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Original article

Genoa lows over Central-Eastern Europe between 2004 to 2024

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ABSTRACT

The study presents the occurrence of Genoa lows over Central and Eastern Europe during the period 2004-2024. The main research aims were: identification of the tracks of Genoa lows, analysis of their seasonal and interannual variability, and determination of their duration, intensity, and relationship with the North Atlantic Oscillation (NAO). For this maps from the Deutscher Wetterdienst, ERA5 reanalysis data, and monthly NAO Index values were used. On this basis, 81 cases of Genoa lows were identified, and it was found that during the study period, fewer than 13% of cyclones originated outside of the Gulf of Genoa, while more than half of all lows disappeared over Central and Eastern Europe. Genoa cyclones moving along the easterly track predominated (48.1% of all cases), while they moved least frequently over the southern and western parts of the study area. Typically, autumn Genoa lows and those following the easterly path were the longest-lasting (often exceeding 100 hours). At the same time, the shortest duration were the summer lows and those following the southern route. The conducted research showed a continuation of the long-term decrease in the number of lows, as described in the literature, especially in summer cyclones. Significant irregularity and very long hiatuses (exceeding even 400 days) in the occurrence of Genoa lows were also confirmed. Similar to other studies, it was found that the negative phase of the NAO and the meridional circulation favour the genesis of the Genoa lows. However, the lows that formed in winter and moved along the southern track were more often associated with the positive phase of the NAO than the others.

KEY WORDS: Genoa lows, atmospheric circulation, Poland, Europe

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1. Introduction

As the effects of climate change become increasingly pronounced, researchers are turning their focus to the occurrence of extreme climatic phenomena, their evolution and impacts (IPCC, 2021). Floods count among the most dangerous events of this type as they pose a threat to human life and cause enormous destruction to housing, infrastructure, crops, and arable land, as well as producing landslides, inland water pollution and damage to river channels (Kundzewicz et al., 1999; Danhelka & Kubat, 2009; Pall et al., 2011; Muller et al., 2015). A sizeable proportion of European floods are caused by rainfall from mid-latitude lows originating from the Atlantic Ocean (Leckebusch et al., 2006; Hofstätter et al., 2018; Rousi et al., 2021; Corner et al., 2025). Equally serious damage, however, especially in Central-Eastern Europe, is caused by Genoa lows arriving from the Mediterranean (Grazzini & van der Grijn, 2002; Ulbrich et al., 2003a, 2003b; Degirmendžić & Kożuchowski, 2015a; Messmer et al., 2015) via van Bebber's Vb track (1891). These systems are relatively infrequent, accounting for just 15% of all the lows occurring over Europe (during the period 1876–1889; Hann, 1906 from Degirmendžić & Kożuchowski, 2014) and for only 5% to 10% of lows in Central Europe (BIELEC-BĄKOWSKA, 2010; MESSMER ET AL., 2015). Nevertheless, research shows that out of the 8-9 such systems that evolve in the Mediterranean every year (HOFSTÄTTER & BLÖSCHL, 2019) 2-7 reach Central and Eastern Europe (MESSMER ET AL., 2015; DEGIRMENDŽIĆ & KOŻUCHOWSKI, 2014).

Despite their low rate of occurrence, these cyclones are responsible for a significant share of the heaviest rainfall in the regions over which they travel. Specifically, as much as 40% of Vb-track cyclones in the River Elbe catchment basin are associated with the highest rainfall totals (95th percentile; NISSEN ET AL., 2013); in the Alpine region the same is true for 30% in summer and 2% in winter (MESSMER ET AL., 2015); in Estonia the number is 10% (MÄNDLA ET AL., 2015); while in the Czech Republic and in eastern Austria it reaches 45% (HOFSTÄTTER ET AL., 2018). Genoa lows also make their mark in Poland as they account for 88% of severe floods (MOROZOWSKA, 1987), for approximately 75% of exceptionally high precipitation and for 25% of precipitation totals over 50 mm (BARTOSZEK, 2006; BUCHERT ET AL., 2013). Overall, depending on the region, between 5% and 14% of the country's annual precipitation is associated with the passage of Mediterranean lows, including the Vb type (DEGIRMENDŽIĆ & KOŻUCHOWSKI, 2015b).

The occurrence of Genoa lows is not only rare, but also irregular (HOFSTÄTTER & BLÖSCHL, 2019). Since the mid-20th century, their long-term frequency has been in decline (MAHERAS ET AL., 2001; BARTHOLY ET AL., 2009; DEGIRMENDŽIĆ & KOŻUCHOWSKI, 2014), although, depending on the area of origin and travel path, their number may not indicate significant changes in their occurrence (LIONELLO ET AL., 2016; HOFSTÄTTER & BLÖSCHL, 2019), or altogether ceased to occur over more extended periods (BIELEC-BĄKOWSKA, 2010). The intensity of Genoa lows and the amount of precipitation associated with them also vary. For this reason, a considerable proportion of the related published research concerns factors determining their formation, tracks and intensity. These include circulation conditions, particularly upper-tropospheric circulation, links with the North Atlantic Oscillation (DEGIRMENDŽIĆ & KOŻUCHOWSKI, 2016, HOFSTÄTTER & BLÖSCHL, 2019), and the impact of climate change - including changes in land-surface and sea-surface conditions - on the occurrence of the pressure systems considered (MESSMER ET AL., 2015, 2020). This research is particularly important in view of the occurrence of progressive climate change, most clearly evident in rising air temperatures (e.g. the 1.5°C threshold for global average temperature increase compared to pre-industrial levels was exceeded in 2024). This process will result in further change in the occurrence of extreme weather events, including droughts and floods (IPCC, 2021), which may lead to further change in atmospheric circulation (PRIESTLEY, 2022), in the amount of transported water vapour (a 1°C increase in air temperature can cause a 7% increase in the amount of water vapour in the air) and in evaporation (FERNÁNDEZ-ALVAREZ, 2023).

For this reason, it was decided to ask whether a considerable change in climatic conditions and in the occurrence of extreme events observed in Central and Eastern Europe during the last two decades was also accompanied by a change in the occurrence of Genoa cyclones. The main aim was to determine the annual and the interannual variability of occurrence of Genoa lows moving over the area in the years 2004-2024. Particular attention was paid to seasonal changes in the occurrence of these lows, to areas of cyclogenesis and cyclolysis, the tracks followed by the systems and their persistence, and, finally, their relationship with the North Atlantic Oscillation (NAO).

