

Characteristics and Potential Forecasting of Thunderstorm Winds in Gansu Province: Post-print

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Abstract

Using hourly maximum wind speed and lightning location data from 2115 meteorological observation stations in Gansu Province from 2017 to 2021, combined with ensemble forecast data from the European Centre for Medium-Range Weather Forecasts, this study analyzes the spatiotemporal characteristics of thunderstorm gales and statistical features of convective parameters in Gansu Province, and conducts research on thunderstorm gale potential forecasting using a multi-index overlay method. The results show that: (1) Thunderstorm gales in Gansu Province mainly occur from April to September, with the frequency from May to July accounting for 65.3% of the annual total. During a day, thunderstorm gales are concentrated between 15:00 and 21:00, peaking at 17:00, with very few occurrences from early morning to forenoon. (2) The distribution of thunderstorm gales is closely related to topography, characterized by more occurrences in the central and western regions and fewer in the eastern region, more on plateaus and fewer in valleys; high-value areas of thunderstorm gales appear in the Gannan Plateau, while low-value areas appear in Longdong and Longnan. Thunderstorm gales are predominantly level 8 and 9 winds, with level 10 and above winds primarily occurring in the Hexi Corridor region and the Gannan Plateau. (3) Based on convective parameters and index thresholds, a probabilistic potential forecasting product for thunderstorm gales in Gansu Province was obtained. Through case verification, the forecasted falling areas show good consistency with the actual occurrence regions. The research results indicate that this method has certain reference value for thunderstorm gale forecasting in Gansu Province.

Full Text

Preamble

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Characteristic and Potential Prediction of Thunderstorm in Gansu Province

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Abstract: Based on hourly extreme wind speed and lightning localization data from 2,115 meteorological observation stations in Gansu Province, combined with ECMWF ensemble forecasting data, this study analyzes the spatiotemporal characteristics and convective parameter statistics of thunderstorm in Gansu Province, and develops a potential prediction method using a multi-index nested approach. Results show that: (1) Thunderstorm in Gansu Province mainly occur from April to September, with May to July accounting for 65.3% of annual occurrences. Throughout the day, thunderstorm are concentrated between 15:00 and 21:00, peaking at 17:00, while occurrences are extremely rare from predawn to morning. (2) The distribution of thunderstorm is closely related to terrain, characterized by higher frequencies in central-western regions than eastern regions, and more occurrences in plateaus than valleys. High-frequency zones appear in the Gannan Plateau, while low-frequency zones occur in eastern and southern Gansu. Thunderstorm predominantly reach categories 8-9, with category 10+ events mainly in the Hexi Region and Gannan Plateau. (3) Potential forecast probability products for thunderstorm were developed based on convective parameters and threshold values. Case verification demonstrates good consistency between forecasted areas and actual occurrence regions, indicating that this method provides valuable reference for thunderstorm forecasting in Gansu Province.

Key words: thunderstorm; activity characteristic; potential prediction; Gansu Province

Thunderstorm refer to surface winds generated when downdrafts in convective storms reach the ground and produce divergence [1]. Characterized by small spatial scales, short duration, and strong destructive power, thunderstorm can destroy forests, buildings, and electrical/communication facilities, obstruct shipping and transportation, and pose severe threats to lives and property [2]. The “Oriental Star” cruise ship disaster in Jianli, Hubei on June 1, 2015, caused by an intense downburst-induced thunderstorm, resulted in 442 fatalities and

ranks among China's three major maritime disasters [3]. Since the 21st century, rapid socio-economic development and urbanization have amplified losses from thunderstorm. Their sudden onset and localized nature make forecasting extremely challenging. In recent years, scholars worldwide have conducted targeted research on thunderstorm spatiotemporal characteristics, physical mechanisms, and prediction methods. Numerous studies [4-7] reveal that thunderstorm in China predominantly occur in summer afternoons and early evenings, with higher frequency at high altitudes than low altitudes, showing significant seasonal, diurnal, and regional variations. The physical mechanisms and early warning of thunderstorm remain research priorities and challenges.

