Fine-scale Characteristics and Mechanisms of a Rare Mountain-crossing Strong Wind in Aksu, August 2019: Postprint

Authors: Rozi Aji, Bixin Yu, Li Ruqi, Li Ruqi

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Abstract

The Aksu region in the central-western part of southern Xinjiang is prone to mountain-crossing strong winds when surface cold air is very strong due to its geographical location and terrain. To gain a deeper understanding of the mechanism of mountain-crossing strong winds in Aksu and improve the forecasting capability for such disastrous strong winds, this study analyzes a rare mountain-crossing strong wind weather process that occurred during August 15–18, 2019. Using conventional meteorological observation data, sounding observation data, model forecast data, NCEP 6-hourly reanalysis data with 1°$×$1° grid spacing, and hourly wind direction and speed data from two surface automatic weather stations (Aksu Station and Tuowanketi Genghonggou Station), we analyzed the detailed characteristics of this strong wind event, its influencing systems, and dynamic and thermodynamic conditions. The results show that: (1) This strong wind event occurred under the situation where the Eastern European blocking high developed and intensified, and the Central Asian low vortex persisted for a long time and split eastward three times; it was a persistent strong wind triggered by the combined action of upper-level jet streams and low-level cold advection, which transformed the potential energy of cold air into kinetic energy. (2) Three strong wind fluctuations occurred during the process, all formed by upper-level troughs guiding cold air to cross the Tianshan Mountains; the first two were caused by short-wave troughs with short durations of strong winds, while the third was triggered by the eastward movement of the main trough with a long duration of strong winds. (3) In the first strong wind fluctuation, convective thunderstorm winds were superimposed, with instantaneous gusts reaching level 12. (4) Strong vertical motion and secondary circulation induced by the upper-level jet stream, mid-level convergence, and low-level divergence were conducive to the intensification and maintenance of the strong winds.

Full Text

Fine Characteristics and Cause Analysis of the Rare Mountain-Crossing Gale in Aksu in August 2019

Rouzi Aji, Yu Bixin, Li Ruqi
(Xinjiang Meteorological Observatory, Urumqi, Xinjiang)

Abstract

Aksu Prefecture, located in the midwest of southern Xinjiang, is prone to mountain-crossing gales due to its unique geographic location and terrain when strong cold air masses are present at the surface. To better understand the mechanism of these events and improve forecast capabilities for such disastrous winds, this study analyzes the fine-scale characteristics, influencing systems, and dynamic and thermal conditions of a rare mountain-crossing gale that occurred from August 15–18, 2019. Using conventional meteorological observations, radiosonde data, NCEP reanalysis data (1°$×$1°), and hourly wind direction/speed data from automatic weather stations at Aksu and Tuowanketigengou, the results show that this persistent gale developed under a circulation pattern featuring a strengthening blocking high over Eastern Europe and a long-lasting Central Asian low vortex that split into three short-wave troughs moving eastward. The gale was generated by the conversion of potential energy to kinetic energy in the cold air mass through the combined action of an upper-level jet stream and low-level cold advection. Three distinct gale waves occurred, all formed by cold air guided over the Tianshan Mountains by upper-level troughs. The first two waves, triggered by short-wave troughs, were brief in duration, while the third wave, induced by the main trough' s eastward movement, persisted much longer. The first wave featured convective thunderstorm winds superimposed on the mountain-crossing flow, producing instantaneous gusts reaching grade 12. Strong vertical motion and secondary circulation generated by the upper-level jet, along with mid-level convergence and low-level divergence, contributed to the gale' s intensification and maintenance.

Keywords: mountain-crossing gale; thunderstorm wind; dynamic conditions; thermal conditions; Aksu Prefecture

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1. Data Sources

This study utilizes conventional surface and upper-air meteorological observations, radiosonde data from the Aksu sounding station, ECMWF model forecast data (0.5°$×0.5° *coarsegridand* 0.125°×0.125° *finegrid, bothwith* 6 − *hourtemporalresolution*), *NCEPreanalysisdata*(1°×$1°), and hourly wind direction/speed data from two surface automatic weather stations (Aksu and Tuowanketigengou) to analyze the dynamic, thermal, and downslope wind theory aspects of this gale event.

