# Effects of Terrain on the Landing of *Locusta migratoria migratoria* (Orthoptera: Acrididae) at the China–Kazakhstan Border[1]

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**Abstract** We conducted a case study on the severe damage caused by the transboundary migration of *Locusta migratoria* (L.) (Orthoptera: Acrididae) in the Tacheng Prefecture and the Altay Prefecture at the China–Kazakhstan border by examining the effects of terrain on their landing behaviors. Based on the time and location of the locusts' mass landings, we used mesoscale weather research and forecasting models to test the sensitivity (horizontal wind, vertical wind, temperature, and rainfall) of the terrain and simulate the effects of different terrain heights (terrain leveling, half terrain height, and actual terrain height) on landing. The results showed that changes in the regional terrain of the Tacheng and Altay prefectures did not enhance the vertical airflow over the landing area. With an elevation of the terrain, the precipitation intensity in the landing area of locusts also did not increase. We did detect a direct impact of wind direction and changes in temperature in the regional terrain on the landing process of *L. m. migratoria*. With an increase in terrain altitude, the wind direction over the landing area changed and the temperature decreased, resulting in large-scale forced landing. The results of this study have important value in predicting and forecasting the arrival of migratory locusts.

**Key Words** *Locusta migratoria migratoria* landing, migratory locusts, meteorological background, terrain, China–Kazakhstan border

The landing process of migratory insects affected by individual orientation or flight capacity is called active landing, whereas landing forced by specific weather systems, weather processes, and geographical conditions is called passive landing (Wu et al. 2018). Because of the limited flight capacity of migratory insects, they must take advantage of airflow to maximize displacement (Drake 1985, Feng 2003, Liu et al. 2021, Wu et al. 2021b). As a result, migratory insects are often forced to land under the influence of terrain, horizontal wind direction, vertical airflow, rainfall, and temperature (Hu et al. 2021, Wang et al. 2017, 2022). Similarly, airflow convergence, rainfall, and low-

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temperature barriers determine the spatiotemporal distribution of migratory insects' congregation and landing and the effect of terrain on the landing of migratory insects is through changing regional climatic conditions (Chen et al. 2019, Tu et al. 2020). For example, mountains affect the direction of carrying airflow, forming circumfluent flow and changing the location of the rainfall center and precipitation intensity. Blocking by high-altitude mountains can lead to the strengthening of airflow convection activities, wind shear, and increased precipitation, forcing migratory insects to congregate and land, leading to massive migratory populations in later periods (Brattström et al. 2008, Noda and Kiritani 1989, Wu et al. 2021a). A change in terrain height can also lead to changes in solar radiation and ground temperature, thereby affecting the flight altitude of migratory insects and their eventual landing (Kimura 2021, Wu et al. 2017). The analysis of the effects of terrain and the clarification of the relationships between main weather factors and terrain conditions that lead to the landing can provide a scientific basis for accurately predicting the landing of migratory insects.

The border between China and Kazakhstan (hereafter, China–Kazakhstan border) lies between 80°45′–85°44′E and 44°35′–48°21′N along the northwestern route, stretching nearly 1,700 km (Yin et al. 2017). The Altay Prefecture, the Tacheng Prefecture, the Bortala Mongolian Autonomous Prefecture, the Ili Kazakh Autonomous Prefecture, and the Akesu Prefecture of the Xinjiang Uygur Autonomous Region in China (hereafter, Xinjiang) share the border with Kazakhstan (Yin et al. 2019). Among them, the Tacheng, Altay, and Bortala Mongolian Autonomous prefectures are the three main entry points for foreign insects invading Xinjiang, mainly due to their unique terrain (Ning 2012). The Tacheng and Altay prefectures are adjacent to the locust areas of Lake Alakol and Lake Zaysan in Kazakhstan, with a typical temperate continental climate characterized by arid and semiarid steppe (Huang and Zhu 2001, Liu et al. 2017). The Tacheng and Altay prefectures are surrounded by mountains to the north and south, forming a channel opening to the west. Here, *Locusta migratoria* (L.) (Orthoptera: Acrididae) invades China on the border of the Tacheng and Altay prefectures in large numbers (Adeke 2011, Ha and Han 2014). Studies on the migration of locusts on the China–Kazakhstan border have mainly focused on weather characteristics and the transboundary migration trajectory of *L. m. migratoria* migrating from the China–Kazakhstan border (Yu et al. 2020, Zha et al. 2021). To our knowledge, there have been no studies focused on the effects of terrain on the mass landing of migratory insect populations. Historical records show that *L. m. migratoria* has moved into the Tacheng and Altay prefectures across the China–Kazakhstan border multiple times, possibly due to the specific weather conditions generated by the regional terrain. To verify this hypothesis, a terrain sensitivity experiment based on a mesoscale weather research and a forecasting (WRF) model was adopted in this study. A case study was conducted on the historical invasion of *L. m. migratoria* of the Tacheng and Altay prefectures on the China–Kazakhstan border, which caused severe and widespread damage, to simulate the effects of different terrain features on the landing of migratory locusts. We aimed to clarify the effects of this regional terrain on the landing of locusts to provide important information for forecasting the landing of migratory locusts.

## Materials and Methods

**Insect data.** Data on the damage caused by the transboundary migration of locusts at the China–Kazakhstan border were provided by the Insect and Rat

**Table 1. Configuration and scheme options of the WRF model.**

| Item | Domain 1 | Domain 2 |
|---|---|---|
| Location | 47.34°N, 86.15°E | 47.34°N, 86.15°E |
| No. of grid points | 179 × 155 | 169 × 199 |
| Distance (km) between grid points | 15 | 5 |
| Start points | 1, 1 | 57, 55 |
| Geog_data_resolution (′) | 2 | 2 |
| Layers | 39 | 39 |
| Map projection | Lambert | Lambert |
| Microphysical process scheme | WSM6 | WSM6 |
| Long-wave radiation scheme | RRTM | RRTM |
| Short-wave radiation scheme | Dudhia | Dudhia |
| Surface layer scheme | Monin-Obukhov | Monin-Obukhov |
| Land/water surface scheme | Noah | Noah |
| Boundary layer scheme | Yonsei University | Yonsei University |
| Cumulus parameterization scheme | Kain-Fritsch | Kain-Fritsch |
| Simulated time | Every 24 h | Every 24 h |

Infestation Forecasting and Monitoring Center of the Xinjiang Uygur Autonomous Region and the Locust and Rat Infestation Forecasting and Controlling stations of the Tacheng and Altay prefectures in Xinjiang. Data included landing time, location, density, and control area of locusts.

**Meteorological data.** The initial field data of the mesoscale WRF model were obtained from the ERA-Interim Global Reanalysis data provided by the European Centre for Medium-Range Weather Forecasts (ECMWF; http://www.ecmwf.int). The temporal and spatial resolution of data was 6 h and 0.75° × 0.75°, respectively, mainly involving parameters such as geopotential height, temperature, relative humidity, and wind speed in longitudinal and latitudinal directions as well as vertical wind speed.

**Terrain data.** Terrain data were obtained from the WRF website (http://www.wrf-model.org). The double-layer nested grid design method adopted by the WRF model in this study established the landing area of locusts as the grid center. The outer grid was set as simulation area 1, with 179 × 155 grid points and a grid spacing of 15 km. Simulation area 2, that is, the inner grid, was further delineated inside simulation area 1, with a total of 169 × 199 grid points and a grid spacing of 5 km.

**Parameter setting for WRF model.** WRF 3.7 was adopted in this study. The scheme selection and parameter setting for WRF were the same as those by Wu et al. (2018). The parameter-setting scheme in combination with the longitude and latitude information on the landing sites of locusts in the Tacheng and Altay prefectures at the China–Kazakhstan border is shown in Table 1.

