Formation and Evolution Mechanisms of Severe Haze Pollution in the Sichuan Basin, Southwest China

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ABSTRACT

Severe haze episodes are important environmental issues, and the rapid formation and evolution mechanisms of such episodes over complex terrain remain poorly understood. The Sichuan Basin (SCB) periodically experienced heavy haze pollution during the winter of 2016, with the maximum regional average PM2.5 concentration reaching almost 120 µg m⁻³. In this study, we characterize a severe haze episode in the SCB from 20 to 30 January 2017 using comprehensive measurements and model analyses. The evolution of this severe episode shows clear stages, with gradual PM2.5 increases under stagnant weather conditions in Stage I (aerosol accumulation stage) and with explosive PM2.5 increases mainly associated with cross-border transport from the southern SCB in Stage III (rapid formation stage). The process analysis results indicated that primary emissions and aerosol processes were the major sources of PM2.5 in these urban regions, whereas vertical transport and dry deposition generally acted as sinks of PM2.5. In the presence of southwesterly synoptic winds, the aerosols emitted from the southern SCB were transported to Chengdu and the surrounding areas through horizontal transport and accounted for 66% of the PM2.5 concentration in Chengdu during Stage III. Our results reveal the detailed formation mechanism of a severe haze episode in the SCB under the effects of regional transport and synoptic forcing patterns to improve the understanding of haze formation in areas with complex terrain.

Keywords: Air quality; Haze pollution; Process analysis; Sichuan Basin.

INTRODUCTION

Due to rapid economic development and the acceleration of urbanization in China, regional haze pollution characterized by high fine particle (PM2.5) concentrations has become a serious environmental issue (Chan and Yao, 2008; Lei et al., 2011). To mitigate haze pollution, the “Air Pollution Prevention and Control Action Plan (APPCAP)” and the “National Ten Measures” were implemented by the Chinese State Council in 2013 to improve the air quality in China. Although the control measures have been generally successful, large challenges remain, especially regarding the formation and evolution mechanisms of episodes of continuously high PM2.5, which are poorly understood (Zheng et al., 2015; Li et al., 2017;).

Because of serious haze pollution resulting from high anthropogenic emissions and unfavorable meteorological conditions, the Sichuan Basin (SCB) has become one of the most polluted city clusters in China over the last few years (Zhao et al., 2018). Extensive studies have been conducted to explore the source and formation of haze pollution in the SCB (Tian et al., 2017; Qiao et al., 2019a). Based on the National Centers for Environmental Prediction (NCEP) reanalysis data and clustering analysis method, Sun et al. (2020) classified the circulation patterns during periods of continuous pollution in the SCB and found that a weak high-pressure system located in the SCB could enhance pollution by suppressing the planetary boundary layer height (PBLH).
By analyzing the chemical composition of \( \text{PM}_{2.5} \), Song et al. (2019) reported that the secondary conversion of \( \text{SO}_2 \), \( \text{NO}_x \) and nonmethane hydrocarbons (NMHCs) to sulfate, nitrate and secondary organic aerosols (SOAs), respectively, made significant contributions to persistent haze episodes in the SCB. The meteorological conditions in the SCB during winter are characterized by high relative humidity and low temperature, which favor the hygroscopic growth of fine particles and accelerate secondary transformations from gaseous precursors to inorganic ions (Kong et al., 2020). Additionally, the complex basin topography of this region was found to increase the accumulation of \( \text{PM}_{2.5} \) and intensify haze formation by reducing the wind speed and increasing the relative humidity (Zhang et al., 2019). Several studies employed the CTM model to investigate the sources of \( \text{PM}_{2.5} \). Zhang et al. (2016) utilized HJ-1 satellite data and simulation results from the WRF-Chem model to explore the formation of a haze event and found that low mean ventilation coefficients and decrease in PBLH were conducive to the occurrence of severe haze events. Using a source-oriented version of the Community Multiscale Air Quality (CMAQ) model, Qiao et al. (2019b) quantified the relative contributions from regions inside the SCB to the \( \text{PM}_{2.5} \) concentration; they concluded that the transport of secondary inorganic aerosols (SIs) and their precursors made significant contributions to haze pollution during the winter. However, previous studies focused on only monitored air pollutants, and the formation and evolution mechanisms of severe haze pollution in the SCB remain unclear. Consequently, thorough investigations involving the quantitative assessment of contributions from local emissions and regional transport to severe haze episodes are urgently needed (Chen et al., 2014; Luo et al., 2020).