2. Weather Situation and Circulation Background

2.1 Overview and Characteristics of the Gale From August 15-18, 2019, continuous gale weather occurred on the southern slopes of the western Tianshan Mountains, with instantaneous maximum winds reaching force 11–12 in Kashgar, Aksu, and Bayingolin Prefectures. In the Aksu region, 46 stations recorded force 10+ winds, with the extreme value observed at Tuowanketigengou in Aysu Township, Aksu City, reaching 35.9 $m \cdot s^{-1}$. Across southern Xinjiang, 35 stations reported blowing sand and 6 reported dust storms. The gale caused 27 passenger trains to be suspended, inflicted severe damage on agriculture and forestry in Aksu, affected 1999.1 hm^2 of crops and 2.1 hm^2 of vegetables and melons, destroyed 59,000 fruit trees, and resulted in direct economic losses of 580 million yuan.

Time series analysis of wind speed variations at Tuowanketigengou and Aksu stations reveals three distinct wind speed fluctuations (Fig. 1, Table 1). At Tuowanketigengou, the first wave maintained force 10+ winds from 20:00 on August 15 to 03:00 on August 16, peaking at 35.9 $m \cdot s^{-1}$. The second wave maintained force 8+ winds from 09:00 to 14:00 on August 16, peaking at 22.6 $m \cdot s^{-1}$. After temporary weakening, winds strengthened again from 14:00 on August 16 to 22:00 on August 17, with the third wave maintaining force 10+ winds for 32 hours and peaking at 29.8 $m \cdot s^{-1}$. Wind speeds at Aksu station were slightly weaker but showed similar trends.

The entire event exhibited sudden onset, large amplitude between peaks and troughs, extensive coverage, strong intensity, long duration, and obvious wind speed fluctuations. At Tuowanketigengou, the wind speed increased from just 4.9 $m \cdot s^{-1}$ (force 3) at 19:00 to the maximum of 35.9 $m \cdot s^{-1}$ within 10 minutes. During the 46-hour period with three wind fluctuations, force 10+ winds persisted for 39 hours. Even when winds dropped below force 10, they generally remained above force 8, with only occasional reductions to force 7. This was a clear case of severe downslope windstorm caused by airflow crossing the mountains, concentrated on the leeward slopes and foothills, where wind speeds were significantly stronger than those on the windward side.

2.2.1 Upper-Level Baroclinic Trough and Strong Frontal Zone This gale event belongs to the "ridge (blocking high) decay" type. At 08:00 on August 15, the 500 hPa chart showed a two-trough, two-ridge meridional circulation across mid-high latitudes of Eurasia, with a developing and strengthening blocking high over Eastern Europe. The Ural low vortex behind the ridge was positioned far south, with its center at 56°N, 65°E and a cold core of -16°C lagging behind the 556 dagpm height center. The ridge top extended to the Ural Mountains, strengthening the northerly flow ahead of the ridge with maximum winds reaching 28 $m \cdot s^{-1}$. The low vortex moved southeastward to west of Lake Balkhash, with its center retrograding. A short wave split along the frontal zone on the vortex' s periphery, moving rapidly southeastward to the vortex base and forming an unstable small trough, while the temperature trough moved faster, leading the height trough. Blocked by the Xinjiang ridge, the low vortex moved less than 5 degrees of longitude eastward by 20:00, allowing energy to accumulate.

By 20:00 on August 15, the polar vortex over the Taymyr Peninsula pressed southward, compressing the European ridge. Positive height tendencies fell southward from the ridge top, pushing the unstable small trough eastward into southern Xinjiang and guiding surface cold air across the western Tianshan Mountains into Aksu and Kashgar, forming downslope winds. Simultaneously, the surface cold front triggered convective development in Aksu, producing short-lived thunderstorm gales. Upper-level winds at 500 hPa increased significantly, and the superposition of systematic mountain-crossing winds and convective thunderstorm winds caused surface wind speeds to surge dramatically, coinciding with the sudden onset and extreme wind speeds observed at Tuowanketigengou.

