Science of the Total Environment 758 (2021) 143710

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Importance of regional $PM_{2.5}$ transport and precipitation washout in heavy air pollution in the Twain-Hu Basin over Central China: Observational analysis and WRF-Chem simulation

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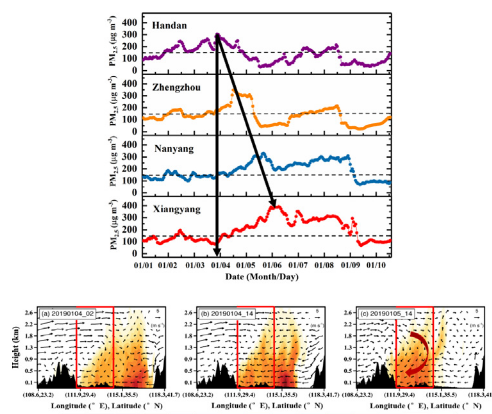
HIGHLIGHTS

- A quasi 2-day regional $PM_{2.5}$ transport from northern to central China
- Cold air invasion and terrain block facilitated air pollution over the THB.
- Regional transport to the THB contributed 70.5% to heavy $PM_{2.5}$ pollution.
- Precipitation washout largely dispelling the THB's heavy $PM_{2.5}$ pollution

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 19 August 2020
Received in revised form 9 November 2020
Accepted 9 November 2020
Available online 14 November 2020

Editor: Pingqing Fu

Keywords:
$PM_{2.5}$ pollution
Twain-Hu Basin
Regional transport
Precipitation washout
WRF-Chem

ABSTRACT

With observational analysis and WRF-Chem simulation on a heavy air pollution event in January 2019 over the Twain-Hu Basin (THB) in Central China, this study characterized the regional transport of $PM_{2.5}$ emitted from the North China Plain (NCP) to the THB region in Central China and quantitatively assessed the influence of the regional $PM_{2.5}$ transport and precipitation washout on $PM_{2.5}$ change in the wintertime heavy air pollution over the THB. It was found that the THB's heavy air pollution event was exacerbated by the strong northeasterly winds driving a quasi 2-day time lag of regional $PM_{2.5}$ transport from the NCP to the THB. The multi-scale atmospheric circulations of cold air invasion influenced by East Asian winter monsoon and the terrain block of THB altered the structures of regional $PM_{2.5}$ transport in deteriorating air quality to the THB. It was assessed for the THB region that the enhancing contribution of regional $PM_{2.5}$ transport to the high air pollution level reached up to 70.5% in the heavy air pollution, and the precipitation washout could contribute the 55.3% $PM_{2.5}$ removal to dissipating the $PM_{2.5}$ pollution over the THB with frequent precipitation and wet environment, distinguishing from the dominance of wind-cleaning air pollution in the other regions in China.

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https://doi.org/10.1016/j.scitotenv.2020.143710

1. Introduction

China is confronted with air pollution of fine particulate matter $PM_{2.5}$ with aerodynamic diameters equal to or less than 2.5 μm in the ambient atmosphere over the recent decades (Guo et al., 2014; T. Wang et al., 2019; Zhao et al., 2017). Apart from posing a threat to human health (Chen et al., 2017; Liu et al., 2016; Pope and Dockery, 2006), severe $PM_{2.5}$ episodes can lead to lower atmospheric visibility (Tao et al., 2012), and long term effects of high $PM_{2.5}$ levels can impact climate changes (Kan et al., 2012; J. Li et al., 2017), which has become an urgent issue in environmental sciences (Yang et al., 2013; Ye et al., 2016).

Air pollution events occur in the stagnantly meteorological conditions with air temperature inversion, weak winds, and stable boundary layers in addition to high anthropogenic emissions of air pollutants (Y. Wang et al., 2019; Xu et al., 2016; H. Zhang et al., 2015; Zhang et al., 2018; Zhong et al., 2019). Furthermore, regional transport of air contaminants is also an important factor that worsens regional air pollution (Z. Li et al., 2017; Miao et al., 2017; L. Chen et al., 2019; Jiang et al., 2015). Governed by strong winds, air pollutants can be transported easily from the upstream source regions to the downwind receptor areas, which can result to the excessive levels of air pollutants including $PM_{2.5}$ at receptors in the downwind region (Wang et al., 2017; Wu et al., 2017; Miao et al., 2019). Regional transport of gaseous precursors of $PM_{2.5}$ could contribute up to 70% secondary particles for the severe haze pollution in Beijing (Hua et al., 2016). The regional transport of polluted air masses over the Central and Eastern China (CEC) was the main factor leading to the increases of wintertime $PM_{2.5}$ concentrations in Wuhan, which could contribute 53.4%~65.0% in the heavy air pollution events (Lu et al., 2017; Lu et al., 2019; Yu et al., 2020). The contribution of regional $PM_{2.5}$ transport was ranged from 29% to 60% to $PM_{2.5}$ pollution in East and South China (Q. Chen et al., 2019; Ji et al., 2018; Kang et al., 2019).