In the present study, we integrate comprehensive monitoring data and the Weather Research and Forecasting-Community Multiscale Air Quality (WRF-CMAQ) modeling system to investigate the sources and formation mechanisms of an extreme regional haze episode in the SCB during the winter of 2016. The paper is organized as follows. In Sect. 2, the model configuration is described. In Sect. 3, the model performance is evaluated by comparison with observations. The formation and evolution mechanisms of the severe haze pollution are presented in Sect. 4. The conclusions are given in Sect. 5.

**METHODS**

**Observational Data**

The simulated meteorological parameters, including temperature, relative humidity, wind speed (WS) and wind direction, are compared with hourly observation data recorded at four typical national standard basic weather stations (Chengdu, Meishan, Ziyang and Neijiang), which were obtained from the China Meteorological Data Service Center (http://data.cma.cn/en). The hourly observed surface \( \text{PM}_{2.5} \) concentrations over the SCB were collected from the China National Urban Air Quality Real-time Publishing Platform (http://113.108.142.147:20035/). The hourly mass concentrations of \( \text{SO}_2^2 \), \( \text{NO}_x^- \), \( \text{NH}_4^+ \), black carbon (BC), elemental carbon (EC) and organic carbon (OC) were determined from samples collected on the roof of the Chengdu Environmental Science Research Institute (approximately 25 m above the ground) in Qingyang District, Chengdu (30°56′N, 104°05′E), from 1 to 31 January 2017. This site (referred as the CDAES site below) is a typical urban site that is close to the mixed commercial and residential area of Chengdu Second Ring Road (Fig. S1). At this sampling site, an in-situ gas and aerosol composition monitor (IGAC/S-611) was used to measure the water-soluble ions (\( \text{SO}_2^2 \), \( \text{NO}_x^- \), and \( \text{NH}_4^+ \)) in \( \text{PM}_{2.5} \) on an hourly basis. Previous studies have verified the accuracy of such monitoring through comparison with the commonly used annular denuder system, and the results showed good agreement (Young et al., 2016; Tao et al., 2018). Hourly concentrations of OC and EC in \( \text{PM}_{2.5} \) were monitored using a Sunset Laboratory Model-4 OC-EC field analyzer with detection limits of 0.4 µg C m\(^{-3}\) for OC and 0.2 µg C m\(^{-3}\) for EC. The organic matter (OM) content was calculated by multiplying the OC content by a factor of 1.4. The hourly concentration of BC in \( \text{PM}_{2.5} \) was monitored at a wavelength of 670 nm using a 5012 multiangle absorption photometer (MAAP, Thermo Fisher Corporation). Additional details were described in previous field studies (Song et al., 2018; Yang et al., 2020).

**WRF-CMAQ Simulation**

The Weather Research and Forecasting (WRF, version 3.9.1) model was applied to simulate meteorological fields, and CMAQ v5.2.1 was utilized to simulate air pollutants in the SCB during winter. The simulation period started on 15 January 2017 and ended on 31 January 2017. The first 5 days were discarded to account for spin-up and not included in the analysis. Fig. S2 illustrates the triple-nested domain with horizontal resolutions of 27 km, 9 km and 3 km. The outer domain covers all of East Asia, and the inner domain covers the SCB, as shown in Fig. 1. Here, we analyzed only the inner domain to minimize the bias from lateral boundary conditions. The vertical dimension had a resolution of 30 sigma layers.