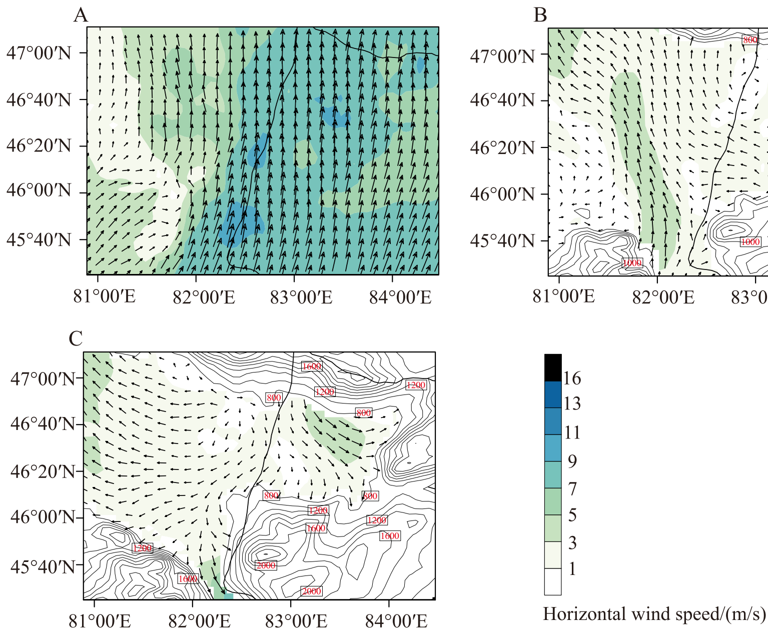


**Fig. 1. Average wind field in the locust landing area at an 800-m height in Tacheng of China–Kazakhstan border area at 1300–2100 h on 10 July 1999 in the reduced and actual topography with no terrain (A), half-reduced terrain (B), and actual terrain (C). Contour line = altitude (m).**

**Atmospheric process simulation and analysis.** By using the advanced research WRF (ARW) model for meteorological research, the integration operation of atmospheric processes in the integration domain was completed through multiple physical parameterization schemes. The operation results were output once every 1 h. In data postprocessing, meteorological analysis software (NCAR command language [NCL]), the meteorological data postprocessing program ARWpost, and the meteorological graph analysis software (Grid Analysis and Display System [GrADS]) were used to extract the required meteorological variables from the operational results of WRF simulation area 2 and convert them into a graphic format. ARWpost is a data interpolator that converts the data results simulated by WRF through an interpolation algorithm, mainly for plotting on GrADS. This study mainly analyzed the average wind field, average temperature, downdraft, and rainfall at the altitude of 800 m (barosphere was ~900 hPa) between 1300 and 2100 h (UTC: 0500–1300 h) on the landing day of migratory locusts by using the parameter settings and results of the migratory flight trajectory of *L. m. migratoria* at the China–Kazakhstan border studied by Yu et al. (2020), while assuming that the locusts landed between 1300 and 2100 h (Wang et al. 2006).

**Terrain sensitivity experiment.** The terrain sensitivity experimental setup followed that of Wu et al. (2018). Three terrain schemes were designed to study the

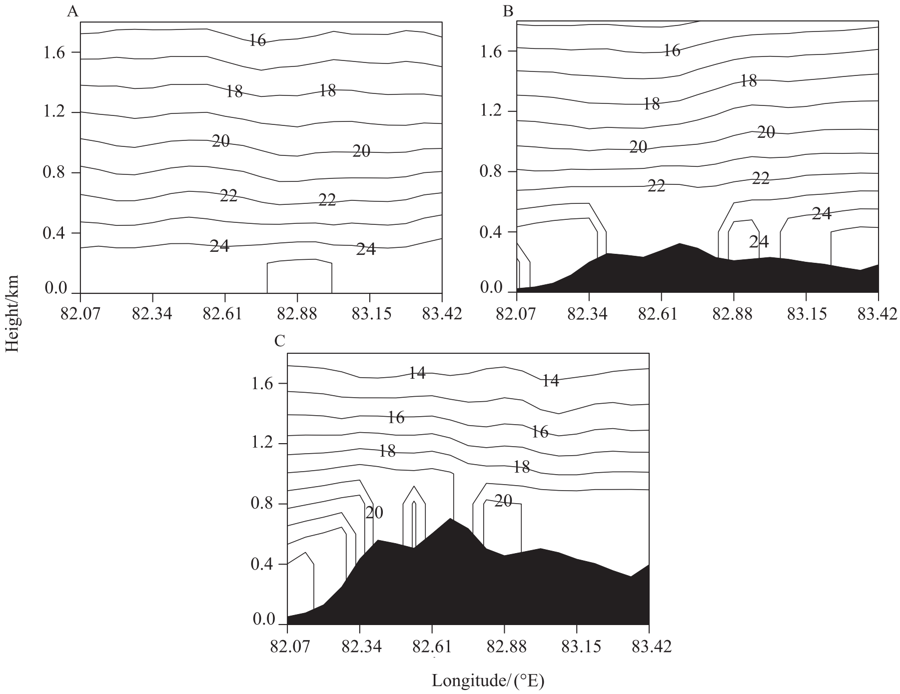


**Fig. 2. Average temperature in the locust landing area at an 800-m height in Tacheng of China–Kazakhstan border area at 1300–2100 h on 10 July 1999 in the reduced and actual topography (vertical profile along 46° 12′N) with no terrain (A), half-reduced terrain (B), and actual terrain (C). The black-filled area indicates the terrain elevation, and the contour line indicates temperature (°C).**

impact of terrain on the horizontal wind, vertical wind, temperature, and rainfall under the conditions of actual terrain height, half (1/2) terrain height, and terrain leveling (0 m). That is, the meteorological analysis software NCL was used to read and process the initial field terrain file and then the WRF model was used to carry out the terrain sensitivity experiment. In the above-mentioned three simulations, the height of the innermost terrain was calculated by the physical quantity field output by the innermost nested region. The climate change over different terrains during the locust landing and its effects on locust landing were analyzed.

## Results

**Effects of terrain on landing of *L. m. migratoria* in the Tacheng Prefecture: terrain sensitivity experiment. Case Study 1: impact of topography on wind direction and temperature during the landing on 10 July 1999.** On 10 July 1999, *L. m. migratoria* crossed the China–Kazakhstan border and landed on the Kulustai Grassland in the Tacheng Prefecture (46°12′N, 82°47′E) in Xinjiang.

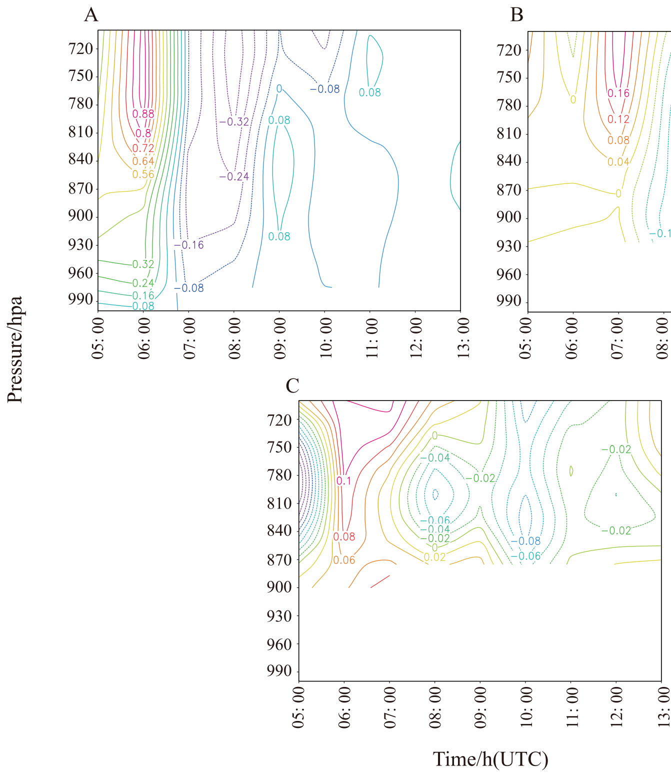


**Fig. 3. Height–time profile of vertical wind speed in the locust landing area (46°12′N, 82°47′E) in Tacheng of China–Kazakhstan border area at 1300–2100 h on 10 July 1999 in the reduced and actual topography with no terrain (A), half-reduced terrain (B), and actual terrain (C). The contour line indicates vertical wind speed (m/s), the positive values represent updrafts, the negative values represent downdrafts, and the date of blank part is missing due to terrain blocking.**

Assuming the condition of terrain leveling, the average wind direction at an 800-m altitude above the landing area was south, with an average wind speed of 7 m/s (Fig. 1A). Assuming 1/2 terrain height, it was southeast, with an average wind speed of 1 m/s (Fig. 1B). Assuming actual terrain height, it was northeast, with an average wind speed in the range of 0–1 m/s (Fig. 1C).

As indicated by the average temperature in the landing area during the locust migration period (Fig. 2), under the condition of terrain leveling, the average temperature at an 800-m altitude above the landing area was 21°C (Fig. 2A); under 1/2 terrain height, it exceeded 21°C (Fig. 2B); and at the actual terrain height, it was lower than the migratory temperature threshold of 19°C (Fig. 2C).