Liao et al. [8] studied Beijing thunderstorm characteristics and nowcasting, finding that downdraft convective available potential energy, wind index, and lower tropospheric temperature lapse rate have predictive significance. Ke et al. [9] found that Hainan thunderstorm are mainly associated with afternoon thermal effects and monsoon trough activities, with primary synoptic patterns being southwestern heat low, monsoon trough, and cold front types. Wei et al. [10] noted that summarizing convective parameter thresholds for different thunderstorm types by region provides more guidance for forecasting and warning in Hubei Province. Yan et al. [11] screened multiple dynamic and thermal indicators during thunderstorm events, calculated thresholds, and established a multi-index nested forecasting method for thunderstorm locations. These studies provide technical support for thunderstorm potential prediction, but research on formation mechanisms and forecasting techniques has focused mainly on central and eastern China, with limited studies on northwestern regions.

Located in China's arid and semi-arid northwest, Gansu Province is influenced by the westerlies, East Asian monsoon, and plateau climate, experiencing diverse meteorological disasters with frequent localized severe convective weather including short-duration heavy rainfall, hail, and thunderstorm [12-14]. While significant progress has been made in forecasting short-duration heavy rainfall and hail in Gansu, thunderstorm research remains limited to case studies, lacking systematic understanding. Gansu's complex terrain and convective weather's weak unstable stratification characteristics differ significantly from plain regions, creating forecasting challenges. To improve thunderstorm understanding and forecast accuracy in Gansu, this study uses surface meteorological observations and lightning data to identify thunderstorm processes, analyzes their spatiotemporal characteristics, combines ECMWF ensemble forecast data to examine convective parameter statistics, and develops a potential prediction method using multi-index nesting, providing valuable reference for thunderstorm forecasting and warning in Gansu Province.

1.3 Identification Criteria and Case Selection

Thunderstorm observations were derived from hourly extreme wind observations and hourly lightning data (2017-2021) using quality-controlled data with outliers removed. The China Meteorological Administration's operational iden-

tification standard for thunderstorm uses nearest-neighbor interpolation [15] to grid lightning locator data onto $0.5^\circ \times 0.5^\circ$ latitude-longitude grids, creating hourly cumulative lightning count grid data, which is then interpolated to verification stations using the nearest-neighbor method. When a station's hourly cumulative lightning count ≥ 1 and hourly gust wind speed $\geq 17 \text{ m} \cdot \text{s}^{-1}$, thunderstorm is identified. According to intensity classification standards, instantaneous or gust wind speeds of $17\text{-}24 \text{ m} \cdot \text{s}^{-1}$ represent general thunderstorm, while $\geq 25 \text{ m} \cdot \text{s}^{-1}$ indicates severe thunderstorm [16].

Based on these criteria, 1,115 thunderstorm station occurrences were identified in Gansu from 2017-2021. Case selection standards required either: (1) process duration ≥ 2 hours, or (2) total station occurrences ≥ 10 times per process. This yielded 28 regional thunderstorm weather processes in Gansu.

1.1 Study Area Overview

Gansu Province features complex and diverse topography, including mountains, plateaus, plains, river valleys, deserts, and Gobi, with terrain sloping from southwest to northeast [17]. The Hexi Corridor is a northwest-southeast oriented narrow zone, approximately 1,000 km long but only tens of kilometers wide, creating a narrow tube between southern and northern mountains that accelerates airflow and strengthens winds. Central Gansu represents typical Loess Plateau landforms, southern Gannan is a high-altitude region, eastern Longdong comprises Loess Plateau hilly-gully areas, and southern Longnan features alternating high mountains, steep ridges, and valleys/basins. Table 1 shows Gansu's regional divisions.