The meteorological inputs for the WRF simulations were obtained from the NCEP Final (FNL) 1.0° × 1.0° reanalysis data (http://dss.ucar.edu/datasets/ds083.2/). To improve the model performance, analysis nudging and observation nudging were adopted, and four-dimensional data assimilation (FDDA) data were obtained from the NCEP Automated Data Processing (ADP) Operational Global Surface (ds461.0) and Upper (ds351.0) Observations. The state variables for the water-vapor mixing ratio, potential temperature, and wind were nudged with strengths of \( 1 \times 10^{-5}, 5 \times 10^{-5}, \text{and} 5 \times 10^{-5} \text{ s}^{-1} \), respectively (Wu et al., 2020; Xing et al., 2017). The initial and boundary conditions for the CMAQ simulation were obtained from the MOZART-4 global chemical transport model (Emmons et al., 2010). We obtained the anthropogenic emissions of air pollutants, with a grid resolution of 0.25° × 0.25°, from the Multiresolution Emission Inventory for China (MEIC) in 2016, which was developed by Tsinghua University (Zheng et al., 2018). To reduce the uncertainty attributed to the outdated spatial surrogates in the spatial-temporal emission allocation process, we utilized the population distribution data from the LandScan 2017 database.
Fig. 1. Average simulated surface PM$_{2.5}$ concentrations in domain I of China (a) and the Sichuan Basin (SCB) (b) in January 2017.

and GDP data from the database of the National Bureau of Statistics of China (NBSC) to allocate the emissions to the grid cells (Deng et al., 2020). The Model of Emissions of Gases and Aerosols from Nature (MEGAN, version 2.1) was used to calculate the biogenic emissions (Guenther et al., 2012). The options for the physical and chemical parameterizations of the WRF-CMAQ model are listed in Table 1.

**Numerical Experiments**

Four sensitivity experiments were performed to quantify the contributions of local emissions and regional transport during the studied episode, as shown in Table 2. In the BASE simulation, all anthropogenic and biogenic emissions were included. In the No-Anth experiment, only biogenic emissions were included. In the NoCD-Anth experiment, the anthropogenic emissions in Chengdu city were turned off. In contrast, we considered only anthropogenic emissions in Chengdu city in the OnlyCD-Anth experiment. Based on the above experiments, the relative contribution from regional transport was determined by comparing the simulation results of BASE to those of OnlyCD-Anth. The contribution from local emissions to the PM$_{2.5}$ concentration was identified by subtracting the NoCD-Anth results from the BASE results.

**Process Analysis**

Process analysis (PA) is a diagnostic method incorporated into the CMAQ model and includes integrated process rate (IPR) analysis and integrated reaction rate (IRR) analysis (Byun and Ching, 1999). The IPR method has been widely used to track the hourly relative contributions of physical/chemical processes to PM$_{2.5}$ concentrations in previous studies (Gao et al., 2014; Fan et al., 2015; Huang et al., 2016). In this study, the IPR method was used to assess the processes that influence simulated PM$_{2.5}$ concentrations. The nine types of processes are gas-phase chemistry (denoted CHEM), emission sources (denoted EMIS), aerosol processes (denoted AERO), cloud processes (denoted CLDS), dry deposition (denoted DDEP), horizontal advection (denoted HADV), horizontal diffusion (denoted HDIF), vertical advection (denoted ZADV) and vertical diffusion (denoted VDIF). It should be noted that horizontal transport (denoted HTRA) is defined as the sum of horizontal advection and horizontal diffusion, and vertical transport (denoted VTRA) is defined as the sum of vertical advection and vertical diffusion.

**MODEL EVALUATION**

**Meteorological Parameters**

We evaluated the performance of the WRF model to demonstrate the capability of the modeling system through verification statistics, including the normalized mean bias (NMB), the index of agreement (IOA), and the root mean square error (RMSE), for the hourly 2-m temperature (T2), 2-m relative humidity (RH2), 10-m wind speed (WS10) and 10-m wind direction (WD10) at the Chengdu, Meishan, Ziyang and Neijiang meteorological stations. As shown in Table 3, the simulated T2 and RH2 agreed well with the observations, with IOA values higher than 0.80, indicating that the model successfully captured the variation in T2 and RH2 in these four cities. For WS10 and WD10, the model displayed negative bias, with NMB values ranging from 16.69 to 42.36 and from 28.79 to 36.29, respectively. This bias may be attributed to the complex basin terrain and planetary boundary layer parameterization. Overall, these comparisons clearly demonstrate that the WRF model adequately reproduced the meteorological conditions.

