Numerical Simulation of the Spatiotemporal Distribution of Dust Devils in Northern China: Postprint

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Abstract

Dust devils are an important source of mineral dust aerosols and may have significant impacts on global and regional environments and climate. To obtain the spatiotemporal characteristics of dust emission by dust devils, a dust devil dust emission parameterization scheme was employed and coupled into the WRF (Weather Research and Forecasting) model to simulate the diurnal and monthly spatiotemporal variation characteristics of dust devils in northern China. The results indicate that: (1) During 10:00–14:00 (Beijing Time), dust devils gradually appear from east to west in the daily spatial distribution, with intensity progressively increasing, and then during 14:00–20:00, the dust devil region gradually contracts from east to west and intensity progressively decreases. The monthly spatial distribution shows that dust devil centers gradually appear in the Taklamakan Desert, Kumtag Desert, and Qaidam Basin starting from March, then gradually expand to all deserts and reach a peak in June. After July, the occurrence region and intensity of dust devils decline sharply, and by October dust devils no longer occur. (2) The diurnal variation of dust devils in both the Taklamakan Desert and Badain Jaran Desert exhibits a unimodal distribution, beginning at 09:00 in the morning, reaching a peak at 14:00–15:00, and then decreasing rapidly. Their monthly variation trends are also generally unimodal, with dust devils appearing and intensifying from March, peaking in June, then declining rapidly and disappearing by the end of September; the amplitude of dust devil fluctuations in the Badain Jaran Desert is greater than that in the Taklamakan Desert. (3) The simulated and observed diurnal and monthly temporal variation characteristics of dust devils differ slightly in detail, but their overall trends are broadly similar, indicating that the dust devil dust emission parameterization scheme has high applicability. This research outcome will contribute to our deeper understanding of dust aerosol sources, environmental changes, and climate change.

Full Text

Abstract

Dust devils are an important source of mineral dust aerosols and may significantly impact global and regional environments and climate. To characterize the spatiotemporal patterns of dust devil dust emissions, we coupled a dust devil parameterization scheme with the Weather Research and Forecasting (WRF) model to simulate the diurnal and monthly variations of dust devils in northern China. The results show that: (1) In terms of daily spatial distribution, dust devils gradually appear from east to west with intensifying strength, reaching peak intensity between 10:00-14:00 (Beijing Time). Subsequently, the occurrence region contracts westward with diminishing intensity, and by 20:00 dust devils largely disappear. Regarding monthly distribution, dust devil centers begin to emerge in March over the Taklimakan Desert, Kumtag Desert, and Qaidam Basin, then expand across all deserts and peak in June. After July, both the areal extent and intensity decline sharply, with no dust devils occurring by October. (2) The diurnal variation of dust devils in both the Taklimakan and Badain Jaran deserts exhibits a single-peak pattern, initiating in the morning, reaching maximum intensity at 14:00-15:00 (local time), and then decreasing rapidly. The monthly variation also follows a unimodal trend, beginning in March, peaking in June, and declining rapidly until dust devils disappear by the end of September. The amplitude of variation is greater in the Badain Jaran Desert than in the Taklimakan Desert. (3) While simulated and observed diurnal and monthly variations of dust devils differ slightly in detail, their overall trends are consistent, demonstrating the high applicability of the dust devil parameterization scheme. These findings contribute to a deeper understanding of dust aerosol sources and their environmental and climatic impacts.

Keywords: dust aerosol; WRF/Chem model; parameterized scheme for dust devil; spatiotemporal distribution

1. Study Area Overview

The study region encompasses the desert areas of northern China (80°-103°E, 32°-40°N), forming an east-west oriented mid-latitude desert belt covering approximately 1.5$×10^{6}$ km^{2} (15.9% of China' s land area). The primary focus areas include the mobile Taklimakan Desert, the semi-stationary Tengger Desert, and the Badain Jaran Desert.

2.1 Dust Devil Parameterization Scheme

The dust devil parameterization scheme follows previous work, with meteorological thresholds for dust devil formation as follows: convective buoyancy (w*), friction velocity (u*), adiabatic lapse rate equal to the interpolated value between surface temperature and ground air temperature (8.5-10.0 K$\cdot$km^{-1}), environmental wind speed between 0-5 m$\cdot$s^{-1}, and no precipitation. All parameters are obtained from WRF model output.

The dust devil intensity (dust emission) formula is:

DAEtot = [expression] × time

where DAEtot represents total emissions, time is dust devil duration, σ is the dust devil emission percentage ($0.7\ \mathrm{g \cdot m^{-2}}$), S is the total emission area, and the emission flux is consistent with Gillette' s observations.

In the formula: is the dimensionless mechanical energy friction loss coefficient (12-24), is air density, p is pressure difference, g is gravitational acceleration ($=9.8\ \mathrm{m \cdot s^{-2}}$), R 9$×10^{n}$, F is the heat flux driving dust devils, T is the timescale of effective solar radiation in the convective boundary layer, and the boundary layer height is also involved.