Determined by air pollutant emissions and meteorological conditions, air pollution events frequently occur in four regions over China including the North China Plain (NCP) (Han et al., 2018; Sun et al., 2016; Zhang et al., 2019), the Yangtze River Delta (YRD) (Huang et al., 2020) in East China, the Sichuan Basin (SCB) (Du et al., 2020; Ning et al., 2018) in Southwest China and the Pearl River Delta (PRD) (Huang et al., 2018) in South China. The Twain-Hu Basin (THB) with the lower lands (mainly less than 200 m a. s. l.) of two provinces Hubei and Hunan in Central China is a geographical junction linking NCP in the north, YRD in the east, PRD in the south and SCB in the west (Fig. 1). In recent years, the THB has been confronting severe air pollution (Bai et al., 2018; X.Y. Zhang et al., 2015) and high AOD values (>0.8) in winter based on 19 years of MODIS data (Shen et al., 2020a, 2020b). Importantly, the THB is situated at a crossroads of regional transport of air pollutants over central and eastern China with the prevailing winds of East Asian monsoons. Previous studies of air pollutants' regional transport were mostly concentrated on the regions of NCP, YRD, SCB and PRD (Chang et al., 2018a, 2018b; Huang et al., 2020; Kang et al., 2019; X. Li et al., 2019; R. Li et al., 2019; Ma et al., 2017; Zhang et al., 2019). However, the structures of regional $PM_{2.5}$ transport with the contribution to the heavy air pollution event in the THB region have been poorly understood.

Wet scavenging is an important process of aerosol removals from the atmosphere, which are sorted as in-cloud and below-cloud scavenging processes (Seinfeld and Pandis, 2006). The in-cloud scavenging process happens when aerosols serve as cloud condensation nuclei (CCN) and ice nuclei (IN), or directly captured by cloud drops, while the below-cloud process is an aerosol washout by precipitating raindrops or snow particles (Chate, 2005). These two wet scavenging processes are regarded as crucial for changing aerosol concentrations in the atmosphere (Luan et al., 2019). Therefore, what extend of aerosol wet scavenging by precipitation in the $PM_{2.5}$ removal over the THB with frequent precipitation and wet environment needs a quantitative assessment.

In this study, we utilized the observed data of air pollutants and meteorology to investigate a heavy air pollution event in January 2019 over the THB associated with regional $PM_{2.5}$ transport from the source regions in Northern China. Furthermore, by employing the air quality model WRF-Chem, we simulated the structures of regional $PM_{2.5}$ transport to the THB and assessed the contribution of regional $PM_{2.5}$ transport and aerosol removal by precipitation washout to heavy air pollution event occurred in the THB. The objective of this study was to understand the importance of regional $PM_{2.5}$ transport and precipitation washout in air pollution over Central China with an implication for regional change of air quality in a downwind region with frequent precipitation and wet environment.

2. Data and methods

2.1. Data

Here, we used the hourly surface $PM_{2.5}$ concentrations over central-eastern China from the China Air Quality Online Monitoring and Analysis Platform (http://www.mee.gov.cn), the data of u- and v-wind components at 10 m from the hourly ERA5-Land data - the reanalysis dataset from ECMWF (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land?tab=form), and the near-surface meteorological data over the THB with a temporal resolution of 1 h from China Meteorological Administration (http://data.cma.cn/), including

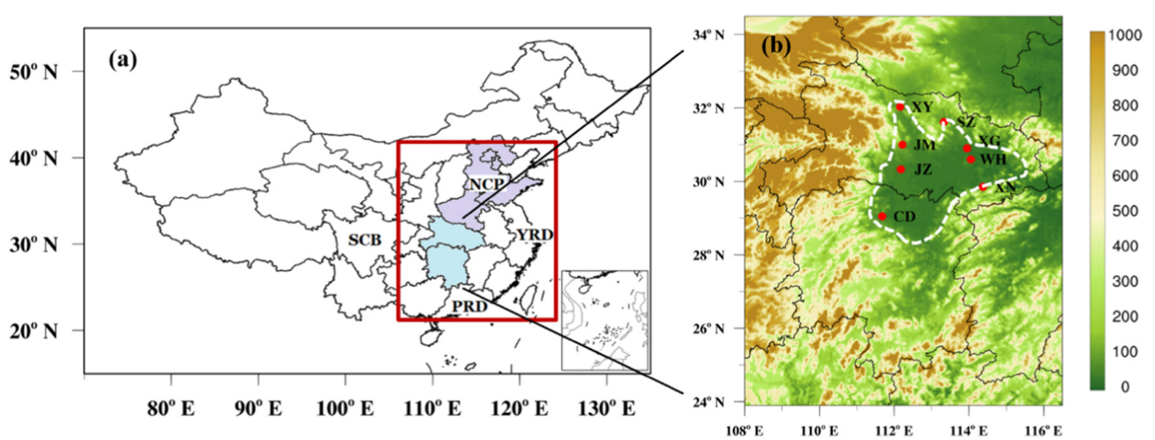

Fig. 1. (a) The geographical positions of two provinces, Hubei and Hunan (blue areas), in Central China with the red frame covering the WRF-Chem simulation domain and the NCP (grey areas), PRD, YRD and SCB region; (b) the terrain height (m in a.s.l.) in the THB (white dashed line) with eight urban sites Xiangyang (XY), Jingmen (JM), Jingzhou (JZ), Changde (CD), Suizhou (SZ), Xiaogan (XG), Wuhan (WH) and Xianning (XN) and surrounding regions.

