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SYNOPTIC AND CLIMATOLOGICAL CHARACTERISTICS OF CONVECTIVE ACTIVITY OVER THE ABSHERON PENINSULA

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Abstract

This study investigates the synoptic-scale air masses influencing convective processes over the Absheron Peninsula during the period 2011–2020, with particular emphasis on their seasonal and interannual frequency. The findings indicate that convective events in the region occurred most frequently under the influence of the Azores High (31.5%) and Arctic Maritime (29.5%) air masses. During the autumn–winter season, convective processes were predominantly driven by intrusions of Arctic Maritime air masses, whereas in the spring–summer period, the Azores anticyclone exerted the dominant influence. This pronounced seasonal variability underscores the critical role of large-scale atmospheric circulation systems in shaping convective weather patterns over the peninsula.

A statistical analysis of cumulonimbus cloud occurrence and related atmospheric phenomena was conducted using archival meteorological data (2005–2021) obtained from Heydar Aliyev International Airport. The results demonstrate that the highest frequency of cumulonimbus clouds occurred in May, July and September (19–22 days), while the lowest frequency was observed in January and February (7–8 days). Thunderstorms were observed throughout the year, except from January to March, with the highest frequency in May and September.

Furthermore, a comparative analysis of thunderstorm-day distribution for the periods 1975–1991 and 2005–2021 demonstrates a marked increase in convective activity. The mean annual number of thunderstorm days has increased

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from 7 in the period 1975–1991 to 11 in the period 2005–2021. In both periods, thunderstorms were absent from January through March. However, whereas no events were recorded in November and December in the period 1975–1991, thunderstorms were documented in these months in the period 2005–2021. This shift suggests a recent extension of the convective season and may reflect evolving regional atmospheric dynamics.

Key words: thunderstorms, cumulonimbus clouds, Absheron Peninsula, air masses, Heydar Aliyev International Airport, convective processes

Introduction. The occurrence of severe weather events negatively impacts the ability of air traffic management systems to ensure the safe transit of passengers and maintain the punctuality of flight arrivals and departures. Several meteorological phenomena, including lightning, heavy precipitation, turbulence, icing, electrification and wind shear are associated with intense convective processes in an unstable atmosphere. These hazardous atmospheric conditions are frequently linked to cumulonimbus clouds, which form as a result of rapidly developing convective processes extending from the middle troposphere to the tropopause [1–3].

The formation of thunderstorms is associated with the passage of cold fronts, convection processes and powerful updrafts in the atmosphere. The occurrence of thunderstorms is closely dependent on orography [4,5]. The formation of thunderstorms is also strongly influenced by factors such as the orientation and elevation of slopes, as well as orographic protection. Azerbaijan's diverse topography plays a significant role in this process. In addition to the high ridges that rise above the snow line, the country features extensive plains and lowlands, some of which are situated below sea level. The distance from the Caspian Sea also impacts thunderstorm activity [6, 7]. Among the factors influencing the processes of atmospheric circulation over the Absheron Peninsula, the dominant role is played by the high mountain ranges of the Main Caucasus. The mountains of the Main Caucasus are a natural barrier that prevents the direct impact of cold air masses from the northwest [8].

The proximity of the sea has a great influence on the atmospheric circulation and transformation of air masses over the Absheron Peninsula. In summer, the sea moderates the warm air originating from the plains of Central Asia and the Caspian Sea, mitigating its heat. In winter, it amplifies the low temperatures of cold air masses moving from the north. This contributes to increased cyclonic activity over the Caucasus and the Caspian Sea. In the cold season, the sea surface is warmer than the surrounding air, leading to a slight warming of the air [9].

Materials and methods. The study area comprised the Absheron Peninsula, a low-relief peninsula on the western coast of the Caspian Sea. It extends approximately 60 km eastward into the Caspian Sea and reaches a maximum width of about 30 km. Geographically, it forms the easternmost termination of the Greater Caucasus orographic system [10].

