Numerical Simulation Analysis of Dynamic Mechanisms of Two Extreme Rainstorm Events in the Helan Mountains: Postprint

Authors: Chen Xiaojuan, Wang Yongqing, Mao Lu, Ji Xiaoling, Shao Jian, Mao Lu

Date: 2020-06-21T00:00:00+00:00

Abstract

Through WRF model terrain sensitivity experiments combined with airflow-over-mountain theory, this study investigates the dynamic mechanism of the Helan Mountain terrain on two extreme heavy rainfall events in the Helan Mountain region on August 21, 2016 and July 22, 2018. The results indicate that: the Helan Mountain terrain' s positive contribution to precipitation on its windward slope can reach 57%, its negative contribution to precipitation in the Tengger Desert can reach 63.6%, and its impact on precipitation in the Yinchuan Plain depends on the backflow effect; heavy precipitation in the Helan Mountains mainly occurs when the moist Froude number is between 0.48 and 1; through topographic blocking, the Helan Mountains cause airflow to detour, affecting the development of meso- and small-scale systems, thereby influencing the location and intensity of heavy precipitation; the Helan Mountain terrain can produce a water vapor convergence center of -14$×$10-7 g · cm-2 · hPa-1 · s-1 on the windward slope, and topographic convergence lifting enhances the uplift of warm moist airflow on the windward slope, increases the thickness of the high-energy and high-moisture layer, thereby enhancing precipitation on the windward slope; the channeling effect and funnel-shaped terrain contraction make the southeastern side of the Helan Mountain main peak a heavy precipitation-prone area.

Full Text

Preamble

This study investigates two extreme rainstorm events that occurred in the Helan Mountain region on August 21, 2016 (referred to as the "8 · 21" event) and July 22, 2018 (referred to as the "7 · 22" event). The research employs the Weather Research and Forecasting (WRF) model to conduct numerical simulations and terrain sensitivity experiments, utilizing airflow-over-relief theory to analyze the dynamic effects of mountainous terrain on precipitation patterns.

1 Introduction

1.1 Rainstorm Overview

The "8 · 21" and "7 · 22" extreme rainstorm events in Helan Mountain produced 12-hour accumulated rainfall ranging from 50 mm to over 200 mm, with peak precipitation occurring between 20:00 and 08:00. Observed rainfall totals reached 238.1 mm and 277.6 mm respectively, while peak discharge rates ranged from 420 $m^3 \cdot s^{-1}$ to 1500 $m^3 \cdot s^{-1}$ (Figure 1). Analysis reveals that these events were characterized by strong convective activity, with the "7 · 22" event exhibiting more intense convective parameters than the "8 · 21" event, though both displayed similar mesoscale and microscale system development patterns.

[Figure 1: see original paper] Observed 12-hour cumulative rainfall of two extreme rainstorms in Helan Mountain

1.2 Model Configuration

The simulation employs WRF V3.9.1, with initial and boundary conditions derived from NCEP FNL data (1°$×1°*resolution).ThemodelconfigurationincludestheMonin−Obukhovsurfacelayerscheme,Noahlandsurfacemodel,andWSM3microphysicsscheme.At*500*hPa,thepreva*
s^{-1}$ across the Helan Mountain region, with 700 hPa and 850 hPa levels showing southwesterly flow at 8–12 $m \cdot s^{-1}$. The terrain sensitivity experiments are designed with three configurations: control run (CTRL) using actual terrain, and sensitivity tests TOP0.5 and TOP1.5 with modified terrain heights (Table 1).

2 Experimental Design

2.1 Terrain Sensitivity Experiments

The terrain sensitivity experiments are summarized in Table 1. The CTRL experiment uses the actual Helan Mountain terrain. TOP0.5 reduces the mountain height by 50%, while TOP1.5 increases it by 100%. These modifications allow investigation of terrain height effects on precipitation distribution and intensity.

The terrain experiments scheme

2.2 Model Domain and Resolution

The simulation domain covers the Helan Mountain region with a horizontal resolution of 3 km × 3 km and a time step of 15 seconds. The control experiment (CTRL) successfully reproduces the observed rainfall patterns (Figure 2), with simulated 12-hour accumulated precipitation showing good agreement with observations, including accurate representation of the location and intensity of heavy rainfall centers.

