Analysis of Hail Climatic Characteristics and Influencing Factors in Longdong from 1978 to 2023: A Postprint

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Abstract

Hail is one of the extreme weather phenomena induced by strong convection, characterized by rapid development and significant destructiveness, posing a substantial threat to the Longdong region where the economy is predominantly agricultural. Against the backdrop of climate warming, in-depth investigation into the climatic characteristics of hail in Longdong and its influencing factors is imperative. Utilizing hail data and disaster records from 15 surface observation stations across the Longdong region from 1978 to 2023, in conjunction with ERA5 reanalysis data provided by ECMWF, this study analyzes the spatiotemporal distribution characteristics and key influencing factors of hail in Longdong through methods including linear trend estimation, Mann-Kendall mutation test, and Morlet wavelet analysis. The results demonstrate that: (1) The spatial distribution of hail days in Longdong is heterogeneous, exhibiting a pattern of higher frequency in the northwest and southeast, and lower frequency in the central and southern areas. Hail-prone regions are primarily situated in downslope terrain, leeward slopes of mountains, and the Ziwuling mountainous area, whereas hail-scarce regions are mainly located in flat plateau areas and the southern Liupan Mountains. (2) Over the past 46 years, the number of hail days has displayed a decreasing trend, with the most pronounced decline occurring in spring; the period from May to August represents the peak occurrence season, accounting for 81.5% of annual hail days. (3) The diurnal variation of hail demonstrates a "unimodal" characteristic, with 15:00–18:00 being the most frequent period; hail events with durations of 0–9 minutes and moderate diameters occur most frequently; the frequency of localized hail far exceeds that of regional hail, yet regional hail exhibits a significant increasing trend. (4) Hail days exhibit a primary oscillation period of 3 years and secondary oscillation periods of 14 years and 35 years. (5) The dominant meteorological factors influencing hail days vary across seasons, with Convective Available Potential Energy (CAPE) and the height of the 0 °C layer exerting the most dominant influence on hail days in Longdong. The research findings can enhance understanding of hail occurrence patterns in Longdong and provide scientific references for optimizing forecast and warning models as well as artificial hail suppression operations.

Full Text

Hail Climate Characteristics and Influencing Factors in Longdong Region from 1978 to 2023

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Abstract

Hail is an extreme weather phenomenon caused by strong convection, characterized by rapid development and high destructiveness, posing a particularly severe threat to the Longdong region where agriculture forms the economic foundation. Against the backdrop of climate warming, it is essential to investigate the climatic characteristics of hail in Longdong and its influencing factors. Using hail observation and disaster data from ground stations in 15 counties/districts of Longdong from 1978 to 2023, combined with ECMWF reanalysis data, this study employs linear trend estimation, Mann-Kendall mutation test, and Morlet wavelet analysis to examine the spatiotemporal distribution characteristics of hail and key influencing factors. The results show: (1) Hail days exhibit uneven spatial distribution, with more frequent occurrences in the northwest and southeast, and fewer in the central and southern regions. Hail-prone areas are mainly located on downslope terrains, leeward mountain slopes, and the Ziwuling mountainous area, while hail-scarce areas are primarily in flat loess tablelands and the southern Liupan Mountains. (2) Over the past 46 years, hail days show a decreasing trend, with the most significant reduction in spring. May to August constitute the high-incidence period, accounting for 81.5% of annual hail days. (3) The diurnal variation displays a single-peak pattern, with 15:00-18:00 being the most frequent hail period. Hail events with short duration (0-9 minutes) and medium diameter occur most frequently. Localized hail is far more common than regional hail, but regional hail shows a significant increasing trend. (4) Hail days exhibit oscillation periods of 3-5 years, 13-15 years, and 34-35 years. (5) The dominant meteorological factors affecting hail days vary by season, with convective available potential energy (CAPE) and the 0°C isotherm height playing the most crucial roles. These findings enhance understanding of hail occurrence patterns in Longdong and provide scientific references for optimizing forecasting and early warning models and artificial hail suppression operations.