When meteorological elements at any point in the simulation domain satisfy all dust devil formation thresholds, a dust devil is deemed to form at that location, and its instantaneous dust emission is calculated through the formula.

2.2 WRF Model Configuration

The Weather Research and Forecasting (WRF) model is recognized as a next-generation mesoscale weather forecasting system widely applied in weather and climate simulations. This study employs WRF-Chem version 3.6.1 with a single nested domain covering 80°-103°E, 32°-40°N at 30 km horizontal resolution. The vertical dimension comprises 32 levels, with the domain center at 105°E. Initial and boundary conditions are derived from the National Centers for Environmental Prediction (NCEP) Final Reanalysis data, updated every six hours. Terrain data utilize high-resolution elevation and land cover classifications from the United States Geological Survey (USGS). The microphysics scheme employs [scheme name], radiation schemes include the RRTM longwave and [shortwave scheme], the boundary layer scheme is the Yonsei University scheme, and the dust emission scheme is [scheme name].

2.3 Research Methods

This study combines 定点观测 with numerical modeling to obtain the spatial distribution of dust devils. Dust devil observations were conducted at Laohuzui in Minqin County, Gansu Province, located at the junction of the Tengger and Badain Jaran deserts. Observations spanned the entire year of 2008, using cameras to document dust devils from 08:00-20:00. Dust devils with diameters exceeding 2 m were manually counted hourly to calculate their occurrence frequency.

The modeling component employs the WRF-Chem model with the dust devil parameterization scheme. Meteorological initial conditions, including air temperature, surface temperature, and wind speed, are obtained from NCEP FNL data. Through interpolation calculations from various parameterization schemes, the model provides grid-point data of surface variables and wind fields for dust devil emission calculations. Using the Deardorff formula to compute w* values and applying dust devil thresholds, the model ultimately yields grid-point dust devil emissions. Simulations cover April–September 2008 across northern China, focusing on the Taklimakan, Tengger, and Badain Jaran deserts.

3.1 Simulated Diurnal Variation of Dust Devil Occurrence and Intensity

Since the simulation only predicts dust devil locations, we use dust devil dust emission amount to represent intensity, where more vivid colors indicate stronger intensity and values greater than [threshold] indicate dust devil occurrence. We randomly selected a clear day in June (June 10, 2008) during the peak dust devil month to examine diurnal characteristics.

[Figure 1: see original paper] shows that at 10:00, dust devils appear primarily in desert areas east of 100°E, with greater intensity further east, centered near the Tengger and Badain Jaran deserts. By 12:00, the occurrence region expands westward, and dust devil centers emerge in the Kumtag Desert and Taklimakan Desert, though with weaker intensity than those in the Tengger and Badain Jaran deserts. At 14:00–16:00, the areal extent reaches maximum intensity with five high-value centers. By 18:00, the region contracts sharply eastward, with few dust devils remaining east of 100°E; centers in the Tengger and Badain Jaran deserts disappear while the Taklimakan center continues intensifying. By 20:00, dust devils have largely vanished across the study region, with only marginal activity in western Taklimakan. No dust devils occur before 10:00 or after 20:00 (figures omitted).

The Taklimakan, Tengger, and Badain Jaran deserts are the three most frequent dust devil regions. Therefore, we selected the Taklimakan and Badain Jaran deserts as representative cases to simulate monthly diurnal variation characteristics. Since northern China spans multiple time zones and dust devil centers shift westward following solar progression, we converted from Beijing Time to local time for unified analysis.

[Figure 2: see original paper] reveals that both deserts exhibit unimodal diurnal emission patterns. Dust devils begin appearing at 08:00–09:00 local time, with emissions increasing sharply until 10:00–13:00, then slowing until peaking at 14:00–16:00, followed by rapid decline. After 18:00, dust devils become rare. Monthly-averaged diurnal variations show that Badain Jaran emissions increase from low values in April–May to peak in June–July, while Taklimakan emissions follow a similar pattern. Although monthly diurnal variations differ slightly between the two deserts, their overall patterns are consistent, with peaks occurring at 14:00–15:00. Taklimakan dust devil intensity exceeds that of Badain Jaran.

3.2 Simulated Monthly Variation of Dust Devil Occurrence and Intensity

[Figure 3: see original paper] illustrates the simulated monthly dust devil distribution from April to September. No dust devils are simulated for the first three months. In March, minimal activity occurs only in the Qaidam Basin (figure omitted). In April, dust devils appear at the margins of the Qaidam Basin and Taklimakan Desert with slightly enhanced intensity. In May, the occurrence region expands dramatically, forming three high-value centers in western Taklimakan, Kumtag Desert, and Qaidam Basin. In June, the spatial distribution resembles May but with peak intensity across all regions, adding two more high-value centers in the Tengger and Badain Jaran deserts. July shows similar extent and centers to June but with reduced intensity. In August, the region contracts sharply westward, resembling May' s distribution but with weakening intensity. September shows further contraction similar to April. After October, dust devils disappear from northern China.

