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Spatial and Temporal Characteristics of Tornadoes in Liaoning Province from 1955 to 2019

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Abstract: In order to study the characteristics of tornadoes in Liaoning province, based on “the Handbook of China Meteorological Disasters”, “the Annual Report of China Meteorological Disasters” and other related data, the intensity classification was carried out by using the standard of improved Fujita Classification, the temporal and spatial distribution characteristics of tornadoes in Liaoning from 1955 to 2019 were statistically analyzed. Given the study results, (1) From 1955 to 2019, there is a mean of 2.3 tornadoes annually in Liaoning, meanwhile, the annual average tornado density is $1.5 \times 10^{-5} / \text{km}^2$, which is about 1/10 of that in the United States. There is a total of 25 significant tornadoes of EF2 and above were recorded, with an average annual occurrence of 0.4, including one time of grade EF4, 3 times of grade EF3, and 21 times of grade EF2. The ratio of adjacent grading is within the range of 0.1–0.36. (2) Tornadoes occur with a maximum from May through October and more than a quarter of the annual total occurred in July. Tornadoes mostly occur in the afternoon to the evening, 13:00–14:00 and 17:00–18:00 are two frequent periods of tornadoes. Approximately 85% of tornado events last within 20 minutes. (3) Most tornadoes occur in the plains, while tornadoes are distributed from the Liaoxi Corridor to northwestern Liaoning area from May to June, in the Liaoxi Corridor and the middle and lower reaches of the Liaohai Plain from July to August and increased significantly in the eastern coastal area of Liaoning from September to October.

Keywords: meteorology; severe weather forecast; tornadoes; spatial-temporal characteristics; disaster feature; Liaoning

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1 Introduction and background

Tornadoes, with measured wind speeds of $125 \text{ m} \cdot \text{s}^{-1}$ to perhaps $140 \text{ m} \cdot \text{s}^{-1}$, are the most violent of atmospheric storms. A tornado is defined as a violently rotating, narrow column of air, averaging about 100 m in diameter, that extends to the ground from the interior of a cumulonimbus (or occasionally a cumulus congestus) cloud and appears as a condensation funnel pendant from cloud base and/or as a swirling cloud of dust and debris rising from the ground^[1]. Tornadoes belong to microscale systems so that their lifecycle usually do not exceed 30 minutes. Significant damage can occur at the ground even when the condensation funnel does not reach the surface. tornadoes are accompanied by huge energy during its

movement which can overturn cars, uproot trees and telephone poles, and destroy houses or even lead to significant property damage and loss of life. For this, architectural design, disaster prevention and mitigation, industrial and agricultural production and property insurance and other various items should give high value to tornadoes^[2].

Due to the small spatial scale, tornadoes are almost rare to pass through the Automatic Weather Stations (AWS)^[3]. Even if it happens to pass by the AWS, the observation instrument would be destroyed and it is impossible to obtain meteorological observation data such as the actual wind speed and pressure of the tornado. Therefore, it is particularly critical to judge the strength of the tornado by the damage survey. In order to define the intensity of tornadoes, Fujita^[4] divided the tornado into 6 scales, from F0 to F5 scale, based on the relationship between the degree of damage caused by buildings (mainly residential), trees, cars, etc. on the tornado path and the

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wind speed, namely “Fujita Scale”. Since then, the “Fujita Scale” has been widely used^[5], and tornadoes above F2 are defined as significant tornadoes. To more accurately reflect the relationship between the destructive force of tornadoes and wind speed, in 2007, the National Weather Service (NWS) adjusted the upper and lower limits of the “Fujita level” wind speed based on the simulation of the tornado by the vortex laboratory, and determined the tornado scale based on the degrees of damage (DOD) of 28 damage indicators (DI) in the United States (including residential buildings, family workshops, mobile homes, automobiles, community fast-food restaurants, wooden telephone poles, reinforced concrete telephone poles, frame structure multi-storey buildings, and different types of trees of different thicknesses, etc.), called Enhanced Fujita Scale^[6], and the categories range from EF0 to EF5.

