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CLASSIFICATION OF THE ATMOSPHERIC CIRCULATION TYPES FOR THE REGION OF BULGARIA AND THEIR RELATION WITH LARGE-SCALE CIRCULATION PROCESSES

ABSTRACT OF A DISSERTATION

for the acquisition of an educational and scientific degree "Ph.D" in the field of higher education 4. Natural sciences, professional direction 4.4. Earth Sciences (Science Major: Climatology)

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INTRODUCTION

Actuality of the topic

The climate at a given point on the earth's surface is determined primarily by latitude, by relief and altitude, by vegetation, and by the proximity of small and larger water bodies. The interaction of all these factors significantly affects the atmospheric circulation The need of typification the variety of synoptic conditions and analyze their frequency on a monthly, seasonal and annual basis necessitates the emergence of the so-called dynamical or synoptic climatology.

The classification of atmospheric circulation types over a period of time is necessary in order to be able to assess its influence over a given area. This influence is not unambiguous and depends on a number of meteorological and geographical factors. Synoptical climatology is a subdivision of meteorology and climatology that deals with the typification of atmospheric processes on longer-term (several, to several decades of years) climatic scales. It resulted from the desire for a better understanding of the synoptic processes in mid-latitudes, namely the movement of air masses, the centres of barrier formations and atmospheric fronts in time and space.

Purpose and tasks of the study

The aim of this dissertation is to classify the circulation types for each day in the period 1871-2020 both at the sea level and at the 500 hPa level for the region of Bulgaria, and also to analyze the frequency of occurrence of each circulation type for this 150 year period. After the development of the classification, a correlation will be sought between the circulation types and the most important meteorological elements - air temperature and precipitation amount at a selected representative meteorological station in the territory of Bulgaria, as well as a correlation between each of the circulation types from the performed classification with some known large-scale circulation processes and their associated circulation indices.

In order to achieve this aim, the following tasks need to be solved:

- A review of other research on the subject, as well as the more well-known classifications of atmospheric circulation performed around the world.

Particular attention should be paid to the classifications on the territory of the European continent and especially on the Balkan Peninsula.

- To do a brief historical overview of the research on the topic for the region of Bulgaria.
- Discuss the main methods used in the classifications and provide a rationale for the choice of method in this study.
- To select a reanalysis for the maps of the barric topography on which to perform the classification.
- To describe each of the circulation types at the two isobaric levels, the direction of movement of air masses in its presence and their climatological influence.
- Examine trends of the types over the 150 year period as well as over 30 year climatological periods
- To group (aggregate) some of the circulation types in order to highlight their climatic importance
- To perform a correlation analysis on a seasonal and annual basis of circulation types and groups of types with temperature and precipitation at a selected representative meteorological station
- To study the databases with archives of large-scale circulation indices and for each of them to determine the study period depending on their availability and reliability in order to investigate the relationships with the typification of atmospheric circulation for Bulgaria.
- To perform a correlation analysis of each of the circulation types at the two baric levels with each of the aforementioned large-scale circulation indices.

Limitations of the study

The present study concerns a territorial area enclosed between the fortieth and forty-fifth parallels and the twentieth and thirtieth meridians, comprising the whole territory of Bulgaria and parts of the neighbouring countries, namely northern Greece and the European part of Turkey, the eastern parts of Serbia and northern

Macedonia and southern Romania. The resolution of the synoptic reanalysis maps used to produce the daily atmospheric circulation classification is 2.5 X 2.5 geographical degrees. The exact identification of the different circulation categories is not without some difficulties, as the definition of the boundary between the different types can be difficult in some cases, either due to the great dynamics of the atmospheric processes or under some boundary conditions. This problem is pretty much minimized by the use of barric field maps on every six hours or four times a day. Also, the barric systems can vary in intensity and with less prominent ones, especially in summer, classification could be more difficult. **The scientific new feature of** the research is the daily classification of the atmospheric circulation over Bulgaria at two barric levels (Sea Level Pressure (SLP) and the 500 hPa level in the middle troposphere), for the first time and for such a large - 150 year period (1871-2020). **The scientific** importance of the results of the study consists in the identification of certain changes in circulation types in seasonal and annual basis and the corresponding changes in atmospheric circulation over Bulgaria. These changes are also assessed in the context of climate change. To demonstrate the significance of such a study, the relationships of circulation types with the meteorological elements temperature and precipitation are also shown as examples. Certain relationships between large-scale circulation processes and the frequency of occurrence of circulation types over Bulgaria are identified and how they directly affect the climate in Bulgaria through the influence of atmospheric circulation.

CHAPTER ONE

COMMONLY USED CLASSIFICATIONS OF ATMOSPHERIC CIRCULATION TYPES IN DIFFERENT PARTS OF THE WORLD

This chapter discusses the founding and established over the years classifications of atmospheric circulation such as: the Vangengeim-Giers (Vangengeim, 1935), initially for the Atlantic-European region and later for the Pacific-American sector (Girs, 1948); the Hess and Brezowsky (Hess and Brezowsky, 1952), (James et al, 2007), - reflecting atmospheric circulation in central Europe, and Lamb (Lamb, 1972), (Jenkinson and Collison, 1977) - for the

British Isles. A historical review is made of various developments at the Bulgarian National Institute of Meteorology related to atmospheric circulation. A special attention is paid to the fundamental work for Bulgaria on synoptic/dynamic climatology "Weather types over Bulgaria" (Stefanov et al., 1960), as well as to the classification of atmospheric circulation for the region of Greece (Maheras et al., 2000), on the basis of which the classification for Bulgaria is developed in the present work.