**PM$_{2.5}$ and its Chemical Components**

Fig. 2 shows the time series of simulated hourly PM$_{2.5}$ concentrations in the BASE simulation and the observed PM$_{2.5}$ levels in the four cities from 20 to 30 January 2017.
Generally, the CMAQ model reasonably reproduced the temporal evolution of the observed PM$_{2.5}$ concentrations in the four cities, with IOAs of 0.89, 0.84, 0.80, and 0.93 and mean biases of $-12.3 \, \mu g \, m^{-3}$, $-16.8 \, \mu g \, m^{-3}$, $-23.6 \, \mu g \, m^{-3}$ and $-5.8 \, \mu g \, m^{-3}$ for Chengdu, Meishan, Ziyang and Neijiang, respectively. In general, the CMAQ model captured the peaks and temporal variations in the PM$_{2.5}$ concentrations from 20 to 28 January in these cities but underestimated the peak PM$_{2.5}$ concentration on 28 January in Zigong.

Fig. 3 compares the simulated and observed OM, SO$_2^-$, NO$_3^-$, and NH$_4^+$ concentrations at the CDAES site averaged from 20 to 30 January 2017. The CMAQ model underestimated the concentrations of OM, SO$_2^-$ and NO$_3^-$ by 0.8 $\mu g \, m^{-3}$, 2.3 $\mu g \, m^{-3}$, and 5.1 $\mu g \, m^{-3}$, respectively, but overestimated the NH$_4^+$ concentration by 1.3 $\mu g \, m^{-3}$. For OM, the underestimation may have been attributed to the lack of SOA parameterizations in the AERO06 aerosol module. The bias associated with SIAs (including NH$_4^+$, SO$_2^-$ and NO$_3^-$) has also been noted in previous studies and potentially derives from the lack of heterogeneous reactions in the chemistry mechanisms in the models, the allocation bias for emission inventories, and the failure to capture relevant changes in meteorological conditions (Zheng et al., 2015).

RESULTS AND DISCUSSION

Spatiotemporal Evolution of Severe Haze Formation
The weather conditions and air pollutant concentrations in four highly polluted cities during this episode are presented in Fig. 4. During this severe haze episode, the PM$_{2.5}$ concentrations in these cities all reached peak values on January 28th; notably, the surface PM$_{2.5}$ concentration rapidly increased from 100 $\mu g \, m^{-3}$ to more than 600 $\mu g \, m^{-3}$ in less than a day in Neijiang and Zigong; these peaks were the highest values recorded in 2017. The weather conditions in the SCB were characterized by persistent high relative humidity greater than 90% and low WS10 (less than 3 m s$^{-1}$) during this period.

Fig. 5 shows the spatial distributions of the simulated daily mean surface PM$_{2.5}$ concentrations within the SCB from 20 to 28 January 2017. Before the haze episode (e.g., on January 20), the daily PM$_{2.5}$ concentration in most areas

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Table 1. Modeling configuration used for the WRF-CMAQ simulations.

| Model attribution | Configuration |
|-------------------|---------------|
| Simulation period | 15 January 2016 to 31 January 2017 (5-day spin-up period) |
| Domain            | Sichuan Basin; Center = 30°N, 104°E |
| Horizontal resolution | 27 km/9 km/3 km |
| Vertical resolution | 30 layers from the surface to 50 hPa |
| Microphysics      | Lin scheme |
| PBL physics scheme | Yonsei University (YSU) scheme |
| Shortwave and longwave radiation | Rapid Radiative Transfer Model for GCMs (RRTMG) |
| Land surface model | Noah land surface model |
| Gas-phase chemistry | Carbon bond chemical reaction mechanism (CB06) |
| Aerosol module/size | AERO06/3 modes |