Globally, the United States is the country with the highest frequency of tornadoes, with more than 1000 tornadoes per year^[7]. Florida and the central and southern plains of the United States are areas of high incidence of tornadoes, among which are related to sea breeze front forcing, mostly non-supercell weak tornadoes, while the central and southern plains from central Texas to the north to northern Iowa, and from central Kansas and eastern Nebraska to western Ohio are the high-incidence areas of significant tornadoes in the United States, accounting for approximately 25% each year, so this area is also nicknamed “Tornado Alley”^[7]. There are suitable environmental background for the generation of long-lived supercell storms in this area, such as upper-level westerly jet, warm moist flow from the Gulf of Mexico on the southeast side of the lower layer, dry warm flow from New Mexico on the southwest side of the middle layer, and dry warm air flow from New Mexico on the southwest side of the middle layer. The convergence of multiple airflows of different natures here creates robust dynamic and thermally unstable environmental conditions.

Compared with Europe and the United States, the study of tornadoes in China started late and is struggling. On the one hand, as microscale systems, tornadoes are difficult to captured by conventional observations. On the other hand, due to the relatively backward communication and traffic conditions in the early days, It is difficult to go to the scene for investigation in the first time when a disaster occurs. So there are not systematic disaster statistics

up to now in China. Insufficient accumulation in the early stage has caused great difficulty in the study of tornadoes so that the temporal and spatial characteristics of tornadoes are merely based on the “Chinese Meteorological Disaster Dictionary” and “Chinese Meteorological Disaster Yearbook” at early stages. In recent years, due to the widespread use of communication devices (especially mobile phones) and the rapid development of self-media, more and more tornadoes can quickly appear in the public’s field of vision, making people pay more and more attention to tornadoes. In terms of tornado disaster investigations, China has gradually established a tornado disaster investigation system and formulated its own “Tornado Scale”^[8], which is divided into four levels, corresponds to EF0, EF1, EF2 and EF3, EF4 and EF5, respectively. In particular, the use of drones can clearly show the lodging characteristics of disaster-stricken crops and trees which is able to characterize the path of tornado.

Located in the lower reaches of the Northeast Plain, Liaoning Province is one of the three major tornado-prone areas in China^[9–10]. Liaoning Province, where is low-lying and flat, with uneven soil distribution and intertwined rivers and lakes, has the similar land-sea contrast and the topography to the American “Tornado Alley”. In addition, located in the transitional zone from the humid zone to the semi-arid zone makes it easy to accumulate unstable energy in this area. suitable dynamic conditions cause the development of convection and tornado generation. However, as mentioned above, there is no systematic comprehensive statistics of tornadoes in Liaoning at present. Depending on multiple approach to collect tornadic cases in Liaoning, we want to finding the climate characteristics of tornadoes in this region, so as to lay the foundation for weather forecasting of tornadoes in future.

2 Data and Method

2.1 Research data

Without a complete and detailed record of tornadic cases before 2000, it is extremely difficult to conduct comprehensive statistics on tornadoes in Liaoning, which is also one of the difficulties faced by the tornado research institute in China. In order to carry out detailed and comprehensive statistics of Liaoning tornadoes as much as

possible, the search scope of data has been expanded, and reference materials collected for tornadic cases include: “Chinese Meteorological Disasters-Comprehensive Volume”^[11], statistics of Liaoning from 1961 to 2000 The tornado event and China’s “Chinese Meteorological Disaster Dictionary”(Liaoning Volume), the statistical period is 1951–1983, and the “China Meteorological Disaster Yearbook”(China Meteorological Administration, 2005–2019) statistical period is 2004–2018; Manual observation of tornado records by meteorological observatories, the statistical period is from 1951 to 2008; county-level historical meteorological disaster data, the statistical period is from 1984 to 2018; “Liaoning Province Chronicles”(Meteorological Chronicle), the statistical period is from 1986 to 2005. At the same time, the tornado case was supplemented by the tornado pictures and videos published by various media such as meteorological websites, television, and newspapers.