CHAPTER TWO

CLASSIFICATION OF ATMOSPHERIC CIRCULATION TYPES FOR BULGARIA

There are two main approaches to the classification of atmospheric circulation types - subjective and objective. The **subjective method** (approach) is based entirely on the experience of the specialist in his assessment of determining a situation and classifying it into a particular type. **The objective method**, on the other hand, requires the satisfaction of some conditions and precisely defined rules in classification. In general, it requires the execution of some numerical algorithm in order the circulation type to be accurately determined. At the next stage, when compiling and naming the circulation types, it is necessary to decide whether the **direction of movement of air masses** over the region of interest or the **direction of the centre** of the barric formation (cyclone or anticyclone) relative to the region for which the classification is made will be the leading one. The classification subject of the present work is based on the direction of the center of the cyclone or anticyclone relative to the region for which the classification is made. After studying all the more significant and generally accepted typifications and classifications of atmospheric circulation, as well as the methods used to compile them, the **subjective method** was chosen. When defining the circulation types, the method of the **direction of the centre** of the barriц formation relative to Bulgaria was also used. The complex topography not only on the territory of Bulgaria, but also on the surrounding territories throughout the Balkan Peninsula determined the choice of this method as far more appropriate, due to the fact that the terrain strongly deforms the wind direction at any particular point and therefore the other method of wind direction in determining and defining circulation types would be very inappropriate for the territory of Bulgaria. To perform the classification, data of 500 hPa baric level and sea level (SLP) from the 20th Century Reanalyses meteorology (Compo GP, Whitaker JS et al., 2011), NCEP CFSR/GFS Reanalyses (Saha S. et al., 2010), and NCEP/NCAR (Kalnay et al., 1996) were used. For each day in the 150 year period 1871-2020, the 500 hPa and surface level types were determined from barric maps at 0, 6, 12 and 18 h GMT, in the area (30º-75ºN and 20ºW-50ºE). The visualizations of (http://www1.wetter3.de/Archiv/) were mainly used. At the 500 hPa level 13 types are distinguished (5 anticyclonic and 8 cyclonic) and 16 types at the sea level (6 anticyclonic, 8 cyclonic and 2 low gradient). Most of them are schematically presented in (Fig. 28) and (Fig. 29) for the anticyclonic and cyclonic types, respectively, with the leading direction of the centres of the bar formations relative to Bulgaria and at the same time covering its territory. As natural separators between circulation types were used as follows: The 45th parallel between anticyclonic types A1 and A4; the 25th meridian, between A1 and A2; the 40th parallel between A4 and A5; the 20th meridian, between A4 and A5; A3 limited between the 20th and 30th meridians. The logic is similar for the cyclonic types, but there the dividing lines between the types are the 20th and 30th meridians and the 40th and 45th parallels, and between Cne and Cse it is the 43rd parallel. The three types not illustrated in (Figs. 28 and 29) are Mt2, an anticyclonic type covering the entire European continent, Mb1, a low-gradient cyclonic type with a barric gradient less than 2.0hPa/2.5º, and Mb2, a low-gradient anticyclonic type with a gradient less than 2.5hPa/2.5º.

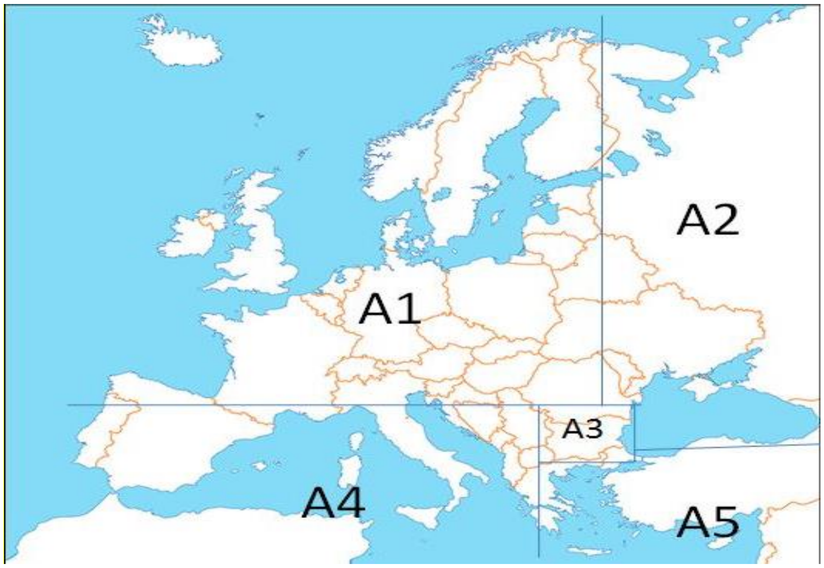


Figure 28 – Scheme of the location relative to Bulgaria of the centres of the anticyclonic types at 500 hPa and at sea level (SLP)

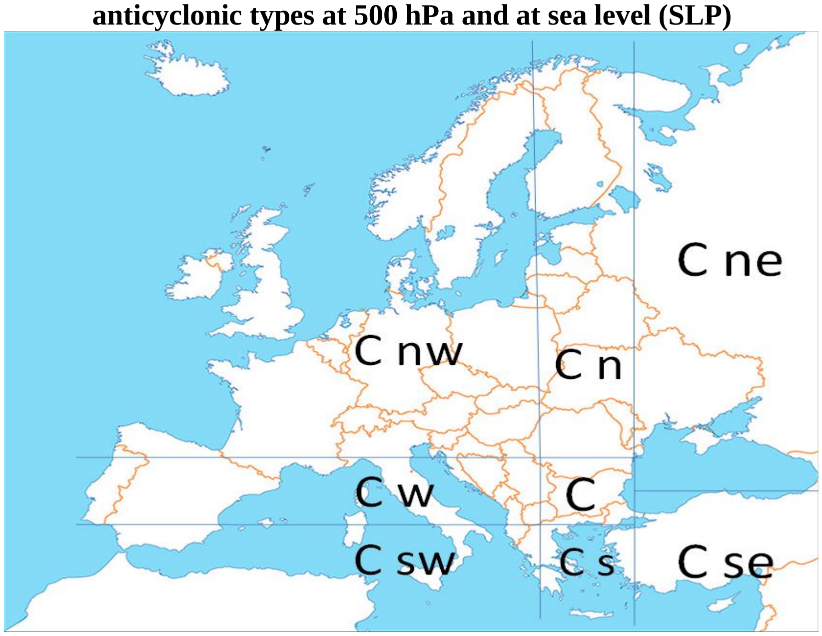


Figure 29 – Scheme of the location relative to Bulgaria of the centres of the cyclonic types at 500 hPa and at sea level (SLP)

Climatological manifestations of circulation types at the two isobaric levels: **A1** – wind direction is from the northern quarter of the horizon, associated with cold air intrusion, especially at ground level. **A2** – wind is from the east, northeast or north, associated with cold continental intrusions in winter and spring (Siberian anticyclone ridge). **A3** – little or no wind, associated with inversion conditions, fogs and low stratus clouds during the cold part of the year. **A4** – westerly or southwesterly winds at both isobaric levels, warm in all seasons (crest of the

Azores anticyclone). **A5** – southeasterly flow, at the surface level it is a warm type but at hight, especially in summer it could transport cooler air. **Cnw, Cw** – Bulgaria is in the warm, frontal part of these cyclones, significant precipitation is possible ahead of the warm front, but also fjonal conditions during large barric gradients. **Csw** – typical Mediterranean cyclone, more precipitation in the southern regions of Bulgaria. **Cs** – precipitation conditions, more significant in southeastern Bulgaria. **Cse** – precipitation is more significant in eastern Bulgaria, snowstorms are possible in winter. **Cn** – possible high temperature differences between western and eastern Bulgaria and significant precipitation. **C** – significant precipitation across the country. **Cne** – more significant precipitation is possible in northeastern Bulgaria, strong northwesterly and northerly winds in northern Bulgaria and areas in eastern Bulgaria, south of the Balkan Mountains, susceptible to "bora" such as region of Sliven. **Mb1** – significant precipitation is possible in summer, occurs most often in combination with a high cyclone or trough at 500 hPa. **Mb2** – precipitation is less possible than in Mb1. **Mt2** – an intrusion of very cold air over the whole Europe, combined usually with a high trough from the northeast.