Table 2. Statistical metrics for comparing the observations and simulations.

| Simulation | Description |
|------------|-------------|
| BASE       | All anthropogenic and biogenic emissions are included |
| No-Anth    | Only biogenic emissions are included |
| NoCD-Anth  | Anthropogenic emissions in Chengdu city are excluded |
| OnlyCD-Anth| Considers only anthropogenic emissions in Chengdu city |

Table 3. Statistical metrics between the observations and simulations.

|                    | Chengdu | Meishan | Zigong | Neijiang |
|--------------------|---------|---------|--------|----------|
| 2-m Temperature    |         |         |        |          |
| NMB                 | -6.62   | -3.69   | -9.68  | -11.36   |
| RMSE                | 4.16    | 2.12    | 6.47   | 6.81     |
| IOA                 | 0.94    | 0.97    | 0.91   | 0.91     |
| 2-m Relative Humidity |       |         |        |          |
| NMB                 | -6.69   | -10.49  | -11.2  | -13.2    |
| RMSE                | 15.81   | 14.64   | 12.28  | 16.49    |
| IOA                 | 0.86    | 0.80    | 0.89   | 0.79     |
| 10-m Wind Speed     |         |         |        |          |
| NMB                 | 16.69   | 22.85   | 37.41  | 42.36    |
| RMSE                | 2.03    | 2.19    | 3.32   | 2.94     |
| IOA                 | 0.72    | 0.62    | 0.66   | 0.69     |
| 10-m Wind Direction |         |         |        |          |
| NMB                 | 28.79   | 36.29   | 35.78  | 29.46    |
| RMSE                | 46.97   | 56.81   | 42.23  | 49.44    |
| IOA                 | 0.60    | 0.56    | 0.64   | 0.58     |
of the SCB was less than 100 µg m\(^{-3}\) under a prevailing clean southerly air flow. On 21 January, a uniform pressure field was present over the basin, and the regional average WS was less than 3 m s\(^{-1}\). The boundary layer became stable (see Fig. S3), which was favorable for constraining the aerosol particles within the low mixing layer. Consequently, a high PM\(_{2.5}\) belt formed over the western SCB, with the daily mean PM\(_{2.5}\) concentration exceeding 140 µg m\(^{-3}\). During this stage, a uniform pressure field continuously controlled most regions of the SCB, resulting in PM\(_{2.5}\) concentrations higher than 120 µg m\(^{-3}\). However, on 26 January, the SCB was affected by effective convection caused by synoptic conditions, resulting in a temporary decrease in the concentration of PM\(_{2.5}\) due to wet scavenging by precipitation. On 27 January, the weather pattern over the SCB was characterized by strong anticyclonic circulation. Moreover, the SCB is located behind a ridge centered in eastern Tibetan (Fig. S4(g)), which causes the prevailing regional wind field to transition to strong southeasterly winds. Therefore, air masses were transported from south to north, leading to a significant increase in the PM\(_{2.5}\) concentration in Chengdu and the surrounding areas, with the maximum daily mean value exceeding 270 µg m\(^{-3}\). After 28 January, the SCB was affected by northerly winds that brought dry and clean air masses into the basin. The PM\(_{2.5}\) concentrations in most areas of the SCB decreased to 40–100 µg m\(^{-3}\).

Based on the evolution pattern of simulated PM\(_{2.5}\) concentrations over the SCB, we divide this episode into four stages:

(I) The aerosol accumulation stage (20–25 January). In Stage I, the daily mean PM\(_{2.5}\) concentrations averaged over the SCB slowly increased from 30.8 to 240.7 µg m\(^{-3}\), and these levels persisted for five days.

(II) The clearance stage (26 January). The PM\(_{2.5}\) concentrations in the SCB decreased to 80 µg m\(^{-3}\), which was caused by precipitation.