When analysing long-term trends in the occurrence of Genoa lows, Pearson correlation coefficients were applied, while the significance of the changes was verified using the Mann-Kendall test (MANN, 1945; KENDALL, 1975).

2. Materials and methods

The main source of data used in this study included synoptic maps from the German Meteorological Service (Deutscher Wetterdienst - DWD), which were obtained from the Wetter3 website and cover the main measurement times (00, 06, 12 and 18 UTC) for the period 2004-2024 (https://www.wetter3.de). Due to the lower resolution of the synoptic maps prepared before the beginning of 2015, their analysis was supported by using the ERA5 reanalysis database (HERSBACH ET AL., 2023), available through the Copernicus Climate Change Service and downloaded from the Climate Data Store (COPERNICUS CLIMATE CHANGE... 2023; https://cds.climate.copernicus.eu), These data were also used to determine the pressure values at the centre of the Genoa lows.

Two data sets were used to examine the occurrence of Genoa lows and their relationship with atmospheric circulation represented by the

NAO index. The first set consists of monthly values of the Hurrell NAO Index (PC-based; hereinafter referred to as NAO_{PC}) obtained from the website of the NSF National Centre for Atmospheric Research (https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-pc-based; Hurrell et al., 2003). The second set contains the monthly values of the NAO index defined as the first leading mode of Rotated Empirical Orthogonal Function (REOF) analysis of monthly mean 500 hPa height during the 1950-2000 period (hereinafter referred to as NAO_{500}). These data were obtained from the NOAA National Weather Service Climate Prediction Centre (https://ftp.cpc.ncep.noaa.gov/cwlinks).

The research was divided into two stages. The first involved an analysis of synoptic maps from January 1, 2004, to December 31, 2024, and the identification of lows passing through the Gulf of Genoa (Fig. 1a), regardless of their origin. Next, based on a track analysis, it was determined which low-pressure systems strengthened, reorganized, regenerated, or generated secondary low pressure systems while passing through this area. This applied to lows that originated primarily over the Iberian Peninsula, the Atlantic Ocean, the Mediterranean Sea, or the northwestern edge of Africa (Degirmendžić & Kożuchowski, 2015a; Hofstätter et al., 2016). Those (81 cases in total) that subsequently entered Central and Eastern Europe, which is the study area included in the analysis, were selected for further study (Fig. 1b). This area was defined based on previous works on the movement of Genoa lows (Degirmendžić & Kożuchowski, 2016; Hofstätter et al., 2016) and a preliminary analysis of their tracks in the considered study period. The area was divided into the western sector "W" bounded by the parallels and meridians: 47°20′ - 54°00′N; 7°00′ - 14°20′E, the central sector "C": 47°20′ - 54°00′N; 14°20′ - 20°20′E, the eastern sector "E": 47°20′ - 54°00′N; 20°20′ - 26°40′E and the southern sector "S": 46°00′ - 47°20′N; 14°20′ - 26°40′E. Then, depending on the location of cyclolysis, each of the considered lows was determined as a "W", "C", "E" or "S" track low. In the case of cyclolysis outside the study area, the affiliation of the lows to the track was determined based on its last path segment, with an "x" added.

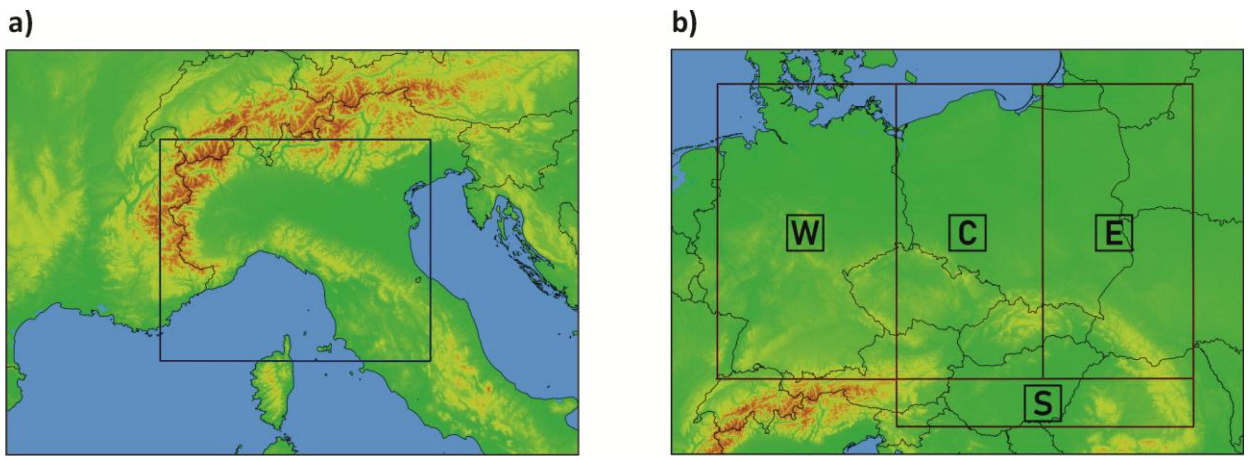

Fig. 1. The main cyclogenesis area for the Genoa lows (a) and the study area divided into the western "W", central "C", eastern "E" and southern "S" regions (b)

The low tracks were determined using the synoptic maps selected during the previous procedural step and georeferenced using cartographic software. The system's centre would be located on the synoptic map and its movement tracked, including a computer-generated one-degree wide buffer.

A track was considered to begin on the day and at the time of the system's first appearance on the synoptic map, and to end at the last hour before the centre disappeared from that map. A system that rearranged itself outside of the Gulf of Genoa but remained with a system of fronts belonging to the original low, was still considered a Genoa low and its track after rearrangement was considered a continuation of the original track. Rearrangements of lows are linked to the nature of the study area and to the terrain covered. This phenomenon is discussed by Degirmendžic & Kożuchowski (2016), who highlight the uniqueness of the Genoa lows due to their good combination of lower- and upper-tropospheric circulation. The lows observed near the Earth's surface are often controlled by an upper system, which is free of orographic disturbance (e.g., as it crosses mountain chains) and usually affect the lower systems.

In the second stage of the research, interannual and annual changes in the occurrence of specific features of the low pressure systems were determined. Particular attention was paid to the regions of their cyclogenesis and cyclolysis, the persistence of the systems, the pressure values at their centres (determined by the innermost closed isobar) and the relationship with the North Atlantic Oscillation.