The trends in the circulation types over the studied period was performed using the widely used non-parametric Mann-Kendal method (Mann, 1945) for estimating trends of various parameters in meteorology and climatology. The Sen-slope method was used to determine the steepness and direction of the trends (Sen, 1968). The statistical significance of the trends was calculated at a selected significance level of 5%. The **correlation analysis** between circulation types frequencies and large-scale circulation indices, along with the given examples with seasonal temperatures and precipitation amounts, were performed using Pearson's method (SHAQIRI et al., 2023). The statistical significance of the obtained correlation coefficients were evaluated at a significance level of 5%.

CHAPTER THREE

SEASONAL, ANNUAL REGIME AND TRENDS IN CIRCULATION TYPES AND THEIR RELATION WITH TEMPERATURE AND PRECIPITATION

3.1. Annual frequencies of the circulation types

On average over the 150-year period (1871–2020) at an isobaric level of 500 hPa, the atmospheric circulation over Bulgaria is cyclonic in more than 65% of the days of the year, and anticyclonic in almost 35% of the days (Fig. 57).

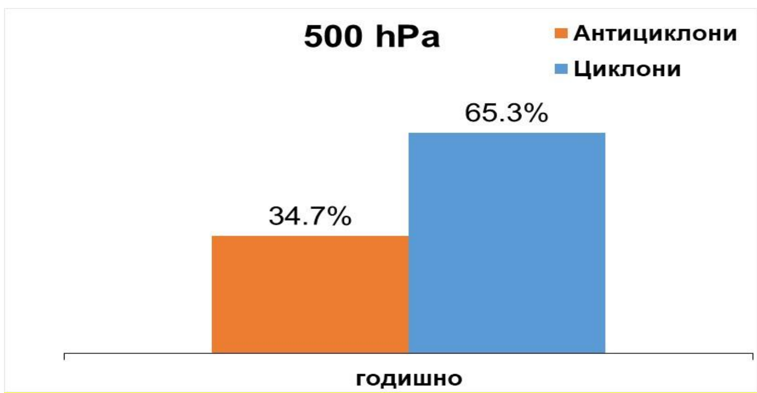


Figure 57 – Summary frequencies of anticyclonic (brown) and cyclonic (blue) circulation types at 500 hPa level (1871–2020)

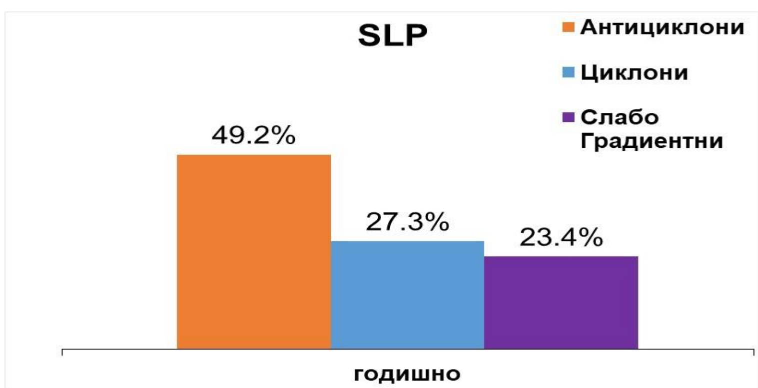


Figure 58 – Summary frequencies of anticyclonic (brown) and cyclonic (blue) and low-gradient (violet) circulation types at sea level (1871–2020)

At the sea level, however, anticyclonic types predominate with almost half of the days per year on average, cyclonic types are present over 27% of the time, and the two low-gradient types occur on over 23% of the days per year (Figure 58). The high cyclonic types at 500 hPa level south of the country are so-called (cut off) cyclones, detached from the high polar frontal zone and existing separately from it at more southerly latitudes around the Mediterranean. As seen from (Fig. 59), their frequency is significantly lower than that of northern cyclonic types. The same but reversed sign applies to the anticyclones at 500 hPa level, the southern anticyclones being of much greater frequency than those situated to the north of the country, which are detached anticyclones from the zone of higher atmospheric pressure in the more southerly latitudes at this barric level.

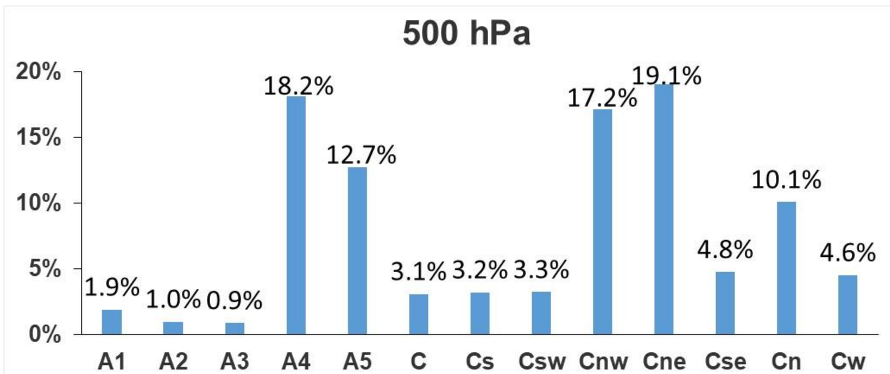


Figure 59 – Frequencies of the circulation types at 500 hPa level (1871–2020)

At the sea level the situation is quite different, which is also clear from (Fig.60)

