007; Deng et al., 2008; Sun et al., 2016), with likely consequences on the human health (Kampa and Castanas, 2008; Shang et al., 2013; Feng et al., 2016; Xing et al., 2016; Liu et al., 2017), ecosystems (Carslaw et al., 2010; Allen et al., 2019), and climate (Carslaw et al., 2013; Kelly and Zhu, 2016). In addition to factors such as high emissions, the role of meteorological conditions associated with large topography is also considered to be a crucial factor (Wang et al., 2013; Wang X. et al., 2018; Liao et al., 2018; Ning et al., 2019; Zhang et al., 2019; Shu et al., 2022b; Hu et al., 2022). It is generally accepted that topography has an important influence on synoptic circulation, atmospheric boundary layer, and local meteorology (Poulos and Pielke, 1994; Hu et al., 2014; Wang X. et al., 2018; Liu et al., 2018; Zhu et al., 2018; Zhang et al., 2019), and therefore alter chemical and physical processes of pollutants.

Topography can alter the thermodynamic and dynamic structure of the atmosphere, resulting in flows representing a systematic characteristic of large topography weather and climate (Zardi and Whiteman, 2013; Wagner et al., 2015; Giovannini et al., 2017), and thus affects the exchange of energy and mass in the atmosphere (Wang H. et al., 2018; Wang et al., 2019; Shu et al., 2022b). One of the main effects is the thermodynamic forcing caused by inhomogeneous surface properties, disturbing horizontal wind flows and altering vertical momentum mixing (Schmidli and Rotunno, 2010). In addition, topographic effects can cause strong temperature inversions (Whiteman et al., 1999), low-level jets (Ting and Wang, 2006; Tuononen et al., 2015), lee-side vortices (Gao and Ping, 2005), and gusts (Letson et al., 2019). These phenomena are of worldwide significance, as nearly a quarter of the Earth's land mass can be classified as mountainous (Blyth, 2002), such as the European Alps, the Tibetan Plateau (TP) and the Qinling and Taihang Mountains in China, and the Rocky Mountains in North America. Especially, eastern China has been identified as more climatically stable than Europe and the United States in terms of air conditions, partly due to the country's larger size and more complex terrain (Wang X. et al., 2018).

Among the mountainous areas, atmospheric environment in the Sichuan Basin (SCB) is of particular interest in recent years (Yin et al., 2020; Chang et al., 2021; Kong et al., 2021; Wu et al., 2022), due to both its unique bowl-shaped topography and its high levels of air pollution. The SCB is flanked by mountains—that is, bordered to the west by the TP, to the north by the Daba Mountains, to the east by the Wu mountains, and

to the south by the Yunnan-Guizhou Plateau, which together serve to shield the basin from external winds and trap air penetrating the basin via large-scale weather disturbances (Zhang et al., 2019; Guo et al., 2022). The basin is one of the regions with the highest values of atmospheric aerosols and clouds in China (Li et al., 2015; Qiao et al., 2015), with an annual average AOD (550 nm) value of 0.848 from 2000 to 2010, which is very significantly different from that in the TP (about 0.1) (Luo et al., 2014), which is immediately to the west of the basin. Previous studies showed that the average visibility in the SCB from 1973 to 2010 was basically no higher than 20 km, and below 10 km for most of the time in the central and southern regions, while the visibility on the western Sichuan Plateau (WSP) in the immediate west of the region remained above 25 km all year round (Chen and Xie, 2012). The principal causes of the visibility impairment in SCB were identified to be high levels of aerosol concentrations, as well as low wind speed and high relative humidity conditions due to terrain effects (Wang et al., 2017). Previous studies have examined the influence of terrain effects on haze pollution in the SCB using individual cases of  $PM_{2.5}$  pollution and seasonal  $PM_{2.5}$  pollution aspects (Ning et al., 2018; Ning et al., 2019; Zhang et al., 2019; Shu et al., 2022b). Using sensitivity simulations of topography, Zhang et al. (Zhang et al., 2019) found that the topography could increase near-surface  $PM_{2.5}$  concentrations in the SCB by close to  $50\ \mu\text{g}/\text{m}^3$  during a severe haze episode in winter 2014, corresponding to an increase of roughly 45%. Shu et al. (Shu et al., 2022b) then went on to investigate the three-dimensional distribution of terrain-induced  $PM_{2.5}$  concentrations over the SCB in different seasons, and they found that the increases in  $PM_{2.5}$  concentrations can increase from  $30\ \mu\text{g}/\text{m}^3$  in summer to  $90\ \mu\text{g}/\text{m}^3$  in winter at surface layer and increase from summertime  $10\ \mu\text{g}/\text{m}^3$  to wintertime  $30\ \mu\text{g}/\text{m}^3$  in the lower free troposphere.