3. Results

3.1. Tracks of Genoa lows

The Gulf of Genoa dominated as the main area of Genoa low cyclogenesis during the study period with 67.9% of all systems (55 out of 81 cases; Table 1). The remaining parts of the Mediterranean accounted for 19.8% (16 cases). This brings to 87,7% (Fig. 2a) the proportion of the pressure systems under study originating in the Mediterranean, thus confirming the important role played by this region in shaping the climate of not just the surrounding regions, but also of Central and Eastern Europe. The remaining 10 systems originally formed over the Iberian Peninsula (3), France (4), the North Atlantic (2) and Africa (1).

The analysed lows formed least frequently in summer, accounting for 9.9% of all systems. The bulk of the Genoa low cyclogenesis occurred between September and March, accounting for as much as 79.0% of the lows considered and the highest frequency was recorded in November at 19.8%. Interestingly, the frequency of Genoa lows between January and March, at 35.8% of all cases, was almost the same as that in autumn (32.1%). This confirms the results of other studies indicating an intensified Genoa low cyclogenesis from March to April (especially the weaker systems) and from September to December (Hofstätter et al., 2018). Although the long-term mean is 1.0-1.6 lows per month, some years recorded 2-3 lows per month during September-March, reaching a maximum of six lows in November 2010.

Table 1. Classification of the Genoa lows moving over Central and Eastern Europe according to the area of their cyclogenesis and cyclolysis in the years 2004-2024

Area/tracks	Season				Year
	Spring (MAM)	Summer (JJA)	Autumn (SON)	Winter (DJF)	
Area of cyclogenesis					
Gulf of Genoa	11	6	20	18	55
Mediterranean Sea	4	1	8	3	16
Iberian Peninsula	1	0	0	2	3
France	2	1	0	1	4
North Atlantic	0	0	0	2	2
North Africa	0	0	1	0	1
Sum	18	8	29	26	81
Area of cyclolysis					
W	2	2	1	1	6
Wx	0	0	4	1	5
C	5	0	4	3	12
Cx	1	0	5	1	7
E	2	3	5	7	17
Ex	6	1	6	9	22
S	1	2	3	4	10
Sx	1	0	1	0	2
Sum	18	8	29	26	81

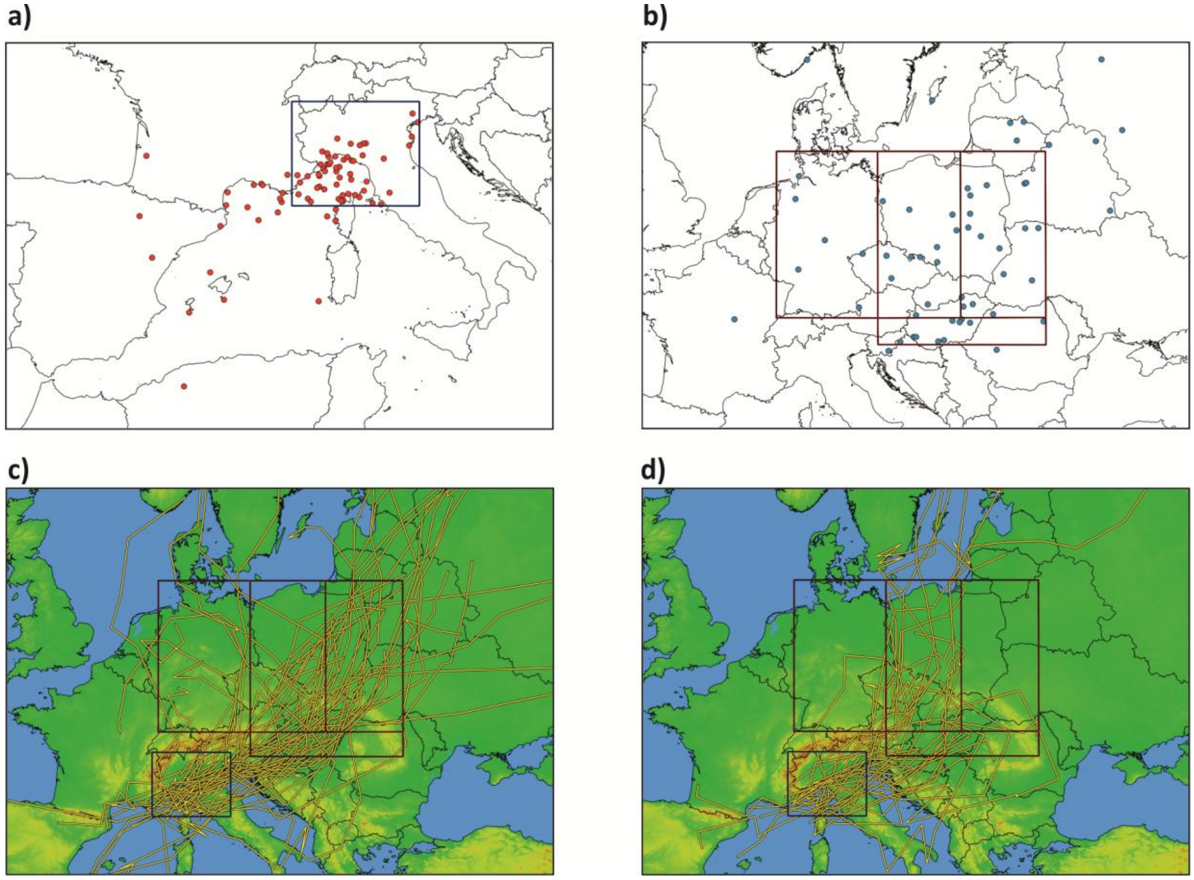

Fig. 2. Areas of (a) cyclogenesis (red dots) and (b) cyclolysis (blue dots) and tracks of the Genoa lows moving over Central and Eastern Europe over (c) W and E, (d) C and S regions in 2004-2024

The Genoa lows are characterised by a specific direction of movement. A vast majority of these systems travel from the Gulf of Genoa towards the east, north-east and north, which is linked with the specific location of the jet stream within which the lows usually form. An analysis of the tracks of Genoa lows clearly indicates their high frequency over the source area and over the southern part of Central and Eastern Europe, through which they must pass before reaching the central (C) and eastern (E) sectors of the study area (Fig. 2c). That density diminishes over the borderlands between Austria, Italy, Slovenia and Hungary, as the systems disperse towards the north, north-east and east. The area of change in direction of movement of individual Genoa lows is probably related to changes in the upper tropospheric conditions, e.g. the shape of the jet stream, and in the position of the upper tropospheric trough, within which, given appropriate conditions, the Genoa low forms (DEGIRMENDŽIĆ & KOŻUCHOWSKI, 2016). From that area, some of the lows follow a western track (W), travelling mainly through Germany, and dissipate to the north or west of that region (Fig. 2c). The tracks of those lows moving centrally (C) dissipate either over the study area or to the north of it, while those moving across the eastern part of the study area (E) tend to cover the longest distances dissipating far beyond its boundaries, sometimes as far as beyond the Ural Mountains or the Arctic Circle.