air temperature, relative humidity, sea level pressure, wind speed, wind direction and precipitation. Time we mentioned in this study was the local time in China (UTC + 8:00 h).

2.2. Model configuration

The Weather Research and Forecasting model with Chemistry (WRF-Chem) version 3.4.1 online coupling model (Grell et al., 2005) was employed to simulate a $PM_{2.5}$ pollution event over the THB. The simulation domain (Fig. 1) was centred at 30.5° N and 114.06° E with 9 km × 9 km horizontal resolution. The vertical 38 hybrid layers were set from the surface to 50 hPa, the lowest 21 levels in the planetary boundary layer (PBL) to better reproduce the air pollution event. The NCEP Final Global Forecast System Operational Analysis (FNL) 6-hourly dataset with a horizontal resolution of $1^0 \times 1^0$ was selected to be the meteorologically initial driving fields and boundary conditions.

Nudging-based four-dimensional data assimilation (FDDA) was used to effectively reduce model errors with the nudging coefficient of 3.0×10^{-4} for wind, air temperature and water vapour mix ratio, and we selected spectral nudging matching 10 and 5 wavenumbers in zonal and meridional directions respectively.

The parameterization used in the model configuration for the WRF-Chem simulation experiment were summarized in Table 1.

The Multi-resolution Emission Inventory for China (MEIC) with a high spatial resolution (0.25° × 0.25°) (http://www.meicmodel.org/) from 2016 was applied for the anthropogenic air pollutant emissions.

A heavy air pollution event with surface $PM_{2.5}$ concentrations over 150 μg m^{-3} was observed from January 4–9, 2019 in the THB region (Fig. S1). In order to simulate the heavy air pollution event, a period of WRF-Chem modelling was chosen from 00:00 a.m. of January 2 to 07:00 a.m. of January 10, 2019, with the spin-up time of the first 36 h.

2.3. Numerical experiments

In addition to the control experiment (CE), we designed two sensitivity experiments TE (transport experiment) with closing all anthropogenic emissions of air pollutants over the THB, and WE (washout experiment) with closing wet scavenging from precipitation to $PM_{2.5}$ concentrations to evaluate the contribution of regional $PM_{2.5}$ transport and precipitation wet removal to $PM_{2.5}$ changes in the heavy air pollution event occurred over the THB. The detail information of the simulation experiments performed in this study is listed in Table 2.

2.4. Modelling validation

The CE modelling results of meteorology and $PM_{2.5}$ concentrations were validated with the observational data in the THB (Figs. 2, S2 and Table 3). The statistical metrics, including correlation coefficient (R), mean bias (MB), the root mean square error (RMSE), the normalized mean bias (NMB), the mean fractional bias (MFB), and the mean fractional error (MFE), were used in the modelling validation. The CE simulated meteorology generally agreed well with the observations (Figs. 2, S2). Meanwhile, the simulated $PM_{2.5}$ values were reasonably consistent with the observations (Table 3), meeting the good modelling performance proposed by Boylan and Russell (2006). Overall, the simulations of meteorology and $PM_{2.5}$ predicted by WRF-Chem over the THB presented the good agreements with the observations. Therefore, the simulation data could be used to investigate the regional transport and precipitation washout of $PM_{2.5}$ in the heavy air pollution over the THB.

Table 1
Parameterization schemes used in the WRF-Chem model.

Options	WRF-Chem
Microphysics	Lin scheme
Longwave radiation	RRTMG scheme
Shortwave radiation	Goddard shortwave scheme
Surface layer	MM5 similarity surface layer
Land-surface	the unified Noah land surface model
Urban canopy model	Single-layer UCM scheme
Boundary layer	YSU boundary layer scheme
Cumulus	Grell 3-D ensemble scheme
Photolysis	Fast-J
Chemistry	CBMZ
Aerosol	MOSAIC (4 bins)
Spectral nudging	On

Table 2
The description of three simulation experiments in this study.

