Study on dust occurrence and transportation related to boundary layer height in Northwest China

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Abstract

Boundary layer development has a significant influence on dust emission and transportation. The effects of surface heat flux on distribution of dust related to BLH (boundary layer height) during a dust event in Northwest China are discussed by numerical simulation. The results show that: the dust emissions start in Dunhuang and strengthen in Minqin with large dust emission fluxes (as high as 3000 μg m⁻² s⁻¹) and surface wind speed (up to 20 m s⁻¹). The dust at the early stage mainly concentrates below 500 m above the ground, then lifts over 3000 m above the ground at the strengthening stage, and the concentration in high value center is more than 24,000 μg m⁻³ at the dust source Dunhuang. The high dust concentration in Minqin maintains at about 1000 m above the ground. Weak dust emission in Minqin makes the dust concentration near the ground less than that in the upper air. The BLH in the high dust concentration center is higher than that in the surrounding area at the emission stage in Dunhuang. Sensitivity experiment with turning off surface heat flux shows obvious decrease of the dust concentration in Dunhuang, with more than four times reduction of the surface dust concentration. The BLH near the high dust concentration area reduces significantly in the sensitivity experiment. However, the gap between the two experiments reduces with the dust development. The BLH in the sensitivity experiment has small spatial differences with uniform distribution in Dunhuang. It means that the thermodynamic contribution is main reason for the distribution differences. The two experiments in Minqin also show that the height of high concentration dust has a difference of about 500 m. The dust lifts with the boundary layer development, but shows different distribution characteristics and influencing factors between Dunhuang and Minqin.

KEYWORDS

boundary layer height, dust event, surface heat flux, WRF-Chem
1 | INTRODUCTION

Dust event is a major disastrous weather in arid and semi-arid areas, which has a serious impact on air quality, human health, industrial, agricultural production and traffic safety (Bell et al., 2008; Chan & Ng, 2011; Fitzgerald et al., 2015; Kang et al., 2013). It does not only affect air quality in dust source such as Northwest China, but also transport over long distance to southeast China, or even transmit to overseas under the westerlies (Chen et al., 2009; Fang et al., 1999; Liu et al., 2009). As an important natural component in atmospheric aerosols, dust has significant influences on climate for its radiation effect and condensation nucleus of cloud (Choobari et al., 2014; Huang et al., 2010; Jia et al., 2018; Liu et al., 2019). The long transportation of dust can also impact the marine ecosystem and the biogeochemical cycle by a large amount of organic matters and minerals (Mahowald et al., 2014; Shao et al., 2011).

Radiative forcing of dust acts on atmospheric thermodynamic and dynamic processes and impacts on atmospheric structure. In turn, the atmospheric turbulence, entrainment and horizontal motion can change spatial and temporal distribution of dust. Boundary layer structure is an important factor in the occurrence, variation and transportation of dust event. Dust emission is generally forced by the turbulence in the boundary layer and dynamic structure of strong surface wind shear in vertical direction. Yao (2005) and Peng et al. (2007) pointed out that the change in boundary layer structure can trigger the development of dust event. Deep atmospheric boundary layer height (BLH) is observed in arid climatic areas in China where dust events frequently occur as a product of interaction between strong wind, turbulence and surface cover. Zhang (Zhang, 2003) considered that the atmospheric boundary layer during dust event is mainly manifested in forcing effect of macro-vertical motion caused by strong dry convection and contribution to transport process, as well as the forcing effect of abnormal dust distribution on radiation process. Dust event mainly occurs near the surface, so the surface characteristics have a significant impact on dust event. Thermal condition of the surface determines boundary layer development directly. Wang et al. (2004) studied the distribution characteristics of sensible heating and latent heating during typical sandstorms in China and pointed out the source and sink of the heat during sandstorm process. Sun and Yao (2002) have simulated and analyzed influence characteristics of surface heat flux on sandstorms. However, there are few studies investigated the dust emission and dust transportation from the view of the boundary layers structure.

In recent years, the development of numerical models has made it possible to investigate and forecast dust event. As a two-way feedback model between meteorology and chemistry, WRF-Chem (Weather Research and Forecasting model coupled with Chemistry) can be used to simulate dust event with processes of dust emission, transportation and deposition. Wu and Lin (2014) applied WRF-Chem model coupled with GOCART (Georgia Tech/Goddard Global Ozone Chemistry Aerosol Radiation and Transport) and Shao04 dust emission schemes to investigate the effects of the different schemes on sandstorm simulation and found the two schemes can simulate the main areas of the dust emission, the variation and the spatiotemporal distribution of dust concentration reasonably.