(III) The rapid formation stage (27–28 January). During this
stage, the daily average PM$_{2.5}$ concentrations in most cities of the SCB reached the “heavily polluted” air quality threshold value (24-h average PM$_{2.5}$ concentration $> 150$ µg m$^{-3}$). In Neijiang and Leshan, the PM$_{2.5}$ concentration even reached 897 and 724 µg m$^{-3}$, respectively.

(IV) The aerosol dispersion stage (29-31 January). In this stage, the PM$_{2.5}$ concentration gradually decreased dramatically to low levels (50–72 µg m$^{-3}$) with increasing WS10.

**Contributions from Local Emissions versus Regional Transport**

Previous studies have indicated that local anthropogenic emissions are the major source of high PM$_{2.5}$ concentrations during severe haze episodes in the SCB (Fan et al., 2020). Despite the dominant contribution from local emissions, the contribution of regional transport to PM$_{2.5}$ concentrations has not been fully quantified in the SCB (Zhao et al., 2019). Regional transport is responsible for more than 30% of the PM$_{2.5}$ concentration variations in the SCB during winter.
(Qiao et al., 2019b). In this section, we discuss the contributions of local anthropogenic emissions and regional transport to the PM$_{2.5}$ concentration in the SCB to determine the relative importance of each factor during the studied severe haze episode.

Fig. 6 illustrates the relative contributions of local emissions and regional transport to the simulated PM$_{2.5}$ level in Chengdu city. The episode featured different evolution processes, with a gradual PM$_{2.5}$ increase in Stage I and an explosive PM$_{2.5}$ increase in Stage III. In Stage I, the stagnant conditions near the surface and low WS10 were not conducive to the dispersion of air pollutants, which led to the local accumulation and chemical production of secondary pollutants. Therefore, the relatively high PM$_{2.5}$ concentration (141.1 µg m$^{-3}$) was principally caused by local emissions during Stage I. In Stage II, the PM$_{2.5}$ concentration in Chengdu was mainly associated with the combined effects of local emissions and regional transport. The contributions of local emissions and regional transport to the PM$_{2.5}$ concentration were comparable in this stage (44% versus 52%, respectively). The cross-border transport of polluted air masses from the southern SCB under prevailing southeasterly winds was the main contributor to haze formation in Stage III, with the contribution of regional transport reaching 66% and that of local emissions reaching 32%. During Stage IV, the PM$_{2.5}$ levels in Chengdu were dominated by local contributions (58%), and the contribution from regional transport decreased to 38%.

Fig. 5. The spatial distributions of simulated daily PM$_{2.5}$ concentrations (shaded, µg m$^{-3}$) and wind vectors (arrows, m s$^{-1}$) from 20 to 28 January 2017.
Fig. 6. Contributions of local emissions (red) and regional transport (blue) to the surface PM$_{2.5}$ concentrations averaged over Chengdu from 20 to 30 January 2017. The absolute contributions (µg m$^{-3}$) are shown using bars, and the percent contributions (%) are shown using lines. The PM$_{2.5}$ concentration and the percent contributions averaged over each stage are listed at the bottom of the figure. Note: The “others” contribution represents the PM$_{2.5}$ concentration biased from the brute force method.

However, it should be noted that the brute force method used in this study to attribute the contribution of local emissions and regional transport has limitations due to nonlinearities of the chemistry of PM$_{2.5}$ formation (Clappier et al., 2017; Thunis et al., 2019). Although the brute force method has been widely used in estimating the contributions of PM$_{2.5}$ sources (Kim et al., 2017; Chen et al., 2019; Cheng et al., 2019), further investigations using source-oriented methods such as CAMx-PSAT and CMAQ-ISAM should be considered to reduce the nonlinear effects in future studies.