An analysis of the cyclolysis areas of individual systems revealed that just over half of the lows studied (55.6% – 45 cases) dissipated over Central and Eastern Europe, with 36 lows breaking up outside this area (Fig. 2b). Among the considered low-pressure systems there were:

– 39 cases of Genoa lows moving on the eastern track (E/Ex); 17 dissipated within an eastern of part of this area and 22 cases were outside of it;
– 19 lows which moved along the central track (C/Cx);12 dissipated in the central part of the study area and 7 outside the region;
– 11 lows which followed the western track (W/Wx), and dissipated in the western part of the study area (6 cases) or outside the study area (5 cases), and

– 12 lows moved along the southern track (S/Sx); only 2 dissipated outside this part of the study area (Table 1).

The eastern track (E/Ex) clearly dominates, accounting for 48.1% of all the lows analysed. This direction of movement is controlled by the direction of air flow in the upper troposphere (including the long wave), the position of the jet stream, and the direction of movement of the upper tropospheric trough (at 300 hPa geopotential height). Lows originating from cut-off moving upper-level systems can be more dynamic and can stray from the standard tracks (as far as towards east, south-east and south (DEGIRMENDŽIĆ & KOŻUCHOWSKI, 2016; HOFSTÄTTER ET AL., 2016). Lows passing through the central sector (C – 23.5%) are recorded half as frequently, while those travelling through the western (W) and southern (S) sectors of account for just 13.6% and 14.8% of all cases respectively.

Over the study period, the duration of Genoa lows ranged from 18 to 180 hours. On average, the shortest duration (42.8 hours) was found in the summer months, while those occurring in spring (65.0 hours) and winter (70.6 hours) were significantly longer, and the longest duration was found in autumn systems (78.9 hours). This would likely be related to weaker baroclinicity, a weakening and northward shift of the polar current, less frequent occurrence of upper-level troughs over the northwestern part of the Mediterranean and Alps and upper-level "cut-off" lows, as well as a more frequent occurrence of high-pressure systems, which prevent the formation of low-pressure systems. Even the longest-lasting of the summer lows dissipated after less than 3 days (66 hours), which is notably less than the typical durations of more than 5 days during other seasons. The longest-lasting systems included 5 days and 18 hours in spring (138 hours), 6 days and 6 hours (150 hours) in winter and 7 days and 12 hours (180 hours) in autumn.

The duration of lows is also influenced by the track it follows. Compared to the lows that dissipate within the study area, the systems that break up outside it tend to last between 32.0 hours (Cx track) and 46.3 hours (Ex track) longer (Table 2). One exception here is provided by lows following the S/Sx track, which have only 6-hour longer life-spans and persist on average for 42.0 (S) and 48.0 (Sx) hours. When compared with the average durations of lows moving along other tracks, i.e. 52.2-58.0 h (W, C, E) and 85.5-98.5 h (Wx, Cx, Ex), it is clear that lows moving along S/Sx tracks are short-lived and rarely overshoot the study area.

Table 2. Duration of the Genoa lows moving over the distinct regions of Central and Eastern Europe in the years 2004-2024

Duration of low [h]	Tracks			
	W	C	E	S
The shortest	18	36	24	18
Average	53.0	58.0	52.2	42.0
The longest	96	84	150	78
Duration of low [h]	Tracks			
	Wx	Cx	Ex	Sx
The shortest	54	78	48	36
Average	85.5	90.0	98.5	48.0
The longest	144	120	180	60

It is also worth noting that while the average duration of lows moving along tracks W, C and E is similar, there is a difference between their longest duration: the lows travelling along the W and C tracks never exceeded 100 hours, while on two occasions E-track systems lasted considerably longer, including one case of 150 hours (in January 2010). Also, apart from two cases (one each for the Wx and Cx tracks), only lows moving along the Ex track lasted longer than 100 h, with as many as 9 cases (40.9% of all Ex lows).

Individual cyclones differed in the lowest pressure recorded at their centre, which ranged from 973 hPa to 1010 hPa. Values in the 990-999 hPa range were most common (43.2% of all events), while lows with pressures lower and higher by about 10 hPa were observed comparably frequently, accounting for 25.9% and 28.4% of cases, respectively.

The lowest average pressure at the system centres were recorded in lows occurring in autumn and winter, respectively 991.8 hPa and 992.5 hPa (Table 3), while in spring and summer the respective values were 996.5 hPa and 1001.4 hPa. The deepest lows also occurred in winter (978 hPa in January 2015) and autumn (978 hPa in November 2011), and these were the only systems with pressure below 980 hPa during the entire study period. Also, the period between September and March accounted for the highest share of lows with pressures in the ranges of 980-989 hPa and 990-999 hPa (23.4% and 30.8% of all cases, respectively). At the other end of the spectrum, lows with the highest pressure values occurred mainly in spring and summer (8.6% each).

Table 3. Atmospheric pressure in the centre of the Genoa lows moving over Central and Eastern Europe in particular seasons in the years 2004-2024

Pressure value [hPa]	Season			
	Spring (MAM)	Summer (JJA)	Autumn (SON)	Winter (DJF)
The lowest	985	998	978	973
Average	996.5	1004.4	991.8	992.5
The highest	1008	1010	1010	1009
Frequency [%]				
<980	0.0	0.0	1.2	1.2
980-989	2.5	0.0	12.3	11.1
990-999	11.1	1.2	16.0	14.8
≥1000	8.6	8.6	6.2	4.9

At the same time, the lowest (<990 hPa) and the highest (≥1000 hPa) pressure values occurred mainly in lows moving along the E/Ex (16.0% and 8.6% of all cases, respectively) and C/Cx (7.3% and 9.8%) tracks. However, taking into account the frequency of lows representing individual tracks, the pressure values considered in lows of the W/Wx and S/Sx tracks were ≥990 hPa in over 80% of cases.