As indicated by the vertical airstream velocity in the landing area during the locust migration period (Fig. 3), under the condition of terrain leveling, the

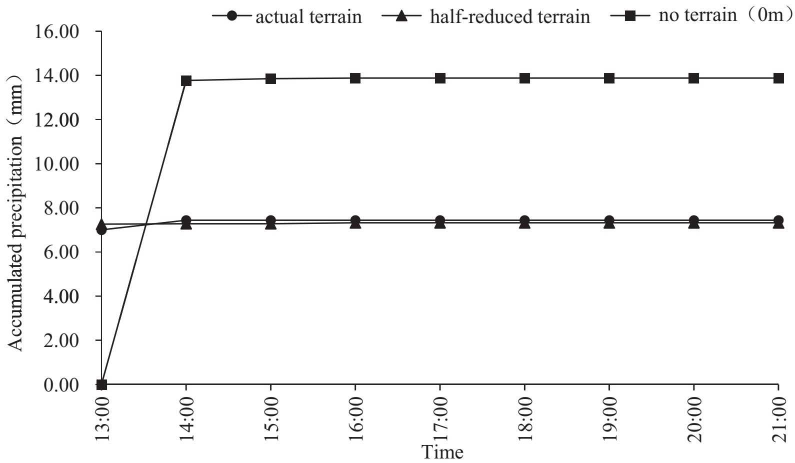


**Fig. 4. Dynamic changes of accumulated precipitation in the locust landing area in Tacheng of China–Kazakhstan border area on 10 July 1999 in the reduced and actual topography.**

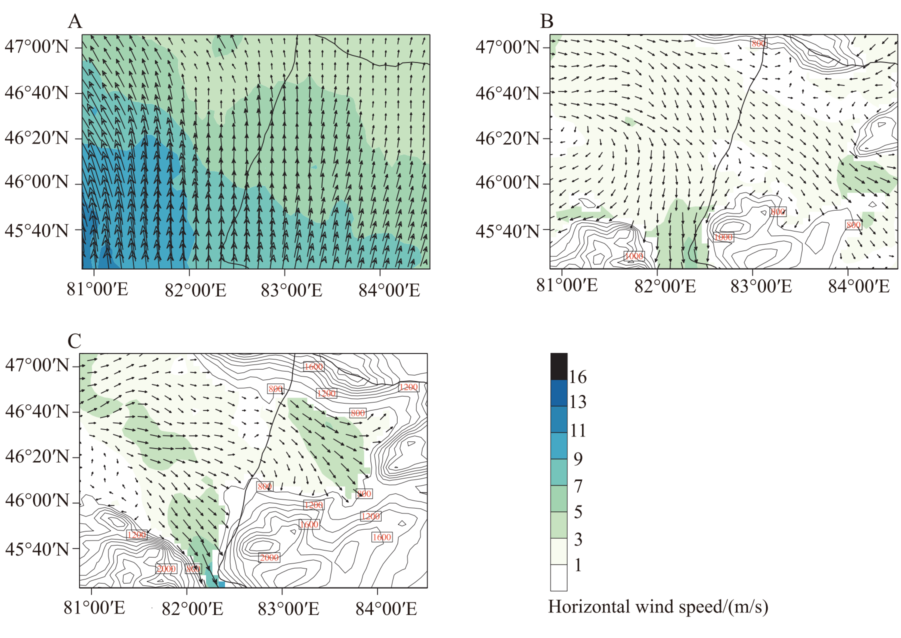


**Fig. 5. Average wind field in the locust landing area at an 800-m height in Tacheng of China–Kazakhstan border area at 1300–2100 h on 7 July 1999 in the reduced and actual topography with no terrain (A), half-reduced terrain (B), and actual terrain (C). Contour line = altitude (m).**

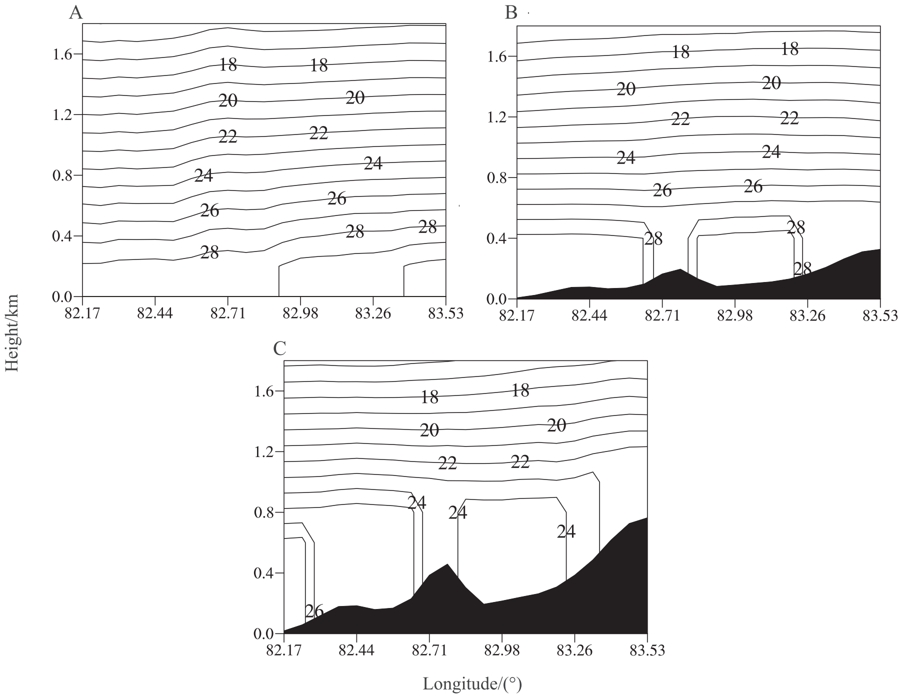


**Fig. 6. Average temperature in the locust landing area at an 800-m height in Tacheng of China–Kazakhstan border area at 1300–2100 h on 7 July 1999 in the reduced and actual topography (vertical profile along 46° 50′N) with no terrain (A), half-reduced terrain (B), and actual terrain (C). The black-filled area indicates the terrain elevation, and the contour line indicates temperature (°C).**

maximum wind speed of the updraft at a 900-hPa altitude above the landing area was >0.40 m/s, whereas that of the downdraft was 0.16 m/s (Fig. 3A); under 1/2 terrain height, the former reached 0.08 m/s, whereas the latter was >0.12 m/s (Fig. 3B); and at the actual terrain height, the highest wind speed of the updraft and downdraft in the landing area was 0.06 m/s (Fig. 3C).

As indicated by the changes in cumulative rainfall in the landing area during the locust migration period (Fig. 4), under the condition of terrain leveling, the cumulative rainfall in the landing area reached 13.85 mm; under 1/2 terrain height, it was 7.32 mm; and at the actual terrain height, it was 7.44 mm.

**Case Study 2: impact of topography on wind direction and temperature during the landing of *L. m. migratoria* on 7 July 1999.** On 7 July 1999, *L. m. migratoria* crossed the China–Kazakhstan border and landed on the border area in the Tacheng Prefecture (46°50′N, 82°53′E) of Xinjiang. Assuming the condition of terrain leveling, the average wind direction at an 800-m altitude above the landing area was south, with an average wind speed of 5 m/s (Fig. 5A). Assuming 1/2