Although previous studies have manifested the terrain effects of the SCB on regional atmospheric environments, the current understanding is still inadequate, especially from a long-term climate perspective. In the context of the westerly wind belt, the dynamic and thermal effects of the TP significantly influence the regional weather and climate characteristics of China, particularly the SCB region. Therefore, there is a great need for an in-depth analysis of the large topographic dynamics and thermal effects on the long-term spatial and temporal distribution changes of aerosols in the SCB. Due to the lack of long-term aerosol concentration observations, this study uses visibility as a proxy for analysis, and a description of data and method used are presented in Section 2. Section 3 describes the spatial and temporal variability of visibility in relation to topography and analyses the mechanisms by which topography affects it using reanalysis data. Finally, the major conclusions are summarized in Section 4.



**FIGURE 1**

Topography map (shading, unit: m) with the locations of TP, WSP, and SCB. The solid red line marks the basin boundary with a topographic elevation of 750 m. The 191 meteorological stations used to collect visibility and wind speed are marked with red dots.

## 2 Materials and methods

This paper uses observations from meteorological stations in the SCB and its surrounding areas (191 stations in total as shown in Figure 1) for a period of 51 years (1960–2010). The meteorological selected for analysis includes atmospheric visibility as a proxy for aerosol concentration, relative humidity, air temperature, and wind speed, as well as the air temperature, pressure, and wind in the FNL reanalysis data from 1999 to 2010. The AOD from MODIS remote sensing data were used. Data from 2010 onwards is avoided because of the substantial impact on air pollution due to the large number of emission reduction measures undertaken in SCB (Liu et al., 2021; Shu et al., 2022a). Visibility observations in China were classified according to 10 classes before 1980, after which they were expressed in kilometers. In order to make the visibility data comparable before and after 1980, we adopt the method of Qin (Qin et al., 2010) to homogenize the data. With the method, the day-by-day visibility data of all stations from 1980 to 2005 are accurately converted into visibility classes, and the visibility distances are averaged under the limits of each visibility class to obtain a more suitable proxy for the visibility distances corresponding to the 10 visibility classes (Table 1).

The Chinese meteorological stations conduct at least three regular visibility observations per day, i.e., 08:00, 14:00, and 20:00 Beijing time (BJT), with an additional observation at 02:00 BJT for the base meteorological stations. Since the visibility observation at 02:00 BJT and 20:00 BJT are carried out at night, the targets selected for observation are different from those during the daytime (i.e., 14:00 BJT), resulting in inconsistent observation data. In addition, the visibility at 08:00 BJT is easily affected by early morning radiation fog.

Therefore, only the observations at 14:00 BJT were selected for analysis. Observations of visibility under weather conditions such as fog, high winds, precipitation, and high humidity (relative humidity  $RH > 90\%$ ), which may affect visibility, have been excluded. The filtered visibility data was then revised for humidity according to the method of Rosenfeld (Rosenfeld et al., 2007) to obtain “dry visibility”, based on which the climatic characteristics of atmospheric visibility in the SCB and its surrounding areas were analyzed. In conjunction with the wind, air temperature, humidity, etc. from FNL, the effects of meteorological elements and the potential impact mechanism on the transport and dispersion of pollution in the special topography were investigated.