2.2 Tornado grading method

Due to the fact that Chinese Tornado Scale provides fewer disaster indicators and the description of disaster characteristics is vague, this article identify the strength of the tornado based on the EF Scale. As mentioned above, There is a corresponding relationship between the Chinese Tornado Scale and EF Scale, which also conven-

ient for the later transfer to Chinese Tornado Scale. Many of the 28 DI used to determine the EF grade of the tornado have American characteristics^[12]. For example, the most important DI(one or two-story residential buildings) in the United States are mostly wooden structures, which are completely different from those of Chinese residential buildings in terms of material and strength. More importantly, the structure and solidity of American residential buildings have basically not changed in the past 100 years, while the structure and solidity of Chinese residential buildings have undergone tremendous changes during the same period. Other markers such as wooden telephone poles have basically disappeared in China, and they have all been replaced by cement poles. The cement poles in the United States are usually much stronger than ordinary cement poles in China. Only trees, the same hardwood or softwood, roughly the same thickness, can be regarded as a marker with better comparability. Therefore, in order to adapt to the conditions of Liaoning, some of the original criteria for determining the F scale were retained when the criteria for determining the EF scale were given, combined with the criteria of the new 28 DI. Forming the Liaoning region’s EF scale of tornado intensity criteria (Table 1). Usually tornadoes of EF0 and EF1 are called weak tornados, and tornados of EF2 or higher are called significant tornados.

Table 1 Destruction phenomena summarized based on the “Enhanced Fujita Scale”

EF-Scale	Wind speed/($\text{m} \cdot \text{s}^{-1}$)	Damage description
EF0	29–38	Mild damage. Some damage to chimneys and TV antennae; breaks twigs off trees, pushes over shallow-rooted trees(Mostly conifers)
EF1	39–49	Moderate damage. Peels surfaces off roofs; windows broken; light trailer houses pushed over or overturned; some trees uprooted or snapped; moving automobiles pushed off road;Weak wooden poles and street lights destroyed; Tower damaged; softwood trees broken; hardwood (mostly broad-leaved trees) trees uprooted
EF2	50–60	Considerable damage. Roofs torn off frame houses leaving strong upright walls; weak buildings in rural areas demolished; trailer houses destroyed; large trees snapped or uprooted; railroad boxcars pushed over; light object missiles generated; cars blown off highway
EF3	61–73	Serious destruction. Roofs and some walls torn off frame houses; some rural building completely demolished; trains overturned; steel-framed hangar-warehouse type structures torn; cars lifted off the ground; most trees in a forest uprooted, snapped, or leveled;most of the trees in the forest uprooted or broken;leaves of the trees peeled off to the trunk.
EF4	74–89	Destructive destruction. Whole frame houses leveled, leaving piles of debris; steel structures badly damaged; trees debarked by small flying debris; cars and trains thrown some distance or rolled considerable distances; large missiles generated
EF5	≥ 90	Incredible destruction. Whole frame houses tossed off foundations; steel-reinforced concrete structures badly damaged; automobile-sized missiles generated; incredible phenomena can occur

2.3 Deviation description

The accuracy of the tornado climate characteristics can be improved to a certain extent by limiting the statistical object to the significant tornado, but it is also inevitable to make the sample small. In addition, several tornado disasters focus more on economic losses rather than maximum intensity , Which makes it very difficult to determine the strength of the tornado. Because the lifecycle of tornadoes is short and the scope of influence is relatively small. In individual cases, there are very few records of occurrence at night, and there are no statistics in sparsely populated areas, which makes the number of nighttime occurrences in the daily-scale distribution of tornadoes extremely small, while the spatial distribution also presents the characteristics of small-scale clustering.