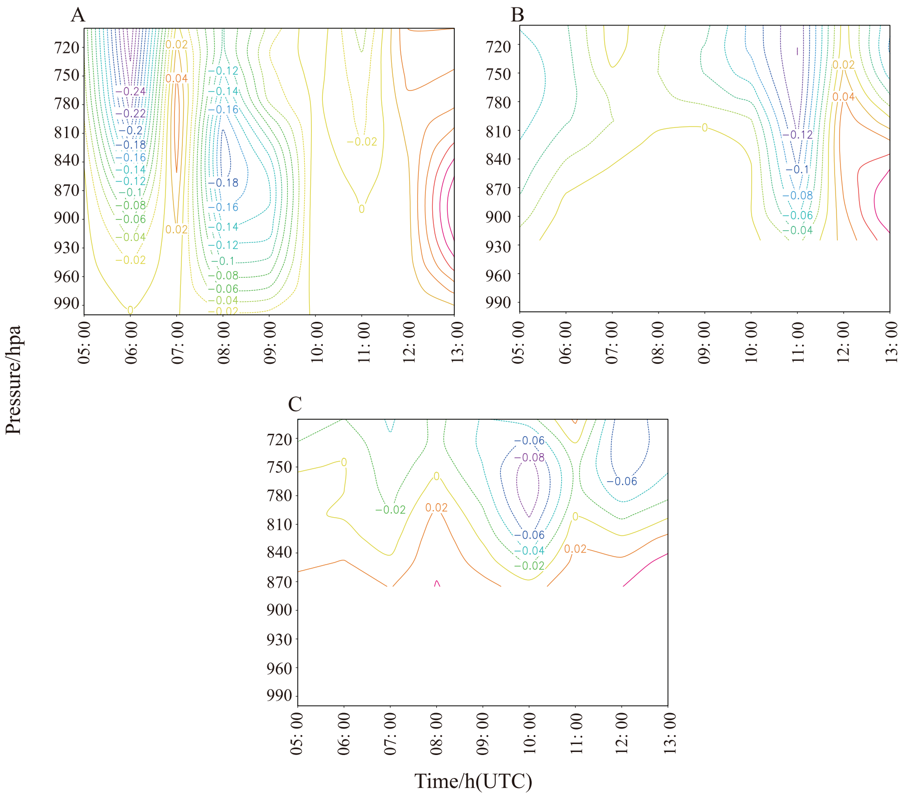


**Fig. 7. Height–time profile of vertical wind speed in the locust landing area (46°50′N, 82°53′E) in Tacheng of China–Kazakhstan border area at 1300–2100 h on 7 July 1999 in the reduced and actual topography with no terrain (A), half-reduced terrain (B), and actual terrain (C). The contour line indicates vertical wind speed (m/s), the positive values represent updrafts, the negative values represent downdrafts, and the date of blank part is missing due to terrain blocking.**

terrain height, it was a westerly wind, with an average wind speed in the range of 0–1 m/s (Fig. 5B). Assuming actual terrain height, it was northwest, with an average wind speed of 1 m/s (Fig. 5C).

As indicated by the average temperature in the landing area during the locust migration period (Fig. 6), under the condition of terrain leveling, the average temperature at an 800-m altitude above the landing area was 24°C (Fig. 6A); under 1/2 terrain height, it exceeded 25°C (Fig. 6B); and at the actual terrain height, the average temperature at an 800-m altitude above the landing area was in the range of 23–24°C (Fig. 6C).

As indicated by the vertical airstream velocity in the landing area during the locust migration period (Fig. 7), under the condition of terrain leveling, the

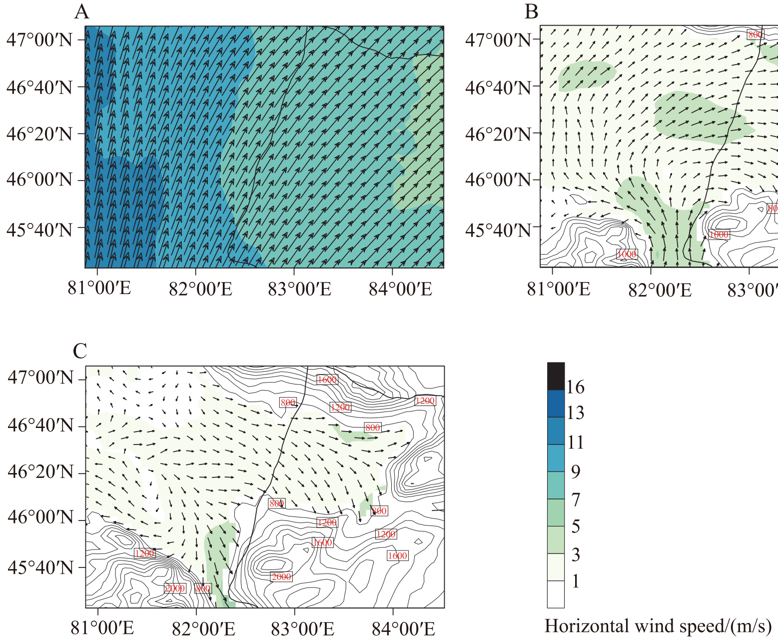


**Fig. 8. Average wind field in the locust landing area at an 800-m height in Tacheng of China–Kazakhstan border area at 1300–2100 h on 9 July 1999 in the reduced and actual topography with no terrain (A), half-reduced terrain (B), and actual terrain (C). Contour line = altitude (m).**

maximum wind speed of the updraft at a 900-hPa altitude above the landing area was >0.65 m/s, whereas that of the downdraft was 0.10 m/s (Fig. 7A); under 1/2 terrain height, the highest wind speed of the updraft and downdraft in the landing area was 0.04 m/s (Fig. 7B); and at the actual terrain height, the former reached 0.14 m/s, whereas the latter was >0.06 m/s (Fig. 7C).

**Case Study 3: impact of topography on wind direction and temperature during the landing of *L. m. migratoria* on 9 July 1999.** On 9 July 1999, *L. m. migratoria* crossed the China–Kazakhstan border and landed in Tuoli County in the Tacheng Prefecture (46°08′N, 83°55′E) of Xinjiang. Assuming the condition of terrain leveling, the average wind direction at an 800-m altitude above the landing area was southwest, with an average wind speed of 7 m/s (Fig. 8A). Assuming 1/2 terrain height, it was a westerly wind, with an average wind speed of 3 m/s (Fig. 8B). Assuming actual terrain height, it was southwest, with an average wind speed in the range of 1–3 m/s (Fig. 8C).

As indicated by the average temperature in the landing area during the locust migration period (Fig. 9), under the condition of terrain leveling, the average temperature at an 800-m altitude above the landing area was 24°C (Fig. 9A); under 1/2 terrain height, it exceeded 25°C (Fig. 9B); and at the actual terrain height, the average temperature at an 800-m altitude above the landing area was in the range of 22–23°C (Fig. 9C).

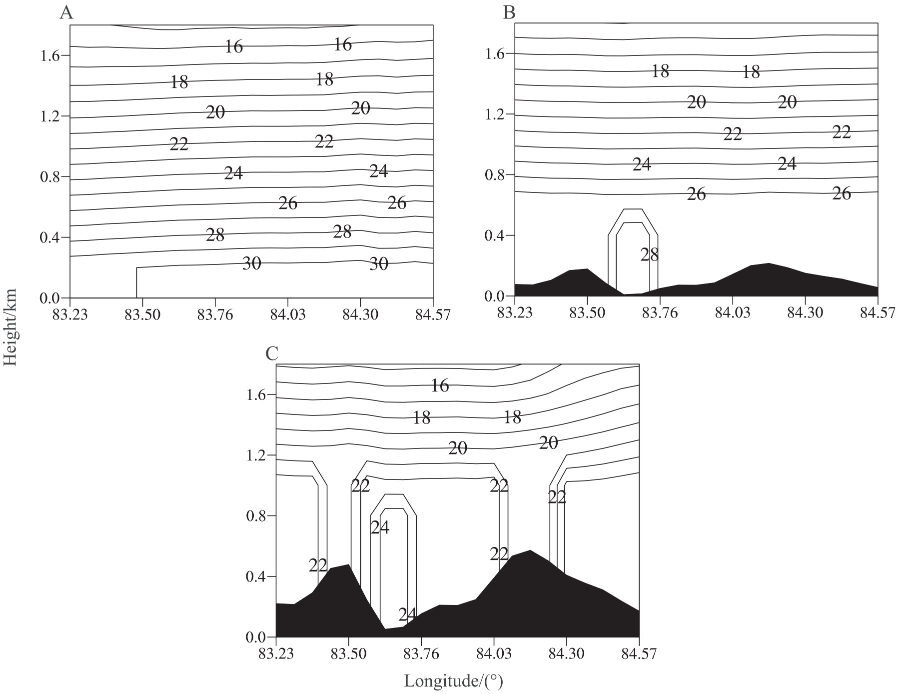


**Fig. 9. Average temperature in the locust landing area at an 800-m height in Tacheng of China–Kazakhstan border area at 1300–2100 h on 9 July 1999 in the reduced and actual topography (vertical profile along 46° 08′N) with no terrain (A), half-reduced terrain (B), and actual terrain (C). The black-filled area indicates the terrain elevation, and the contour line indicates temperature (°C).**

As indicated by the vertical airstream velocity in the landing area during the locust migration period (Fig. 10), under the condition of terrain leveling, the maximum wind speed of the updraft at a 900-hPa altitude above the landing area was >0.02 m/s, whereas that of the downdraft was 0.14 m/s (Fig. 10A); under 1/2 terrain height, the former reached 0.04 m/s, whereas the latter was >0.06 m/s (Fig. 10B); and at the actual terrain height, the highest wind speed of the updraft and downdraft in the landing area was 0.02 m/s (Fig. 10C).