Heydar Aliyev International Airport was selected as the primary observation site because it provides continuous aviation-meteorological observations representative of the central part of the peninsula. The observational dataset comprised archived Meteorological Airport Reports (METAR) and measurements from the Automated Weather Observing System (AWOS) at Heydar Aliyev International Airport. The records included cloud type and amount, present weather, visibility, precipitation, wind, air temperature, and pressure. The station data were supplemented by surface synoptic charts, upper-air charts at 700 and 500 hPa, satellite imagery and atmospheric sounding data [11]. These sources were used together to identify the occurrence of convective weather, evaluate the thermodynamic and dynamic environment, and determine the synoptic-scale circulation pattern during each event. Cumulonimbus cloud, thunderstorm and showery precipitation events were identified from the corresponding cloud and present-weather observations in the METAR and AWOS archives. The event records were checked against the available satellite imagery, synoptic charts and upper-air information to distinguish convective precipitation from stratiform precipitation and to verify the associated atmospheric circulation.

For each convective event identified in the period 2011–2020, sea-level pressure fields and the geopotential-height at 700 and 500 hPa were analyzed to determine the prevailing synoptic regime and the source region of the advected air mass. The events were classified into five synoptic categories: Continental Arctic air, Maritime Arctic air, Azores High, mid-latitude Continental air and Southern Cyclones [12]. The classification was based on the location and evolution of pressure systems, the direction of air-mass advection, the configuration of mid-tropospheric troughs and ridges, and the presence of frontal boundaries or convergence zones.

Air masses of Continental Arctic origin, formed over northwestern Siberia and the Kara and Barents Seas, penetrate the Caspian Sea region and Azerbaijan. These air masses typically undergo significant modification, transforming into cold continental air characteristic of the mid-latitudes. On occasion, when Continental Arctic air masses reach the Absheron Peninsula in winter, they induce an abrupt deterioration in weather conditions.

Arctic Maritime air masses originating from the regions of Spitsbergen and Greenland enter the Caspian Sea and the Caucasus, advancing southward where they gradually transform into cold continental air characteristic of the mid-latitudes. During the warm season, these air masses typically reach Azerbaijan in a significantly modified state, with the degree of transformation being most pronounced in the summer months. This period is often marked by convective activity over the Absheron Peninsula, including frequent occurrences of lightning, thunder and localized showers.

The climate of the Absheron Peninsula is heavily influenced by the Azores High, also known as the Azores Anticyclone. This is a semi-permanent anticyclonic region characterized by relatively consistent high pressure and subsiding air

over the Atlantic Ocean. This phenomenon is particularly prominent during the warm half of the year. The seasonal position of the Azores High varies throughout the year: in winter, it shifts southward, whereas in summer, it expands and migrates northward [5, 13]. The first subtype of the Azores High, or its centre and associated swirl, moves over the northern part of the Atlantic Ocean, passing through Eastern Great Britain towards Central Europe and Ukraine. From there, it takes a northern trajectory, extending from the North Caucasus to the Caspian Sea and Central Asia. By the time these air masses reach the Absheron Peninsula, they have generally cooled. The second subtype of the Azores High, or its centre and swirl, follows a southerly trajectory, covering the Bay of Biscay, southern European areas, southern Ukraine, the Northern Caucasus, the Caspian Sea, and Central Asia. The influence of the Azores High on our territory is most frequently observed during the warm season [9, 12, 13].

The development of cyclones over the southern regions, including the Mediterranean Sea, Iraq, northwestern Iran and the Asia Minor Peninsula, is driven by the intense advection of cold air into these areas. These processes are linked to the formation of a high and deep northern cyclone, with its trough extending toward southern Europe. The passage of southern cyclones creates favourable conditions for the intrusion of cold continental air masses into the Middle Caspian and Absheron regions via the North Caucasus [5, 12].

Discussion. Figure 1 illustrates the frequency of air mass occurrences during convective processes between 2011 and 2020. It indicates that the Azores High

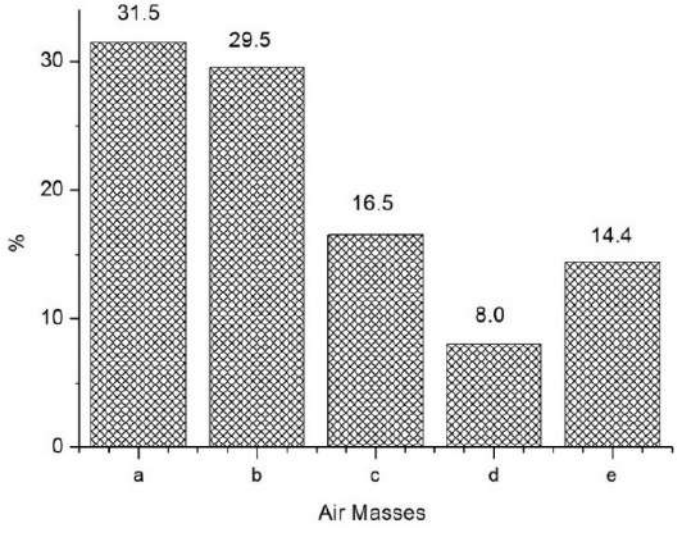

Fig. 1. Frequency (%) of air masses during convective processes from 2011 to 2020. a – Azores High; b – Maritime Arctic air masses; c – continental Arctic air masses; d – continental air of mid-latitudes; e – southern cyclones