In order to improve the standardization and uniformity of the data, various indicators of tornado disasters such as buildings, trees, and electric poles are identified according to the usual structural characteristics of of their time. Due to the differences in architecture between China and the United States, the tornado scale judgment should be appropriately reduced under the damage of houses and electric poles, while trees should be used as the judgment standard as far as possible. In addition, another meteorological expert was invited to make an independent judgment to eliminate the error of personal subjective judgment^[13], by which the difference cases could be subjected in secondary case.

After the above-mentioned method of judging the intensity of tornadoes, the results can generally represent the climatic patterns of tornadic cases in Liaoning(deviation still exists), which laying the foundation for the tornado forecast and early warning in Liaoning.

3 Results and analysis

3.1 Tornado scale features

A total of 158 tornadic cases were recorded in Liaoning from 1955 to 2019, including 10significant tornadoes of EF2 or above (a EF4 tornado). The intensity distribution of tornadoes shows a certain regularity that the ratio of EF(*n*+1) to EF(*n*) intensity is generally 0.1–0.36,

and the larger the supercell tornado, the higher the ratio (non-supercell usually produces weak tornado), which can be used to test the quality and reliability of tornado records^[14].

Take the ratio of EF3 to EF2 as an example, the ratio of tornadoes in China is 0.11, and that in Liaoning is 0.14, respectively. The result may be that the proportion of non-supercell tornadoes in China is higher, or that there are many tornadoes generating associated with tropical cyclones in South China, where the size of supercells is smaller, and the tornadoes are generally weaker. Specifically, the ratio of EF4 tornado to EF3 tornado is 0.33, the ratio of EF4 to EF3 is 0.33, the ratio of EF3 to EF2 is 0.14, and the ratio of EF2 to EF1 is 0.35, which is basically in line with 0.1–0.36 interval above (Table 2). However, the ratio of EF1 to EF0 is about 1, which seem to be a poor statistical result. The reason may be that many weak tornadoes lead to few disaster descriptions, And weak tornadoes are objectively more difficult to monitor and record.

Table 2 EF scale of tornadoes in Liaoning from 1955 to 2020

EF scale	EF5	EF4	EF3	EF2	EF1	EF0
times	0	1	3	21	60	60

3.2 Characteristics of disaster

Although the tornado has a rapid generation and disappearance and a small impact area, its destructive power is strong. Under the impact of extremely high wind speeds, it can produce extremely strong instantaneous loads on the building, and produce great effects in different parts of the building. The sudden drop in pressure generated when the center of the tornado passes through can cause blast damage to closed or semi-closed buildings.

In order to have a more comprehensive understanding of the disaster characteristics and destructive power of the strong tornado, the statistics of the four significant tornadoes recorded from 1955 to 2019 (Table 3), show that the significant tornado is enough to razor ordinary buildings to the ground, twisting or destroying reinforced concrete houses, electric poles and iron towers, overturning or moving heavy machinery, automobiles, airplanes, breaking or rolling up large trees with a diameter of sever-

al meters, blowing or rolling up ships and automobiles, usually resulting in a large number of flying shots objects, such as bricks, trees, furniture and iron plates, etc. Usually a large number of flying objects are generated, such as bricks, trees, furniture and iron plates, etc. ,

and a strong tornado of EF3 or above can roll up cars, houses, ships, etc. and throw them for a certain distance. In addition, the missile itself can cause serious damage and is also an important basis for judging the strength of the tornado.