The observations and numerical simulations show that there are three main paths of dust events in China. The northwest path and the west path pass through Hexi Corridor and Loess Plateau in Gansu in Northwest China (Bai et al., 2018). Gansu Province has a narrow region but with diversified climatic areas, which transits from arid area and semi-arid area to semi-humid area and humid area. The western part of Gansu is an important source of the dust such as Hexi Corridor which is a narrow passage with sparse vegetation and serious desertification. When cold air descends southward, the “narrow tube effect” caused by the topography which easily produces strong wind, forms a boundary layer structure to facilitate dust emission, trigger or strengthen dust event (Li et al., 2014; Zhang et al., 2011). In this study, WRF-Chem model is used to investigate the spatial and temporal distribution of dust over the source region Dunhuang and the path of transportation Minqin which related to the boundary layer.

Variation of surface heat flux has an influence on BLH (Luo & Huang, 2012; Zhao et al., 2014). A sensitivity experiment is designed without surface heat flux to analyze the effects on boundary layer development, dust occurrence and transport. In this study, two experiments are performed during a heavy dust event from 23 to 26 January 2017.

2 | MATERIALS AND METHODS

2.1 | Model and data

WRF-Chem is an atmospheric chemical model developed by NOAA (National Oceanic and Atmospheric Administration), NCAR (National Center for Atmospheric Research), NCEP (National Centers for Environmental Prediction) and other institutions. WRF-Chem couples chemical module based on WRF model. The
The greatest advantage of WRF-Chem is the online coupling of meteorological module and chemical module in time and space. It can not only reflect the influence of the change of meteorological elements on chemical processes, but also realize the feedback of chemical processes on meteorological fields. The model considers the advection transport and turbulent diffusion of atmospheric pollutants, wet and dry deposition, aerosol formation, gas-phase chemistry and photolysis (Grell et al., 2005). The WRF-Chem model v3.0 and later version take dust aerosol emission, transport and deposition into consideration. The version used in this study is WRF-Chem v3.8.

The dust emission schemes in WRF-Chem include the GOCART scheme (Ginoux et al., 2001), the AFWA (Air Force Weather Agency) scheme (Jones et al., 2012) and the Shao04 scheme (Shao, 2004), etc. The GOCART scheme is primarily used for simulation of global dust processes (Ginoux et al., 2004; Huneeus et al., 2011). The Shao04 scheme shows good capability in the simulation of the regional dust processes (Kang et al., 2011) and therefore it is used in this study.

Ground observational data provided by the China Meteorological Administration is used to evaluate the simulation of meteorological elements. MODIS (Moderate Resolution Imaging Spectroradiometer) AOD (Aerosol Optical Depth) at 550 nm with a spatial resolution of 10 km × 10 km obtained from Terra and Aqua satellites, PM₁₀ hourly mass concentration data from China National Environmental Monitoring Center of the Chinese Ministry of Environmental Protection are applied to evaluate the simulation of dust concentration and range. The time used in this study is Beijing Time.

2.2 | Experimental design

The simulations use double-nested grids in a horizontal resolution of 27 and 9 km (Figure 1) with the center point at 93°E, 39°N, 48 layers in the vertical direction, and the top pressure is 50 hPa. 1° × 1° FNL (Final Analysis) global reanalysis data provided by NCEP/NCAR is supplied as the meteorological field initial condition and the boundary condition. The initial conditions for gas and aerosol in the chemical module use the idealized Northern Hemisphere mid-latitude atmospheric chemical field outputted by NOAA Aeronomy Lab Regional Oxidant Model (Liu et al., 1996). The main parameterization schemes are Lin microphysical scheme (Lin et al., 1983), Grell 3D ensemble cumulus parameterization scheme (Grell & Dvnyi, 2002), RRTM (Rapid Radiative Transfer Model) longwave radiation scheme (Mlawer et al., 1997), Dudhia shortwave radiation scheme (Dudhia & Jimy, 1989), RUC (Rapid Update Cycle) land surface scheme (Smirnova et al., 2000), YSU (Yonsei University) boundary layer scheme (Hong et al., 2006) and Monin-Obukhov surface layer scheme (Pahlow et al., 2001). The RACM (Regional Atmospheric Chemistry Modeling) scheme (Stockwell et al., 1997) and the GOCART scheme (Ginoux et al., 2001) are used for the model gas-phase chemical process and aerosol process, respectively. Dust emission scheme adopts Shao04 scheme. This study mainly focuses on the natural dust aerosol with no photochemical processes, regardless of biological aerosols, sea salt aerosols, wet deposition and aerosol feedback on radiation.

3 | SIMULATION AND ANALYSIS

3.1 | Meteorological verification

The 2-m temperature and 10-m wind speed per 3 h from ground observational data are used to evaluate the simulation in Dunhuang and Minqin (Figure 2). The model can well simulate the temperature variation in Dunhuang but the higher temperature than the observation is captured in Minqin. Atmospheric boundary layer development and surface heat fluxes, especially sensible heat fluxes, are closely related to the difference in temperature between surface and atmosphere, and the overestimation of temperature in Minqin by WRF-Chem may lead to an overestimation of surface heat fluxes and boundary layer heights in this region. Although the simulations of wind speed are not as precise as the temperature, they follow the variation of the observation and show the better results in Minqin than that in Dunhuang.
3.2 Simulation verification of the dust

AOD is a variable indicating the atmospheric turbidity and the content of aerosols in the atmosphere which can be used to analyze the occurrence and strength of dust event. The left column of Figure 3 shows the AOD distribution of the MODIS from January 24 to 26, 2017 and the right column is the simulation at the corresponding time.