3.2. Interannual variability of Genoa lows occurrence

Earlier research suggests that the highest frequency of Mediterranean lows moving over the Gulf of Genoa occurred between the 1960s and the second half of the 1970s. More than 12 such cyclones were recorded annually during this period (Degirmendžić & Kożuchowski, 2016; Hofstätter & Blöschl, 2019). Since then, no clear trend has been observed, and their average number has fluctuated between 6 and 8 per year.

The average annual count of such systems during the study period, i.e. 2004-2024 was 3.9. The numbers varied from 1 in 2011 to 8 in 2005 and 11 in 2010. Since 2012, the frequency of occurrence has shown much less significant variation, ranging from 2 to 5 per year (Fig. 3). Although this interannual variability indicates a progressive decline in the number of Genoa lows over Central and Eastern Europe, it is not statistically significant ($p<0.05$), and this may be the result of two exceptional years at the beginning of the period under review. A slight decline is also evident across seasons; notably, no such systems have occurred in summer since 2015 (Fig. 4). It should be noted, however, that the changes described are minor, covering only 21 years, and, except for the number of lows occurring in summer (-0,41 cases/decade; $p<0.05$), are statistically insignificant. Therefore, they should be treated with caution.

Genoa lows moving along tracks S/Sx and W/Wx were the least frequent in individual years (Fig. 3). For most of the study period, they were absent and years with more than one case recorded were only sporadic. Lows reaching the central sector (C/Cx) were generally more frequent, although only three such cases were recorded after 2015. The lows moving across the eastern sector (E/Ex) of the study area were the only ones occurring almost every year. The described long-term changes are statistically significant only for lows moving along the C/Cx track, amounting to -0.70 cases/decade ($p<0.05$).

The occurrence of Genoa lows moving along specific tracks also varies throughout the year. Lows following track E were concentrated between October and March (82.0%, 32 cases) (Fig. 3). In contrast, lows recorded in the central (C) sector of the area were mainly recorded in February, May and in autumn (84.2%, 16 cases). In the western (W) and southern (S) sectors, Genoa lows were rare and usually occurred no more than once in each month. Regardless of the track taken by these systems, the warm half of the year, especially the summer months, is not favourable for their formation.

Genoa lows move irregularly over the study area (Fig. 5). There were periods when these systems developed at very short intervals, such as the lows of 7 and 9 November 2010 (1 day interval), and others when they would be separated by more than a year (lows formed on 16 March 2011 and 1 May 2012, i.e. a 411 day interval). The most frequently observed hiatuses were up to 20 days (20.0% of all cases) and 21-40 days (15.0%). The longest hiatus (≥200 days) occurred 9 times (11.25%), with two occurrences of over 300 days, including one of over 400 days. Six of the longest hiatuses were recorded after 2014. Hiatus lasting more than 200 days typically occurred between December and April. A similar pattern applied to the shortest hiatuses (8 days or fewer), except that these were recorded between November and February.

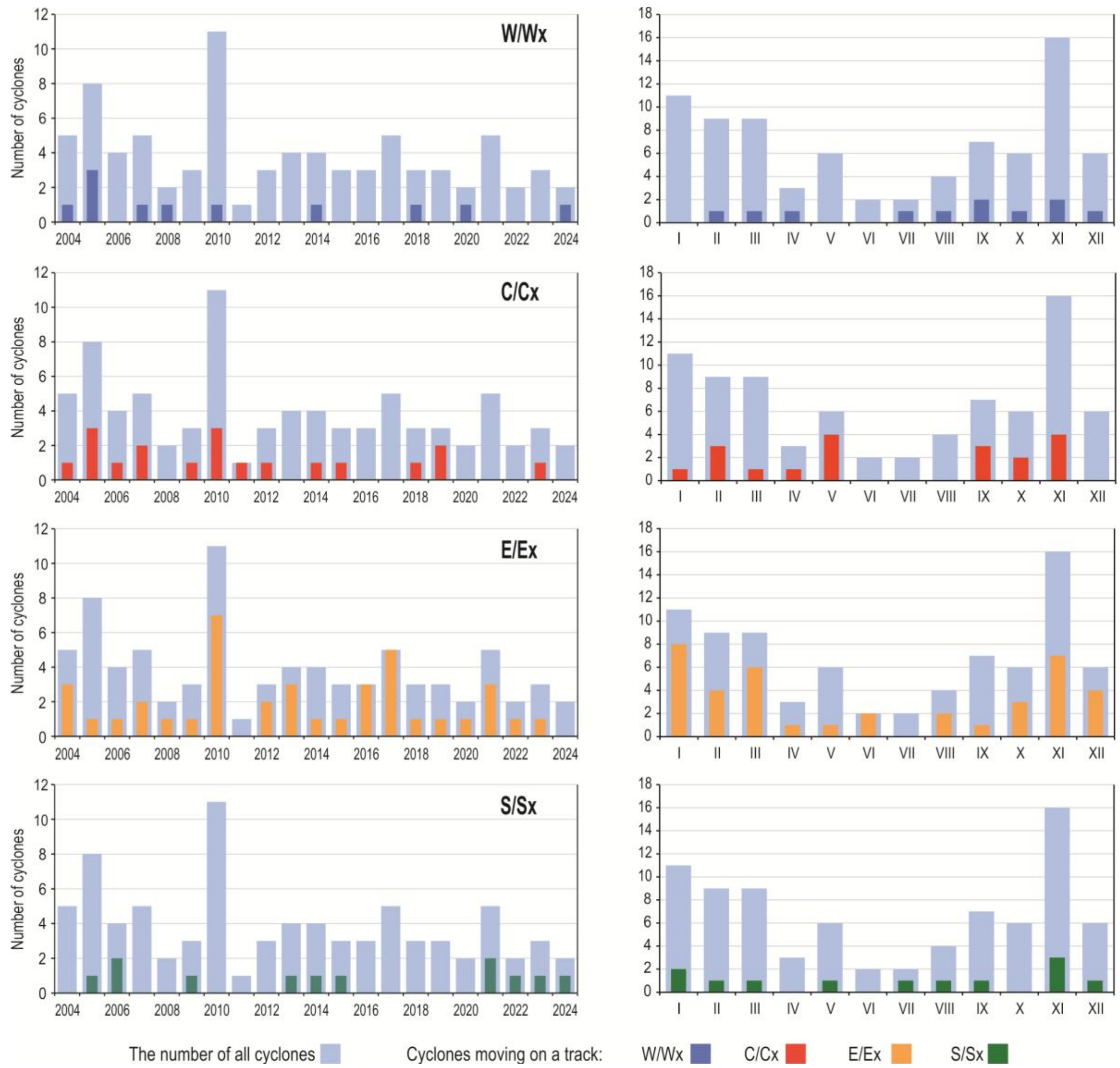

Fig. 3. Annual and monthly number of Genoa lows moving over the distinct regions of Central and Eastern Europe in the years 2004-2024