Keywords: hail; climatic characteristics; influencing factors; climate warming; Longdong region

1. Introduction

Hail is solid precipitation in the form of hard spheres, cones, or irregular shapes that falls from strongly developed cumulonimbus clouds. It represents a hazardous weather phenomenon with distinct seasonality, strong local characteristics, violent onset, and short duration, primarily causing mechanical damage that severely impacts industry, agriculture, and people' s livelihoods. Hail has long been a research focus for meteorologists worldwide. Investigations extend beyond short-term forecasting, early warning, and physical formation mechanisms to encompass climatic characteristics, which help understand local occurrence patterns and inform hail prediction and suppression efforts. Climatic hail characteristics and influencing factors vary across regions. Research on southwestern Germany indicates that while annual thunderstorm days remained essentially constant from 1971-2000, hail days increased significantly.

Since the 1980s, hail frequency in northern and northwestern China has decreased markedly. Studies have analyzed spatiotemporal hail characteristics across China, noting that most hail events occur between 15:00-20:00 local time, though Guizhou and Hubei experience nocturnal events. Region-specific analyses reveal that Qinghai Plateau hail frequency decreased significantly during 1980-2018, with southern high-altitude areas being hail-prone and experiencing longer durations, while large hail primarily occurs in eastern low-altitude regions with fewer events. In Shandong Province, hail mainly appears in central and northern areas, characterized by large convective available potential energy (CAPE), moderate to strong vertical wind shear, significant conditional instability, and appropriate characteristic layer heights. Guizhou hail distributes primarily in central-western areas, with annual frequency positively correlated with altitude and events concentrated between 14:00-02:00, showing decreasing daytime frequency from northwest to southeast.

The Longdong region lies on the Loess Plateau with complex terrain of mountains, hills, and gullies, featuring large elevation differences and temperature variations that create favorable conditions for severe convection. The loose loess soil and fragile ecology make the area particularly vulnerable during spring and summer when hail frequently occurs during critical growth periods for winter wheat, apples, corn, and other economically important crops, causing substantial economic losses and threatening lives. Previous research has investigated hail formation mechanisms, radar characteristics, and forecasting indicators in Longdong, providing foundations for short-term forecasting. However, few studies have focused on hail climate analysis. Existing research based on pre-2010 data primarily examined basic spatiotemporal distributions and forecasting summaries. Given the significant warming and humidification trends in Northwest China, updated climate research on Longdong hail, particularly regarding influencing factors, is urgently needed.

This study utilizes daily hail observations from 15 national meteorological stations in Longdong from 1978-2023, combined with ECMWF ERA5 reanalysis data, to analyze climatic variation characteristics and influencing factors. The objectives are to reveal spatiotemporal patterns and occurrence regularities, providing scientific references for optimizing forecasting and early warning models and improving artificial hail suppression mechanisms.

1.1 Study Area Overview

Longdong region includes Pingliang and Qingyang municipalities in eastern Gansu Province, comprising 15 counties/districts: Kongtong, Jingchuan, Lingtai, Chongxin, Zhuanglang, Jingning, and Huating in Pingliang; and Xifeng, Huanxian, Huachi, Qingcheng, Zhenyuan, Heshui, Ningxian, and Zhengning in Qingyang. Geographically situated between 105°20 -108°45 E and 34°54 - 37°10 N at the intersection of Gansu, Shaanxi, and Ningxia provinces, the region belongs to the Loess Plateau. Influenced by the Liupan, Long, Huajia, and Ziwuling mountains, the terrain forms eastern loess hilly areas, northern loess hilly-gully regions, southwestern mid-mountain zones, and central-southern loess plateau-gully landscapes, with elevations ranging from 885-2857 m. Prevailing northwest winds shift to southeast winds in summer, with precipitation decreasing from south to north and concentrating in summer. As a major agricultural area known as the "Granary of Gansu," Longdong' s complex terrain and large elevation differences make it one of Gansu' s most hail-prone regions, posing severe threats to agriculture and property.