From Figure 3, the AOD of MODIS in Kumutage Desert, in the west of Dunhuang, reaches 2 at 15:00 on January 24 (Figure 3a) and the dust emission occurs. At 12:00 on January 25, the AOD reaches 1 or even exceeds 2 in the middle and west of Gansu (Figure 3c). The dust moves eastward to Minqin at 14:00 on January 25. The dust enlarges its influence area and continues moving eastward (Figure 3e). At 11:00 on January 26, AOD shows the dust event mostly distributes in the southeast Gansu (Figure 3g). Subsequently, the dust moves southeastward and then the dust event ends. The intensity of the dust event in Dunhuang and Minqin are stronger than other areas. The numerical simulation also demonstrates the eastward movement of the dust, but the range of the horizontal distribution is larger than that of the observations. One reason is that many missing values exist in MODIS AOD due to the high albedo in desert areas. According to ground observational data, the dust event occurs in Dunhuang at 20:00 on January 24 and expands to Minqin at 14:00 on January 25, and then transports southeastward to Lanzhou at 20:00 on January 25. The process simulated by WRF-Chem gives reliable dust occurrence and transportation to the observation.

From the natural-looking images which utilizes MODIS Level 1B data from visible bands 1–7 (figure omitted), it can be seen that during the main stage of dust emission in Dunhuang on January 24, there is a large amount of cloud cover over Dunhuang and the Kumutag Desert, the cloud cover greatly affected the identification of aerosols by satellite, thus making the MODIS AOD only has sporadic high value areas through the cloud gaps which causing the observations underestimate, but it is still can find that there are strong dust activities over Dunhuang and its west side. On January 26, there were almost no clouds over eastern Gansu, which could obviously identify the dust that appeared in this region, reducing the observation deviations of MODIS AOD and also making the simulation closer to the observation.

On the other hand, In Shao04 scheme (Shao et al., 2004), from loose sandy loam to cohesive soil, the two sensitive factors influencing the dust emission: the dust emission factor $c_y$ and the soil plastic pressure $P$, vary...
from $c_y \approx 5 \times 10^{-5}$ and $P = 1000 - 5000$ Pa to $c_y \approx 1 \times 10^{-5}$ and $P = 30,000 - 50,000$ Pa. Such a wide range of values will certainly bring great uncertainty to the calculation of dust emission flux, leading to large deviations in the estimation of dust emission flux. RUC scheme (Smirnova et al., 1997, 2000) is available to consider vegetation, snow, and soil. Since the vegetation cover used in WRF-Chem is obtained from multi-year statistics average and is relatively old, the year-to-year changes in vegetation cover, land use type and soil type have a significant impact on the simulation of dust concentrations. The inaccuracy of the soil particle size distribution used in the Shao04 scheme is an important indicator of the simulation performance due to the lack of information on soil properties. The complexity of the RUC scheme for soil moisture, combined with the fact that the actual soil types and vegetation in Dunhuang and Minqin are somewhat different from the model, also contributes to the overestimation of dust concentration, which causes the overestimation of AOD.

In addition, the simulated dust concentration can be evaluated by the hourly PM$_{10}$ mass concentration (Figure 4). From the northwest to the southeast, six observational cites of the PM$_{10}$ mass concentration including Jiuquan, Zhangye, Wuwei, Baiyin, Lanzhou and Dingxi are chosen to compare with the numerical simulation. Generally, concentration of the particles increases sharply when dust event occurs, the variation of PM$_{10}$ mass concentration reflects the dust event variation. The simulations capture the sharp increase of the PM$_{10}$ concentration in the six cites during the dust emission and transportation. The observation of PM$_{10}$ concentration mostly rises
to 3000 – 4000 μg m⁻³ during the dust event. The peak values show great difference between the observations and the simulations in Zhangye, Wuwei and Dingxi. However, the PM₁₀ concentrations drop below 500 μg m⁻³ when the dust event ends. The resolution of second grid in the experimental is 9 km, and there are some deviations in the observational stations and the grid points of the simulation outputs. Besides, the relatively low spatial resolution may not enough to reflect the local circulation and transportation, so the magnitude and duration of the high PM₁₀ concentration values will have some deviations. Moreover, WRF-Chem has a large uncertainty in the simulation of near-surface wind in complex terrain, which also which also leads to deviations in simulation of PM₄₁₀ distribution and variation. At the same time, WRF-Chem also has some bias for the simulation of dust concentration, especially near the dust source area, which also causes the simulation of PM₁₀ at the cities near the dust source area (Jiuquan, Zhangye and Wuwei) to be less effective than other stations. Except Jiuquan, the durations of the high concentration in the other cities match the observations well. In short, the WRF-Chem simulation mostly captures the characteristics of the dust event.