Experiments	Description
CE (control experiment)	the base case
TE (transport experiment)	CE with closing all anthropogenic emissions over the THB
WE (washout experiment)	CE with closing $PM_{2.5}$ below-cloud washout from precipitation

3. Results and discussion

3.1. Observational analysis

3.1.1. Regional $PM_{2.5}$ transport captured over CEC

To investigate the regional $PM_{2.5}$ transport observed over central-eastern China (CEC) to the heavy air pollution happened in the THB, the observed $PM_{2.5}$ concentrations over CEC with the near-surface wind vectors from the reanalysis meteorology of ERA5-Land were averaged from 03:00 p.m. of January 3 to 7:00 a.m. of January 10, 2019 (Fig. 3). During this period, the strong northeasterly winds prevailed over CEC (mainly in the NCP), driving the regional transport of $PM_{2.5}$ pollutants sourced from the upwind northern CEC areas to the downwind THB region (Fig. 3). Strong winds are in favour of the removal of air pollutants for the local areas and air pollutant transport to the downwind areas (Wei et al., 2015; Yang et al., 2015).

To further investigate the regional $PM_{2.5}$ transport from the upstream CEC region to the THB, we explored the hourly variations of $PM_{2.5}$ concentrations over January 1–10, 2019 at four observational sites Handan, Zhengzhou, Nanyang, Xiangyang (Fig. 4). Driven by the strong northeasterly winds (Fig. 3), the surface $PM_{2.5}$ peaks advanced southwards at 10 p.m. of January 3, from site 1 (Handan), at 12 p.m. of January 4 to site 2 (Zhengzhou), at 12 p.m. of January 5 to site 3 (Nanyang) and at 00 a.m. on January 6 to site 4 (Xiangyang), indicating a large impact of regional $PM_{2.5}$ transport on enhancing $PM_{2.5}$ concentrations to 392 μg m^{-3} for heavy air pollution in the THB with a quasi-2d time lag (Fig. 4).

3.1.2. Connection of $PM_{2.5}$ changes with precipitation over the THB

In order to figure out the connection of changes of $PM_{2.5}$ concentrations and precipitation washout during the heavy air pollution over the THB, we compared the hourly variations in regional averages of observed $PM_{2.5}$ concentrations and precipitation over the THB (Fig. 5). As shown in Fig. 5, there were two periods of apparent precipitation with dropping $PM_{2.5}$ concentrations down, and the changes of $PM_{2.5}$ concentrations were estimated to have negative correlations with the R values of −0.57 and −0.44 respectively, passing the significant level of 0.05, reflecting the importance of precipitation in removal $PM_{2.5}$ concentrations for dispelling the heavy $PM_{2.5}$ pollution. The contribution of precipitation removal to heavy $PM_{2.5}$ pollution in the THB was quantitatively assessed in Section 3.2.3, based on the modelling experiments.

3.2. WRF-Chem simulation

The control experiment and two sensitivity experiments with closing all anthropogenic emissions of air pollutants over the THB, and