1.2 Data Description

Data include hourly extreme wind observations from 2,115 meteorological stations (strictly quality-controlled with outliers removed), hourly lightning location data, and ECMWF ensemble forecast data with $1^\circ \times 1^\circ$ grid spacing and 6-hour temporal resolution.

2.1.1 Temporal Variation Characteristics

Thunderstorm station occurrences in Gansu show fluctuating interannual variations, with 286 occurrences in 2021. Monthly variation exhibits a single-peak distribution (Table 1), primarily occurring from April to September, consistent with Gansu's severe convective weather season [18], with peak activity concentrated in May-July, accounting for 65.3% of annual occurrences. After September, occurrences drop sharply, with virtually no thunderstorm from November to March.

Diurnal variation shows concentrated occurrence between 15:00-21:00, peaking at 17:00 and accounting for 83.2% of daily occurrences. This is because afternoon surface heating creates extremely unstable stratification, promoting active

convection favorable for thunderstorm development [19]. Occurrences are minimal from predawn to morning (04:00-12:00).

2.1.2 Spatial Distribution Characteristics

Figure 2 [Figure 2: see original paper] reveals that Gansu thunderstorm spatial distribution features higher frequencies in Hexi, central Gansu, and the Gannan Plateau, and lower frequencies in Longdong and Longnan. The high-frequency zone is in the Gannan Plateau, with most areas exceeding 0.6 occurrences annually and the maximum frequency of 1.4 at Hezuo Shangjiagala station. This distribution primarily results from high altitude, abundant moisture, and frequent plateau low trough influence in this region, which easily triggers convective weather and numerous thunderstorm [21,24-27]. Hexi and central Gansu are secondary high-frequency zones, mostly 0.2-0.6 occurrences annually. The Hexi Corridor's narrow tube effect strengthens winds, and when combined with thunderstorm activity, easily produces thunderstorm. Central Gansu, located downstream of Hexi, is affected by westward thunderstorm cloud propagation, with northern central Gansu prone to thunderstorm. Additionally, influenced by the Tibetan Plateau slope and other terrain features, abundant moisture and heat in summer afternoons easily generate convective cloud clusters moving southward, causing thunderstorm in southern central Gansu. Low-frequency zones in Longnan and Longdong show <0.2 occurrences annually. These lower-altitude regions with numerous valleys and basins experience terrain obstruction and friction when thunderstorm downdrafts reach the surface, reducing wind speeds that often fail to reach thunderstorm levels.

Monthly spatial distributions (figures omitted) show: April thunderstorm mainly in central Gansu, Longnan, and the Gannan Plateau; May sees increased frequency and expanded range across Hexi, central Gansu, northern Longnan, and the Gannan Plateau; June further expands coverage with high-value zones in western Hexi and western Gannan; July reaches peak activity with thunderstorm across most of the province, high-value zones in Hexi, central Gansu, and the Gannan Plateau; August shows gradually decreasing activity and frequency, most notably in Longdong and Longnan; September sees few thunderstorm except in western Gannan.

These differences arise because: April Hexi areas remain in frost zones with low temperatures unfavorable for thunderstorm; May represents Gansu's spring-summer transition with increasing solar radiation and northward subtropical high movement transporting southwestern warm-moist airflow to southern and northern Gansu, where complex terrain activates local mesoscale convective systems, significantly increasing thunderstorm frequency; June-July features prevailing summer monsoons at Gansu's western edge of East Asian monsoon influence, with surface temperature, moisture content, and unstable energy reaching annual maxima while westerly cold air creates cold-warm convergence that intensifies convection; August sees weakened cold air activity to the north and predominant southward moisture transport, making severe convection mainly

heavy rainfall with reduced thunderstorm frequency; September experiences lower temperatures and reduced energy, creating unfavorable conditions for convection, while the high-altitude Gannan Plateau maintains faster near-surface warming and vertical thermal instability that easily produces localized thunderstorm.