Table 3 disaster situations of the top 4 significant tornadoes

Tornadoes location	Date	Scale	Disaster phenomenon
Kaiyuan, Liaoning	2019-07-03	EF4	Reinforced concrete frame structure canteen in the industrial park was razed to the ground.
Chaoyang, Liaoning	2005-06-10	EF3	Asphalt with a length of 10 meters and a width of 1.5 meters was lifted on the road
Donggang, Liaoning	1969-08-25	EF3	A child was carried over a 300-meter hill by a tornado
Xingcheng, Liaoning	1980-06-20	EF3	273 houses were blown down and the truck was thrown 12 meters away

3.3 Temporal distribution of tornadoes in Liaoning

According to statistics, a total of 154 tornadoes occurred in Liaoning Province from 1955 to 2019 (Fig. 1) , of which the number of tornadoes in 1986 was 11, followed by 9 in 2005, 1955, 1956, 1970, 1981, 1997 , 1999, 2014, 2016, 2018 did not appear, the average annual number of tornadoes was 2.3 , and the annual average tornado generation density was $1.5\times10^{-5}/\text{km}^2$. More than 1000 tornadoes are generated in the United States every year, with an average annual density of $1.33\times10^{-4}/\text{km}^2$ [15]. Statistics show that the density of tornadoes in Liaoning is about 1/10 that of the United States.

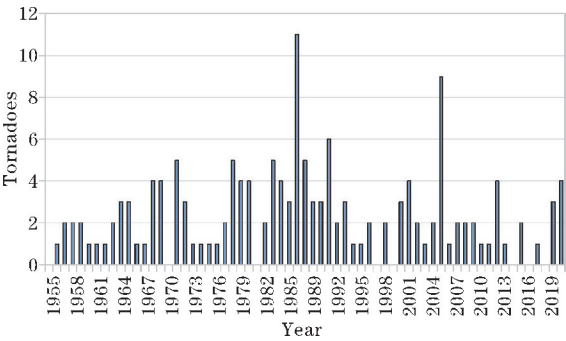


Fig. 1 Number of tornadoes per year, 1955-2019

The tornadoes in Liaoning show obvious characteristics of inter-annual variation. From the 1950s to the 1980s, the tornadoes increased slightly, peak in the 1980s, accounting for 26.3% , and the average annual number of tornadoes is 4.1. After the 1990s, the number of tornadoes decreased, with an average of 2 per year. Since 2001, the number of tornadoes has increased first and then decreased. In 2019, there were 3 tornado incidents (of which a EF4 tornado occurred in Kaiyuan on Ju-

ly 3) , and 4 tornadoes occurred in 2020, which seems to be an increasing trend in the near future.

Tornadoes have obvious seasonal changes (Fig. 2). They occur from May to October each year, accounting for 96.8% of the total number, or even almost no tornadoes in the remaining months, making the periods of high incidence are relatively concentrated. While tornadoes in the United States generally occur in the late spring season (April to June) and throughout all the year. It is worth pointing out that even in the eastern United States (the same latitude as the northeast of China) , tornadoes occur almost every month of the year.

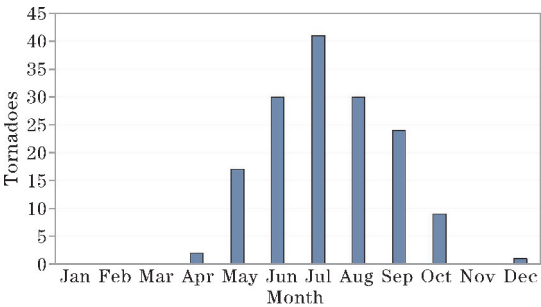


Fig. 2 Monthly average number of tornados for 1955-2019 in Liaoning

Judging from the time of the tornado during the year, tornadoes in Liaoning first occurred on April 15 (1972, Tai'an County, Anshan City) , and the latest occurred on December 21 (1990, Donggang County, Dandong City). Summer (June to August) accounts for 64.7% of the total number of tornadoes throughout the year, with an average of 1.5 per year, of which July is the most, accounting for 26.3% , followed by spring, accounting for 31.8%. The proportion of tornadoes in autumn is 21.4%. One occurred in December, while no tornado incidents were recorded in November and January to

March.