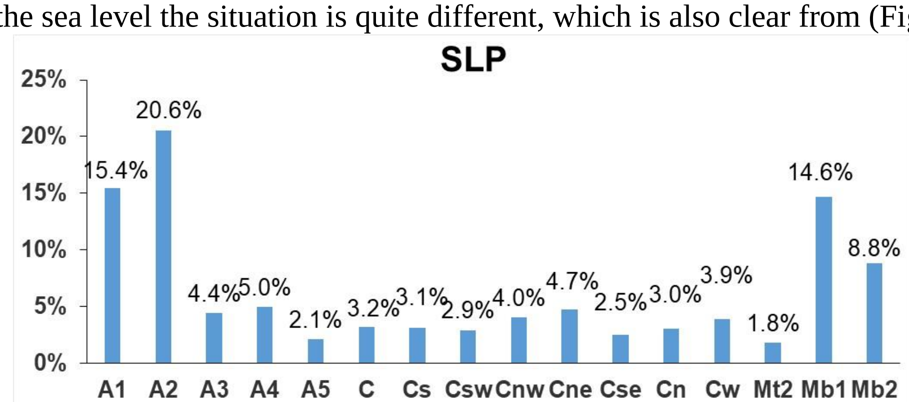


Figure 60 – Frequencies of the circulation types at sea level (1871–2020)

The anticyclonic types located to the northwest (A1 – 15.4%) and northeast of the country (A2 – 20.6%) are the dominant circulation types, on average existing summary in more than a third of the days in the year. Low-gradient types also have a relatively high annual frequency, but their influence is much greater in the warm half of the year. The different cyclonic types at sea level individually have annual frequencies of less than 5%, but each is of very high climatic importance due to the fact that a substantial fraction of the precipitation over the country falls along these barricades.

3.2. Seasonal frequencies of the circulation types

To determine the seasonal frequencies of circulation types, the seasons in this work are defined according to their climatic definition: winter (December, January, February), spring (March, April, May), summer (June, July, August) and autumn (September, October, November). Seasonally, circulation types at the 500 hPa level and at sea level also show their peculiarities. In general, the frequency of anticyclones, cyclones, and, at sea level also low-gradient types, has a seasonal pattern. At the 500 hPa level, cyclonic circulation in the 150-year study period most frequently occurs in winter, on average on 68.8% of winter days, and least frequently in summer, 61.2%. At sea level, anticyclonic types are most frequent in autumn with 56.6% of the days and least frequent in summer – 43.4%. The cyclones are the most frequent barric formation in Bulgaria in the winter – 37.8% of the days of the season on average, while they are least frequent in the summer season in only 13.9% of the casesLow-gradient types occur most frequently in summer – 42.7% and least frequently in winter – 9.0%. The annual and seasonal frequencies for each circulation type are presented separately at the 500 hPa barric level (Table 5) and at sea level (Table 6). The blue, green, yellow and brown colours represent the winter, spring, summer and autumn seasons respectively, in which the respective circulation type has a maximum. The red colour indicates the number of the type that has the maximum among all other types in the respective season and year. In winter and spring at the 500 hPa level, it is Cne, while at sea level in these two seasons A2 dominates. In summer, A4 has the highest frequency of all types at 500 hPa, and at sea level it is the low-gradient type Mb1. In autumn at the 500 hPa level, Cnw is most common, and at sea level, A2. On an annual basis, types Cne and A2 dominate all other types at 500 hPa and at sea level, respectively. In (Table 5) it is shown that almost half of the 500 hPa types (6 out of 13) have a maximum in winter.

Table 5. Annual and seasonal frequencies of circulation types at 500 hPa over Bulgaria in the period (1871-2020)

	Annual	Winter	Spring	Summer	Autumn
A1	1.9%	2.7%	1.6%	1.5%	1.9%
A2	1.0%	0.8%	0.9%	1.4%	1.0%
A3	0.9%	0.6%	0.6%	1.5%	0.9%
A4	18.2%	12.3%	15.4%	26.9%	17.9%
A5	12.7%	14.9%	14.2%	7.5%	14.3%
Anticyclones	34.7%	31.2%	32.7%	38.8%	36.1%
C	3.1%	2.3%	3.8%	3.3%	3.0%
Cs	3.2%	3.0%	3.9%	3.0%	2.9%
Csw	3.3%	4.1%	4.0%	2.1%	2.8%
Cnw	17.2%	16.2%	17.0%	16.8%	18.8%
Cne	19.1%	22.4%	17.7%	18.2%	18.0%
Cse	4.8%	4.3%	6.4%	4.7%	3.7%
Cn	10.1%	11.3%	9.4%	10.1%	9.7%
Cw	4.6%	5.2%	5.1%	3.0%	5.0%
Cyclones	65.3%	68.8%	67.3%	61.2%	63.9%

Table 6. Annual and seasonal frequencies of circulation types at sea level over Bulgaria in the period (1871-2020)

	Annual	Winter	Spring	Summer	Autumn
A1	15.4%	15.2%	11.0%	18.7%	16.7%
A2	20.6%	18.1%	22.2%	14.6%	27.2%
A3	4.4%	6.3%	3.1%	3.2%	5.0%
A4	5.0%	6.4%	3.5%	6.3%	3.6%
A5	2.1%	3.4%	2.6%	0.5%	2.1%
Mt2	1.8%	3.8%	1.3%	0.1%	1.9%
Anticyclones	49.2%	53.2%	43.6%	43.4%	56.6%
C	3.2%	2.9%	4.3%	2.6%	2.9%
Cs	3.1%	5.6%	3.0%	1.5%	2.5%
Csw	2.9%	6.2%	2.9%	0.2%	2.5%
Cnw	4.0%	4.5%	5.5%	1.9%	4.1%
Cne	4.7%	5.7%	5.3%	3.3%	4.5%
Cse	2.5%	3.1%	3.4%	2.0%	1.6%
Cn	3.0%	3.5%	4.1%	1.5%	2.8%
Cw	3.9%	6.4%	4.2%	0.8%	4.3%
Cyclones	27.3%	37.8%	32.6%	13.9%	25.3%
Mb1	14.6%	4.8%	15.9%	26.5%	11.4%
Mb2	8.8%	4.2%	7.8%	16.2%	6.7%
Low-gradient	23.4%	9.0%	23.8%	42.7%	18.1%

Exactly half of the sea-level types (8 of 16) also have a maximum in winter (Table 6). These are four anticyclonic (A3, A4, A5, Mt2) and four cyclonic types (Cs, Csw, Cne, Cw). In spring, three cyclonic types at 500 hPa (C, Cs, Cse) and four sea-level types (C, Cnw, Cse, Cn) have a maximum. Maximum in summer have the anticyclonic types at 500 hPa (A2, A3, A4), the two low-gradient types at sea-level (Mb1, Mb2) and the anticyclonic type A1. In autumn, only Cnw types at 500 hPa level and the anticyclonic sea-level type A2 have maximums. It is clear from (Table 5) that at the 500 hPa barric level, the ridges of the Azores anticyclone in summer (type A4) have the highest seasonal frequency, occurring on average on 26.9% of the days in summer in the studied period. In winter, however, this is not the same and type A5 has the highest frequency among the 500 hPa anticyclonic types. In (Table 6), summer minimums and winter and spring maximums are observed in most southern and western cyclonic types at ground level associated with Mediterranean cyclones. In addition, in spring their frequency is higher than in the autumn season.