During the day on August 16, the surface cold front entered the Aksu region, with the pressure gradient gradually intensifying. By 20:00, the pressure gradient reached 6 isobars, with a pressure difference of 20 hPa between high and low centers. At 08:00 on August 16, the European ridge continued developing eastward, pushing the low vortex slightly southeastward. Southwest winds ahead of the trough increased significantly, and a second short wave split from the vortex base, moving rapidly eastward into Xinjiang and guiding another cold air mass across the western Tianshan Mountains. This marked the beginning of the second gale wave, which lasted until 09:00 on August 17. At 14:00 on August 16, the northern part of the low vortex moved quickly eastward while the southern section lingered over Central Asia. The southern part of the vortex split again at 20:00 on August 16, with the main body slowly moving eastward into southern Xinjiang while some cold air remained over Central Asia, weakening during the day on August 17 and ending the second gale wave.

From 14:00 on August 17, the front of the cold high extended again to south of Lake Balkhash, while the thermal low center strengthened to 990 hPa and moved southeastward over the Kunlun Mountains. Because the main vortex moved slowly after entering southern Xinjiang, it continuously guided surface cold air across the western Tianshan Mountains, causing the third wave of disastrous surface winds to persist for 32 hours. The pressure gradient reached 7 isobars, with a pressure difference of 27.5 hPa between centers. Wind speeds at Tuowanketigengou maintained force 10+ levels, reaching the second-highest value of the event. By the afternoon of August 18, winds dropped below force 7, ending the gale process. Throughout the event, wind directions in the middle and lower troposphere differed from surface winds, and low-level wind speeds did not increase with mid-level winds, indicating that momentum transfer from upper levels was not significant.

2.2.2 Surface Cold Front Before the event, a cold high formed over Europe and slowly moved southeastward. At 20:00 on August 14, the cold high center moved to the Caspian Sea with an intensity of 1022.5 hPa. By 20:00 on August 15, the high' s front extended to Lake Balkhash with the cold high center at 1012.5 hPa. On August 16, as the cold front entered the Aksu region, the pressure gradient intensified. At 20:00, the cold high' s front reached south of Lake Balkhash, with a small center of 1007 hPa forming at its front. By 08:00 on August 17, this small center disappeared, but the cold front remained over the western Tianshan Mountains while the thermal low in the basin changed little. From 14:00 on August 17, the cold high' s front extended again to south of Lake Balkhash, the thermal low center strengthened to 990 hPa, and the pressure gradient intensified to 7 isobars. After 08:00 on August 18, the cold high remained essentially unchanged while the thermal low gradually weakened and moved eastward out of the region, yet the cold front persisted over the western Tianshan Mountains and Tuowanketigengou experienced the third gale wave. These changes indicate that the gale was primarily caused by the splitting and eastward movement of upper-level troughs that guided surface cold air across the mountains, with potential energy converting to kinetic energy after crossing the Tianshan Mountains. The onset times of all three gale waves coincided precisely with the arrival of upper-level short-wave troughs over the western Tianshan Mountains.

3. Dynamic and Thermal Conditions Analysis

3.1 T-lnP Diagram Analysis The temperature-logarithmic pressure diagram at Aksu sounding station on August 15 shows that at 08:00, convective inhibition energy reached 7.3 $J \cdot kg^{-1}$, favoring energy accumulation. Convective available potential energy (CAPE) was 1110 $J \cdot kg^{-1}$, while downdraft convective available potential energy (DCAPE) was weak at only 1726 $J \cdot kg^{-1}$. The lower troposphere was dry, the middle troposphere moist, with some vertical wind shear—conditions favorable for convective triggering and thunderstorm gale formation. By 20:00, convective inhibition dropped to zero, CAPE increased to 1726 $J \cdot kg^{-1}$, and DCAPE surged dramatically to 1110 $J \cdot kg^{-1}$. This sudden increase in DCAPE coincided with the abrupt onset of a short-lived force 12 gale, indicating that the surface cold front triggered convection and thunderstorm winds while the upper-level trough guided cold air across the Tianshan Mountains, converting potential to kinetic energy. The strong DCAPE facilitated rapid downslope motion of the mountain-crossing airflow, forming a downslope windstorm. The superposition of mountain-crossing winds and thunderstorm winds produced the short-lived force 12 disastrous gale. After the thunderstorm winds ended, the cold air guided by the upper short-wave trough continued crossing the mountains, forming downslope winds that maintained force 10+ winds for 7 hours.