4 DUST SIMULATION RELATED TO THE BLH

The dust emission fluxes simulated by the Shao04 scheme are more than 200 μg m⁻² s⁻¹ where at the
center of the dust emission is over 3000 μg m⁻² s⁻¹, the
10-m wind speed in Dunhuang on January 24 is obviously
higher than the other areas (Figure 5a). The wind speed is
more than 10 m s⁻¹ and the central wind speed is about
20 m s⁻¹ (maximum 21.7 m s⁻¹), where the dust emission
fluxes are above 200 μg m⁻² s⁻¹. Compared to the dust
source, both dust emission fluxes (10 – 400 μg m⁻² s⁻¹)
and 10-m wind speed (around 10 – 12 m s⁻¹) near Minqin
are relatively low (Figure 5b), but the dust event
strengthens when it transmits through Minqin.

Figure 6 is the spatial distribution of ground dust concen-
tration from January 24 to 26, 2017 simulated by
WRF-Chem. At the dust emission stage, the ground dust
concentration reaches more than 6000 μg m⁻³ in the dust
source near Dunhuang with central concentration as
high as 61,404 μg m⁻³. At 02:00 on January 25, dust from
Dunhuang begins to spread eastward. The dust event
covers the entire Jiuquan at 06:00 with the dust concen-
tration over 1000 μg m⁻³. The dust continues spreading
eastward to Minqin at 14:00. The area with dust concen-
tration between 3000 and 6000 μg m⁻³ shrinks at 14:00,
but expands at 16:00 in Minqin again, which means dust
event strengthens in Minqin. The dust event continues to
move southeastward from 20:00 on January 25 to 00:00
on January 26, which affects Wuwei, Baiyin Lanzhou
and gradually influences the other cities in southeast of
Gansu. Finally, dust event ends at 22:00 on January 26.

Different characteristics in the vertical distribution of
dust are captured in dust source Dunhuang and Minqin
(where dust event strengthens). It can be detected from
Figure 7a that the high concentration of dust is mainly
concentrated in the layer below 500 m above the ground
in Dunhuang (from 11:00 to 16:00 on January 24) with
the high concentration center about 22,000 μg m⁻³. The
second high concentration dust appears and spreads
upward to 1000 m from 17:00 to 21:00 on January 24, and
the high center increases to above 30,000 μg m⁻³. Then
the high concentration center at the lower layer disap-
ppears and the dust is lifted to the upper air above 2000 m.

However, the vertical distribution is different in Minqin
(Figure 7b). The dust concentration reaches the maxi-

muum with the high concentration center in 800 – 1600 m
above the ground. There is also high concentration near
the ground during 14:00–17:00 for the local dust emis-
sion. Minqin is another dust source in aridification area
and forces the local dust event under the high layer
momentum transfer. The influence of the dust event in
vertical direction reaches up 3000 m under the both dust
transportation and local emission. However, the dust
concentration in Minqin is relatively small and the inten-
sity is weak on the ground compared to Dunhuang.

The cross sections of dust concentration along 39.8°N
in Dunhuang and along 38.6°N in Minqin show more
details about the dust lifting (Figure 8). At the beginning
of dust emission (08:00 – 12:00, Figure 8a–f), vertical con-
vection increases gradually in Dunhuang. The convection
reaches the maximum at 16:00, which makes the inten-
sity of lifting reaches the highest. The high concentration
dust extends to the maximum in the vertical direction
reaching more than 3000 m above the ground. Subse-
xquently, the ascending motion weakens, accompanies
with decrement of the ground dust and shrink of the high
value area of the dust, but the dust still remains over the
upper air. The dust event ends at 16:00 on January 25 with
the ascending motion ending. As previous ana-
lyses, occurrence of the dust event in Minqin is due to
the dust transports from Dunhuang and partly local emis-
sion. The cross sections of the dust in Minqin show a belt
of the high value dust in 1000 m with the center concen-
tration about 5600 μg m⁻³ which is greatly less than that
dust source Dunhuang (Figure 8g–l). The dust shows the mainte-
nance of the high concentration area at about 1000 m
above the ground and that is an obvious feature.

The BLH shows special characteristics in Dunhuang
during dust event (Figure 9a–f). At the main stage of dust
emission (from 08:00 on January 24 to 00:00 on January
25), the two centers of high dust concentration on the
ground correspond well to the high value centers of the

![FIGURE 5 Dust emission fluxes (fill color, unit: μg m⁻² s⁻¹) and 10-m wind field (black vector arrow, unit: m s⁻¹) from January 24 to 25, 2017 simulated by WRF-Chem](image-url)
BLH. At the beginning of dust emission (08:00 on January 24), the BLH at the two high dust concentration area is 400 – 700 m, which is significantly higher than that at the surrounding area without dust emission. The dust emission increases at 12:00, and the BLH increases to 800 – 900 m near the high dust concentration center in the western side. At 16:00, although the BLH decreases near the western center of the high dust concentration, it is still higher than the area without dust emission. The BLH at the eastern center continues to lift, makes the dust event develop. The BLH at the high dust concentration center keeps more than 1000 m until 18:00 and begins to decrease when the dust emission weakens at 20:00. There is no dust emission at the ground after 00:00 on January 25, but the BLH near the dust source maintains above 300 m during 00:00 to 06:00 on January 25.