3.3. Trends in the circulation types

Trends in the annual and seasonal frequencies of each circulation type at the two barric levels over the 150-year studied period (1871-2020) were examined. In addition, the trends in the five 30-year periods (1871-1900; 1901-1930; 1931-1960; 1961-1990 and 1991-2020) contained in it were also examined. The latter was done in order to investigate changes in circulation types and under the World Meteorological Organization's 30 annual climate periods. The Mann-Kendal (Mann, 1945) and Sen-slope (Sen, 1968) methods were used to assess statistical significance and the magnitude/steepness of trends. Calculations were performed at a selected significance level of 5% (α=0.05). If the calculated p-value is less than this value, then the trend is statistically significantThe direction and steepness of the trend is assessed by the sign and the value of the Sen-slope estimator Qm.

3.3.1. Trends in the circulation types at 500 hPa barric level

The trends for types A1, A2 and A3 at 500 hPa are not presented here because, due to their small annual and especially seasonal frequencies, many zero values exist in their series, and thus, resulting in incorrect trend calculation results. In the 150 year period studied, there is a positive trend on an annual basis, although statistically insignificant for type A4 at 500 hPa level. This type has a warming influence on the region and is one of the contributors for the warming in climatological aspect A5 does not show a trend over the study period as a whole, but in the last 60 years it has been negative in summer and autumn, unlike A4. Annual distributions of types A4 and A5 at 500 hPa are presented in (Fig. 68), and their 11-year moving averages are used for clarity and a clearer visual assessment of their trends over the study period. It becomes clear that around the sixties and seventies of the 20th century, the values of the two types annually were almost equalized, while in the last decades the frequency of A4 increased, while that of A5 decreased significantly. There was a similarly great difference between these two types at the beginning of the period of study around the 1870s.

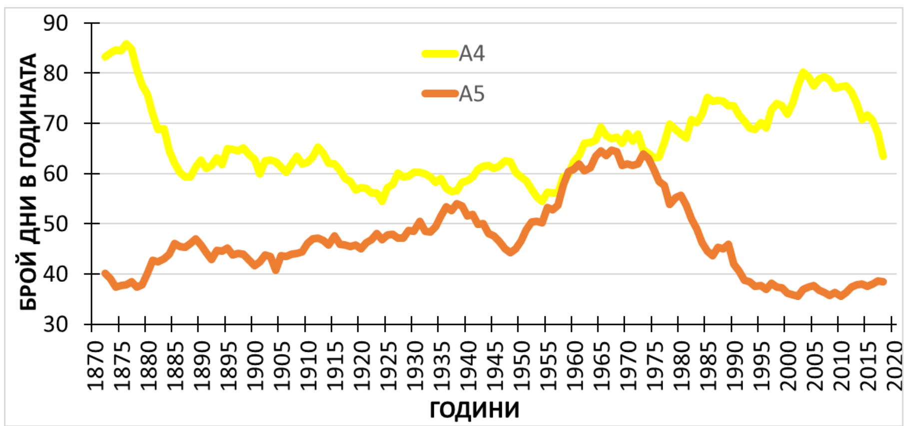


Figure 68 – Annual distribution of the circulation types A4 and A5 at 500 hPa (1871–2020)

The combinations of a particular group of circulation types, no matter at which isobaric level, is a relatively difficult task. Such combination is made in order to group the types by some criterion, most often geographical, in relation to the territory for which they were created, in order to highlight the common features of their climatological influence. Concerning the 500 hPa cyclonic types, three groups of types are selected, the cyclones located west of the country (Cnw, Cw and Csw), with an axis above it (Cn, C and Cs) and east of Bulgaria (Cne and Cse). In the western troughs/cyclones, it is assumed that the country is located at the front of these high troughs or cyclones and that this leads to cyclogenesis in the lower parts of the troposphere near the Earth's surface, and consequently this leads in most of the cases to cloud formation and eventually to precipitation. Summary, the three types Cnw, Cw and Csw also had a statistically significant reduction. Concerning the high troughs (cyclones) at the 500 hPa level located to the east, Bulgaria is located in their rear part and this results in anticyclogenesis and supports the development of anticyclonic circulation at the surface level. That is why the presence of these two cyclonic types at 500 hPa (Cne and Cse) is usually not associated with serious precipitation situations. The annual distribution of troughs or cyclones with an axis west of the country (types Cnw, Cw and Csw) and those east of it (types Cne and Cse) are shown in (Fig. 70), again using 11-year moving averages for clarity. The troughs with an axis over the country are not represented here (types Cn, C, Cs) because they take an intermediate position between the eastern and western troughs, their frequency is relatively lower, and their climatic influence is less pronounced.

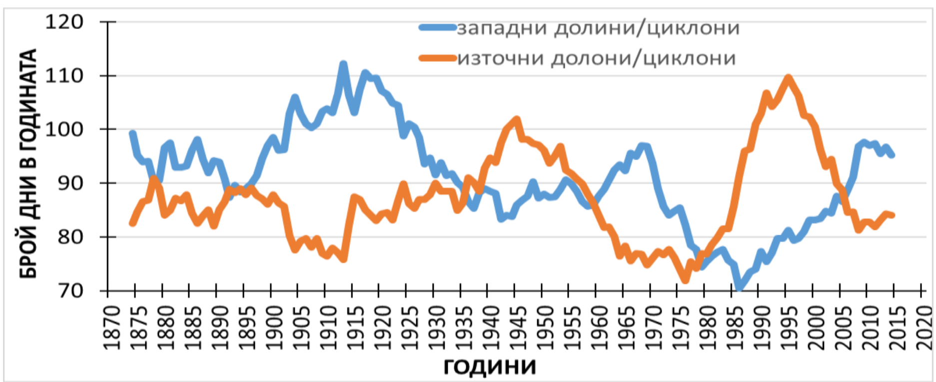


Figure 70 – Annual distribution of western and eastern barric troughs/cyclones at 500 hPa (1871-2020)

Analysis of the data shows that the overall trend of the western troughs is negative and statistically significant and that of the eastern troughs is positive, although not statistically significant. In (Fig. 70) it is noticeable 50, 60 year cycles in both eastern and western troughs, and the interesting point here is that the two types of troughs are almost in opposite phase, i.e. generally the minimum of one almost coincides with the maximum of the other. The proof that there is a relation between the western high (500 hPa) troughs and the amount of precipitation are the maximums observed in the 1960s and in recent years, as well as the minimum around 1990, which match very well the precipitation regime at some meteorological stations in

Bulgaria. This result could have some predictive value in the near or more distant future, after the current maximum rainfall in the next 2, 3 decades some decrease should follow. Further research is of course needed studying the mechanisms behind this high trough cyclicity because the relations in the climatic system are not always unambiguous.