(31.5%) and Maritime Arctic air masses (29.5%) exerted the most significant influence during the study period. In contrast, the impact of mid-latitude Continental air masses was relatively minor, contributing only 8.0% to the total recurrence.

Along with the analysis of the physical and synoptic conditions of the formation of cumulonimbus clouds during the meteorological support of civil aviation flights, the statistical study of the probability of their frequency is also very important from a practical point of view.

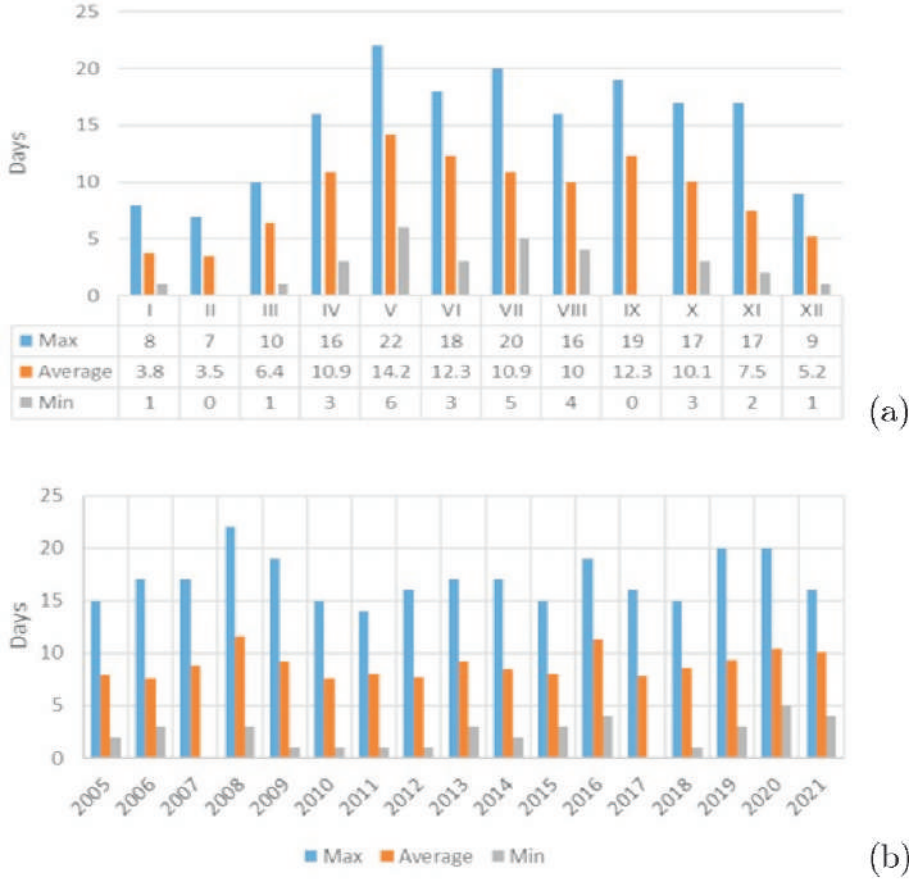

Fig. 2. Monthly (a) and interannual (b) frequency of cumulonimbus clouds at Heydar Aliyev International Airport in the period 2005–2021

Given the importance of understanding cumulonimbus cloud development and associated atmospheric phenomena, this study examines the monthly and annual statistical frequency of cumulonimbus clouds, thunderstorms and related events, using archived meteorological data recorded at Heydar Aliyev International Airport from 2011 to 2021. Figure 2 presents the monthly and interannual frequencies of cumulonimbus-cloud occurrence during the study period.

Cumulonimbus clouds typically develop through deep moist convection, often evolving from cumulus clouds generated by surface heating. They may also form along cold fronts through forced ascent, as warm, moist air is lifted over advancing cold air masses [6, 8].