## 3 Results and discussion

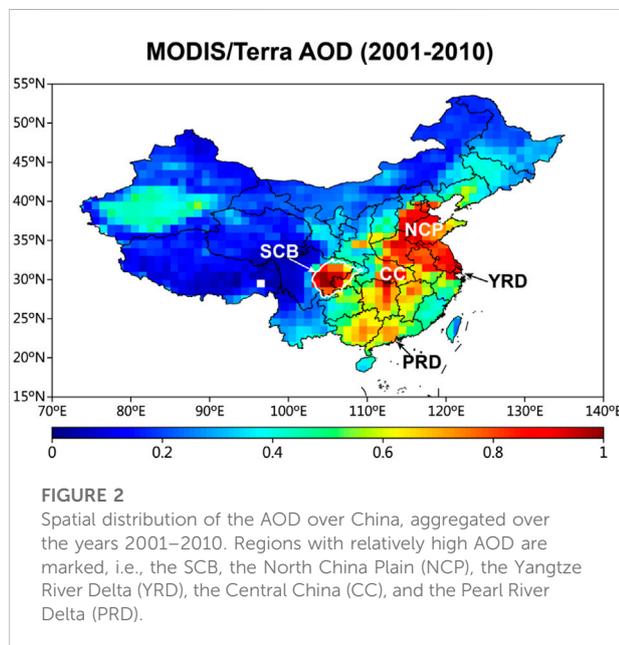
### 3.1 Variation in dry visibility and AOD

Figure 2 shows the spatial distribution of the AOD over China, aggregated over the years 2001–2010. It can be seen that the SCB is one of the several most polluted regions in China, with the AOD comparable with those in NCP and PRD, and that the interior of the basin (marked with white line in Figure 2) is more polluted than the peripheral areas around the basin.

The higher the AOD, the stronger the extinction of the atmosphere. Therefore, visibility is generally inversely proportional to AOD. Atmospheric visibility data can be used to indirectly evaluate the optical properties of aerosols, although the effects of aerosols, air molecules and water vapor on light attenuation should be considered in the calculation. According to the annual average of atmospheric

TABLE 1 Visibility ranges and estimations for visibility levels.

Visibility level	Visibility distance range (km)	Visibility distance estimates (km)
0	< 0.05	0.025
1	0.05–0.2	0.1
2	0.2–0.5	0.28
3	0.5–1.0	0.7
4	1.0–2.0	1.41
5	2.0–4.0	2.67
6	4.0–10.0	6.77
7	10.0–20.0	13.58
8	20.0–50.0	29.04
9	≥50.0	54.27



visibility over the past 51 years in Figure 3A, it can be seen that there is a sharp contrast between the visibility in the SCB and its western plateau region. Visibility within the basin, averaged at 18.9 km, is significantly lower than that in the WSP where the visibility mostly falls within 40–50 km, with the average visibility of about 46.0 km in areas above 1.5 km in altitude. The lowest visibility and highest AOD simultaneously occur in the southern part of the basin, with the former showing a gradual increase from east to west, and the maximum visibility occurs on the WSP, reaching 58.1 km.

According to the distribution of atmospheric visibility variability in Figure 3B, 116 of the 191 stations (60.7% of the total number of stations) showed a decreasing trend in

visibility, with 77 stations (66.4%) passing the 99% confidence test, indicating a clear trend of decreasing visibility. The stations with reduced visibility were mainly located in the basin, concentrated in southwest of the basin area and the southeast of Chongqing (Figure 3B). The most significant reduction in visibility is in Panzhihua, with a climatic tendency of about -7.73 km per decade. Panzhihua is an important industrial city in the south Sichuan province, where highly developed industries emitting a large amount of air pollutants may be the main reason for the reduction in high visibility. On the other hand, 74 stations (38.7% of the total number of stations), mainly located on WSP, showed an increasing trend in visibility, with 39 stations (52.7%) passing the 99% confidence test. The most significant increase reached about 6.39 km per decade.

### 3.2 Visibility in relation to terrain height and wind speed

According to the linear correlation between the average visibility and altitude of each station from 1960 to 2010 (Figure 4), it can be seen that visibility and altitude are positively correlated, and the correlation coefficient is about 0.90 ( $R^2=0.81$ ,  $p<0.01$ ), indicating that there is a close relationship between visibility and altitude, and the higher the altitude, the greater the visibility. When the altitude is less than 750 m, the visibility is mostly less than 25 km, while when the altitude is greater than 1500 m, the visibility is mostly more than 40 km. A linear correlation between the visibility and terrain altitude is also given for the different interdecadal periods (Figure 5). The visibility and terrain height in different periods are highly positive correlated as well, with all the correlation coefficients exceeding 0.8 ( $p<0.01$ ).