3.2 Temperature Advection Analysis According to the geopotential tendency equation and ω equation, warm advection causes isobaric surfaces to rise, producing upward motion and low-level pressure falls, while cold advection causes isobaric surfaces to descend, producing downward motion and surface pressure rises. Different temperature advection patterns in different regions alter surface pressure and create pressure gradients favorable for gale formation. Stronger temperature advection is more conducive to gale development. The height-time cross-section of temperature advection over Aksu (Fig. 6) shows that throughout the event, a strong cold advection center persisted in the lower troposphere. On the night of August 15, the intensity was -40$\times10^{-5}$ K $\cdot$ s^{-1}. During the day on August 16, cold advection weakened, but on the night of August 16, another strong center reached -100$\times10^{-5}$ K $\cdot$ s^{-1}. During the day on August 17, the cold advection center intensity was -40$\times10^{-5}$ K $\cdot$ s^{-1}. The periods with strongest cold advection coincided exactly with the periods of disastrous surface gale maintenance. Persistent cold advection indicates strong atmospheric baroclinicity. Under the action of the solenoid, cold air tends to sink while warm air rises, converting atmospheric potential energy to kinetic energy. Sinking motion favors gale development, while cold air can increase surface pressure tendencies, and tendency winds can enhance surface wind speeds.

3.3 Upper-Level Jet and Divergence Field Analysis The entrance region of an upper-level jet easily triggers secondary circulation, with divergence in the right side (south) and convergence in the left side (north). Upper divergence and lower convergence strengthen the high pressure behind the front, while upper convergence and lower divergence strengthen the low pressure ahead of the front, increasing the pressure gradient across the cold front and enhancing near-surface wind speeds. At 200 hPa, the jet axis was located over the western Tianshan Mountains, with a maximum wind speed of 60 m $\cdot$ s^{-1} at 08:00 on August 15, oriented southwest-northeast, placing Aksu on the south side of the jet axis. The southerly ageostrophic wind component created strong upper-level divergence over the region. The height-time cross-section of divergence over Aksu (Fig. 6) shows a divergence zone of -4$\times10^{-5}$ s^{-1} near 200 hPa, indicating strong divergence near the jet. Meanwhile, 850 hPa remained a convergence zone, with divergence values reaching -10$\times10^{-5}$ s^{-1} during the day on August 16. The strongest convergence was at 700 hPa on the night of August 16, with divergence of -8$\times10^{-5}$ s^{-1}. Below 500 hPa, strong divergence persisted, with maximum divergence of -10$\times10^{-5}$ s^{-1} at 850 hPa during the day on August 17. Upper-level divergence, near-surface divergence, and mid-lower level convergence indicate strong vertical motion and secondary circulation, with low-level convergent sinking airflow favorable for gale maintenance.

3.4 Vertical Velocity Analysis The height-time cross-section of vertical velocity (ω) over Aksu (Fig. 7) shows obvious sinking airflow below 800 hPa throughout the event. On the night of August 15, sinking motion was located near 750 hPa with central intensity of -1.5 Pa $\cdot$ s^{-1}. During the day on August 16, the sinking motion extended upward to 500 hPa with central intensity of -3 Pa $\cdot$ s^{-1}. The strongest sinking was in the near-surface layer. During the first two wind fluctuations, although the sinking motion extended upward to 500 hPa and strengthened significantly, upward motion remained above 500 hPa, again indicating no significant momentum transfer from upper levels. During the second wave, the sinking motion range extended upward to 800 hPa, but upward motion persisted above 500 hPa, indicating that the weaker short-wave trough causing the second wave produced only weak upward motion after the cold air descended along the southern slopes of the Tianshan Mountains, resulting in relatively shorter duration and weaker intensity.

On the night of August 16 (figure omitted), upward motion occurred below 300 hPa, with the strongest upward motion located east of Aksu. After the second wave, weak upward motion persisted over Aksu. However, on August 17, the entire region west of Aksu experienced strong sinking airflow below 500 hPa, with the day' s strongest sinking motion centered near 800 hPa over Aksu at -7$×10^{-1}$ Pa · s^{-1}, while east of Aksu showed strong upward motion. On August 17, the main trough passed over the region. Based on timing, the trough line was located over Aksu (80.21°E, 41.17°N) at 14:00, with upward motion ahead of the trough and sinking motion behind it. This pattern of ascent ahead of and descent behind the trough converted large amounts of eddy available potential energy into eddy kinetic energy, forming baroclinic instability that increased wind speeds during the downslope process and maintained them for an extended period. Therefore, the third wave persisted for 32 hours, with wind speeds reaching force 10–11, while the first wave reached force 12 instantly with the addition of thunderstorm winds.