The upward longwave radiation from the ground is absorbed by the boundary layer in the night due to the dust, and maintains the BLH in the area from the middle night to the early morning. By contrast, the dust event passes through Minqin which has the same conditions as the high dust concentration area is corresponding to the high BLH, but it is not so obvious as that in Dunhuang (Figure 9g–l). When the dust event moves eastward from 12:00 to 14:00 on January 25, the BLH lifts gradually from 200 – 400 m to 400 – 800 m. The reason may be

**FIGURE 6** Spatial distribution of dust concentration from January 24 to 26, 2017 simulated by WRF-Chem (unit: μg m\(^{-3}\))
related to the reduction of the shortwave radiation caused by the transported dust and therefore limits the energy to develop the boundary layer. However, there is little of dust emission in Minqin at 16:00 with the BLH rising to more than 1000 m at 18:00 and then reducing to around 500 m at 20:00 at the end.

5 | SENSITIVITY EXPERIMENT

Surface thermodynamic process, which contributes to the boundary layer development, could be mainly reflected by surface heat flux. In this study, a sensitivity experiment of turning off surface heat flux is used to investigate the influence of surface heat flux on BLH distribution and dust concentration.

5.1 | Variation of the dust concentration on the ground

Sensitivity experiment is performed as turning off surface heat flux in the model. As shown in Figure 10, the simulation can only capture one high dust concentration center at the early stage of dust emission, which is different from the two high centers in the control experiment. The dust concentration in the center in sensitivity experiment with $6000 - 12,000 \, \mu g \, m^{-3}$ is also less than that in anyone of the two centers in control experiment (Figure 10). The right high concentration center is not captured until 18:00 and its concentration ($3000 - 6000 \, \mu g \, m^{-3}$) is also much smaller than that ($24,000 - 48,000 \, \mu g \, m^{-3}$) in the control experiment. At 02:00 on January 25, there is still a little process of dust emission over Dunhuang in the control experiment, but the process is terminated early in the sensitivity experiment.

During dust transporting eastward, the sensitivity experiment also can capture the enhancement of the dust event in Minqin from 14:00 to 20:00, but the dust emission area is slightly northerly and the intensity is also smaller than that in the control experiment. At the end of the dust event (about 22:00 on January 26), the high dust concentration center has a value of $500 - 1000 \, \mu g \, m^{-3}$ in control experiment while it drops below $100 \, \mu g \, m^{-3}$ in sensitivity experiment. Thus, the dust concentration reduces obviously in the sensitivity experiment, the difference is 4 – 6 times to the control experiment, especially at the dust emission stage. The difference indicates that the surface heat flux is a main factor to the formation and transportation of dust event. The enhancement of the dust event in the path is greatly influenced by the dynamic moving process.

5.2 | Influence on dust vertical distribution with BLH

The result of the sensitivity experiment shows synchronization between the dust concentration variation and the boundary layer development in Dunhuang, which is similar to the control experiment. The high concentration center at the dust emission stage corresponds well to the high value center of the BLH which shows more obvious feature than the control experiment (Figure 11). The synchronization of the high concentration center and the BLH in Minqin is similar to that in Dunhuang. The region of the dust emission is relatively northward in Minqin in the sensitivity experiment, the high value center of the BLH is also northward relatively.

At the early stage of the dust emission (08:00 on January 24), the difference of the dust concentration between control experiment and sensitivity experiment is relatively small in Dunhuang. The difference of the BLH in the high dust concentration area is within $\pm 100$ m between the two experiments. During the strengthening stage, the difference of dust concentration between the two experiments increases rapidly (12:00 on January 24) with obviously lower BLH in the sensitivity experiment. At 16:00, the dust event strengthens with a feature of two high dust concentration centers in the sensitivity
experiment as well as in the control experiment. The BLH of the two centers is lower in the sensitivity experiment than that in the control experiment, and especially more obvious in the eastern one (Figure 9c). The BLH is mainly affected by dynamic factor mainly caused by vertical movement after turning off the surface heat flux. However, the ascending motion is still strong in the dust emission stage (Figure 11c). The dust concentration of the eastern side changes greatly in the sensitivity experiment. The BLH decreases obviously and therefore the dust is more sensitive to surface thermal factors influenced by the surface heat flux. At 18:00, the BLH of the western high center in the sensitivity experiment is obviously lower than that in the control experiment with differences more than 300 m. The ascending motion of the western side in the control experiment is relatively strong (Figure 9d), but there is no more ascending motion in the western center in the sensitivity experiment (Figure 11d). However, there is ascending motion over the eastern high concentration center in the sensitivity experiment which maintains the dust concentration in a level. This means that there is still a vertical movement in the eastern high concentration center, resulting in the dynamic factor mainly caused by vertical movement plays an important role on the maintaining. In the next stage, the BLH in the sensitivity experiment is not
much different from the control experiment. In addition, in the sensitivity experiment, the distribution of the BLH between the high concentration center and the surrounding area is relatively uniform. The distribution of BLH varies greatly in the control experiment, which is mainly due to the large regional difference of distribution of dust concentration and surface heat flux in the control experiment. However, in the sensitivity experiment, the distribution of dust is relatively uniform without the surface heat flux. BLH is only affected by dynamic factors caused by the vertical movement. Thus, the thermal factor influenced by the surface heat flux contributes to the difference of the inhomogeneous distribution in the control experiment.