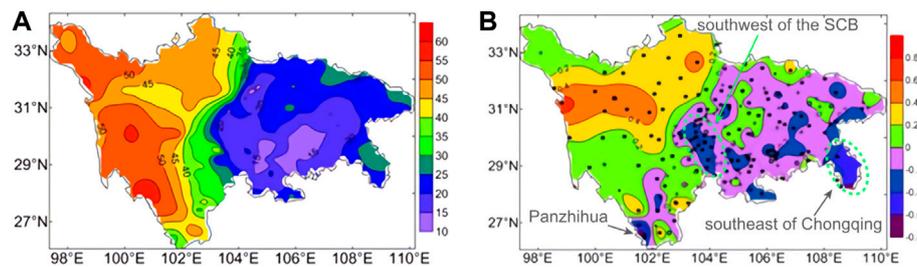


FIGURE 3

Distribution of (A) atmospheric visibility and (B) atmospheric visibility variability in the SCB and its surrounding areas over the 51 years (1960–2010). The makers \*, ●, and ○ indicate passing the 99%, 95% and 90% confidence tests, respectively.

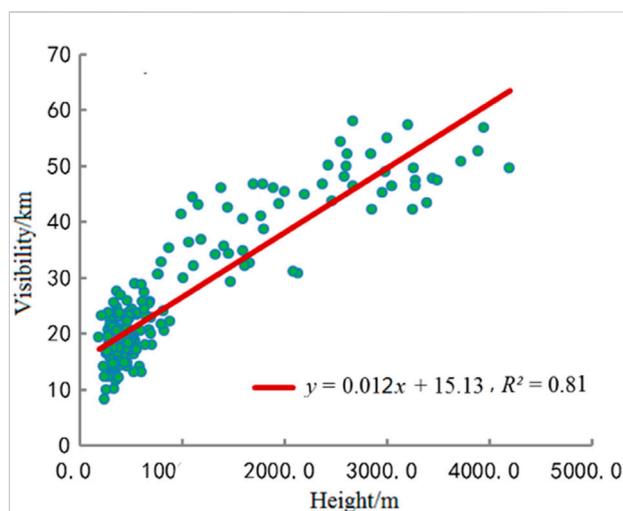


FIGURE 4

Scatter plots and correlation coefficient ( $R$ ) of the visibilities and terrain heights over the years from 1960 to 2010. There are 191 scattered points in the figure, representing the values of 191 meteorological observation stations.

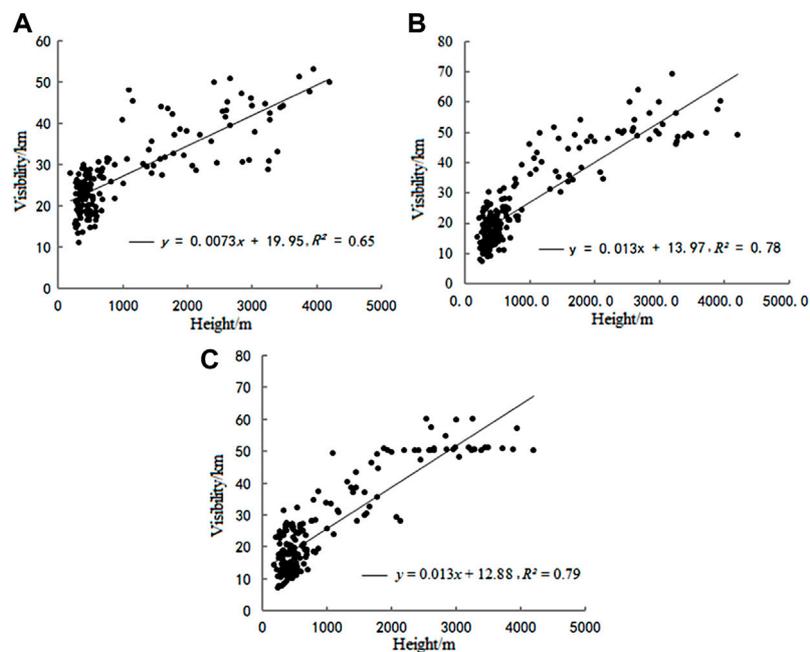
As the relationship between visibility and wind speed is relatively complex, it is discussed here separately for the SCB (below 750 m elevation) and the WSP (above 1500 m elevation). It reveals that visibility in the SCB was positively correlated with the wind speed (Figure 6A), with a correlation coefficient of 0.57 ( $p < 0.1$ ), indicating that wind speed is an important factor influencing visibility changes within the basin. On the contrary, visibility and wind speed on the WSP region are basically negatively correlated (Figure 6B), i.e., visibility decreases with increasing wind speed. As a rule of thumb, in heavily emitting areas such as the SCB, higher wind speeds are more conducive to the dispersion and outward transport of pollutants, while in relatively clean areas, higher wind speeds are more

conducive to the transport of external pollutants into the local area causing local pollution.