2.2 Intensity Distribution

Classified by wind force levels, Gansu thunderstorm predominantly reach categories 8-9 (Figure 3 [Figure 3: see original paper]), with category 10+ winds mainly distributed in Hexi and the Gannan Plateau. Most areas in Longdong and Longnan have maximum winds $<17 \text{ m} \cdot \text{s}^{-1}$. Category 10+ winds appear as scattered isolated points, with the strongest winds in southern Lanzhou, southern Linxia, and eastern Gannan Prefecture.

The wind speed box plot (Figure 3 [Figure 3: see original paper]) shows that stations with speeds exceeding $25 \text{ m} \cdot \text{s}^{-1}$ (category 10+) account for only 2.9% of total stations, beyond the upper control limit. Within control limits, median wind speeds show small monthly variations, with May slightly higher than other months. Median values correspond to approximately $19 \text{ m} \cdot \text{s}^{-1}$, $18 \text{ m} \cdot \text{s}^{-1}$, and $21 \text{ m} \cdot \text{s}^{-1}$ respectively, indicating winds generally between categories 8-9, consistent with spatial distribution patterns.

2.3 Statistical Characteristics of Convective Parameters in Thunderstorm Processes

The above analysis shows strong seasonality and diurnal variation in Gansu thunderstorm, with their generation closely related to thermal and dynamic environments of convective system development [19,28]. Numerous parameters characterize moisture, thermal, and dynamic fields. Based on correlation analysis between thunderstorm observations and physical quantities, 10 key parameters were selected: moisture parameters (water vapor flux FH700, FH500; water vapor flux divergence IFVQ700, IFVQ850); thermal parameters (convective available potential energy CAPE, K index, lifted index LI, A index, Showalter index SI); and dynamic parameters (divergence D, vertical velocity W).

2.3.1 Convective Parameter Statistical Characteristics

Water vapor flux and divergence represent moisture transport and accumulation. Key moisture parameters for Gansu thunderstorm are mid-lower layer water vapor flux FH700 and water vapor flux divergence IFVQ700. Table 2 shows median indices for April-September: FH700 and FH500 are positive, indicating moisture transport; IFVQ700 and IFVQ850 are negative, indicating moisture convergence.

Thermal instability parameters include numerous indices. ECMWF ensemble forecasts provide commonly used CAPE, K, LI, A, and SI indices, which show

good correlation with Gansu thunderstorm. Table 2 shows median indices for 10 physical quantities. May–July medians are stronger than other months, but overall differences are small, with median means of $116.8 \text{ J} \cdot \text{kg}^{-1}$, 18.4°C , -0.8°C , 6.5°C , and 4.5°C respectively.

Divergence describes horizontal velocity field convergence/divergence intensity, while vertical velocity indicates air parcel vertical motion—both showing good correlation with Gansu thunderstorm activity. Through interpolation and correlation analysis, low-level convergence combined with mid-level ascending motion favors convective development. Table 2 shows 500 hPa divergence and 700 hPa vertical velocity median indices. April only appears in central Gansu, making April dynamic parameter thresholds unrepresentative. Therefore, reference values use May–September median indices, with small differences and mean values of $-0.6 \text{ Pa} \cdot \text{s}^{-1}$ and $-0.6 \times 10^{-2} \text{ Pa} \cdot \text{s}^{-1}$ respectively.

2.3.2 Convective Parameter Index Selection and Forecasting Method

Based on three essential conditions for severe convective weather and considering median indices from 10 physical quantities plus empirical forecasting, threshold indices for Gansu thunderstorm physical quantities were established (Table 3), creating a multi-index nested thunderstorm forecasting model. The ECMWF ensemble contains 51 members. Each member is evaluated against the thresholds, and probability values are calculated for each grid point. The probability value (P) expression is:

$$P = \frac{m}{n} \times 100\%$$

where m is the number of members simultaneously satisfying all 10 factor thresholds, and n is the total number of forecast members. When probability value $P \geq 60\%$, thunderstorm occurrence is considered likely; conversely, it is unlikely.