The feature of the high BLH captured in the control experiment is more obvious than that in the sensitivity experiment in Minqin. During the dust moves eastward to Minqin from 12:00 on January 25, the height difference increases gradually. At 16:00, the BLH of control experiment is more than 300 m higher than sensitivity experiment in the most areas, and even more than 500 m at some areas such as the southern part of Minqin. However, the high dust concentration mainly occurs in the north of Minqin for the most reason of the dynamic factor caused by vertical movement. After the dust event, the difference of the BLH decreases between the two experiments.
From the cross section of dust concentration (Figure 12), the dust concentration at each vertical level in the sensitivity experiment is lower than that in the control experiment in both Dunhuang and Minqin. During the early dust emission stage, the center of the high dust concentration at Dunhuang is always below 400 m above the ground in the sensitivity experiment, but the high concentration center can reach about 1000 m in the control experiment and the dust can even spread to over 2000 m above the ground (at 16:00 on January 24). During the development stage of the dust event, the dust spread to over 3000 m above the ground in the control experiment, while the dust keeps below 2000 m in the sensitivity experiment. For the vertical velocity, there is a strong ascending motion in the high dust concentration center from 12:00 to 18:00 in the control experiment but relatively weak in the sensitivity experiment. The experiment of turning off surface heat flux inhibits the
development of boundary layer and the vertical spread of
dust. It indicates that the thermal process influenced by
the surface heat flux plays a key role in the vertical distri-
bution of dust.

6 | CONCLUSIONS

The characteristics of dust concentration and BLH
(Boundary Layer Height) and the effects of surface heat flux
on them during a dust event in Northwest China are stud-
ied by WRF-Chem. The main conclusions are as follows.

The dust emission flux in the center of Dunhuang is
more than 3000 μg m⁻² s⁻¹, and the 10-m wind speed is
about 20 m s⁻¹. The high concentration dust in the early
stage of dust emission is mainly concentrated below
500 m above the ground in the control experiment. With
the dust transporting to Minqin, the dust concentration
decreases, but then increases due to the local dust emis-
sion. The high value area of dust in Minqin always main-
tains with a height about 1000 m above the ground. The
BLH of high dust concentration in Dunhuang is higher
than that in the surrounding area during the dust emis-
sion. The high concentration dust maintains at about
1000 m level due to the dust transported from Dunhuang.

The range of dust area decreases and the surface dust
concentration greatly reduces in the sensitivity experi-
ment of without surface heat flux. The BLH at high dust

**FIGURE 11** Boundary layer height (filled color, unit: m) and dust concentration (contour, unit: μg m⁻³) during dust event in Dunhuang (a–f) and Minqin (g–l) without surface heat flux simulated by WRF-Chem
concentration area in the sensitivity experiment is significantly lower than that in the control experiment. However, with the increase of dust concentration, the gap of BLH between the two experiments reduces. In the control experiment, the high value center of dust in Dunhuang reaches about 1000 m above the ground during the dust emission stage. While in the sensitivity experiment, it remains below 400 m above the ground. The two experiments in Minqin also show that dust concentration centers have a height gap of about 500 m. The BLH has a significant influence on the dust diffusion range and vertical distribution. In the sensitivity experiment, the BLH is mainly affected by dynamic factor caused by vertical movement, while in the control experiment, there are both dynamic caused by vertical movement and thermal factors influenced by surface heat flux which make the variation of the BLH in the control experiment more complicated.

In addition, the overestimation of temperature in Minqin may lead to an overestimation of surface heat fluxes and the BLH, resulting in overestimation of the impact of surface heat fluxes. Besides, due to the inaccurate surface property parameters and insufficient simulation of wind in complex terrain in WRF-Chem, the dust concentration will have some deviations. In the future simulation, we will try to improve the modeling ability.