3.3.2. Trends in the circulation types at sea level

The anticyclones over the country (type A3) and those south of it (A4 and A5), undergo a statistically significant increase in the study period. These are the circulation types that in most of the cases lead to warming during their presence. A2 as an anticyclone located in the eastern European lowland could also represent a ridge of the Siberian anticyclone and is generally associated with cold air transport to Bulgaria. Its negative trend is statistically significant. In (Fig. 71), the annual distributions of the surface anticyclonic types A1, A4, A5, and the sum frequency of (A4+A5) are shown.

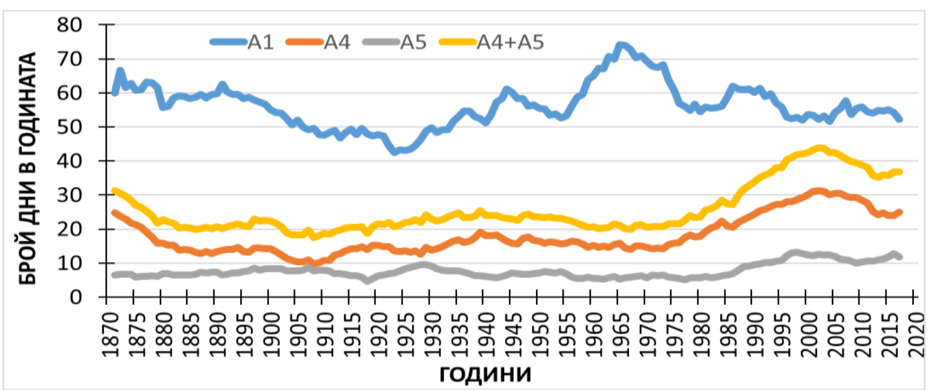


Figure 71 – Annual distribution of surface anticyclonic types A1, A4, A5 and A4+A5 (1871–2020)

Type A1, located northwest of the country, is in most cases the reason why air masses from more northern latitudes descend south along its eastern periphery, resulting in cooler or colder weather over the Balkans and Bulgaria in particular. Types A4 and A5, being situated to the south, conversely, help warmer air masses from the Mediterranean region or northern Africa to reach the country. For this reason, their sum frequency is also applied on the graph, moreover the distribution of the two types is quite similar. There has been a marked increase in them since 1980, and in sum they almost reached the frequency of A1 after 2000, whereas in the past the difference in their frequencies was 2, 3 times in favour of A1. The frequency of A1 increased slightly over the entire 150-year period, but especially in the previous climatic period 1961-1990 shows a statistically significant decrease. The anticyclones with center northeast of the country (type A2) experienced a statistically significant decrease over the 150-year period, while those centered over Bulgaria had a statistically significant increase, mostly due to its more frequent occurrence in the second half of the 20th century (Fig. 72). The fact that the frequency of southern anticyclones at sea level has increased over the last few decades, while that of northern anticyclones has decreased, is another reason for the warming over Bulgaria in the terms of the atmospheric circulation.

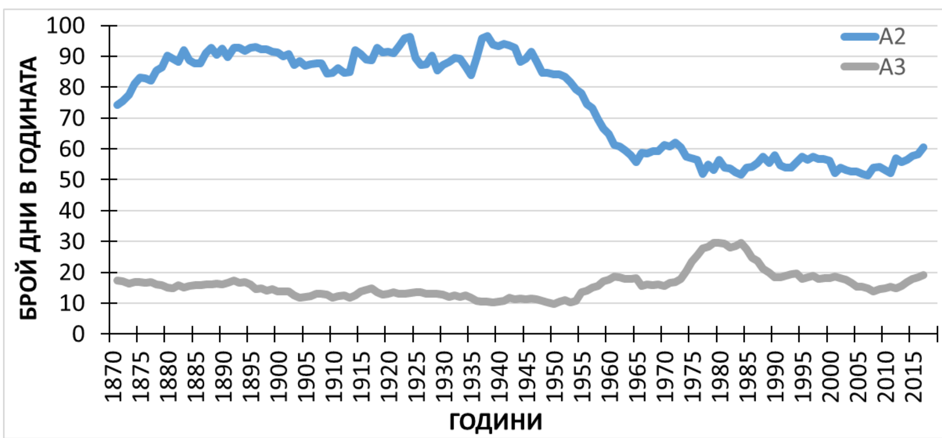


Figure 72 – Annual distribution of surface anticyclonic types A2 and A3 (1871–2020)

Concerning the sea level cyclonic types, was chosen an approach to divide them into two categories – Mediterranean (Cw, Csw, C, Cs, Cse) and northern (Cnw, Cn, Cne). The presumption is that cyclones centred over the country or to the south and west of it certainly have a Mediterranean origin and could be classified as such. Cyclones centred north of the country are mostly of Atlantic origin, passing north of the country through central and eastern Europe. Considered individually, the Mediterranean cyclonic types show a slight decrease in the cyclones located west of the country, and this is the most significant in the period 1961-1990. The decrease is statistically significant for the cyclones centred over

Bulgaria, while an increase is observed for the cyclones centred south and especially south-east of Bulgaria. There are also some seasonal differences in the same periods, such as the fact that Cse show a slight increase in winter, while their numbers decrease significantly in the spring season in the last climatic period 1991-2020. As a whole, over the 150 year period, there is no trend in Mediterranean cyclones, with decreasing frequency in autumn and winter and increasing in spring and summer.

The northern cyclonic surface types experienced a statistically significant increase over the studied period, and this was the greatest positive trend of all types at both isobaric levels. Considered separately, Cn and Cne have statistically significant trends, while only Cnw does not have one on an annual basis. The annual distributions of Mediterranean and northern cyclones are presented in (Fig. 73).