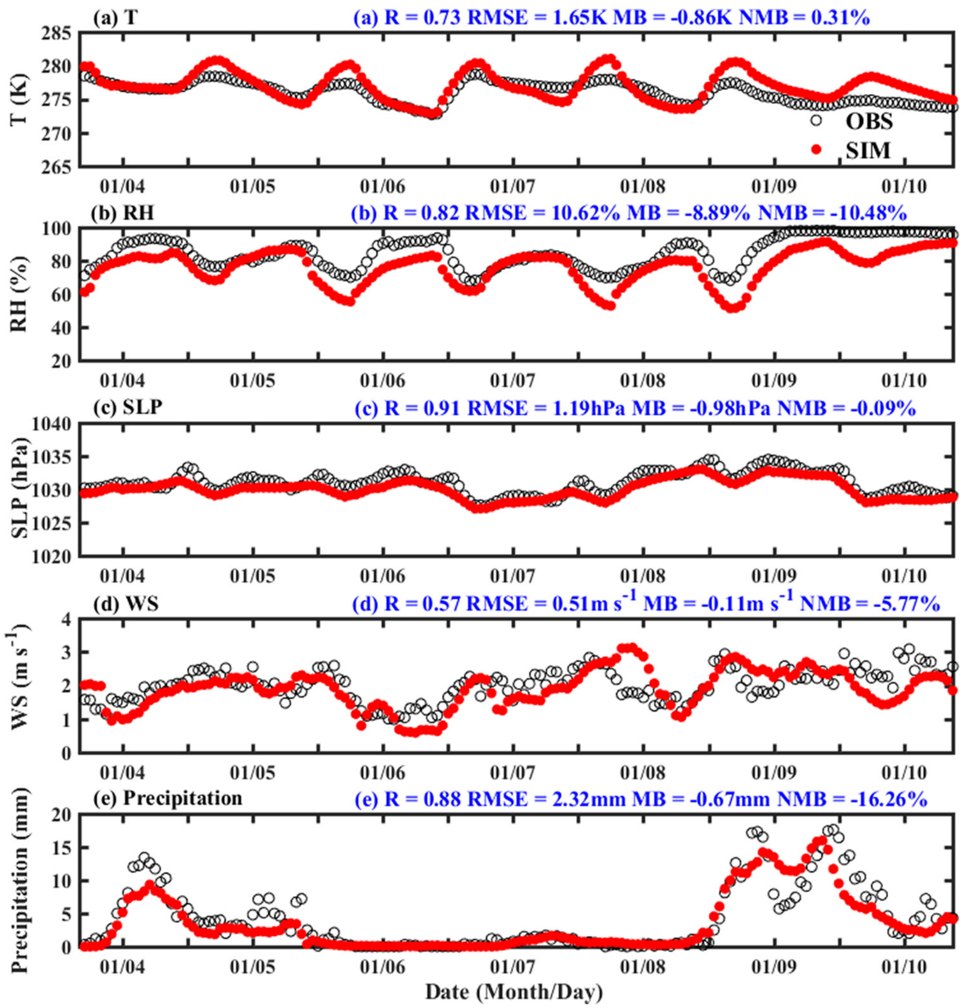

Fig. 2. Hourly changes of observed (black dot lines) and simulated (red dots) meteorological elements including surface air temperature (T), relative humidity (RH) and sea level pressure (SLP) as well as near-surface wind speed (WS) and precipitation averaged over the THB from 03:00 p.m. of January 3 to 7:00 a.m. of January 10, 2019.

with closing $PM_{2.5}$ wet scavenging of precipitation were conducted in this study (Table 2). Based on the three WRF-Chem simulation experiments, we investigated the structures of regional $PM_{2.5}$ transport and also assessed the contribution of regional $PM_{2.5}$ transport and the precipitation wet removal to $PM_{2.5}$ changes to the heavy air pollution observed in the THB in the following sections.

3.2.1. The vertical structures of regional $PM_{2.5}$ transport

To characterize the vertical structures of regional $PM_{2.5}$ transport during the heavy air pollution, Fig. 6 presented the vertical sections (based the back dashed line as shown in Fig. 3) of $PM_{2.5}$ concentrations and wind vectors along the prevailing northeasterly wind direction at 02:00 a.m. of January 2, 02:00 p.m. of January 4 and 5, 2019 based on the control experiment of WRF-Chem simulation. Accompanying a cold air invasion during East Asian winter monsoonal season (Fig.S1), the regional $PM_{2.5}$ transport from the northern CEC region (mainly the NCP) to the THB was generally constrained below 2.6 km in the lower troposphere, where the northerly winds in the lower layers and the southerly winds in the high level made up the vertical circulations in the regional $PM_{2.5}$ transport (Fig. 6). Meteorologically, an invasion of cold air in the northerly winds uplifts warm air in the southerly winds along the surface southward cold front with cold air subsidence behind the cold front (Ding, 1993), which was clearly reflected in the temporal evolution of vertical circulations in the lower troposphere (Fig. 6).

The near-surface $PM_{2.5}$ peaks in the upstream NCP could be emitted from the air pollutant sources there (Fig. 6a–b), the southward movements of the atmospheric column with high $PM_{2.5}$ concentrations along the regional transport were retarded, by blocks of the southerly winds and the windward basin terrain in the THB, and the distinct downward airflow in the regional $PM_{2.5}$ transport with the terrain block of THB was conductive to accumulate near-surface $PM_{2.5}$. Governed by the multi-scale atmospheric circulations, the external transport of $PM_{2.5}$ pollutants emitted from the source region can be transported easily to the downstream receptor areas which can exacerbate acceptor regions' air quality, resulting in a complicated relation of source and receptor in regional transport of air pollutants.

Table 3
Statistical metrics of the comparisons from hourly observed and simulated surface $PM_{2.5}$ concentrations at eight urban sites in the THB.

Indices	NMB (%)	MFB (%)	MFE (%)	RMSE (μg m^{-3})	R
XY	−27.41	−34.58	36.75	81.55	0.85
JM	−23.70	−32.37	41.16	63.41	0.66
JZ	−9.88	−22.63	46.20	57.35	0.55
CD	−24.92	−33.41	44.69	71.12	0.69
SZ	−10.46	−10.73	18.65	35.23	0.86
XG	−6.40	−13.84	29.12	28.10	0.86
WH	−7.89	−10.95	22.46	30.47	0.85
XN	3.39	−4.04	33.31	31.91	0.74