1.2 Data Sources

This study employs hail disaster data from 15 counties/districts obtained through China' s national comprehensive natural disaster risk survey, important weather reports from national basic stations, and disaster information reported by observers. These sources provide records of hail timing, maximum diameter, frequency, and start/end times (precise to minutes) for analyzing spatiotemporal distribution, diameter, duration, scope, and periodic characteristics. To ensure data quality, stations with complete records throughout the study period were selected, yielding 15 stations with details including station ID, altitude, coordinates, and hail parameters. Atmospheric physical quantity data were extracted from ECMWF' s fifth-generation global reanalysis (ERA5) with 0.1°$×$0.1° spatial resolution, including monthly averages of CAPE, K-index, 0°C layer height, cloud base height, total precipitation, and convective precipitation. This dataset, sharing the same source as ECMWF data frequently used by forecasters, serves as a standard reanalysis product for weather analysis and mechanism research. Correlation analysis between these atmospheric parameters and hail days helps validate their applicability for Longdong hail forecasting and provides scientific references for objective algorithm development.

Following established definitions, a hail day is defined as a day when $ 2*stationsreporthailwithintheentireregion, witheachstationcountingasonestation−timeregardlessofmultipleevents.Thedailyboundaryfollowsmeteorologicalobservationstandardsfrom*20 :

00to19 : 59.Haildurationusestheintegerminutevaluefromstarttoendtime, withevents < 1minuterecordedas1minute.Haildiameter(D)isclassifiedaccordingtonationalstandards : small(D < 5mm), medium(5 D < 20mm), large(20 D < 50mm), andextremelylarge(D $50 mm). Hail scope is categorized as regional (involving $ $3 counties/districts) or localized (<3 counties/districts). Seasons are defined as spring (March-May), summer (June-August), autumn (September-November), and winter (December-February).

1.3 Research Methods

Spatial distribution of hail days was mapped using ArcGIS inverse distance weighting interpolation. Linear trend estimation quantified climatic tendency rates, with significance tested using the Mann-Kendall method. Morlet wavelet analysis examined periodic variations. Python processed ERA5 data and calculated correlations between atmospheric parameters and hail days. The study period spans 1978-2023, with significance levels of P<0.001 (r>0.469), P<0.01 (r>0.376), and P<0.05 (r>0.291).

2. Results and Analysis

2.1 Spatial Distribution Characteristics

From 1978-2023, Longdong' s hail days showed marked spatial heterogeneity [Figure 2: see original paper]. Huanxian County in the north recorded the most hail days (150), followed by Zhenyuan County (131), while Qingcheng County had the fewest (53). The difference between maximum and minimum reached 2.8-fold, revealing extremely uneven distribution with a pattern of more hail in northwest and southeast, less in central and southern areas. Huating, Chongxin, Zhuanglang, and Lingtai counties located on the southern Liupan Mountains also experienced relatively fewer hail days, consistent with previous research.

To understand this spatial pattern, station elevation was linearly fitted against hail days, revealing weak correlation. This likely stems from Longdong's complex terrain, as meteorological stations are often built on flat tablelands or in valleys that cannot objectively represent entire counties. Further analysis of terrain relationships indicates that hail-prone areas fall into three categories: (1) Huanxian in the far north with extreme elevation differences (2089 m maximum, 1136 m minimum), low vegetation coverage, and downslope terrain where convective systems from the Daluo Mountains in Ningxia enhance activity as they move southeastward; (2) Kongtong District and Zhenyuan County on the eastern foothills of southern Liupan Mountains, where systems from Haiyuan County, Ningxia intensify after crossing the mountains; and (3) Zhengning County in the Ziwuling mountainous area with complex terrain and abundant moisture, serving as a primary hail source region at the Shaanxi-Gansu border. Hail-scarce areas include the flat loess tablelands of Xifeng, Qingcheng, and Heshui with high vegetation coverage that inhibits hail cloud development, and the southern Liupan Mountains where leeward slopes reduce hail formation.