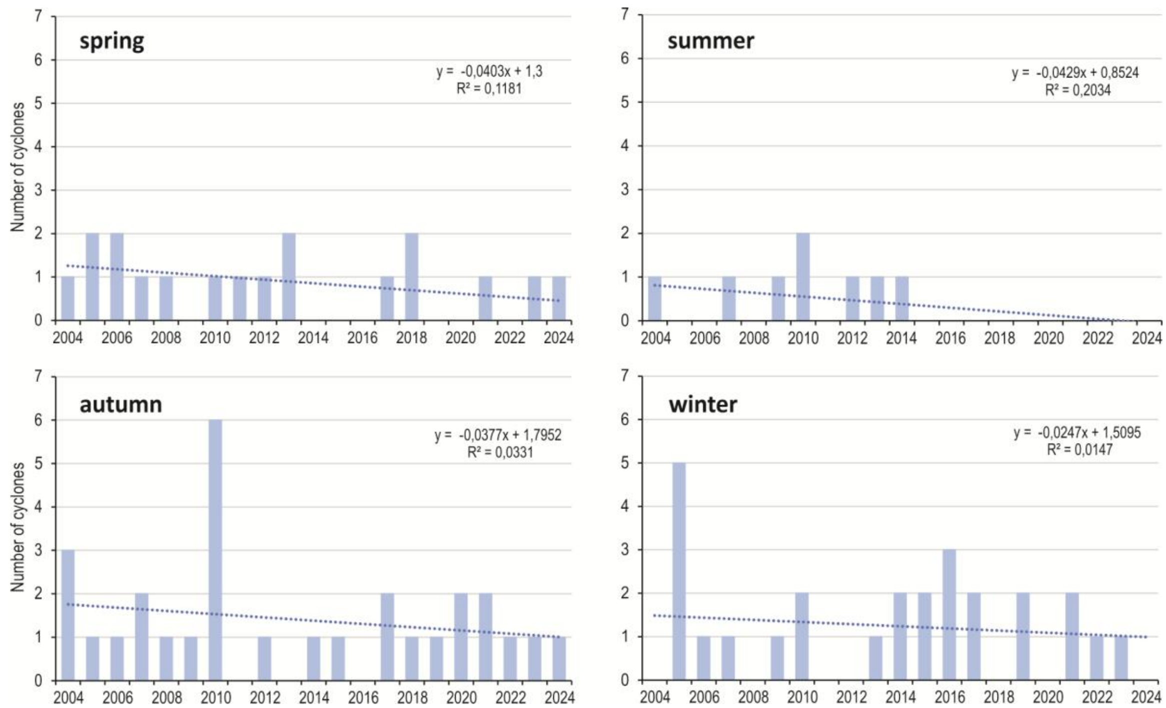

Fig. 4. Number of Genoa lows over Central and Eastern Europe in particular seasons in the years 2004-2024

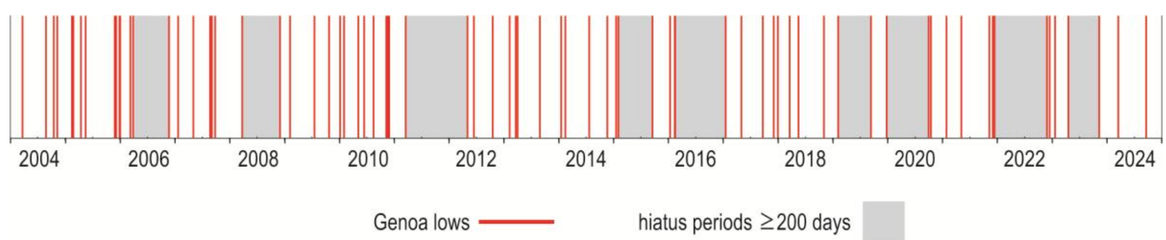

Fig. 5. Genoa lows over Central and Eastern Europe in the years 2004-2024

3.3. The North Atlantic Oscillation and the occurrence of Genoa lows

An atmospheric circulation pattern known as the North Atlantic Oscillation (NAO) has a significant influence on weather and climate in areas affected by the North Atlantic, including Europe. It defines the relationship between the two centres of atmospheric action over the North Atlantic, i.e. the Azores High and the Icelandic Low. The result of this interaction determines the amount of energy and moisture resources and the way they are transferred to Europe. The NAO modulates the large-scale circulation, thereby influencing regional circulation and, in turn, the cyclogenesis and tracks of Genoa lows, which are particularly favoured by a negative phase of the NAO, i.e., a weakening of the zonal circulation in favour of meridional circulation. Under these conditions, cold air masses are moved from the polar regions into southern Europe, where they come into contact with warm, humid air, leading to the development of Genoa lows (Hofstätter & Blöschl, 2019). This pattern is also confirmed here, indicating that the dominant role of the meridional circulation in the formation of Genoa lows is evident across all features that describe their occurrence.

When considering the occurrence of Genoa lows reaching Central and Eastern Europe in 2004–2024, it was found that most of them occurred during the negative NAO phase. Specifically, this was found in 60.5% (49 cases) when the NAO_{500} index was included in the analysis and 67.9% (55 cases) for the NAO_{PC} index (Fig. 6).

The proportion of Genoa lows associated with negative NAO phase does not depend on the NAO index used; it equals 66.7% in spring, 87.5% in summer and 67.0% in autumn. Only in winter did systems forming during the positive phase of the oscillation dominate, and during the negative NAO phases it dropped to 38.5% for NAO_{500} and 53.8% for NAO_{PC}.