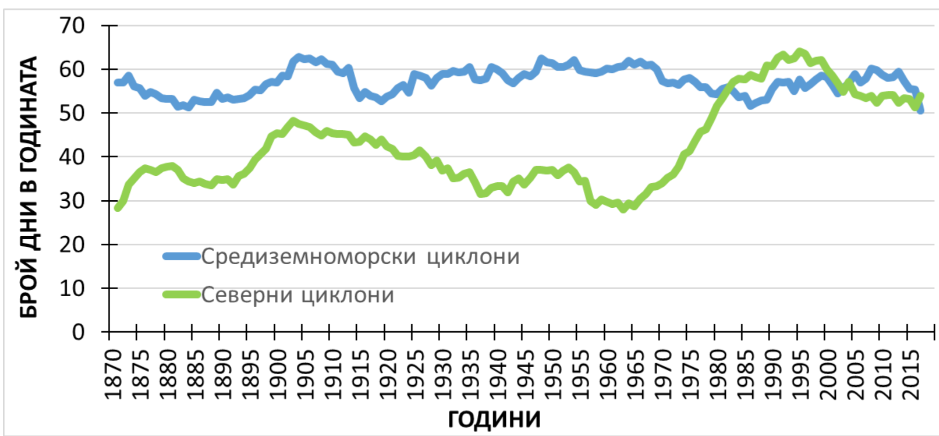


Figure 73 – Annual distribution of surface Mediterranean and northern cyclonic types (1871–2020)

One of the possible reasons for the significant increase in cyclones located north of the country since the 1970s is related to the Arctic and polar fronts from the 500 hPa high frontal zone. The Arctic front schematically separates, generally, the polar colder air masses from the moderate latitude warmer air masses, and the so-called polar front is located further south and separates the moderate latitude air masses from the subtropical air masses. These are relative separations that are not strictly distributed along the parallels in the northern hemisphere, and these frontal zones are meandering, sometimes they are not even visible or clearly distinguishable on barric maps. They have a mid-seasonal spatial distribution, generally moving northward in the warm half of the year and moving to more southerly latitudes in the cold half of the year. It is suggested that as a consequence of global warming in recent decades, their mean seasonal positions in the northern hemisphere have moved to some extent in a northerly direction.

Taken together, the low-gradient types increase their frequency statistically significantly. Over the last 30-year climatological period, both types have increased in frequency. Many heavy precipitation events with significant rainfall amounts in the summer season fall specifically in barric conditions with a low-gradient cyclonic field at the sea level combined with the presence of a trough or cyclone in the middle troposphere at the 500 hPa isobaric level.

In (Table 15) are presented the trends for the whole studied period summarily of all anticyclonic and cyclonic types at both barric levels and also of the low-gradient types at the sea level.

Table 15. Trends at 500 hPa and at sea level types (SLP) over the period (1871–2020).

500 hPa	1871 – 2020
Anticyclones	+
Cyclones	–
SLP	1871 – 2020
Anticyclones	– –
Cyclones	+ +
Low. Gradient	+ +

At 500 hPa level there is an increase in the anticyclonic circulation and a reciprocal decrease in the cyclonic circulation. Although the trends at the 500 hPa level are not statistically significant over the 150 year period considered, it can be assumed that the increase in anticyclonic circulation in the mid-troposphere over mid-latitudes is also driven to some extent by climate warming. The extension of the Azores anticyclone is proven for both barric levels of the present study, in particular for the Bulgaria region, but there are studies that link this to anthropogenic warming (Cresswell-Clay et al., 2022) in the industrial era, after the second half of the 19th century and especially in the last decades of the 20th century. On the other hand, it is known that high anticyclones are warm barric formations and their more frequent occurrence should lead to higher temperatures at the Earth's surface as well, which is particularly characteristic of the warm half of the yearAt sea level, there is a statistically significant negative trend for anticyclones and a statistically significant positive trend for cyclones and low-gradient types. This is also a reasonable result in the present warming, because the warmer land surface initiates upward movements, which is in the basis of cyclogenesis near the earth's surface. The positive trend in low-gradient types can also be considered as a consequence of climate warming, because the reduced temperature contrast between the equator and the poles results in weaker barric gradients in the moderate latitudes. This statement is valid for all seasons, but especially for the summer season.

3.4. Relations between circulation types and the temperature and precipitation

The purpose of this section in this chapter is to show some of the relations found between circulation types at the two barric levels with the two most basic meteorological elements, temperature and precipitation. The central meteorological station of the National Institute of Meteorology and Hydrology in the city of Sofia was selected for this purpose. It was selected as the one with reliable and correct meteorological information, accessible and sufficiently long series of climatological data.

3.4.1. Relations between surface anticyclonic types and the temperature

The relation between all six anticyclonic circulation types at sea level and the seasonal temperature was examined. Seasonal temperature values was calculated considering climatological seasons. Winter is formed by the three calendar months (December, January and February), spring (March, April, May), summer (June, July, August) and autumn (September, October, November). Seasonal temperatures are averaged from the monthly temperatures and the monthly temperatures are averaged from the daily average temperatures.

The study period is 1952–2020 and marks the first year since the weather station in Sofia was located at its current location. Pearson correlation coefficients were calculated to investigate the relations between circulation types and temperature. The statistical significance of the correlation coefficient was also calculated using t-test at the selected significance level α = 0.05. A Mann-Kendall test is also used to assess the significance of the trend of the types over the period 1952–2020Values of significant correlation coefficients are marked red for positive (straight) correlation and blue for negative (inverse) correlation. Arrows indicate the trend directions and purple highlights only significant trends. Before that, a table with the frequencies of sea level anticyclonic types in the period 1952-2020 is presented informatively (Table 17).

Table 17. Seasonal frequencies of anticyclonic sea level types in the period (1952–2020).

	Winter	Spring	Summer	Autumn
A1	17.1%	10.8%	17.4%	19.0%
A2	14.1%	16.5%	11.3%	22.9%
A3	6.1%	3.7%	4.7%	5.8%
A4	7.4%	4.2%	7.0%	5.0%
A5	3.5%	2.9%	0.6%	2.1%
Mt2	1.9%	1.1%	0.2%	1.2%
Anticyclones	50.0%	39.2%	41.2%	56.0%

The more frequent presence of anticyclonic type A1 results in lower temperatures in all seasons, which is the most noticeable in autumn and winter (Table 22). During these two seasons, cold air masses originating in central, northern Europe, Greenland or the North Sea or Baltic Sea regions reach more southerly latitudes, and the presence of such an anticyclone helps to transport them southward, along its eastern peripheryOver the Balkans and Bulgaria in particular, such air masses penetrate from the northwest, north or northeast depending on the location of the isobars of the particular barric formation. The tendency of this type is negative in all seasons but is not statistically significant.