2.4 Thunderstorm Potential Forecasting Experiments

To verify the index nesting method's effectiveness and threshold rationality, two regional thunderstorm processes were selected for potential forecasting experiments: (1) April 23–24, 2022 thunderstorm in central Gansu and the Gannan Plateau (13:00–21:00), and (2) July 20, 2023 thunderstorm across most areas east of Zhangye (05:00–08:00). Observations and ECMWF ensemble forecast data were compared with probability forecast products.

Case 1: On April 23, 2022, influenced by eastward-moving plateau vortices, thunderstorm developed over eastern Qinghai and affected the Gannan Plateau from 16:00, rapidly expanding to central Gansu. Due to prolonged vortex maintenance over southern Gansu, numerous thunderstorm stations occurred, with maximum wind speed of $28 \text{ m} \cdot \text{s}^{-1}$. Figure 4 [Figure 4: see original paper] compares observations (left) and probability forecasts (right) for 16:00–18:00, 19:00–

21:00, 22:00–00:00, and 01:00–03:00. Thunderstorm mainly occurred in southern Wuwei, Lanzhou, Linxia, Gannan Prefecture, southeastern Qinghai, and northern Sichuan. Probability forecasts showed values $\approx 60\%$ in Lanzhou, Linxia, Gannan, southeastern Qinghai, and northern Sichuan, providing good guidance, though with lower probabilities for southern Wuwei and over-forecasting for Dingxi, Longnan, and Pingliang.

Case 2: On July 20, 2023, from afternoon to night, influenced by a vortex over the Hetao region, thunderstorm occurred in Zhangye and Jinchang, expanding as the vortex intensified. From 13:00–15:00, thunderstorm mainly appeared in southern Zhangye, Jinchang, Wuwei, Lanzhou, and Baiyin. Probability forecast high-value zones also extended southward, showing generally consistent performance and reflecting actual locations well, though with slightly smaller forecast areas in Zhangye and Jinchang. From 16:00–18:00, northern thunderstorm weakened while southern areas (Dingxi, Tianshui, Pingliang) developed. Probability forecasts indicated $\sim 60\%$ probability in these regions, showing consistent development in both scope and intensity. From 19:00–21:00, thunderstorm weakened in northern areas and developed in southern Dingxi, Tianshui, and Pingliang, with probability forecast centers reaching $\approx 60\%$ but over-forecasting in southeastern Gannan, southern Baiyin, Pingliang, and Qingyang.

Overall, for large-scale thunderstorm events in Gansu, the multi-index nested probability forecast product based on ECMWF ensemble data demonstrates reference value, with thunderstorm activity centers corresponding well to $\approx 60\%$ probability zones and consistent trends in intensity and scope, though with some over-forecasting in Longnan, Tianshui, Pingliang, and Qingyang.

3 Conclusions

- 1) Thunderstorm are most active in the Gannan Plateau with highest frequency, followed by Hexi and central Gansu as relatively high-frequency regions, while Longdong and Longnan show lowest frequency. Monthly analysis indicates earlier onset in higher-altitude regions, with active periods in May–July for the Gannan Plateau and central Gansu, July for Longdong, June–July for Hexi, and July–August for Longnan.
- 2) Thunderstorm mainly occur from April to September, with May–July accounting for 65.3% of annual occurrences and peak activity at 17:00. Diurnally, thunderstorm concentrate between 15:00–21:00 (83.2% of daily occurrences), decreasing significantly after 22:00 and rarely occurring from 04:00–12:00. Thunderstorm predominantly reach categories 8–9, with category 10+ events mainly distributed in Hexi and the Gannan Plateau.
- 3) Based on essential severe convective weather conditions, 10 convective parameters with high correlation to Gansu thunderstorm were selected from ECMWF ensemble forecast data. Median forecasting thresholds for these parameters were calculated, and a multi-index nested method was applied to develop thunderstorm potential forecast probability products.