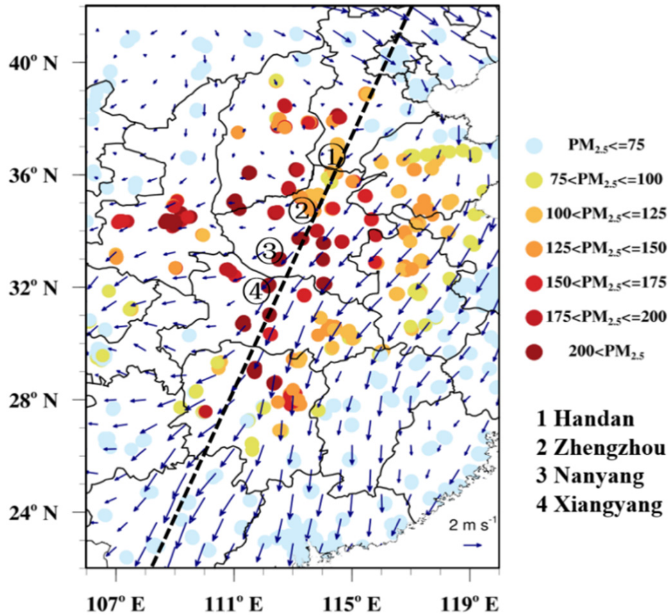

Fig. 3. Spatial distribution of surface $PM_{2.5}$ concentration averages (μg m^{-3}) observed at the sites (coloured dots) and 10 m wind vectors of ERA5-Land from 03:00 p.m. of January 3 to 7:00 a.m. of January 10, 2019, over CEC with the black dash line and four observational sites (numbers with circles) along the direction of prevailing northeasterly winds during the heavy air pollution event.

3.2.2. Contribution of regional $PM_{2.5}$ transport to the heavy air pollution in the THB

In addition to the control experiment (CE), we designed the transport experiment (TE) with closing all anthropogenic emissions of air pollutants over the THB in CE (Table 2). As the TE-simulated $PM_{2.5}$ concentrations were divided by those simulated with CE, the contribution of regional $PM_{2.5}$ transport from the upstream CEC to heavy air pollution in the THB was quantitatively estimated. The spatial distribution of the contribution for regional $PM_{2.5}$ transport presented the significantly decline gradients in the general north-south direction over the THB (Fig. 7). Governing by northeasterly winds, the regional transport of $PM_{2.5}$ pollutants dominated the surface $PM_{2.5}$ changes during the air pollution event with the contribution up to 80–85% in the northern THB, where the western areas were greater than the eastern areas (Fig. 7), demonstrating the effect of the large terrain gap in the western THB (Fig. 1b) on the regional $PM_{2.5}$ transport.

Furthermore, the regional $PM_{2.5}$ transport contribution was averaged over the THB region under conditions of light air pollution (75 μg m^{-3} ≤ $PM_{2.5}$ < 150 μg m^{-3}) and heavy air pollution ($PM_{2.5}$ ≥ 150 μg m^{-3}) respectively, as listed in Table 4. The contributions of regional $PM_{2.5}$ transport to THB were estimated with 58.9% and 70.5% during the light and heavy air pollution periods, respectively. The results provide an important information that regional $PM_{2.5}$ transport played an vital role in $PM_{2.5}$ sources over the THB.

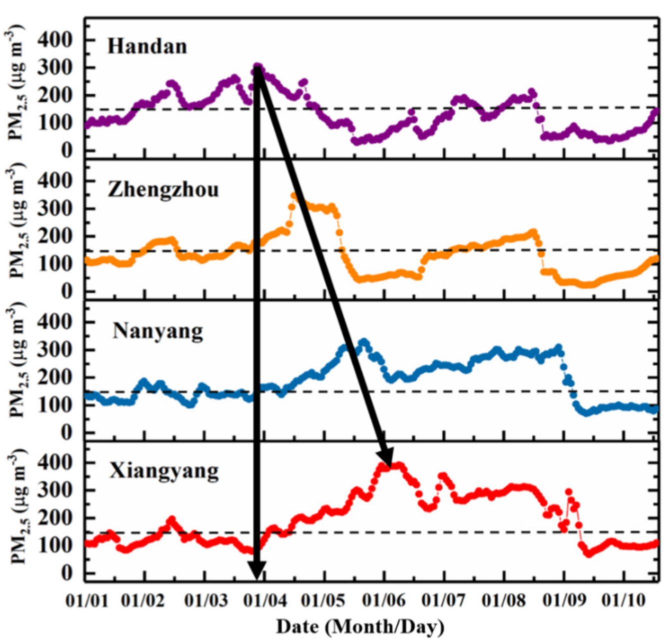

Fig. 4. Hourly changes of $PM_{2.5}$ concentrations observed in three upwind sites, Handan, Zhengzhou and Nanyang (sites 1, 2, 3 in Fig. 3) and the downstream THB's site Xiangyang (site 4 in Fig. 3) during 1–10 January 2019. The grey dash lines indicate the heavy air pollution level of 150 μg m^{-3} for surface $PM_{2.5}$ concentrations. The two arrows indicated the intervals of lag time along with the regional $PM_{2.5}$ transport from Handan to Zhengzhou, Nanyang and Xiangyang during the heavy air pollution episode.