FIGURE 12  Cross section of dust concentration along 39.8°N (a–f) in Dunhuang and along 38.6°N (g–l) in Minqin without surface heat flux simulated by WRF-Chem (filled color: Dust concentration, unit: μg m⁻³; arrows: synthetic wind vectors of u and w × 100 in Dunhuang and u and w × 200 in Minqin, unit: m s⁻¹)
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CONFLICT OF INTEREST
The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

AUTHOR CONTRIBUTIONS
Ziyuan Tan: Software; validation; writing – original draft. Minjin Ma: Conceptualization; methodology; supervision; writing – review and editing. Wanlong Huang: Software; writing – review and editing. Changrong Tan: Investigation; writing – review and editing. Zhenzhu Zhao: Writing – review and editing. Fan Ding: Visualization.

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REFERENCES
Bai, B., Zhang, Q., Chen, X. & Han, H. (2018) Moving paths and spatial characteristics of three typical dust processes in East Asia. Journal of Arid Meteorology, 36, 11–16.
Bell, M.L., Levy, J.K. & Lin, Z. (2008) The effect of sandstorms and air pollution on cause-specific hospital admissions in Taipei, Taiwan. Occupational & Environmental Medicine, 65, 104–111.
Chan, C.C. & Ng, H.C. (2011) A case-crossover analysis of Asian dust storms and mortality in the downwind areas using 14-year data in Taipei. Science of the Total Environment, 410, 47–52.
Chen, W.N., Chen, Y.W., Chou, C., Chang, S.Y., Lin, P.H. & Chen, J.P. (2009) Columnar optical properties of tropospheric aerosol by combined lidar and sunphotometer measurements at Taipei, Taiwan. Atmospheric Environment, 43, 2700–2708.
Choobari, O.A., Zawar-Reza, P. & Sturman, A. (2014) The global distribution of mineral dust and its impacts on the climate system: a review. Atmospheric Research, 138, 152–165.
Jimy D. (1989) Numerical study of convection observed during the winter monsoon experiment using a mesoscale two-dimensional model. Journal of the Atmospheric Sciences, 46, 3077–3107.
Fang, M., Zheng, M., Wang, F., Chin, K.S. & Kot, S.C. (1999) The long-range transport of aerosols from northern China to Hong Kong - a multi-technique study. Atmospheric Environment, 33, 1803–1817.
Fitzgerald, E., Ault, A.P., Zascher, M.D., Mayol-Bracero, O.L. & Prather, K.A. (2015) Comparison of the mixing state of long-range transported Asian and African mineral dust. Atmospheric Environment, 119, 15–25.
Ginoux, P., Chin, M., Tegen, I., Prospero, J.M., Holben, B., Dubovik, O. et al. (2001) Sources and distributions of dust aerosols simulated with the GOCART model. Journal of Geophysical Research: Atmospheres, 106, 20255–20273.
Ginoux, P., Prospero, J.M., Torres, O. & Chin, M. (2004) Long-term simulation of global dust distribution with the GOCART model: Correlation with North Atlantic oscillation. Environmental Modelling & Software, 19, 113–128.
Grell, G.A. & Dvnyi, D. (2002) A generalized approach to parameterizing convection combining ensemble and data assimilation techniques. Geophysical Research Letters, 29(14), 38–1–38–4.
Grell, G.A., Peckham, S.E., Schmitz, R., Mckeen, S.A., Frost, G., Skamarock, W.C. et al. (2005) Fully coupled “online” chemistry within the WRF model. Atmospheric Environment, 39, 6957–6975.
Hong, S.Y., Noh, Y. & Dudhia, J. (2006) A new vertical diffusion package with an explicit treatment of entrainment processes. Monthly Weather Review, 134, 2318–2341.
Huang, J., Minnis, P., Yan, H., Yi, Y., Chen, B., Zhang, L. et al. (2010) Dust aerosol effect on semi-arid climate over Northwest China detected from A-train satellite measurements. Atmospheric Chemistry and Physics, 10, 6863–6872.
Huneeus, N., Schulz, M., Balkanski, Y., Griesfeller, J., Prospero, J., Kinne, S. et al. (2011) Global dust model intercomparison in AeroCom phase I. Atmospheric Chemistry and Physics, 11, 7781–7816.
Jia, R., Liu, Y., Hua, S., Zhu, Q. & Shao, T. (2018) Estimation of the aerosol radiative effect over the Tibetan plateau based on the latest CALIPSO product. Journal of Meteorological Research, 32(5), 707–722.
Jones, S.L., Adams-Selin, R., Hunt, E.D., Creighton, G.A. & Cetola, J.D. (2012). Update on modifications to WRF-CHEM GOCART for fine-scale dust forecasting at AFWA. AGU Fall Meeting A33D-0188.
Kang, J.H., Liu, T.C., Keller, J. & Lin, H.-C. (2013) Asian dust storm events are associated with an acute increase in stroke hospitalisation. Journal of Epidemiology & Community Health, 67, 125–131.
Kang, J.Y., Yoon, S.C., Shao, Y. & Kim, S.W. (2011) Comparison of vertical dust flux by implementing three dust emission schemes in WRF/Chem. Journal of Geophysical Research: Atmospheres, 116, D09202.
Li, Y., Shen, J., Zhao, J., Hu, T. & Yin, H. (2014) Simulation of terrain effect to the development of sandstorm in Minqin—Take a heavy sandstorm for example. Journal of Desert Research, 34, 849–860.
Lin, Y.L., Farley, R.D. & Orville, H.D. (1983) Bulk parameterization of the snow field in a cloud model. Journal of Applied Meteorology, 22, 1065–1092.
Liu, S.C., Mckeen, S.A., Hsie, E.Y., Lin, X., Kelly, K.K., Bradshaw, J.D. et al. (1996) Model study of tropospheric trace species distributions during PEM-West A. Journal of Geophysical Research: Atmospheres, 101, 2073–2085.
Liu, T.H., Tsai, F., Hsu, S.C., Hsu, C.W., Shiu, C.J., Chen, W.N. et al. (2009) Southeastward transport of Asian dust: source, transport and its contributions to Taiwan. Atmospheric Environment, 43, 458–467.
Liu, Y., Zhu, Q., Huang, J., Hua, S. & Jia, R. (2019) Impact of dust-polluted convective clouds over the Tibetan Plateau on downstream precipitation. Atmospheric Environment, 209, 67–77.
Luo, X. & Huang, Q. (2012) Effects of surface heat flux on convection rolls. Science Technology and Engineering, 12, 6720–6724.
Mahowald, N., Albani, S., Kok, J.P., Engelstaeder, S., Scanza, R., Ward, D.S. et al. (2014) The size distribution of desert dust aerosols and its impact on the Earth system. Aeolian Research, 15, 53–71.
Mlawer, E.J., Taubman, S.J., Brown, P.D., Iacono, M.J. & Clough, S.A. (1997) Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave. *Journal of Geophysical Research: Atmospheres*, 102, 16663–16682.