Verification of two regional thunderstorm processes shows good correspondence between observed locations and 60% probability forecast areas, with consistent trends in development intensity and scope. However, over-forecasting occurs in Longnan, Tianshui, Pingliang, and Qingyang, requiring forecasters to adjust based on specific lifting trigger conditions.

References

- [1] Yu Xiaoding, Wang Xiuming, Li Wanli, et al. Near forecast of thunderstorm and severe convection [M]. Beijing: China Meteorological Press, 2020: 298-299, 295.
- [2] Sun Jisong, Dai Jianhua, He Lifu, et al. Basic principles and technical methods of strong convective weather forecast: China strong convective weather forecast manual[M]. Beijing: China Meteorological Press, 2014: 13-18.
- [3] Zheng Yongguang, Tian Fuyou, Meng Zhiyong, et al. Survey and multi-scale characteristics of wind damage caused by convective storms in the surrounding area of the capsizing accident of cruise ship Dongfangzhixing [J]. Meteorological Monthly, 2016, 42(1): 1-13.
- [4] Hou Shumei, Li Yuwei, Zhang Peng, et al. Cause of a thunderstorm gale event over grade 10 along the Shandong coast on 29 April 2021[J]. Meteorological Monthly, 2022, 48(10): 1242-1256.
- [5] Chen Xiaoxin, Yu Xiaoding, Wang Xiuming. A study of large-scale thunderstorm gale events (Derechos) in China: Spatiotemporal distribution, environmental background and convective system morphology[J]. Acta Meteorologica Sinica, 2022, 80(1): 67-81.
- [6] Fang Chong, Wang Xigui, Sheng Jie, et al. Temporal and spatial distribution of north China thunder gust winds and the statistical analysis of physical characteristics[J]. Plateau Meteorology, 2017, 36(5): 1368-1385.
- [7] Qin Weijian, Shou Shaowen, Wang Yongqing, et al. Analysis of distribution characteristics and damage causes of thunderstorm in Guangxi[J]. Journal of Natural Disasters, 2009, 18(2): 131-138.
- [8] Liao Xiaonong, Yu Bo, Lu Lihua. Climatology and nowcasting methods for thunderstorm gale in Beijing[J]. Meteorological Monthly, 2009, 35(9): 18-29.
- [9] Ke Yuanhui, Ma Zheng Yan, et al. Analysis of synoptic situation and environmental parameters of thunderstorm gales in Hainan[J]. Torrential Rain and Disasters, 2022, 41(1): 86-93.
- [10] Wei Huihong, Xu Guanyu, Liu Xiwen, et al. Spatial-temporal distribution and environmental parameter characteristics for different types of thunderstorm gales in Hubei Province[J]. Torrential Rain and Disasters, 2022, 41(1): 66-75.
- [11] Yan Shiyao, Li Yunying, Qi Linlin, et al. Analysis and application of thermodynamical and dynamical indexes associated with thunderstorm gale in north