Process Analysis of Variations in the PM$_{2.5}$ Concentration

Fig. 7 shows the hourly contributions of individual atmospheric physical and chemical processes to variations in the surface PM$_{2.5}$ concentration over Chengdu in different stages. In the beginning of Stage I, EMIS was the dominant source of surface PM$_{2.5}$ in Chengdu and was responsible for 72.8% of the accumulated PM$_{2.5}$. Compared with the dominant effect of EMIS on the PM$_{2.5}$ concentration, the contribution of AERO to surface PM$_{2.5}$ was relatively small, accounting for only ~8.8% of the accumulated PM$_{2.5}$ mass concentration. The contribution of CLDS was almost negligible in the surface layer. DDEP, HTRA and VTRA were the major removal pathways of PM$_{2.5}$, accounting for ~66.6, ~14.8% and ~76.4% of the removal, respectively. The maximum positive contribution of EMIS was observed during rush-hour periods (07:00–08:00 and 16:00–19:00), whereas the maximum negative contributions of VTRA appeared at midnight. The PA results in the middle of Stage I (January 21–22) differed from those at the beginning of Stage I. Even though EMIS still acted as the predominate contributor to PM$_{2.5}$, HTRA gradually became the second largest source of surface PM$_{2.5}$, accounting for 24.3%. In Stage II, the contribution of AERO to the surface PM$_{2.5}$ was quite low compared with that in Stage I. Notably, the PM$_{2.5}$ concentration decreased dramatically during this stage, which can be attributed to wet deposition as a result of precipitation events (as discussed before). When the episode reached Stage III, the contribution from HTRA increased dramatically, as an important source of PM$_{2.5}$ in addition to primary emissions. This phenomenon reflected the important role of regional PM$_{2.5}$ transport from the southern SCB to Chengdu and the surrounding areas under the prevailing wind fields (see Fig. 5(h)–5(i)). Additionally, VTRA still had a negative influence on the PM$_{2.5}$ concentration and was responsible for ~88% of the reduction. It should be noted that the maximum negative contributions of VTRA in Stage III appeared at night due to the strong southeasterly winds. During Stage IV, although EMIS still acted as a stable source of PM$_{2.5}$, HTRA became the main process of PM$_{2.5}$ removal, leading to a gradual decrease in the PM$_{2.5}$ concentration. In summary, the rapid increase in PM$_{2.5}$ in Chengdu was mainly attributed to HTRA, which reflected the influence of regional transport from the southern and southeastern SCB. Furthermore, the essential role of primary EMIS, which acted as a stable positive contributor to PM$_{2.5}$, cannot be neglected.

CONCLUSIONS

In this study, we comprehensively investigate the formation and evolution mechanisms of a severe regional haze episode that occurred over the SCB from 20 January 2017 to 31 January 2017. The roles of local emissions and regional transport in the haze episode were identified by sensitivity experiments. Additionally, the IPR method was used to quantify the contributions of each physical/chemical process to the variation in the PM$_{2.5}$ concentration.

Four haze stages were identified, with a record-breaking hazy episode with a peak concentration of nearly 400 µg m$^{-3}$...
was observed on 27 January. Sensitivity experiments indicated that the local emissions in Chengdu accounted for 46% of the total PM$_{2.5}$ concentrations on average, thus acting as a stable positive contributor. In Stage I, the concentration of surface PM$_{2.5}$ was controlled by local emissions (68%). The contribution of regional transport from the areas within the simulation domain, excluding Chengdu, increased significantly (Stages II and III), which was the main cause of the persistent severe episode. Therefore, joint emission control is the most effective way to mitigate regional haze pollution.

Based on the IPR analysis, emissions (EMIS) and aerosol chemistry (AERO) were the major sources of pollutants and were responsible for 1.3% and 5.2% of the PM$_{2.5}$, respectively. In contrast, the main sinks were VTRA and DDEP during the study period, accounting for 9.4% and 5.2% of reduction, respectively. However, the substantial PM$_{2.5}$ increase in Chengdu during the rapid formation stage was attributed to the positive contribution of HTRA, indicating that regional transport is significant in regional haze formation. To further promote our understanding on severe haze episodes occurred over SCB in wintertime, future work should be considered on elucidating the formation of organic aerosols under high RH and cloudy conditions. Additional work is also needed to identify the contribution from different source regions to the PM$_{2.5}$ and major transport pathways at different heights in order to further understand the regional transport mechanism (Huang et al., 2020).

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SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at https://doi.org/10.4209/aaqr.2020.04.0173

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