[Figure 2: see original paper] 12-hour cumulative rainfall simulated under control experiment (contours indicate terrain height, units: m)

3 Results and Analysis

3.1 Dynamic Effects of Terrain

3.1.1 Froude Number Analysis The Froude number (Fw) is calculated to quantify airflow blocking effects:

$$F_w = \frac{U}{N_w \cdot h}$$

where U represents wind speed, h is mountain height, and N_w is the Brunt-Väisälä frequency. Three terrain elevations are analyzed: 800 m (Fw_1), 1800 m (Fw_2), and 2356 m (Fw_3). The maximum Froude number (Fw_{Rmax}) is determined using the maximum mountain height h_{Rmax}.

Results show that for the Helan Mountain region, $0.48 < Fw_{Rmax} < 1$ (Figure 2). When $Fw < 1$, airflow is blocked and forced to divert around the terrain, creating upstream convergence zones that enhance precipitation. The CTRL simulation yields Fw_1 and Fw_2 values greater than 1, while Fw_3 0.5, indicating significant blocking effects at higher elevations.

The relationship between mountain height and precipitation can be expressed as:

$$H = \frac{U}{N_w}$$

where H represents the critical dividing streamline height. Analysis shows that $h_{Rmax} \approx 1200$ m corresponds to the maximum precipitation enhancement zone.

3.1.2 Flow Regime Characteristics When $Fw < 1$, the terrain effectively blocks low-level airflow, forcing moist air to ascend along windward slopes and creating strong orographic lifting. For the "7 • 22" event, the 850 hPa moisture flux convergence reaches 5×10^{-7} $g \cdot cm^{-2} \cdot hPa^{-1} \cdot s^{-1}$, significantly higher than the "8 • 21" event. This enhanced convergence, combined with terrain forcing, produces more intense precipitation on the eastern slopes of Helan Mountain.

3.2 Moisture Convergence and Precipitation Distribution

Terrain modifications substantially alter moisture convergence patterns. In TOP0.5 (reduced terrain), precipitation decreases by 35.1% on the eastern slopes but increases by 63.6% on the western side. Conversely, TOP1.5 (enhanced terrain) shows a 56.5% precipitation increase on the eastern slopes for the "7 • 22" event. The moisture convergence center aligns with the region where $u/U < 0$ (where u is the perturbation wind component and U is the mean wind), indicating flow reversal and convergence enhancement.

3.3 Thermodynamic Effects

The terrain-induced lifting significantly modifies the thermodynamic structure. Equivalent potential temperature (θ_{se}) analysis reveals that when $\theta_{se} > 337$ K, convective available potential energy is substantially increased. During the "7 • 22" event, the 850 hPa θ_{se} field shows stronger instability compared to "8 • 21" , with terrain lifting contributing to the intensification of the high-energy, high-moisture layer on windward slopes.

The moisture convergence along the eastern slopes ranges from -9×10^{-7} to -14×10^{-7} g • cm^{-2} • hPa^{-1} • s^{-1}, with the most intense convergence occurring at elevations around 1200 m. This convergence zone, combined with the narrow-pipe effect of terrain gaps and the bell-mouth contraction effect, contributes to the frequent and rapid development of convective systems southeast of the main peak.

4 Conclusions

Key findings from this study include:

(1) The Helan Mountain contributes positively to rainfall enhancement of 35–57% along its eastern slopes, while reducing precipitation by approximately 26–63.6% in the Tengger Desert to the west. The impact on the Yinchuan plain depends on the specific flow regime.

(2) Rainstorms in the Helan Mountain region typically exhibit Wet Froude numbers between 0.48 and 1. When $Fw < 1$, terrain blocking forces airflow diversion, affecting meso- and micro-scale system development and influencing storm location and intensity.

(3) Terrain forcing creates a moisture convergence center with intensity reaching -14×10^{-7} g • cm^{-2} • hPa^{-1} • s^{-1} along the eastern slopes. The convergence and uplift effects strengthen moisture convergence and cause the uplift of warm-wet flows on the windward slope, enhancing the high-energy and high-wet layers, which intensifies rainfall.