2.2 Temporal Variation Characteristics

2.2.1 Interannual Variation From 1978-2023, Longdong experienced 649 total hail days with considerable interannual fluctuation. The maximum occurred in 1979 (23 days) and the minimum in 2021 (3 days). The overall trend shows decline at -0.426 days/decade, though not statistically significant. Decadal analysis reveals 16.1 days/year during 1978-1989 (most frequent), decreasing to 12.5 days/year in 2010-2023 (least frequent).

2.2.2 Mann-Kendall Mutation Test Mann-Kendall testing identified a downward trend in annual hail days with a mutation point around 1999 [Figure 4: see original paper]. The forward sequence (UF) shows increasing trend before 1999 and decreasing trend after, with post-2000 values exceeding the confidence interval, indicating significant reduction. Spring hail days show an increase-decrease pattern with a mutation point around 1999, while summer displays a decrease-increase-decrease pattern with a mutation point around 2002. Autumn shows a consistent significant decreasing trend, particularly after 2000.

2.2.3 Monthly Variation Monthly distribution reveals distinct seasonal characteristics [Figure 5: see original paper]. Hail occurs in spring, summer, and autumn, with summer (May-August) being the peak season accounting for 81.5% of annual events. The pattern shows a single peak in June (188 days) and July (144 days), with August and September having minimal occurrence (1 day each). After April, rising surface temperatures combine with northwest upper-level flows and frequent cold air activity, increasing atmospheric instability conducive to hail formation. The earliest hail days occurred in southern Longdong (Zhengning: April 12; Lingtai: April 14), demonstrating thermal conditions' influence on hail timing.

2.2.4 Diurnal Variation Diurnal analysis of 7870 station-times shows a single-peak pattern [Figure 6: see original paper]. Hail occurrences increase significantly after 12:00, with 15:00-18:00 being the primary period (50.8% of total). The peak hour is 17:00-18:00 (18.3%). Four time intervals recorded no hail (02:00-03:00, 04:00-05:00, 06:00-07:00, 20:00-21:00), all in early morning hours. Afternoon and evening dominance reflects maximum daily temperatures enhancing low-level atmospheric warming and thermal contrast with upper levels, promoting unstable stratification favorable for hail development.

2.3 Hail Duration

Analysis of 7870 station-times shows most hail events are short-duration [Figure 7: see original paper]. Events lasting 0-9 minutes account for 63.2% of occurrences, decreasing rapidly with longer durations. Only 15 events exceeded 40 minutes, including one 60-minute event in Huachi County (June 4, 2010). Longer-duration events more frequently involve multiple stations, consistent with previous research.

2.4 Hail Diameter

Statistics from 7870 station-times indicate medium-diameter hail occurs most frequently (63.2%), followed by large hail (18.5%) [Figure 8: see original paper]. The maximum recorded diameter reached 10 cm in Zhenyuan County (June 13, 2005), meeting the extremely large hail criterion. According to severe convective weather definitions, D$ 5cmqualifiesassevereconvection, andD $5 cm as extreme severe convection. Longdong recorded 25.7% of events meeting severe convection standards and 18.5% reaching extreme severe convection standards. Historical records document catastrophic events, such as the June 5, 1930 hailstorm in Huanxian that killed 11 people and destroyed 1172.4 hectares of crops, and the July 23, 2012 regional hailstorm affecting 7 counties with egg-sized hail causing ¥250 million in direct economic losses. Though infrequent, extreme severe convection events cause devastating impacts.