4. Predictability Analysis

This disastrous gale was missed in operational forecasts for two main reasons. First, model forecast errors. Comparison of ECMWF fine-grid model data with observations shows that at 500 hPa, the low vortex position, shape, and intensity at 20:00 on August 15 were similar to observations, but the orientation of the split short wave differed significantly. The forecast showed a stronger Xinjiang ridge, with the short wave moving northeastward along the southwest flow behind the ridge, sweeping across western Xinjiang and then the whole region moving slowly eastward into Xinjiang—a pattern favorable for precipitation across most of Xinjiang from west to east. The observed pattern at 20:00 showed the low vortex splitting three times, with the short waves and finally the main trough entering the southern Xinjiang basin, guiding cold air across the Tianshan Mountains—a pattern favorable for mountain-crossing gales on the southern slopes. The EC-thin 10 m wind field forecast (figure omitted) predicted no gale weather on the southern Tianshan slopes but weak irrigation flows, also favoring precipitation in western southern Xinjiang. Therefore, the first reason for the missed forecast was model error in predicting the system' s evolution.

The second reason was the superposition of convective thunderstorm winds and mountain-crossing winds at 20:00 on August 15, which increased wind strength and added forecast difficulty.

5. Conclusions

(1) This gale event was primarily caused by deep baroclinicity in the system. After cold air crossed the Tianshan Mountains, gravity accelerated the conversion of atmospheric potential energy to kinetic energy. The first wave included superimposed convective thunderstorm winds, producing instantaneous force 12 winds.

(2) The pumping effect of the upper-level jet created an ascending branch of secondary circulation beneath it, favoring convective development and promoting energy exchange between upper and lower levels. During this event, strong secondary circulation produced mid-level convergence and low-level divergence, contributing to gale intensification and maintenance.

(3) This event represented three persistent gale episodes under a pattern of blocking high development and long-term low vortex maintenance. The upper-level baroclinic trough and strong surface cold front persisted for an extended period. As the low trough split and moved eastward three times, it guided surface cold air across the Tianshan Mountains. Under the combined action of the upper-level jet and low-level cold advection, this produced long-duration gales on the southern Tianshan slopes.

References

[1] Sun Yulian, Ren Yulong, Wei Bolong, et al. Contrast analysis of two cold wave weather processes with sand dust in the middle region of Gansu Province[J]. Journal of Meteorology, 2013, 31(1): 150-156.

[2] Wu Ziyu, Yao Wen, Li Chao, et al. Study on the characteristics and causes of strong wind during the meso scale of squall line process in Beijing Tianjin Hebei area[J]. Meteorological and Environmental Sciences, 2016, 39(2): 90-98.

[3] Cheng Yuexing, Sun Jisong, Dai Gaoju, et al. Study on a thunderstorm event over Beijing in 2016[J]. Meteorological Monthly, 2018, 44(12): 1529-1541.

[4] Ma Hongqing, Zhang Jiangtao, Li Yan, et al. Environmental field and storm features of a destructive thunderstorm gale in Baoding of Hebei Province on 9 July 2017[J]. Journal of Arid Meteorology, 2019, 37(4): 613-621.

[5] Pan Xinmin, Zhu Xuefan, Huang Zhiqiang, et al. The relation between the strong wind region along one hundred kilometer of railway and the topography in Xinjiang[J]. Meteorological Monthly, 2012, 38(2): 234-237.

[6] Aji Rouzi, Zibibula Ayixiemuguli, Shalamu Akedai. Comparative analysis of two disastrous winds in winter of 2014 in Artux of Xinjiang[J]. Desert and Oasis Meteorology, 2017, 11(3): 72-78.

[7] Aji Rouzi, Ablikim Ablimitjan, Li Ruqi, et al. Synoptic causation analysis of a strong southeast gale over Urumqi on March 30, 2012[J]. Journal of Arid Meteorology, 2015, 33(3): 474-480.

[8] Yin Jinyong, Cao Yuenan, Zhao Wei. A diagnostic analysis of the gale process in Laizhou gulf on April 27, 2010[J]. Meteorological Monthly, 2011, 37(7): 897-905.