Throughout the study period, thunderstorms were observed at Heydar Aliyev International Airport all year round, with the exception of the period from January to March. The highest frequency of these phenomena was recorded in May and September, with thunderstorms recorded on six days in each of these months. By contrast, the frequency was lowest in November and December, with lightning occurring on only one day in each of these months. The highest number of days with thunderstorms was recorded in 2008, which may be due to the increased convective activity observed in September of that year (Fig. 3).

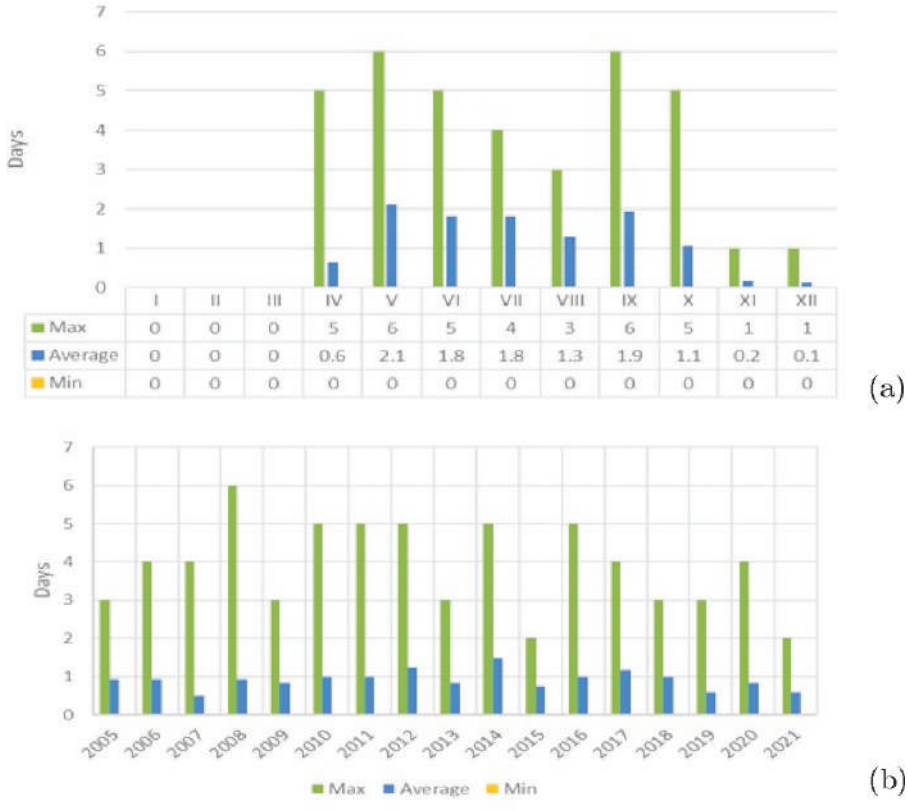

Fig. 3. Monthly (a) and interannual (b) frequency of thunderstorm days at Heydar Aliyev International Airport in the period 2005–2021

Figure 3 shows a notable increase in frequency in 2016. Research by Huseynov et al. [14] shows that 2016 experienced the highest level of convective activity over the Absheron Peninsula. The intense lightning and rain showers recorded on

September 28 and October 17, 2016, on the Absheron Peninsula, can be attributed to the incursion of Arctic Maritime air masses. The September thunderstorm maximum may result from the interaction between Maritime Arctic air intrusions and the relatively warm Caspian Sea. Cold-air advection over the warm sea can increase moisture and lower-tropospheric instability, favouring cumulonimbus development and lightning over the Caspian Sea and the adjacent Absheron coast, particularly in the presence of synoptic-scale ascent or convergence.

This interpretation is consistent with findings from comparable mid-latitude maritime regions. Petrova et al. [15] reported that, during autumn, lightning activity over the Black Sea exceeded that observed over Bulgaria and reached a maximum over the sea in September. Their analysis also revealed a positive relationship between sea-surface temperature and mean flash frequency during nighttime, with correlation coefficients of 0.92–0.98, whereas this relationship was less pronounced during daytime. Similarly, using a 10-year lightning dataset for the Mediterranean, Kotroni and Lagouvardos [4] found a positive correlation between lightning frequency and sea-surface temperature in autumn, when maximum lightning activity occurred over the sea. They suggested that warmer sea-surface temperatures destabilize the lower troposphere and thereby enhance convective activity.