- China[J]. *Torrential Rain and Disasters*, 2013, 32(1): 17-23.
- [12] Tan Dan, Huang Yuxia, Sha Hongxia, et al. Characteristic analysis of severe convective weather in Gansu Province[J]. *Journal of Natural Disasters*, 2022, 31(2): 222-232.
- [13] Bao Wenzhong, Zhang Qiang, Tao Jianhong, et al. *Gansu climate*[M]. Beijing: China Meteorological Press, 2018: 1-2, 122-123, 215-216.
- [14] Wang Junde, Su Zhenjuan, Zhang Lina, et al. Characteristics of temporal and spatial variation of extreme precipitation index in Gansu Province[J]. *Research of Soil and Water Conservation*, 2022, 29(4): 270-276, 291.
- [15] Zhang Hongfang, Ju Xiaoxuan, Lu Shan, et al. Comparison of parsing methods for fine grid precipitation forecasting[J]. *Advances in Meteorological Science and Technology*, 2019, 9(3): 7-14.
- [16] Yu Xiaoding, Wang Xiuming, Li Wanli, et al. *Near forecast of thunderstorm and severe convection* [M]. Beijing: China Meteorological Press, 2020: 298-299, 295.
- [17] Bao Wenzhong, Zhang Qiang, Tao Jianhong, et al. *Gansu climate*[M]. Beijing: China Meteorological Press, 2018: 1-2, 122-123, 215-216.
- [18] Tan Dan, Huang Yuxia, Sha Hongxia, et al. Characteristic analysis of severe convective weather in Gansu Province[J]. *Journal of Natural Disasters*, 2022, 31(2): 222-232.
- [19] Lei Lei, Sun Jisong, Wei Dong. Distinguishing the category of the summer convective weather by sounding data in Beijing[J]. *Meteorological Monthly*, 2011, 37(2): 136-141.
- [20] Jing Yu, Chen Chuang, Zhao Qiang, et al. Spatial-temporal distribution and meteorological conditions of thunderstorm gales in Shaanxi[J]. *Journal of Arid Meteorology*, 2024, 42(4): 576-587.
- [21] You Wei, Zang Zengliang, Pan Xiaobin, et al. Statistical analyses on characteristic and environmental aspect of summer thunderstorm over the Tibetan Plateau[J]. *Plateau Meteorology*, 2012, 31(6): 1523-1529.
- [22] Yang Mei, Danzeng Gelie, Dawa Zeren, et al. The trend and distribution of thunderstorm activity and influencing factors in Nagqu Prefecture[J]. *Journal of Applied Meteorological Science*, 2014, 25(6): 751-760.
- [23] Liu Zhaoxu, Liu Jing, Fan Ziang. Characteristics of lightnings disasters in Xinjiang from 2005 to 2020[J]. *Arid Land Geography*, 2022, 45(5): 1402-1414.
- [24] Xu Lin, Yao Rong, Wang Xiaolei, et al. Study of temporal-spatial distribution and variation characteristics of thunderstorm gales in Hunan[J]. *Plateau Meteorology*, 2017, 36(4): 993-1000.
- [25] Chai Donghong, Yang Xiaoliang, Wu Ziyu, et al. The statistical analysis of thunderstorm gales over Beijing-Tianjin-Hebei region[J]. *Torrential Rain and*

Disasters, 2017, 36(3): 193-199.

[26] Li Li, Wan Xueli, Qi Dapeng, et al. Temporal and spatial distribution of Guizhou thunderstorm gales and the characteristic analysis of convective parameters[J]. Mid-low Latitude Mountain Meteorology, 2020, 44(2): 1-8.

[27] Fei Haiyan, Wang Xiuming, Zhou Xiaogang, et al. Climatic characteristics and environmental parameters of severe thunderstorm gales in China[J]. Meteorological Monthly, 2016, 42(12): 1513-1521.

[28] Chen Sirong, Zhu Weijun, Zhou Bing. Climate characteristic and variation tendency of thunderstorm in China[J]. Transactions of Atmospheric Sciences, 2009, 32(5): 703-710.

[29] Wang Mingming, Liu Weicheng, Huang Yuxia, et al. Climate distribution characteristics and trends of thunderstorm during 1961-2011 in Gansu, China[J]. Journal of Desert Research, 2015, 35(5): 1346-1352.

[30] Aji Rouzi, Yu Bixin, Li Ruqi. Fine characteristics and cause analysis of rare gale over Tianshan Mountains over Aksu Prefecture in August, 2019[J]. Arid Land Geography, 2023, 46(2): 222-232.

[31] Gao Jing, Jing Lijun, Li Xindong, et al. Temporal and spatial distribution of thunderstorm and its change features in Tacheng Prefecture[J]. Arid Land Geography, 2010, 33(1): 37-44.

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