**Effects of terrain on the landing of *L. m. migratoria* in the Altay Prefecture: terrain sensitivity experiment. Case Study 4: impact of topography on wind direction and temperature during the landing of *L. m. migratoria* on 19 July 2004.** On 19 July 2004, *L. m. migratoria* crossed the China–Kazakhstan border and landed in Beishawo (47°21′N, 86°19′E), Jimunai County, Altay Prefecture. Under the condition of terrain leveling, the average wind direction at an 800-m altitude above the landing area was northeast, with an average wind speed of 3 m/s (Fig. 11A); under 1/2 terrain height, it was northwest, with an average wind speed

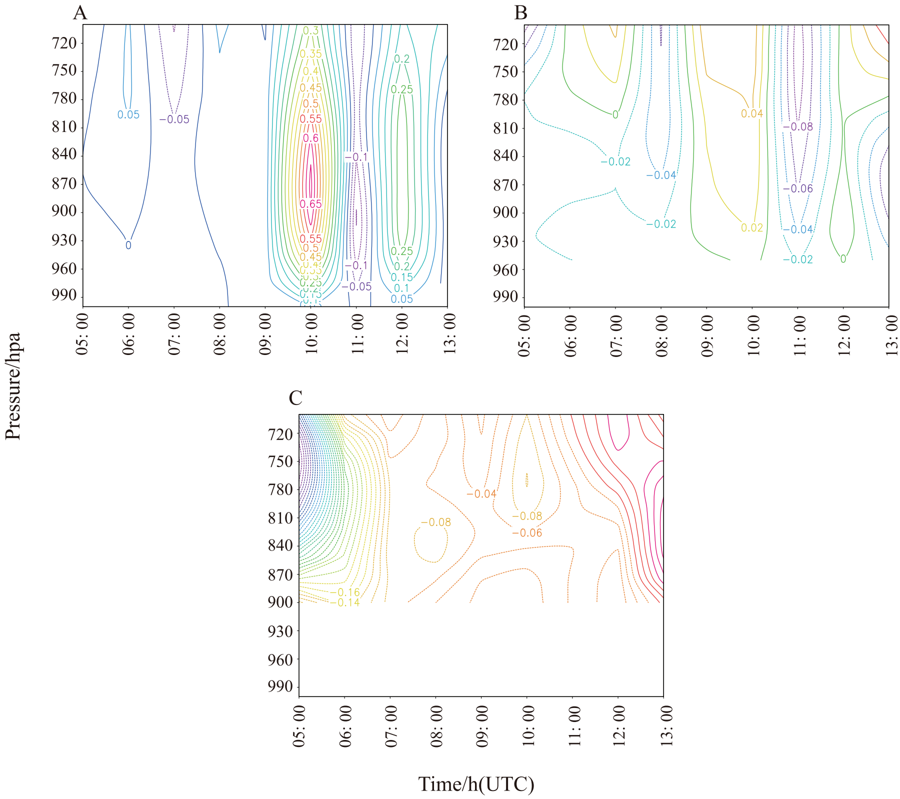


**Fig. 10. Height–time profile of vertical wind speed in the locust landing area (46°08′N, 83°55′E) in Tacheng of China–Kazakhstan border area at 1300–2100 h on 9 July 1999 in the reduced and actual topography with no terrain (A), half-reduced terrain (B), and actual terrain (C). The contour line indicates vertical wind speed (m/s), the positive values represent updrafts, the negative values represent downdrafts, and the date of blank part is missing due to terrain blocking.**

of 5 m/s (Fig. 11B); and at the actual terrain height, it was west, with an average wind speed of 3 m/s (Fig. 11C).

As indicated by the average temperature in the landing area during the locust migration period (Fig. 12), under the condition of terrain leveling, the temperature at an 800-m altitude above the landing area was in the range of 18–19°C (Fig. 12A); under 1/2 terrain height, it was >20°C (Fig. 12B); and at the actual terrain height, it was lower than the migratory temperature threshold of 19°C (Fig. 12C).

As indicated by the vertical airflow speed in the landing area during the locust migration period (Fig. 13), under the condition of terrain leveling, the maximum wind speed of the updraft at a 900-hPa altitude above the landing area was 0.56

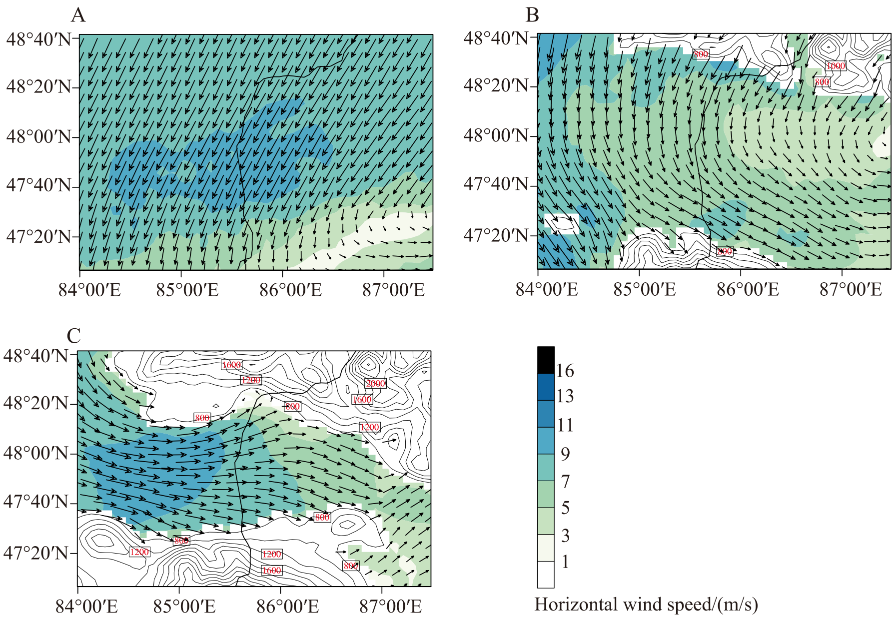


**Fig. 11. Average wind field in the locust landing area at an 800-m height in Altay of China–Kazakhstan border area at 1300–2100 h on 19 July 2004 in the reduced and actual topography with no terrain (A), half-reduced terrain (B), and actual terrain (C). Contour line = altitude (m).**

m/s and that of the downdraft was 0.08 m/s (Fig. 13A); under 1/2 terrain height, the former was 0.08 m/s (Fig. 13B), whereas the latter was 0.12 m/s; and at the actual terrain height, the maximum wind speeds of the updraft and downdraft in the landing were both 0.10 m /s (Fig. 13C).

As indicated by the changes in the cumulative rainfall in the landing area during the locust migration period (Fig. 14), under the condition of terrain leveling, the cumulative rainfall in the landing area reached 12.50 mm; under 1/2 terrain height, it was 2.12 mm; and at the actual terrain height, it was 3.61 mm.

**Case Study 5: impact of topography on wind direction and temperature during the landing of *L. m. migratoria* on 27 July 2004.** On 27 July 2004, *L. m. migratoria* crossed China–Kazakhstan border and landed in Jimunai County (47° 33′N, 85°59′E) in Altay Prefecture. Under the condition of terrain leveling, the average wind direction at an 800-m altitude above the landing area was northwest, with an average wind speed of 1 m/s (Fig. 15A); under 1/2 terrain height, it was northwest, with an average wind speed of 3 m/s (Fig. 15B); and at the actual terrain height, it was west, with an average wind speed of 7 m/s (Fig. 15C).