[9] Tang Hao, Wang Xu, Chu Changjiang, et al. Formation mechanism of a southeast gale event in Urumqi urban area: The coupling of gravity wave and ultra low level jet[J]. Arid Land Geography, 2019, 42(6): 1229-1238.

[10] Liang Jianyu, Sun Jianhua. The formation mechanism of damaging surface wind during the squall line in june 2009[J]. Chinese Journal of Atmospheric Sciences, 2012, 36(2): 316-336.

[11] Scorer R S. Theory of wave in the lee of mountains[J]. Quarterly Journal of the Royal Meteorological Society, 1949, 7(1): 41-56.

[12] Klemp J B, Lilly D K. The dynamics of wave induced downslope winds[J]. Journal of the Atmospheric Sciences, 1975, 32: 320-339.

[13] Lilly D K. A severe downslope windstorm and aircraft turbulence event induce by a mountain wave[J]. Journal of the Atmospheric Sciences, 1978, 35(1): 59-77.

[14] Doyle J D, Durran D R. The dynamics of mountain induced rotors[J]. Journal of the Atmospheric Sciences, 2002, 59(2): 186-201.

[15] Doyle J D, Smith R B. Mountain waves over the Hohe Tauern: Influence of upstream diabatic effects[J]. Quarterly Journal of the Royal Meteorological Society, 2003, 129(588): 799-823.

[16] Ye Duzheng. Topographical effect on the airflow[J]. Acta Meteorologica Sinica, 1956, 27(3): 241-262.

[17] Sang Jianguo. Analytical solutions of downslope motions[J]. Acta Meteorologica Sinica, 1989, 47(2): 191-198.

[18] Zang Zengliang, Zhang Ming. Theoretical study on trapped lee waves on three layers model[J]. Acta Meteorologica Sinica, 2004, 62(4): 395-400.

[19] Lu Bing, Shi Yongqiang, Wang Guanghui, et al. Numerical study of severe downslope winds at Kelamayi, Xinjiang[J]. Acta Meteorologica Sinica, 2014, 72(6): 1218-1230.

[20] Tang Hao, Wang Xu, Chu Changjiang, et al. Mesoscale analysis of severe downslope windstorm caused by gap jet in Tianshan Mountain canyon[J]. Meteorological Monthly, 2020, 46(11): 1450-1460.

[21] Zhang Junlan, Zhang Li. Diagnostic analysis and forecast of a strong windy weather across Tianshan Mountains[J]. Desert and Oasis Meteorology, 2011, 5(1): 13-17.

[22] Zhou Hong, Yang Lihong, Hu Suqin, et al. An analysis on a strong windy weather process over the west of south Xinjiang in 2014[J]. Desert and Oasis Meteorology, 2015, 9(5): 50-55.

[23] Zhang Xuewen, Zhang Jiabao. Xinjiang meteorological manual[M]. Beijing: China Meteorological Press, 2006: 185-189.

[24] Zhang Jiabao, Su Lu, Qiyuan, Sun Shenqing, et al. Guide manual of the short term weather forecast in Xinjiang[M]. Urumqi: Xinjiang People Press, 1986: 271-318.

[25] Lü Meizhong, Hou Zhiming, Zhou Yi. Dynamics meteorology[M]. Beijing: China Meteorological Press, 2004: 142-143.

[26] Zhu Qiangen, Lin Jinrui, Shou Shaowen, et al. The principle and method of weather[M]. Beijing: China Meteorological Press, 1981: 249.

[27] Wu Xiulan, Ma Yu, Chen Ruiyong. Temporal and spatial variation characteristics of wind disaster and its causes in northern Xinjiang from 1980 to 2019[J]. Journal of Arid Meteorology, 2021, 39(2): 262-268.

[28] Zhang Taixi, Wang Hui, Yu Xingjie. Spatial temporal distribution of wind disasters in Xinjiang[J]. Arid Land Geography, 2021, 44(5): 1281-1289.

[29] Wang Jijun, Zhu Leilei, Hu Caihong, et al. Return periods of annual maximum wind speed and maximum snow depth along the Lianyungang-Lanzhou railway and Beijing-Guangzhou railway in Henan Province[J]. Meteorological and Environmental Sciences, 2016, 39(3): 9-14.

[30] Ding Yihui. Advanced synoptic meteorology[M]. Beijing: China Meteorological Press, 2005: 138-149.

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