There are 71 tornadoes in Liaoning with a clear time record (Fig. 3), in most of which occurred in the afternoon to the evening. The number of tornadoes that appear from 12:00 to 19:00 accounts for 77.5% of the total number, of which 13:00 to 14:00 and 17:00 to 18:00 are two frequent periods, accounting for 12.7% and 16.9%, respectively. The two secondary frequent periods are from 14:00 to 15:00 and from 18:00 to 19:00. Over half of tornadoes in the United States, where it mainly appears in the afternoon and night, occurred between 15:00 and 20:00^[7] (local time, the same below), and the peak time is also between 17:00 and 18:00.

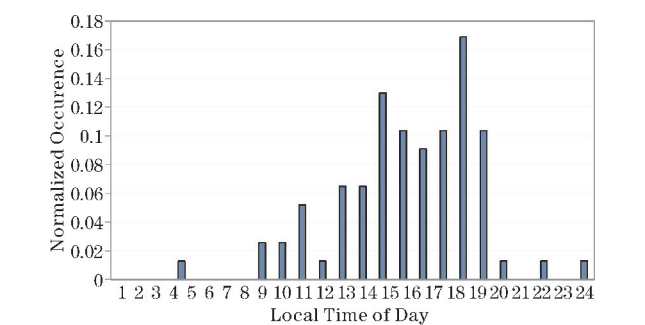


Fig. 3 Daily changes of tornado occurrence for 1955–2019 in Liaoning

There are 66 tornadoes with a clear duration record in Liaoning Province (Table 4). The duration of tornadoes is mostly less than 20 minutes, accounting for 85% of the total number. Among them, the tornadoes lasting 5–10 minutes are the most, accounting for 38% of the total number, followed by 10 to 20 minutes, accounting for 26%.

Table 4 Duration of tornadoes for 1955–2019 in Liaoning				
	$t \leq 5$	$5 < t \leq 10$	$10 < t \leq 20$	$t > 20$
Duration/min	14	25	17	10
Proportion/%	21	38	26	15

3.4 Spatial distribution of tornadoes in Liaoning

From 1955 to 2019, a total of 158 tornadoes occurred in Liaoning Province (Fig. 4), of which 45 were directly observed by meteorological observation stations, and the remaining 109 were from tornado disaster records. In terms of the density of the meteorological observatories, it is expected that a considerable part of tornadic cases are still unrecorded.

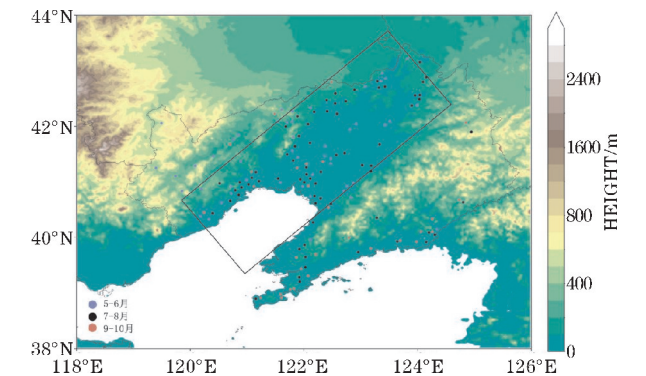


Fig. 4 Distribution of tornadoes in Liaoning Province from 1955 to 2019 (the black box indicates a schematic area of “Tornado Alley in Liaoning”)

Tornado is distributed in the low altitude areas of Liaoning Province on the whole, mainly including the eastern and western coastal areas and the Liaohhe Plain. It can be clearly seen that before the flood season of Liaoning (May to June), tornadoes mainly occur in the western region. The high-incidence area is distributed in the Liaoning West Corridor and extends to the Fuxin area in the northwest. It rarely occurs after the flood season. This climatic feature can be used as an important reference for tornado forecasting in the region; from July to August, as the subtropical summer monsoon pushes northward, Liaoning enters the main flood season, and the number of tornadoes increases significantly. Relatively scattered, but concentrated in low-altitude areas, mainly in the Liaoxi Corridor and the middle and lower reaches of the Liaohhe Plain; the number of tornadoes decreased significantly from September to October, mainly distributed in the eastern coastal areas of Liaoning.