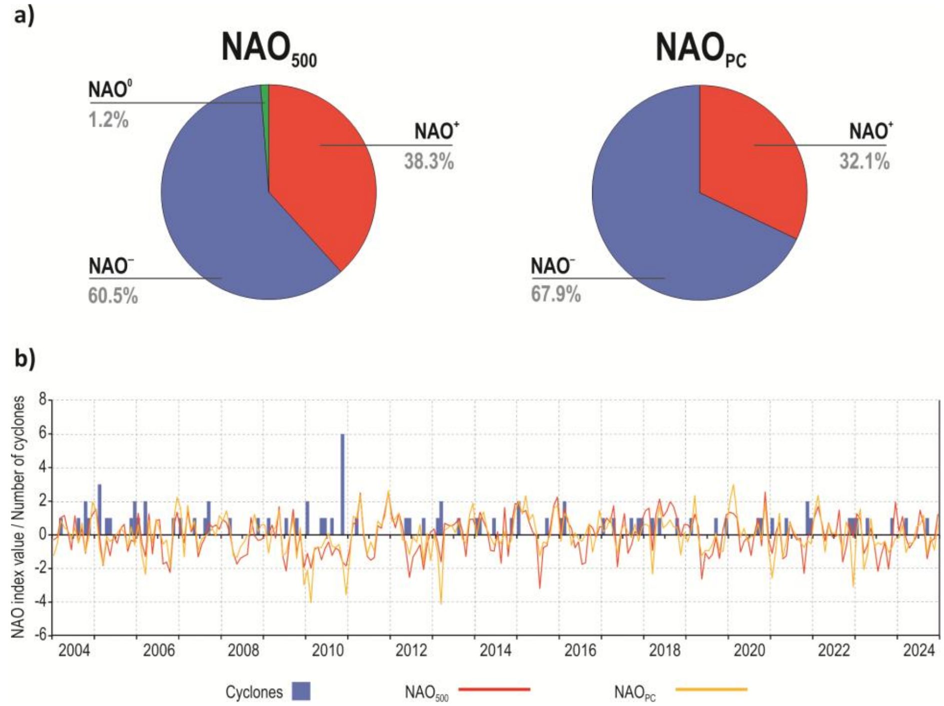

Fig. 6. Frequency [%] of NAO phases calculated for the NAO_{500} and NAO_{PC} indices (a) and monthly number of Genoa lows over Central and Eastern Europe and index values for the NAO_{500} and NAO_{PC} (b) in 2004-2024

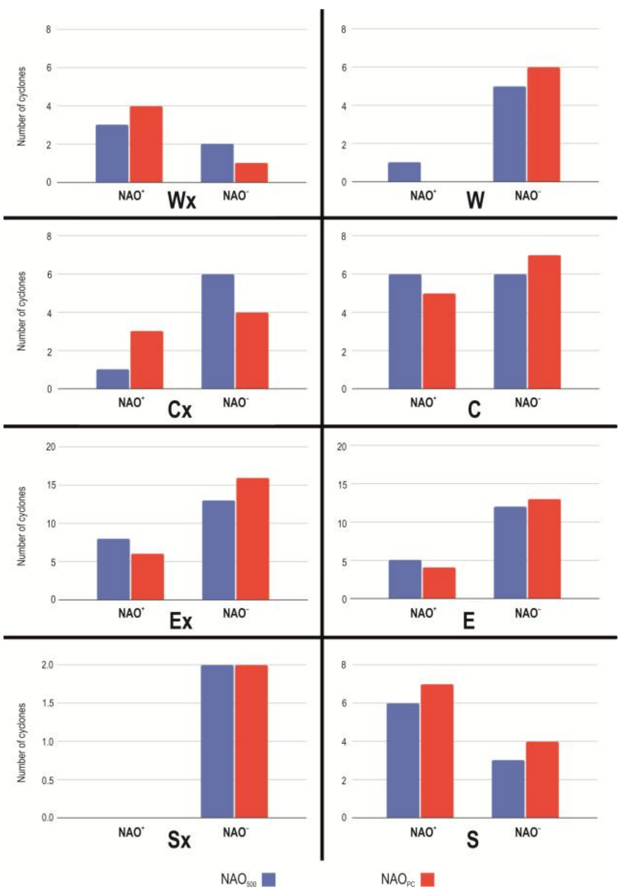

Fig. 7. The number of Genoa lows formed in individual NAO phases and moving over the distinct regions of Central and Eastern Europe in the years 2004-2024

Considering the area of cyclogenesis of the lows being studied, i.e. within or outside the Gulf of Genoa, it was found that out of 55 lows originating over the Gulf of Genoa, about 60% (32/33 cases, depending on the index adopted) formed during the negative NAO phase. Their dominance was even greater when they originated outside the Gulf of Genoa, with frequencies of 65.4% for NAO_{500} and 76.9% for NAO_{PC}.

Looking at individual tracks, the dominance of the systems that accompanied the negative NAO phase is also evident (Fig. 7). Their share ranged from 57.9% to 74.4% depending on the track (taken as a whole, regardless of area of cyclolysis) and the index adopted. The exception is the southern track, where 41.7% (NAO_{500})/50.0% (NAO_{PC}) of all systems were associated with the negative NAO phase. Considering the location of cyclolysis, the systems formed during the positive NAO phase were dominant among those moving along the Wx and S tracks, while the movement of the C track lows was distributed with a similar frequency between both NAO phases.

Considering the pressure at the centre of the low (CCP), we found that lows occurring during the negative NAO phase were most dominant among the shallower - yet more frequent - systems with CCP of 990-999 hPa and 1000-1010 hPa. Their frequency, depending on the index adopted, ranged from 65.7% (NAO_{500}) to 71.4% (NAO_{PC}) and from

60.9% (NAO_{500}) to 65.2% (NAO_{PC}), respectively. However, the frequencies of the deeper systems were similar in both circulation phases. For lows with CCP less than 980 hPa these amounted to 50.0% in each NAO phase (however, only two such cases occurred), while for the 980-989 hPa range they were split between 52.4% (NAO_{500}) and 57.1% (NAO_{PC}) in the negative phase.

4. Summary

This article provides an updated, consistently classified inventory of Genoa lows affecting Central and Eastern Europe for 2004-2024, extending recent evidence on frequency changes and linking track-type differences to persistence and intensity metrics. Individual lows (81 cases) were grouped by the tracks they followed. Their characteristics, including the cyclogenesis and cyclolysis sites, duration, and the lowest recorded pressures in the centre, were assessed. Particular attention was paid to seasonal and multi-year changes in the occurrence of the systems under consideration and their relationship with the North Atlantic Oscillation.