As indicated by the average temperature in the landing area during the locust migration period (Fig. 16), under the condition of terrain leveling, the temperature at an 800-m altitude above the landing area was >23°C (Fig. 16A); under 1/2

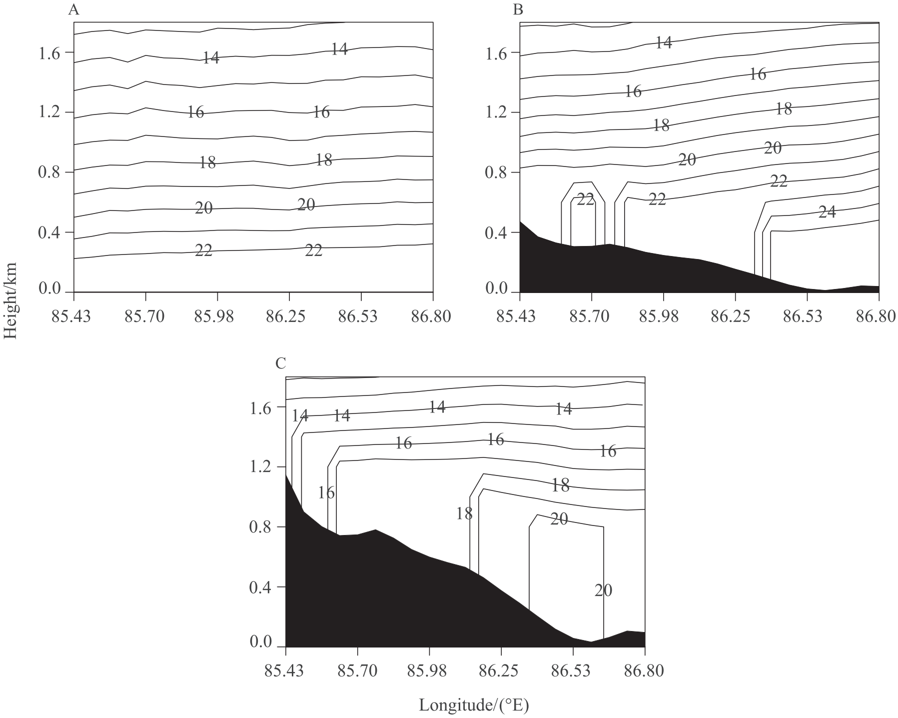


**Fig. 12. Average temperature in the locust landing area at an 800-m height in Altay of China–Kazakhstan border area at 1300–2100 h on 19 July 2004 in the reduced and actual topography (vertical profile along 47°21′N) with no terrain (A), half-reduced terrain (B), and actual terrain (C). The black-filled area indicates the terrain elevation, and the contour line indicates temperature (°C).**

terrain height, it was 23°C (Fig. 16B); and at the actual terrain height, it was in the range of 22–23°C (Fig. 16C).

As indicated by the vertical airflow speed in the landing area during the locust migration period (Fig. 17), under the condition of terrain leveling, the maximum wind speed of the updraft at a 900-hPa altitude above the landing area was 0.18 m/s and that of the downdraft was 0.12 m/s (Fig. 17A); under 1/2 terrain height, the former was 0.04 m/s (Fig. 17B), whereas the latter was 0.02 m/s; and at the actual terrain height, the maximum wind speeds of the downdraft in the landing at a 900-hPa altitude above the landing area was 0.06 m/s, with no noticeable upward airflow (Fig. 17C).

**Case Study 6: impact of topography on wind direction and temperature during the landing of *L. m. migratoria* on 1 August 2003.** On 1 August 2003, *L. m. migratoria* crossed China–Kazakhstan border and landed in Jimunai County (47°20′ N, 86°09′ E) in the Altay Prefecture. Under the condition of terrain leveling, the average wind direction at an 800-m altitude above the landing area was south,

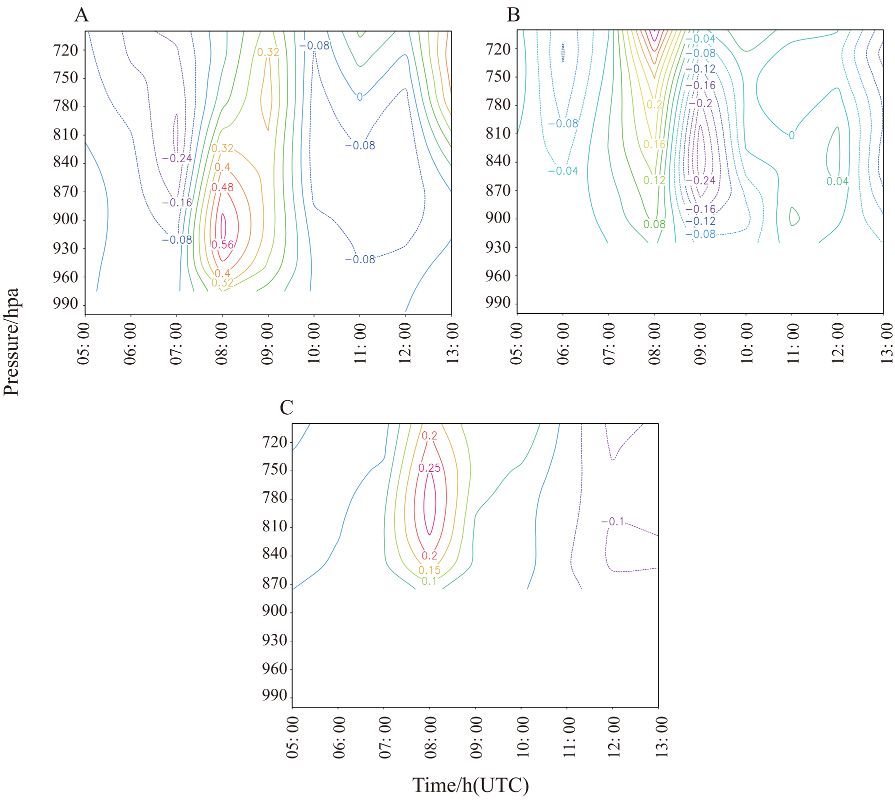


**Fig. 13. Height–time profile of vertical wind speed in the locust landing area (47°21′N, 86°19′E) in Altay of China–Kazakhstan border area at 1300–2100 h on 19 July 2004 in the reduced and actual topography with no terrain (A), half-reduced terrain (B), and actual terrain (C). The contour line indicates vertical wind speed (m/s), the positive values represent updrafts, the negative values represent downdrafts, and the date of blank part is missing due to terrain blocking.**

with an average wind speed of 1 m/s (Fig. 18A); under 1/2 terrain height, it was northwest, with an average wind speed of 1 m/s (Fig. 18B); and at the actual terrain height, it was west, with an average wind speed of 1 m/s (Fig. 18C).

As indicated by the average temperature in the landing area during the locust migration period (Fig. 19), under the condition of terrain leveling, the temperature at an 800-m altitude above the landing area was >21°C (Fig. 19A); under 1/2 terrain height, it was >23°C (Fig. 19B); and at the actual terrain height, it was lower than the migratory temperature threshold of 19°C (Fig. 19C).

As indicated by the vertical airflow speed in the landing area during the locust migration period (Fig. 20), under the condition of terrain leveling, the maximum wind speeds of the updraft and downdraft in the landing were both 0.04 m/s (Fig. 20A); under 1/2 terrain height, the maximum wind speed of the

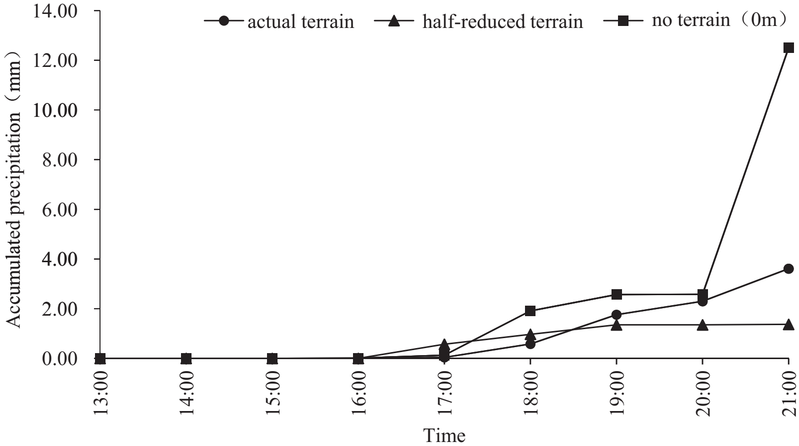


**Fig. 14. Dynamic changes of accumulated precipitation in locust landing area in Altay of China–Kazakhstan border area on 19 July 2004 in the reduced and actual topography.**