3.2.3. Removal contribution of precipitation washout to surface $PM_{2.5}$ concentrations

As designed in the WRF-Chem modelling experiments (Table 2), the $PM_{2.5}$ washout experiment WE was with closing aerosol below-cloud washout from precipitation in the control experiment CE. Using the method of Feng and Wang (2012) to calculate the precipitation removal contributions, what extend of aerosol wet scavenging by precipitation in the removal of $PM_{2.5}$ over the THB could be quantitatively assessed from WE and CE. There were two apparent precipitation processes from 09:00 p.m. of January 3 to 01:00 p.m. of January 4 (the formation stage) and from 01:00 p.m. of January 8 to 09:00 p.m. of January 9 (the dissipating episodes), respectively (Fig. 5). Therefore, we evaluated the washout contributions of precipitation to surface $PM_{2.5}$ concentrations in the two apparent rainfall processes (Table 5). In the formation stage of heavy $PM_{2.5}$ pollution, the removal $PM_{2.5}$ contribution of precipitation washout removal contribution reached to 17.0%, which could be offset by the $PM_{2.5}$ accumulation during the evolution to heavy air pollution. In the dissipating stage of heavy air pollution, precipitation removal of $PM_{2.5}$ concentrations was accounted for 55.3%, exhibiting that the precipitation washout has a large influence on dispelling the heavy $PM_{2.5}$ pollution over the THB with frequent precipitation and wet environment, differing from the role wind-cleaning air pollution in the other areas in China.

The integrated source apportionment method in CMAQ model (CMAQ/ISAM) is a reliable method evaluating the local/regional contributions to the air pollution, while the sensitivity experiments of zero local emissions conducted by WRF-Chem is also a reasonable way to assess local and regional contributions in many simulation studies (L. Chen et al., 2019; Q. Chen et al., 2019; L. Zhang et al., 2015; Gao et al., 2011). In order to support the sensitivity test results of zero out the local emission to $PM_{2.5}$ levels, CMAQ/ISAM could assess the contribution of regional transport and local emissions to $PM_{2.5}$ concentrations in the THB with a comprehensive comparison with WRF-Chem sensitivity tests in further study.

4. Conclusions

In this paper, we studied a heavy air pollution event occurred in January 2019 over the THB in terms of regional $PM_{2.5}$ transport and precipitation washout by using meteorological and environmental observations, high spatial-resolution reanalysis data of meteorology and WRF-Chem simulations to explore the importance of regional $PM_{2.5}$ transport and precipitation washout in heavy air pollution over Central China.

The strong northeasterly winds prevailed over the NCP, driving the regional transport of $PM_{2.5}$ from the upwind northern NCP areas to

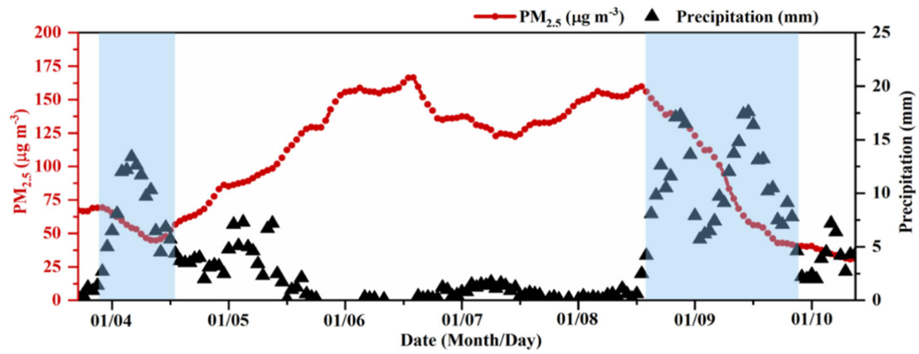

Fig. 5. Hourly changes of average $PM_{2.5}$ concentrations (red line) and precipitation (black triangles) observed over the THB with the light blue shades marking the periods of apparent precipitation.

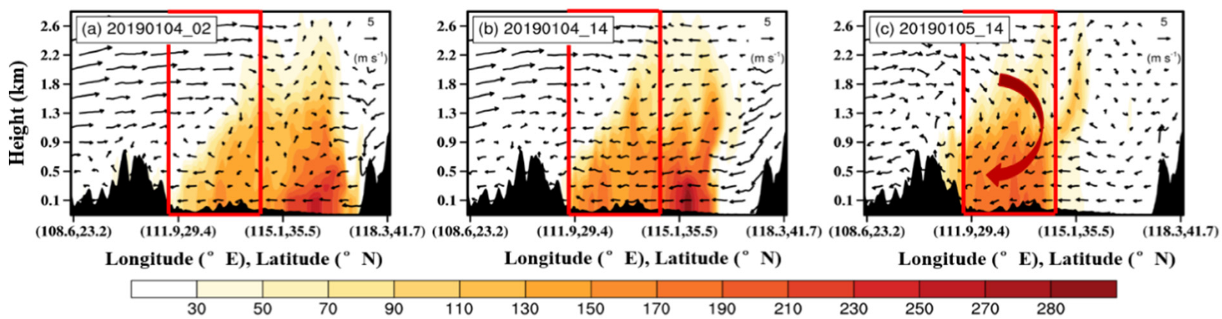

Fig. 6. Vertical cross-sections of simulated $PM_{2.5}$ concentrations (colour contours; μg m^{-3}), wind vectors and terrain (black shades) along the prevailing wind direction (black dash line in Fig. 3) at (a) 02:00 a.m. of January 4, (b) 02:00 p.m. of January 4, and (c) 02:00 p.m. of January 5, 2019, during the heavy air pollution event. Note that the vertical speeds of wind vectors (arrows) are multiplied by 100 for the illustration of vertical circulations. The red frames denote the atmospheric columns over the THB.