Figure 4 shows that most of the tornadic cases in Liaoning (about 72%) occurred in the area shown in the black box in the figure, mostly concentrated in June to August. According to the administrative divisions, they mainly include Huludao City (Except for Jianchang County), Jinzhou City, Panjin City, Fuxin City, Shenyang City, Anshan City, Liaoyang City, Yingkou City (except Gaizhou County), we define the general area shown in the above box as “Tornado Alley in Liaoning” so that the forecast and early warning business can pay more attention to the possibility of tornadoes in this area in the high-incidence season of tornadoes.

4 Summary

In this paper, the Liaoning tornado event is counted

based on the “Chinese Meteorological Disasters Dictionary” and other data, and classified by EF scale based on the disaster description. Finally, we analyzed the spatial and temporal distribution characteristics of the tornado in Liaoning in detail and came to the following main conclusions:

From 1955 to 2019, a total of 158 tornadoes were recorded in Liaoning. The ratio of significant tornado of EF4 to EF3 is 0.33, the ratio of EF3 to EF2 is 0.14, and the ratio of EF2 to EF1 is 0.35, which is within the range of 0.1 to 0.36.

Tornadoes in Liaoning occur on average 2.3 per year, and the annual average tornado density is $1.5 \times 10^{-5}/\text{km}^2$, which is about 1/10 of that of the United States. The months of tornado generation are relatively concentrated, mainly from May to October, with the most tornadoes in July, exceeding 1/4 of the annual total. Tornadoes mostly appear in the afternoon to the evening, especially between 13:00 to 14:00 and 17:00 to 18:00. The duration of tornadoes is relatively short, about 85% of tornadic cases last within 20 minutes.

The spatial distribution of tornadoes in Liaoning showed that Most tornadoes occurred in low-elevation plain areas in addition to western mountainous areas before the flood season occasionally. The spatial distribution of tornadoes also showed the characteristics of temporal changes. From May to June, tornadoes were distributed from the Liaoxi Corridor to the northwestern part of Liaoning which in a northeast-southwest zonal direction; from July to August, the number of tornadoes increased significantly and their distribution was relatively scattered, mostly concentrated in the Liaoxi Corridor and the middle and lower reaches of the Liaohe Plain; The number of tornadoes decreased significantly from September to October, mainly distributed in the eastern coastal areas of Liaoning.

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1955–2019 年辽宁龙卷时空分布特征

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摘要:为研究辽宁地区龙卷气候特征,基于《中国气象灾害大典》《中国气象灾害年鉴》和其他相关资料,采用“改进藤田分级”标准进行强度分类,对 1955–2019 年辽宁龙卷的时空分布特征进行统计分析,得到以下主要结论:(1) 1955–2019 年辽宁地区平均每年出现龙卷 2.3 个,年龙卷密度为 1.5×10^{-5} 个/ km^2 ,约为美国的 1/10。EF2 及以上等级强龙卷共记录到 25 次,年均 0.4 次,含 EF4 级 1 次,EF3 级 3 次,EF2 级 21 次,相邻分级比例在 0.1~0.36。(2) 龙卷主要出现在 5–10 月,其中 7 月最多,超过年总数的 1/4。龙卷大多出现在午后到傍晚,13–14 时、17–18 时是两个龙卷多发时段。约 85% 的龙卷事件持续时间在 20 分钟以内。(3) 多数龙卷发生在平原地区,5–6 月多分布于辽西走廊至辽宁西北部地区;7–8 月集中于辽西走廊和辽河平原中下游地区;9–10 月辽宁东部地区龙卷明显增多。

关 键 词:气象学;灾害性天气预测;龙卷;时空分布;灾情特征;辽宁