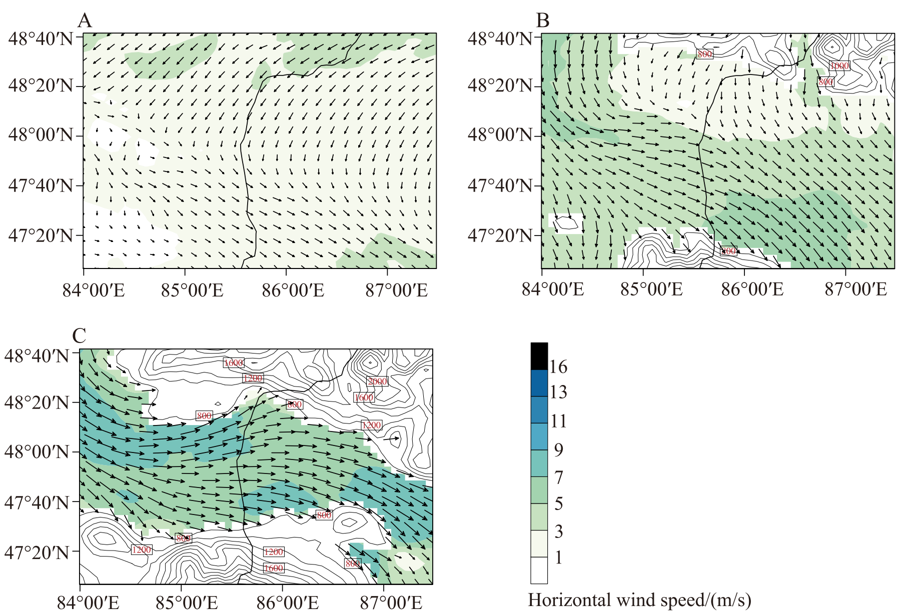


**Fig. 15. Average wind field in the locust landing area at an 800-m height in Altay of China–Kazakhstan border area at 1300–2100 h on 27 July 2004 in the reduced and actual topography with no terrain (A), half-reduced terrain (B), and actual terrain (C). Contour line = altitude (m).**

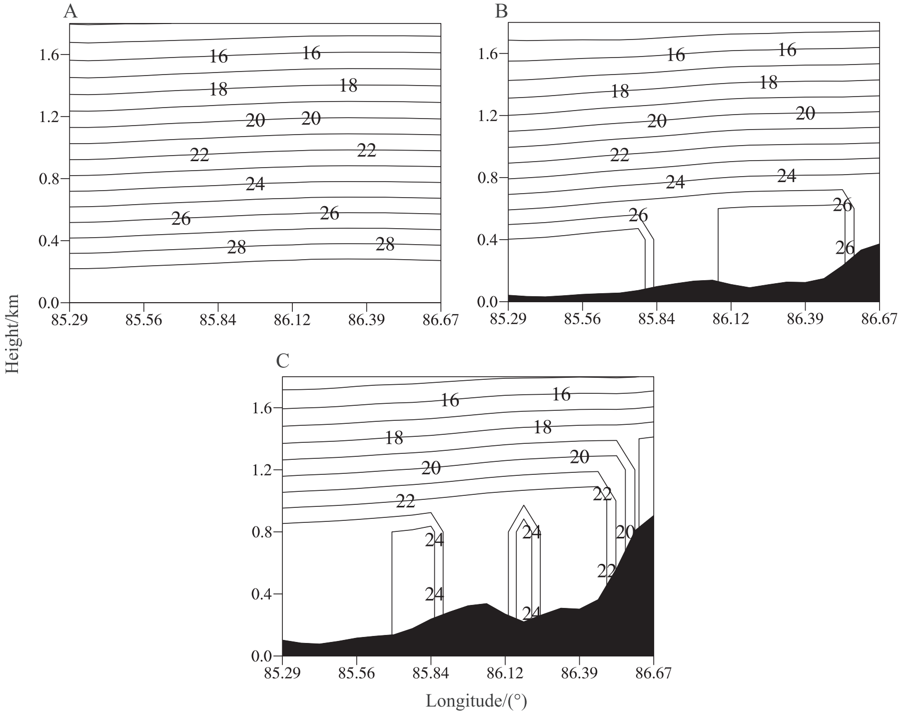


**Fig. 16. Average temperature in the locust landing area at an 800-m height in Altay of China–Kazakhstan border area at 1300–2100 h on 27 July 2004 in the reduced and actual topography (vertical profile along 47°33′N) with no terrain (A), half-reduced terrain (B), and actual terrain (C). The black-filled area indicates the terrain elevation, and the contour line indicates temperature (°C).**

updraft at a 900-hPa altitude above the landing area was 0.24 m/s and that of the downdraft was 0.02 m/s (Fig. 20B); and at the actual terrain height, the maximum wind speeds of the upward in the landing at a 900-hPa altitude above the landing area was 0.24 m/s, with no noticeable downdraft airflow (Fig. 20C).

## Discussion

Results of the terrain sensitivity experiments based on the WRF simulation showed that the terrain in the Tacheng and Altay prefectures did not enhance vertical airflow. With the inclining terrain, rainfall in the landing area of locusts did not increase substantially and the direct influence of the terrain in these two regions on the landing process of *L. m. migratoria* is reflected in changes in wind direction

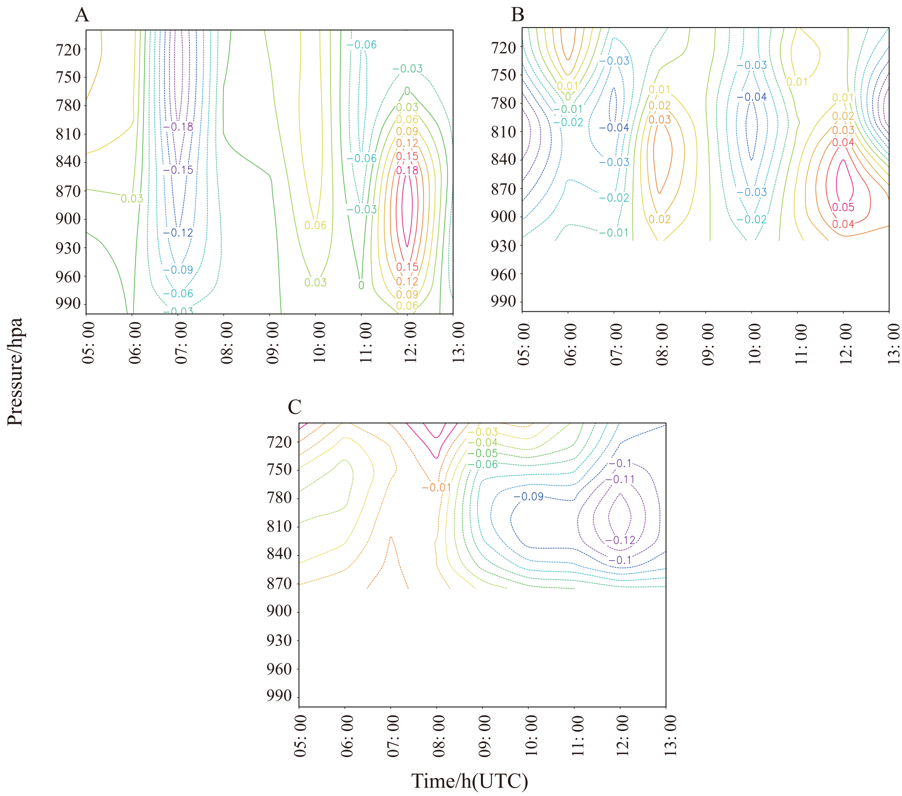


**Fig. 17. Height–time profile of vertical wind speed in the locust landing area (47°33′ N, 85°59′E) in Altay of China–Kazakhstan border area at 1300–2100 h on 27 July 2004 in the reduced and actual topography with no terrain (A), half-reduced terrain (B), and actual terrain (C). The contour line indicates vertical wind speed (m/s), the positive values represent updrafts, the negative values represent downdrafts, and the date of blank part is missing due to terrain blocking.**

and temperature. The presence of the mountain changed the wind direction and decreased the temperature, creating a natural barrier to migrating locusts and forcing them to land. Previous studies have shown that the rice planthoppers *Nilaparvata lugens* (Stål) and *Sogatella furcifera* (Horváth) (Hemiptera: Delphacidae) landed in a congregated manner under the influence of a small vertical circulation formed by mountain obstruction and ground friction, the night mountain breeze, and canyon wind between valleys and that they mainly landed in the valley on the windward slope of the mountain (Noda and Kiritani 1989, Wu et al. 2015). Carrier airflow is forced to rise when mountains converge; with the rising terrain, the temperature decreased, forcing migratory insects to lower