### 3.3 The mechanism of topography on visibility

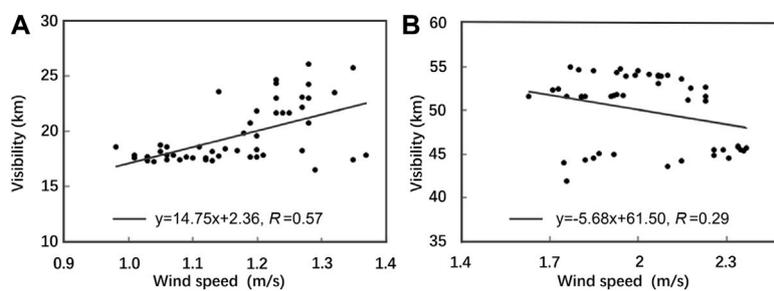
According to the analysis of visibility and altitude correlation for 1960–2010 and for each inter-decade period (1960–1970, 1980–1990, 2000–2010), it can be seen that visibility and altitude do not vary with the inter-decade period, but show a significant positive correlation, indicating that there is indeed a close influence effect between atmospheric environment and topography, and it can be inferred that the conclusions of this study would be still valid if the data are extended to present. In addition, visibility and wind speed are significantly positively correlated in the SCB area, while are weakly negatively correlated in the WSP area, demonstrating the regional differences in visibility variability, and its relationship with influencing factors, which are tightly affected by the topography. It is needed to understand how topography affects the atmospheric environment. In this section, the characteristics of atmospheric dynamic and thermal characteristics (reflected by wind and temperature, respectively) under the influence of the special topography are studied.

Figure 7 illustrates the vertical profile distribution of the latitudinal zone average (28°N–32°N) of horizontal and vertical wind speeds for different seasons. It can be seen that the atmospheric circulation structure over the region is relatively similar in winter, spring and autumn. During the three seasons, the low-level atmosphere in the SCB, where harbored by the Tibetan Plateau (TP) with its impact on midlatitude westerly winds, is characterized by weak winds and updrafts, while the high-level atmosphere is generally characteristic of strong winds and downdrafts, forming a “harbor” effect over the basin on the leeward slopes of the TP (Xu et al., 2015; Xu et al., 2016). On the contrary, the surface wind speed in the WSP area is substantially higher than those within the basin. A minimal horizontal wind



**FIGURE 5**

Scatter plots and correlation coefficients ( $R$ ) of the visibilities and terrain heights over the years from (A) 1960 to 1970, (B) 1980 to 1990, and (C) 2000 to 2010, respectively. There are 191 scattered points in each of the three subplots, representing the values of 191 meteorological observation stations.