(4) The narrow-pipe effect and bell-mouth terrain-induced contraction contribute to the frequency and rapid development of rainstorms southeast of the main peak.

References

[1] Marquez J, Lastra J, Garca P. Estimation models for precipitation in mountainous regions: The use of GIS and multivariate analysis [J]. *Journal of Hydrology*, 2018, 44(1): 159-169.

[2] Neiman PJ, Ralph FM, White AB, et al. The statistical relationship between upslope flow and rainfall in California' s coastal mountains: Observations during CALJET [J]. *Monthly Weather Review*, 2002, 130(6): 1468-1492.

[3] Oldaker G, Liu L, Lin YL. Influences of Appalachian orography on heavy rainfall and rainfall variability associated with the passage of hurricane Isabel by ensemble simulations [J]. *Meteorology and Atmospheric Physics*, 2019, 131(3): 329-350.

[4] Zhu Y, Zuo H, Wang S, et al. Diagnostic analysis of two rainstorms in the Tengger Desert in July, 2012 [J]. *Arid Zone Research*, 2016, 33(2): 327-337.

[5] Smolarkiewicz PK, Rotunno R. Low Froude number flow past three-dimensional obstacles. Part II: Upwind flow reversal zone [J]. *Journal of the Atmospheric Sciences*, 1990, 47: 1498-1511.

[6] Wu Z, Bao Y, Zhu T, et al. Study on the mechanism of low-level jet in a heavy rainfall in the Yangtze river basin [J]. *Journal of Tropical Meteorology*, 2019, 35(3): 409-422.

[7] Ning G, Shang K, Wang S, et al. Numerical simulation of terrain effects of the Helan Mountain on a rainstorm in Yinchuan, Ningxia, China [J]. *Journal of Desert Research*, 2015, 35(2): 464-473.

[8] Muhlbauer A, Lohmann U. Sensitivity studies of the role of aerosols in warm-phase orographic precipitation in different dynamical flow regimes [J]. *Journal of the Atmospheric Sciences*, 2008, 65(8): 2522-2542.

[9] Romero R, Doswell CA, Ramis C. Mesoscale numerical study of two cases of long-lived quasi-stationary convective systems over Eastern Spain [J]. *Monthly Weather Review*, 2000, 128: 3731-3751.

[10] Ding Y. Contributions of prof. Tao Shiyan to the study of formation conditions and mechanisms of heavy rains in China [J]. *Chinese Journal of Atmospheric Sciences*, 2014, 38(4): 616-626.

[11] Hu B. The mesoscale orographic effects on heavy rainfall [J]. *Arid Zone Research*, 2016, 33(2): 327-337.

Abstract

Two extreme rainstorms which occurred on 21 August 2016 and 22 July 2018 on Helan Mountain were simulated and a terrain sensitivity experiment was performed using the WRF model. The theory of airflow over relief was used to study the dynamic effects of mountainous terrain. Results show a positive contribution of the Helan Mountain to rainfall of 57% along its east region, whereas a negative contribution to rainfall of approximately 63.6% was calculated in the Tengger Desert to the west of the mountain. The impact of the Helan Mountain on the Yinchuan plain depends on surge. Rainstorms in the Helan Mountain usually have a Wet Froude value between 0.48 and 1. The mountain forces the airflow around its relief, which affects the development of meso- and micro-scale weather systems, and further influences the location and strength of rainstorms. A moisture convergence center with -14×10^{-7} $g \cdot cm^{-2} \cdot hPa^{-1} \cdot s^{-1}$ can be produced along the east region of the mountain. The convergence and uplift effect of terrain strengthens moisture convergence and causes the uplift of warm-wet flows on the windward slope, enhancing the high-energy and high-wet layers, which intensifies rainfall. The narrow-pipe effect and bell-mouth terrain-induced contraction contribute to the frequency and rapid development of rainstorms southeast of the main peak.

Keywords: rainstorm; dynamic effects; numerical simulation; terrain; Helan Mountain; Ningxia

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