These findings suggest that the September maximum observed at Heydar Aliyev International Airport may be associated with the interaction between Maritime Arctic air-mass intrusions and the thermal influence of the Caspian Sea. A similar mechanism may also contribute to the broader September–November maximum in showery precipitation and to autumn thunderstorm activity more generally. However, because SST was not included as an explicit predictor in the present analysis, this mechanism should be considered a plausible interpretation rather than a demonstrated causal relationship. Further research incorporating SST data, atmospheric soundings, reanalysis fields and lightning observations would be required to quantify its contribution.

Figure 4 presents an analysis of the average annual thunderstorm days in the periods 1975–1991 and 2005–2021. The frequency of thunderstorm days on the Absheron Peninsula from 1975 to 2021 reveals significant variations in thunderstorm frequency across the years. The data indicates changes in both seasonal patterns and long-term trends in lightning activity during this period. Between 1975 and 1991, the average annual thunderstorm days on the Absheron Peninsula was relatively lower, with an average of 7 days per year. However, from 2005 to 2021, this number increased to an average of 11 days annually, reflecting a noticeable rise in thunderstorm occurrences during this latter period. Figure 4 also highlights that no thunderstorms were observed during the months of January to March in either period, which suggests that thunderstorms on the Absheron Peninsula are not typical of the winter months. It is also worth noting that, during the period 2005–2021, thunderstorms were recorded in November and December,

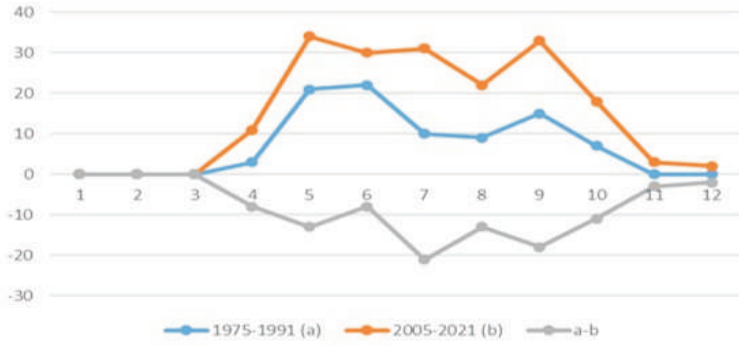

Fig. 4. Distribution of thunderstorm days on the Absheron Peninsula for the period 1975–2021

whereas no such events were recorded during the earlier period 1975–1991 [10,16].

Conclusion. This research evaluates the dominant air masses associated with convective development over the Absheron Peninsula between 2011 and 2020, assessing their annual recurrence and distribution characteristics. Furthermore, long-term observational data (2005–2021) from Heydar Aliyev International Airport were statistically analyzed to determine the monthly and annual frequency of cumulonimbus clouds and related hazardous atmospheric events.

The analysis revealed that convective processes in the region occurred most frequently under the influence of the Azores High (31.5%) and Arctic Maritime (29.5%) air masses. During the autumn–winter period, convective activity was mainly associated with the intrusion of Arctic Maritime air masses, accounting for approximately 32–42% of events. In contrast, during the spring–summer period, convective processes were predominantly driven by the Azores High, with its influence observed in 34–63% of cases.

During the study period, the highest frequency of cumulonimbus clouds was recorded in May (22 days), followed by July and September (19–20 days), while the lowest frequency occurred in January and February (7–8 days). Thunderstorms were recorded throughout the year except from January to March. The highest frequency of thunderstorms occurred in May and September, while isolated cases were observed in November and December.

These findings underscore the seasonal variability of convective weather phenomena on the Absheron Peninsula. In particular, the frequency and intensity of thunderstorm events demonstrate clear fluctuations between the warm and cold seasons. The pronounced September maximum in thunderstorm days may reflect the combined influence of synoptic-scale air-mass advection and the thermal characteristics of the Caspian Sea. Relatively cold Arctic Maritime air over the comparatively warm sea may enhance heat and moisture fluxes and lower-tropospheric instability, favouring the development of cumulonimbus clouds and lightning over the Caspian Sea and the adjacent Absheron coastal zone.

The interaction between regional circulation features and local topographic influences further amplifies the spatial and temporal variability of these events. As a result, understanding seasonal dynamics is essential for improving forecasting accuracy, risk assessment and disaster preparedness strategies in the region.

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