2.5 Hail Scope

From 1978-2023, Longdong experienced 157 hail events, predominantly localized (136 events, 86.6%) versus regional (21 events, 13.4%). Localized hail occurs in all months, peaking in June, while regional hail peaks in July (6 events). Interannual variation shows regional hail increasing significantly ($P<0.01$), with 2022 recording the highest proportion (28.6%). Localized hail shows a decreasing trend. Most large and extremely large hail events are associated with regional processes. For example, the July 23, 2012 regional event affected 7 counties with maximum diameter 75 mm, and the June 4, 2010 event affected 6 counties with maximum diameter 72 mm, demonstrating that regional hail more readily produces large-diameter hailstones.

2.6 Hail Periodicity

Morlet wavelet analysis reveals strong oscillations across three time scales: 3-5 years, 13-15 years, and 34-35 years [Figure 10: see original paper]. The wavelet variance shows peaks at these periods, indicating a primary oscillation cycle of 3 years and secondary cycles of 14 and 35 years. As 2023 falls within a high-incidence period of the 13-15 year cycle, the region may continue experiencing increased hail activity in the near future.

2.7 Correlation Between Atmospheric Physical Parameters and Hail Days

Hail formation requires favorable synoptic conditions, low-level moisture convergence, atmospheric instability, and triggering mechanisms. Cloud physics, vertical wind shear, and characteristic layer heights like the -20°C level also play crucial roles. Based on these physical requirements, seven atmospheric parameters from ERA5 were correlated with hail days: CAPE, K-index, 0°C layer height, cloud base height, dewpoint temperature, total precipitation, and convective precipitation .

Spring hail days show significant positive correlations with CAPE, K-index, convective precipitation, total precipitation, dewpoint temperature, and cloud base height, and negative correlation with 0°C layer height. CAPE and K-index show the strongest correlations ($P<0.001$), indicating that instability energy parameters are most predictive for spring hail when atmospheric temperatures are relatively low. Summer hail days exhibit significant negative correlation only with 0°C layer height ($P<0.05$), as lower heights favor hail formation during the season when high temperatures and moisture conditions are generally favorable. Autumn hail days show significant positive correlation with CAPE ($P<0.001$), reflecting the dominant role of instability energy when thermal conditions weaken but moisture and characteristic layer heights remain suitable.

3. Conclusions

This study analyzed 46 years of hail data from Longdong region, revealing the following key findings:

(1) Spatial distribution is highly uneven, showing a pattern of more hail in northwest and southeast, less in central and southern areas. Hail-prone zones cluster in three regions: northwestern Huanxian, eastern foothills of southern Liupan Mountains (Kongtong and Zhenyuan), and the Ziwuling mountainous area. Hail-scarce zones include flat loess tablelands (Xifeng, Qingcheng, Heshui) and southern Liupan Mountains. This distribution closely relates to terrain, with hail favoring downslope areas, leeward slopes, and mountainous regions.

(2) Interannual variation shows a declining trend, most pronounced in spring. Mann-Kendall tests identify mutation points around 1999 for annual and spring hail, and around 2002 for summer hail, with autumn showing consistent decline. Seasonally, May-August accounts for 81.5% of hail days, with June being the peak month. Diurnally, a single peak occurs between 15:00-18:00. Short-duration (0-9 minutes) and medium-diameter events are most common. Localized hail dominates but regional hail is increasing significantly.

(3) Hail days exhibit oscillation periods of 3-5 years, 13-15 years, and 34-35 years, with a primary cycle of 3 years. The region is currently in a high-incidence phase of the 13-15 year cycle, suggesting continued elevated hail activity.

(4) Seasonal analysis reveals different dominant factors: spring hail is most sensitive to CAPE, K-index, 0°C temperature, and cloud base height; summer hail is primarily controlled by 0°C layer height; and autumn hail is dominated by CAPE. These findings provide scientific guidance for optimizing forecasting models and artificial hail suppression strategies in Longdong.

Limitations and Future Work

This study relies on manually observed data limited to county-level resolution, preventing precise township-scale analysis. Additionally, the analysis focused on terrain and seven atmospheric physical parameters, which is not comprehensive. Future research should integrate multi-source data to conduct more thorough investigations of hail climate influencing factors.

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