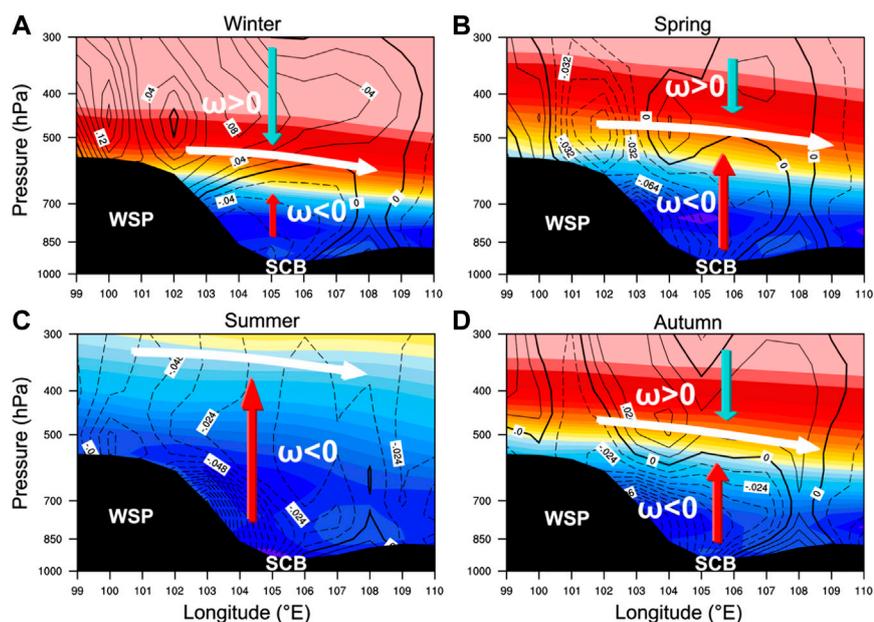


**FIGURE 6**

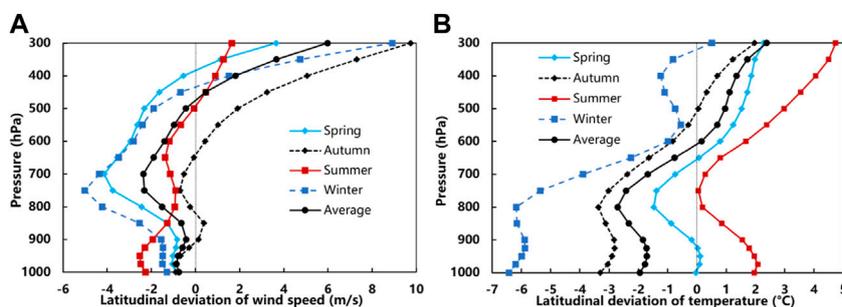
Scatter plots and correlation coefficients ( $R$ ) of the visibilities and wind speeds in the stations with the altitude (A) below 750 m and (B) above 1,500 m.

speed zone exists between 700 hPa and 850hPa, where is typically the center of a lee-side vortex of immediately upstream TP (Zhang et al., 2019; Shu et al., 2021). The zero vertical velocity layer is at approximately the same altitude as the WSP. It is worth noting that sinking air aloft is stronger in winter than those in spring and autumn, with the updrafts being suppressed within a lower altitude range and at their weakest strength, forming a more unfavourable vertical structure for the transport and dispersion of pollutants. In contrast, although

there are also areas of weak winds over the basin in summer, the atmosphere is almost entirely in upward motion, which is more conducive to the upward transport of pollutants. The pronounced difference in the vertical movement of the atmosphere in winter and summer should be related to the thermal effect of the TP, i.e., acting as a cold source in winter and heat source in summer (Zhang et al., 2000). The dynamical structure of the atmosphere under the influence of large topography may partly explain why haze is the most



**FIGURE 7** Vertical west-east cross-sections of horizontal (shading) and vertical (contour) wind speed averaged from 28°N to 31°N in (A) winter, (B) spring, (C) summer, and (D) autumn for the period 1999 to 2010. The solid and dashed lines indicate rise ( $\omega < 0$ ) and descend ( $\omega > 0$ ) of the airflow, respectively.



**FIGURE 8** Overall and seasonal deviations of wind speed (A) and temperature (B) from the same latitudinal band for the period 1999 to 2010 in the range 104°E–109°E and 28°N–31°N (corresponding to the SCB region).

severe in the basin in winter, followed by spring and autumn, and least severe in summer (Cai et al., 2018). Overall, on the basis of the preceding analysis, diffusion conditions for pollution are poor in the SCB under the particular large topography, and become progressively better with increasing altitude. Besides, higher anthropogenic emissions within the basin would further reduced the visibility in the basin areas.

In order to isolate the effect of large topography on the atmospheric dynamic and thermal structure of the SCB, the latitudinal deviations in wind speed and temperature within the

basin area (28°N~31°N, 104°E-109°E) were calculated. As shown in Figure 8, in terms of average wind speed deviations, the topography reduced the wind speed below 500 hPa in the basin by about 0.5–2 m/s, while increased the wind speeds above 500 hPa significantly. The topography causes the most significant decrease in wind speed over the basin at 700–800 hPa, especially in winter and spring (Figure 8A), which are not conducive to the transport and dispersion of pollutants and tend to cause the accumulation of pollutants in the basin. The large topographic dynamic effects described above are present in different seasons, only to varying degrees. Based on the overall