Dust devils first appear in March in the Qaidam Basin, likely due to its high altitude on the Tibetan Plateau where enhanced radiation creates larger surface-air temperature differences that satisfy the primary dust devil threshold. Despite large weather condition differences between years, the monthly variation pattern remains similar, suggesting relationships with boundary layer height and surface-air temperature differences that require further investigation.

Due to extreme scarcity of dust devil observations, synchronous validation is impossible. However, observations from other periods can still broadly verify the simulation. Using recent observations of dust devil frequency from Xiaotang meteorological station in the Tarim Basin, the diurnal variation characteristics match simulated results well, though the simulated peak center occurs at 15:00, one hour later than observed. Comparisons with observations from Laohuzui, Minqin, at the junction of the Tengger and Badain Jaran deserts in 2008 show that the observed diurnal variation pattern generally matches simulation results, though the observed increase before 15:00 is more gradual while the increase around 15:00 is steeper than simulated. Overall, the simulated dust devil emissions demonstrate high credibility despite deficiencies, primarily because the model assumes constant emission per dust devil while real emissions vary with dust devil size.

[Figure 4: see original paper] compares simulated monthly emissions with observed monthly frequencies. The simulated monthly emission variation in the Taklimakan Desert shows a unimodal pattern, with low values from late March through mid-May, rapid increase in late May, peaking in early June, then rapid decline, approaching zero by late September. This trend generally matches the observed monthly variation of dust devil frequency at the Kongque River meteorological outpost in the Tarim Basin. The simulated monthly variation for the Badain Jaran Desert shows a multi-peak distribution with three peaks, but the largest peak occurs in early June, consistent with the Taklimakan peak.

Filtering minor fluctuations reveals an overall trend matching the Taklimakan monthly variation. Compared with Minqin observations, the monthly variation characteristics are broadly consistent.

4. Discussion

Through coupling the dust devil parameterization scheme with WRF-Chem, this study successfully simulates the diurnal, monthly, and spatial variation characteristics of dust devils in northern China, confirmed by observations. Previously, we only knew that dust devils occur primarily in desert and gobi regions, with sporadic observations at individual sites. Most studies provided only estimated dust devil emission values, while no research could specify the detailed distribution and emission amounts over large areas. This simulation and validation not only confirms qualitative understanding but also provides specific locations and emission quantities. However, the simulation conclusions still require extensive observational verification.

The model' s 30 km horizontal resolution masks surface heterogeneity in desert regions. Assimilation data also contain errors compared to actual meteorological data, particularly for simulated surface temperatures in summer which differ substantially from measured desert surface temperatures. Additionally, numerous parameterization schemes in the model introduce uncertainties through scheme selection. The simulation shows no dust devils in March, contradicting observations, indicating remaining deficiencies or errors that require further investigation with enhanced observations.

5. Conclusions

Using the dust devil parameterization scheme coupled with the WRF-Chem model, this study simulates the diurnal and monthly spatiotemporal variation characteristics of dust devil emissions in northern China. Selecting the Taklimakan and Badain Jaran deserts as representative cases, we compare simulated diurnal and monthly emission variations with actual observations, yielding the following conclusions:

1. The simulated daily dust devil occurrence region in northern China deserts shows a progressive pattern from morning onward, with dust devils appearing gradually from east to west and intensifying, peaking between 12:00-14:00 (Beijing Time). The region then contracts westward with diminishing intensity, and by 20:00 dust devils largely disappear.
2. In local time, the simulated diurnal dust devil emission variation follows a unimodal distribution, initiating at 08:00-09:00, increasing sharply until 10:00-13:00, peaking at 14:00-15:00, then declining rapidly. The Taklimakan and Badain Jaran deserts show generally consistent diurnal patterns with some differences.
3. The simulated monthly dust devil emission variation across the study

region also follows a unimodal distribution from March to September, with maximum areal extent and intensity in June, forming five high-value centers in western Taklimakan, Kumtag Desert, Qaidam Basin, Tengger Desert, and Badain Jaran Desert. After July, the region contracts sharply and intensity declines, approaching zero by late September.

4. The simulated diurnal and monthly dust devil emissions from the two representative deserts show trends broadly consistent with observed dust devil frequencies at station sites, despite minor differences in detail. This indicates that the simulated diurnal and monthly variation characteristics are generally successful and possess certain reliability.

This study demonstrates that dust devils are an important source of dust aerosols, contributing to our understanding of environmental and climate change impacts.

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Note: Figure translations are in progress. See original paper for figures.