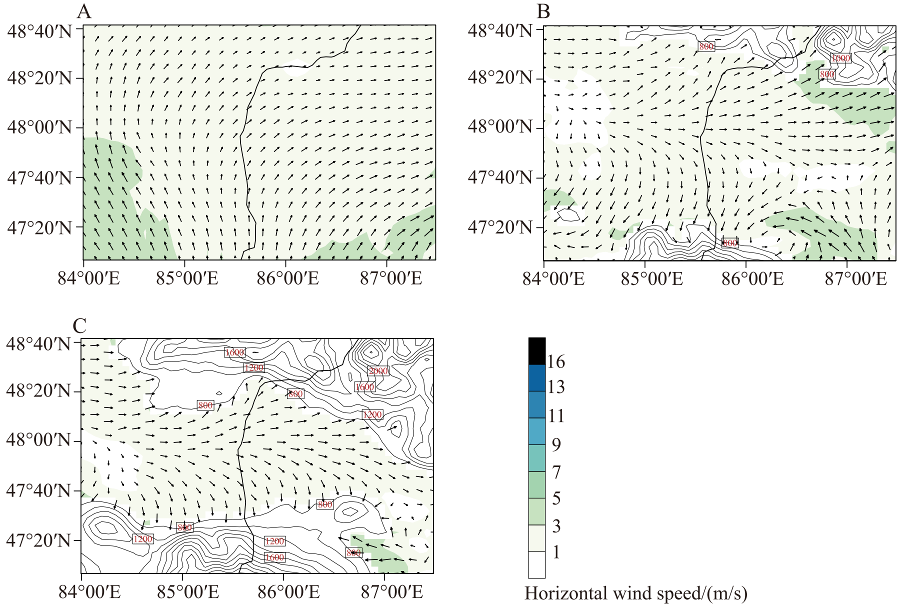


**Fig. 18. Average wind field in the locust landing area at an 800-m height in Altay of China–Kazakhstan border area at 1300–2100 h on 1 August 2003 in the reduced and actual topography with no terrain (A), half-reduced terrain (B), and actual terrain (C). Contour line = altitude (m).**

their flight altitude due to physiological adaptation and finally land on the ground (Cang 2020, Shen et al. 2011, Wu 2018). This supports the findings of our study.

The effect of terrain on wind direction in the Tacheng Prefecture is manifested in the blocking of the south wind by high-altitude mountains, whereas that in the Altay Prefecture is manifested in the blocking of the northerly wind by high-altitude mountains. The Tacheng and Altay prefectures are located in the northwestern part of Xinjiang, far from the ocean, belonging to typical arid and semiarid climate zones, with a vast territory and complex terrain. At the northern end is the Altai Mountains known for changing the airflow direction and speed (Luo and Jing 2013, Wang et al. 2014). Migratory insect populations usually adopt certain migratory strategies according to strong convergent airflow, precipitation, and other external factors. In general, mountain rainfall increases with the surface elevation rising (Li et al. 2020). However, we found that the rainfall in the Tacheng and Altay prefectures did not increase substantially with an increase in elevation and that the predicted rainfall was the highest under the terrain leveling simulation. This might be due to the Tacheng and Altay prefectures being located in northwestern China, far inland with a hot climate and little rain in summer. Without the obstruction of mountains, the influx and convergence of cold and warm air increases, resulting in rainfall. With the increasing elevation, airflow is forced to form circumfluence flow

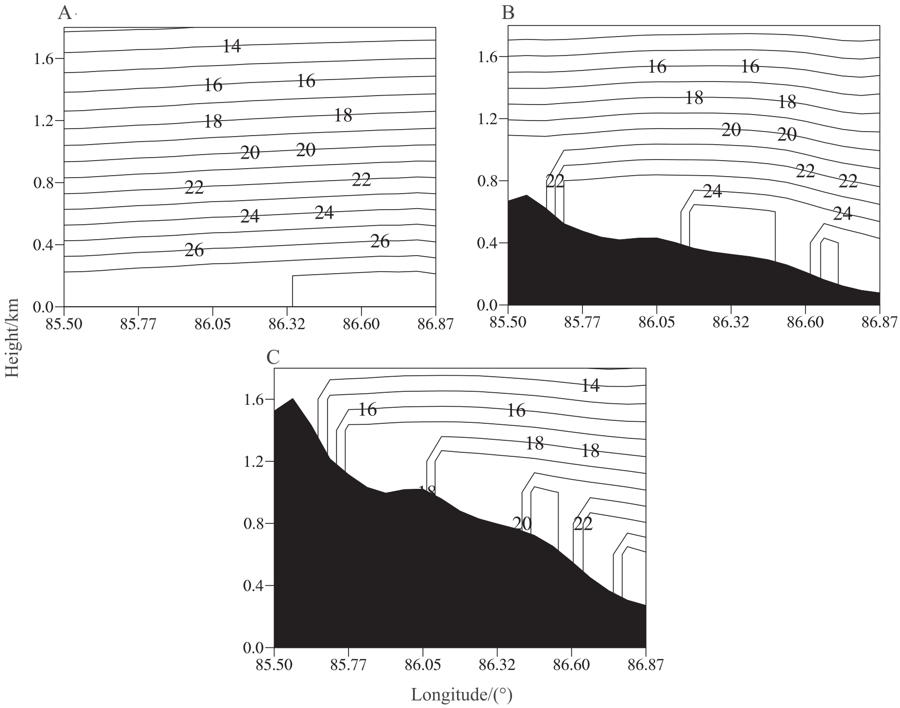


**Fig. 19. Average temperature in the locust landing area at an 800-m height in Altay of China–Kazakhstan border area at 1300–2100 h on 1 August 2003 in the reduced and actual topography (vertical profile along 47°20′N) with no terrain (A), half-reduced terrain (B), and actual terrain (C). The black-filled area indicates the terrain elevation, and the contour line indicates temperature (°C).**

or enter through the mountain valley, altering the location of the rainfall center and the precipitation intensity (Yan et al. 2020). Previous studies have shown that increased elevation contributes to an increase in rainfall. Rainfall will peak with rising air at a certain height along the mountainside; thereafter, the rainfall intensity will not continue to increase with an increase in elevation and may even decrease (Wu 2018).

The landing process of migratory insects is influenced by their flight capacity and the environment. This study focused on the analysis of the effect of terrain on the landing of transboundary migratory locusts. In subsequent research, it is necessary to conduct more empirical studies to analyze the association between meteorological conditions, terrain, and the landing of migratory insects to assess the effect of regional terrain on landing. This would improve the accuracy of forecasting and early warning systems for migratory locusts and other migratory insects.

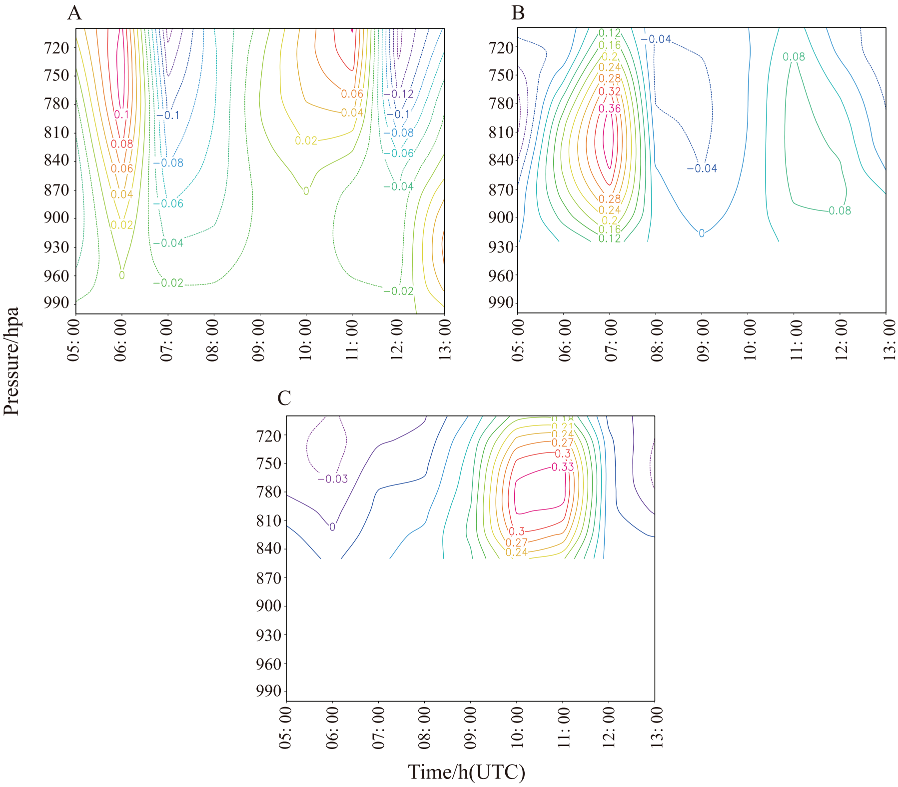


**Fig. 20. Height–time profile of vertical wind speed in the locust landing area (47°20′N, 86°09′E) in Altay of China–Kazakhstan border area at 1300–2100 h on 1 August 2003 in the reduced and actual topography with no terrain (A), half-reduced terrain (B), and actual terrain (C). The contour line indicates vertical wind speed (m/s), the positive values represent updrafts, the negative values represent downdrafts, and the date of blank part is missing due to terrain blocking.**

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