the downwind THB region. A quasi 2-day time lag impact of regional $PM_{2.5}$ transport was found on peaking $PM_{2.5}$ concentration in the heavy pollution over the THB region. The multi-scale atmospheric circulations of cold air invasion of East Asian winter monsoon and block of THB terrain could determine the structures of regional $PM_{2.5}$ transport in deteriorating air quality to the THB. The regional transport contribution displayed the obviously decline gradients from north to south over the THB with the regional average reaching to 70.5% during heavy air pollution stage. A strong influence of precipitation washout on dispelling the heavy $PM_{2.5}$ pollution over the THB, and the removal contribution of precipitation to $PM_{2.5}$ was accounted for 55.3%, which was different from the other air pollution regions with the dominant wind-cleaning air pollution.

Based on the investigation of a wintertime heavy air pollution in the THB region, Central China, this study revealed the regional $PM_{2.5}$ transport over CEC with large contributions of regional $PM_{2.5}$ transport and precipitation washout of aerosols to the THB's heavy air pollution. Further exploration can be done with the support of climatic analyses of multi-source data of long term observations and more accurate

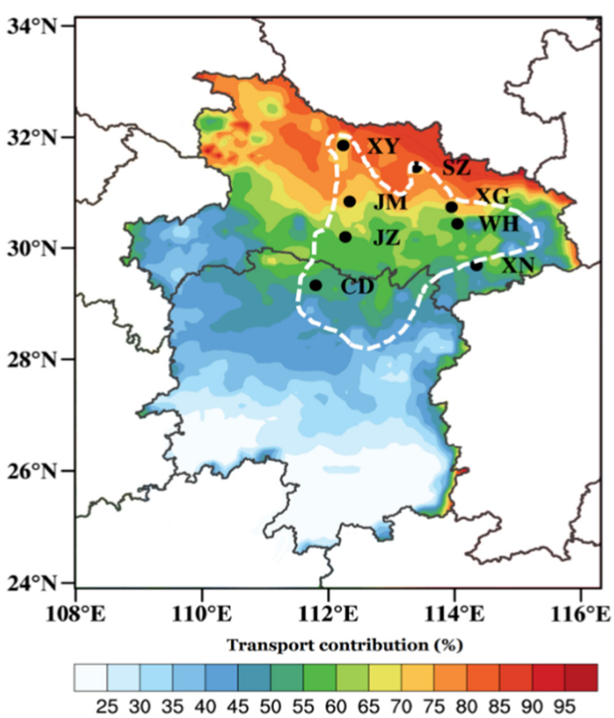

Fig. 7. Spatial distribution of regional $PM_{2.5}$ transport contribution over the THB averaged from 03:00 p.m. of January 3 to 7:00 a.m. of January 10, 2019, with the THB region encircled by the white dash line.

Table 4
Contribution of regional transport and local emissions to surface $PM_{2.5}$ pollutants under different $PM_{2.5}$ pollution levels over the THB.

Air quality	$PM_{2.5}$ levels (μg m^{-3})	Regional transport	Local emissions
Light pollution	$75 \le PM_{2.5} < 150$	58.9%	41.1%
Heavy pollution	$PM_{2.5} \ge 150$	70.5%	29.5%

Table 5
Removal contributions of precipitation washout to surface $PM_{2.5}$ concentrations.

Periods of heavy air pollution	Removal contributions
The formation stage	17.0 %
The dissipating stage	55.3 %

numerical models with the comprehensive parameterizations of physical and chemical processes in the atmosphere.

CRediT authorship contribution statement

Weiyang Hu: Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing. **Tianlaing Zhao:** Conceptualization, Methodology, Funding acquisition, Writing - review & editing, Supervision. **Yongqing Bai:** Conceptualization, Writing - review & editing, Supervision. **Shaofei Kong:** Conceptualization. Data curation, Resources. **Jie Xiong:** Software. Investigation. **Xiaoyun Sun:** Data processing, Investigation. **Qingjian Yang:** Conceptualization. **Yao Gu:** Investigation. Huicheng Lu: Investigation.

Declaration of competing interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled "Importance of Regional $PM_{2.5}$ Transport and Precipitation Washout in Heavy Air Pollution in the Twain-Hu Basin over Central China: Observational analysis and WRF-Chem Simulation".

Acknowledgement

This research was financially funded by grants from National Natural Science Foundation of China (41830965; 42075186; 91744209), the National Key Research and Development Program of China (2016YFC0203304), and the Postgraduate Research & Innovation Project of Jiangsu Province (KYCX20_0951).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.143710.

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