Pahlow, M., Parlange, M.-B. & Port-Agel, F. (2001) On Monin–Obukhov similarity in the stable atmospheric boundary layer. *Boundary Layer Meteorology*, 99, 225–248.

Peng, Z., Liu, X., Hong, Z. & Wang, B. (2007) Characteristics of atmospheric boundary-layer structure and turbulent flux transfer during a strong dust storm weather process over Beijing area. *Climatic and Environmental Research*, 12, 267–276.

Shao, Y. (2004) Simplification of dust emission scheme and comparison with data. *Journal of Geophysical Research: Atmospheres*, 109, D10202.

Shao, Y., Wyrwoll, K.H., Chappell, A., Huang, J., Lin, Z., McTainsh, G.H. et al. (2011) Dust cycle: an emerging core theme in Earth system science. *Aeolian Research*, 2, 181–204.

Smirnova, T., Brown, J. & Benjamin, S. (1997) Performance of different soil model configurations in simulating ground surface temperature and surface fluxes. *Monthly Weather Review*, 125(8), 1870–1884.

Smirnova, T.G., Brown, J.M., Benjamin, S.G. & Kim, D. (2000) Parameterization of cold-season processes in the MAPS land-surface scheme. *Journal of Geophysical Research: Atmospheres*, 105, 4077–4086.

Stockwell, W.R., Kirchner, F., Kuhn, M. & Seefeld, S. (1997) A new mechanism for regional atmospheric chemistry modeling. *Journal of Geophysical Research: Atmospheres*, 102, 25847–25879.

Sun, J. & Yao, X. (2002) Simulating diagnostic analyses for frontogenesis and surface sensible heat flux of a sand-dust storm process. *Plateau Meteorology*, 21, 488–494.

Wang, J., Yu, Y. & Zhao, J. (2004) Analysis on surface heating field characteristics of typical severe dust storms in northern China. *Journal of Desert Research*, 24, 599–602.

Wu, C. & Lin, Z. (2014) Impact of two different dust emission schemes on the simulation of a severe dust storm in East Asia using the WRF/Chem model. *Climatic and Environmental Research*, 19, 419–436.

Yao, W. Characteristics of urban boundary layer turbulence dynamical structure and its effect in Beijing. Thesis, Chinese Academy of Meteorological Sciences, Beijing, 2005.

Zhang, Q. (2003) Review of atmospheric boundary layer meteorology. *Arid Meteorology*, 21, 74–78.

Zhang, Q., Huang, R. & Wang, S. (2011) Discussion about special function of land surface process and atmospheric boundary on regional climate in arid area of Northwest China. *Journal of Arid Meteorology*, 29, 133–136.

Zhao, C., Lv, S., Li, Z., Li, J. & Han, B. (2014) Numerical simulation of influence of land surface thermal condition on Badain Jaran Desert atmospheric boundary layer height in summer. *Plateau Meteorology*, 33, 1526–1533.

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