temperature-latitude deviation, it can be seen that, compared with other regions in the same latitudinal zone, the topography reduces the atmospheric temperature below 600 hPa over the basin, with the largest drop of 2.5–3°C at 800 hPa (Figure 8B), which is about the same as the height at which the topography reduces the wind speed over the basin most significantly. This suggests that the topography tends to make this layer of the basin more susceptible to off-ground inversions, which may be closely related to the overall downward warming of the leeward flow over the Tibetan Plateau (Xu et al., 2014). Under the warming effect of the leeward-slope airflow, inversions aloft are prone to form over the basin, with the highest likelihood and frequency of occurrence in winter (Figure 8B). The inversions would make the atmospheric stratification in the basin region more stable and the vertical transport of pollutants would be weakened, leading to the accumulation of pollutants in the basin and thus deteriorating air quality. There is a large seasonal variation in the effect of topography on temperature, with an overall decrease in temperature of a more pronounced magnitude in autumn and winter, and a relatively more pronounced inversion effect at 800–600 hPa. Combining the above analysis of the terrain effects on the wind-temperature structure over the basin shows that the most significant effects are experienced in winter, with both wind speed and temperature changing considerably due to the topography, and that an inversion layer is more likely to be generated than those in the other seasons. It is therefore important to pay more attention to the deteriorating effect of topography on air quality when developing pollution prevention and control in winter.

## 4 Conclusion

The topography of the Sichuan-Chongqing region is very complex, i.e. the SCB and the surrounding mountains are highly undulating, especially the TP that lies immediately to the west, resulting in a significant topography-dependent atmospheric environment. Studies have been conducted to quantify the influence of topography on atmospheric pollution in the SCB. In this study, the atmospheric environmental effects of topography in the Sichuan-Chongqing region are examined in terms of long-term changes in visibility, a proxy of aerosol concentration, and its connections with topography.

Visibility in the Sichuan-Chongqing region is significantly and positively correlated with the terrain height. Visibility in the SCB (defined as altitude less than 750 m) shows a significant positive correlation with wind speed, while at higher altitudes (larger than 1,500 m), visibility shows a negative correlation with wind speed. The effects of the large topography on the atmospheric environment of the region are mainly manifested in the following ways: The SCB is located on the leeward slope of the WSP. Under the influence of its special large topography, the leeward-slope effect leads to a weak wind area accompanied by ascending

motions at low altitude, and descending motions with westerly winds at high altitude during the winter, spring, and autumn. A zone of minimal wind speed exists between 700 and 800 hPa in winter, spring and autumn, which corresponds to the height of the centre of the leeward-slope vortex. The descending motions could form a huge “vault” over the basin, which are not conducive to vertical transport and dispersion of pollutants. The “vault” effect is strongest in winter, followed by autumn and spring, and disappears in summer, being one of the key factors for the worst winter pollution in the basin. Therefore, more attention should be paid to the exacerbating effect of topography on pollution during winter pollution control. In addition, topography has a significant effect on the temperature structure over the basin, leading to a tendency for inversions to form near the surface of the basin as well as at high altitudes above 800 hPa, particularly at the high altitudes where the intensity of the off-ground inversion is very strong in the winter, autumn, and spring. The inversions will further lead to a more stagnant atmosphere over the basin, which is not conducive to the upward transport and dispersion of pollutants.

This study attempts to investigate the atmospheric effects of topography around the SCB from a long-term climatic perspective, which is important for furthering the understanding of the effects of topography on the atmospheric environment and the protection of the atmospheric environment within the basin. There may exist uncertainties in this study, such as the fact that most of the analysis in this study was carried out using statistical methods, such as the difference in meteorological conditions between areas within the basin and the same latitude zone was used in studying the role of topography, in which the interference of some other factors, such as differences in underlying surface and/or climatic background, may not be excluded. Therefore, future studies could combine a variety of methods, such as conducting long time scale topographic sensitivity tests in conjunction with chemical transport models, to reduce uncertainties and improve the quantitative understanding of the effects of topography in the SCB.

## Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

## Author contributions

LZ and TZ conceived of the presented idea and designed the research framework with support from XG, XX, XZ, YL and LL. LZ and XG reviewed the literature and drafted the manuscript. LZ and YZ led the data analysis and interpreted the results together with KG. ZS provided critical feedback and constructive comments. All authors were involved in the discussion of the results.

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## Conflict of interest

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