In line with the results of other research (CAMPINS ET AL., 2011; HOFSTÄTTER & BLÖSCHL, 2019) a vast majority of the lows (approximately 68%) formed over the Gulf of Genoa and only less than 13% originated outside the Mediterranean basin (over the Iberian Peninsula, France, the North Atlantic or North Africa), and then transformed as they passed over the Gulf of Genoa. The cyclogenesis of these systems typically occurred between September and March (79.0%), with half occurring between January and March; the least frequent Genoa lows were in the summer, accounting for only 9.9% of all cases.

An analysis of cyclolysis areas showed that slightly more than half of the lows decay within the study area. The eastern track was dominant (E/Ex – 48.1%), followed by the centre of the study area with half of that count (C/Cx – 23.5%). The western (W/Wx) and southern (S/Sx) tracks were characterised by significantly less cyclonic activity (13.6% and 14.8%, respectively). The vast majority of Genoa lows passed through the southern sector of the study area before reaching its central and eastern parts.

The persistence of the Genoa lows depended both on the season and the track chosen, although it did not significantly differ from that of other Mediterranean cyclones (LIONELLO ET AL., 2016). Lows forming in autumn had the longest lifespan (70.6 hours on average, up to 180 hours), while those forming in summer had the shortest (42.8 hours). Systems whose cyclolysis occurred outside the study area tended to last about 1-2 days longer than those dissipating over Central and Eastern Europe. The exception were the S/Sx lows, which usually dissipated within the area and had the shortest duration (on average 42.0 hours – S and 48.0 hours – Sx). This means they lasted about 10 hours less than systems moving along other tracks, which lasted 52.2-58.0 hours (W, C, E) and 85.5-98.5 hours (Wx, Cx, Ex). Among the longest-lasting systems (≥100 hours), those moving along the eastern track (E/Ex, 11 out of 13 cases) were clearly dominant, whereas only two such long-lasting lows were recorded for the Wx and Cx tracks.

Mediterranean lows are usually small and short-lived, but often quite intense (CAMPINS ET AL., 2011). During the analysed period, most of the systems studied did not qualify as deep lows (<990 hPa, KOŻUCHOWSKI, 1995). This was particularly true of short-lived summer lows, which were characterised by higher pressure values compared to other systems, a feature that may indicate a predominance of local and surface-level thermal lows typically forming at this time of year. The deepest systems included those developing in autumn and winter, with the average minimum values at the centre of the system ranging from 991.8 hPa to 992.5 hPa, and the lowest value below 980 hPa. However, most systems recorded pressures in the range of 990-999 hPa (43.2% of all cases), which is typical of Mediterranean lows (LIONELLO ET AL., 2016; KOTSIAS ET AL., 2023). Considering the tracks of the lows and their intensity, the deepest ones (<990 hPa) most frequently followed the E/Ex track (about 25% of all cases) and the C/Cx track (about 17%). Lows moving along these tracks were also often characterised by very heavy precipitation. However, heavy rainfall in south-eastern Poland is also often caused by lows moving along the S/Sx track (DEGIRMENDŽIĆ & KOŻUCHOWSKI, 2015a).

The interannual variability of Genoa lows moving across Central and Eastern Europe indicates a slight decrease in their number during the study period. However, apart from the change in the summer season and lows moving along the C/Cx track, these changes are not statistically significant. The number of lows ranged from 1 to 11 per year, but most often remained within 2-5 per year (average 3.9/year), especially after 2010. It is also worth noting that only lows moving along the E/Ex track occurred almost every year, while along the other tracks, they appeared less frequently, and years with more than one such system were extremely rare. Another characteristic of the recent climatic changes is the very low number of summer lows; in fact none have been observed since 2014. This may be explained by increasingly warmer, drier summers, which may deepen unfavourable conditions for the cyclogenesis in the Genoa region (Messmer et al., 2017). Also noteworthy is the irregular nature of the occurrence of the systems studied and although the dominant ranges are those occurring at intervals of up to 20 and 21-40 days, more than 11% of the systems occur at intervals exceeding 200 days, similar to the deepest systems that appear once every several years (Bielec-Bąkowska, 2010; Bielec-Bąkowska & Piotrowicz, 2013).

When considering the circulation conditions for the formation of Genoa lows, a pattern suggested by other research (Nissen et al., 2010; Hofstätter & Blöschl, 2019) indicating that a negative NAO phase favours their formation has been confirmed. Lows forming in winter and moving along the southern track, which were more often favoured by the positive NAO phase, indicated a slightly different relationship. This confirmed the studies which reported that the conditions favouring the formation of Genoa lows included meridional circulation (form E according to the Vangengeim-Girs classification) and a distinct trough and long wave developed at the 300 hPa isobaric surface over Europe (Degirmendžić & Kożuchowski, 2016). However, it is worth noting that this type of circulation does not necessarily imply the occurrence of Genoa lows.

5. Conclusions

Despite the low frequency of Genoa lows reaching Central and Eastern Europe, the heavy rainfall that usually accompanies them poses a significant threat and causes significant damage to the environment and human life. The research conducted has shown that, in the first decades of the 21st century, the main directions of their movement have not shown any significant changes. This primarily concerns the predominance of the eastern pathway, which supports the long-term stability of the classic track scheme first described by van Bebber (1891). This is all the more important because lows moving along the E/Ex and C/Cx (the second-most-frequent) tracks are usually among the longest-lasting and most intense systems, often accompanied by heavy precipitation that can cause floods. In the period under consideration (2004-2024), interannual changes in the frequency of Genoa lows indicate a slight decrease. This is consistent with the changes described by other authors, concerning both all Mediterranean lows and Genoa lows moving along the Vb track (Degirmendžić & Kożuchowski, 2016; Hofstätter & Blöschl, 2019; Kotsias et al., 2023). It also aligns with projected reductions later in the century, indicating that their number may decrease by as much as 1/3 by the end of the 21st century (Messmer et al., 2020). The observed changes seem to have a lesser impact on the deepest Vb lows (<990 hPa), a category occurring extremely rarely (about 0.5/year), mainly in spring (III-IV – over 55%; Bielec-Bakowska, 2010; Bielec-Bąkowska & Piotrowicz, 2013). An important aspect of these changes is the very low number of summer Genoa lows and their absence after 2014 (they were recorded again in 2025). This may indicate increasingly unfavourable conditions for cyclogenesis during the warm season in the Genoa region and/or reduced persistence of these systems.

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