Table 22. Seasonal correlations with the air temperature and trends of type A1

A1	Winter	Spring	Summer	Autumn
Correlation	**-0,286**	-0,182	-0,209	**-0,343**
Trend	↓	↓	↓	↓

In Table 23 are shown the correlation coefficients and trends in the seasons for the type A2. It affects the Balkans and Bulgaria transporting continental air masses from the eastern quarter of the horizon. These air masses can be formed in areas of the eastern European plain, western Siberia or further south in the Kazakh steppes and even Asia MinorThe interesting thing about type A2 is that it brings lower temperatures in spring and higher temperatures in autumn. On the one hand, this is probably partly due to the inertia of the sea-water temperature of the Black Sea, but also to the fact that, at least in the first half of autumn, the continental air masses coming to the Balkans from these latitudes are still relatively warm, while, at least in the first half of spring, a considerable part of these areas is still with a snow cover.

Table 23. Seasonal correlations with the air temperature and trends of type A2

A2	Winter	Spring	Summer	Autumn
Correlation	-0,003	**-0,249**	0.165	**0.256**
Trend	↓	↓	↓	↔

In summer the positive correlation is weaker and in winter there is no correlation with the seasonal temperature in Sofia. The trend for this type is negative except for the autumn season. Its negative trend is statistically significant only in spring. These results indicate that trends in type A2 also contribute to the warming climate.

Anticyclonic type A3 formed over the Balkans and over the country, but it may also have previously been type A1 or A2It is characterized by the near-absence of wind, and the air mass gradually acquires the properties of the underlying surface over which it is formed. There is no correlation with the average temperature in Sofia in spring and summer, it is slightly negative in autumn and positive in winter, but there is no season when it is statistically significant. This indicates that this type can manifest itself in different ways depending on the condition of the underlying surface prior to its formation, the presence of moisture in the atmosphere, and in winter, the presence of snow cover. The trend is positive in spring and summer and negative in winter, but not statistically significant (Table 24).

Table 24. Seasonal correlations with the air temperature and trends of type A3

A3	Winter	Spring	Summer	Autumn
Correlation	0,125	0.008	0.003	-0.139
Trend	↓	↑	↑	↔

The correlation of type A4 with the seasonal temperature in Sofia is statistically significant only during the summer months, but it is the highest of all types and all seasons. This type leads to the most significant increase in average temperature in summer. The trend is also statistically significant in three of the seasons. The increased frequency of this type in recent years is probably one of the significant reasons for the warming summers of the last forty years. The lack of correlation in spring is probably due to the lower sea water temperatures in the Mediterranean compared to the faster warming land, and in autumn the opposite, with the influences probably are compensated each other depending on whether the air masses reaching Bulgaria are of maritime or continental origin (Table 25).

Table 25. Seasonal correlations with the air temperature and trends of type A4

A4	Winter	Spring	Summer	Autumn
Correlation	0,159	0,055	**0,557**	0.083
Trend	↑	↑	↑	↑

In type A5, located southeast of the country, the direction of air flow is from the south and southeast, from the region of the eastern Mediterranean, from where warmer and more humid air masses invade in winter and spring, and this is also clear from the coefficients in these seasons. In summer the correlation is again positive but slightly weaker, and in autumn no correlation with seasonal temperature is observed. The trend of this anticyclonic type is positive and statistically significant in all seasons (Table 26).

Table 26. Seasonal correlations with the air temperature and trends of type A5

A5	Winter	Spring	Summer	Autumn
Correlation	**0,415**	**0,236**	0,197	-0.026
Trend	↑	↑	↑	↑

Mt2 type is presented in Table 27. This type occurs mostly in winter and autumn, yet in the past it occurred in all seasons, its frequency being the lowest at slightly over 1% of all types. Despite this, its correlation with mean temperature is markedly significant in the winter season. It is essentially a huge anticyclone over the entire continent, including the southern peninsulas, the British Isles and Scandinavia. As such, it could have the characteristics of the smaller anticyclonic types A1, A2 or A3. In the winter season is accompanied by the intrusion of very cold polar air masses over large areas of the continent, and in the anticyclonic environment the air masses can become even colder for radiative cooling reasons. In most cases it is accompanied by an extended high trough at 500 hPa, which means that the air over large areas of Europe is cold not only near the surface but also at height. In all seasons Mt2 shows a statistically significant decline.

Table 27. Seasonal correlations with the air temperature and trends of type Mt2

Mt2	Winter	Spring	Summer	Autumn
Correlation	**-0.508**	-0,173	-0,075	-0,189
Trend	↓	↓	↓	↓

During the 68 year period under consideration, the number of days with anticyclonic circulation at sea level have decreased! The number of days with the types of anticyclones that could cause colder weather is decreasing, while the number of days of anticyclonic types that lead to the intrusion of warmer air masses over Bulgaria is increasing. This proves that there are also circulation drivers for the current warming, at least as far as surface anticyclones are concerned.

3.4.2. Relations between troughs at 500 hPa barric level and precipitation

To show the relation between circulation types and precipitation, the 500 hPa barric level and in particular barric troughs or cyclones were selectedThe meteorological station in the city of Sofia was again chosen for the rainfall data series, but the period id different and starts in 1893 from the beginning of the station's existence. In (Table 28), the annual and seasonal Pearson correlation coefficients between rainfall amount and number of days are presented with troughs/cyclones located west of Bulgaria - types (Cnw+Cw+Csw) and troughs located east of the country - types (Cne+Cse). Statistically significant correlation coefficients are presented in bold.

Table 28. Annual and seasonal value of the Pearson correlation coefficient between precipitation in Sofia and the western (Cnw+Cw+Csw) and eastern (Cne+Cse) troughs at 500 hPa

	Western	Eastern
Annual	**0.38**	**-0.19**
Winter	**0.44**	**-0.19**
Spring	**0.33**	**-0.20**
Summer	**0.20**	**-0.44**
Autumn	**0.45**	-0.17

The data demonstrate without a doubt that the correlation between precipitation and the western valleys is positive and statistically significant in all seasons. It is the highest in autumn and winter. In summer it is lowest although statistically significant. This is probably because during the summer season in the Sofia area also falls a lot of precipitation of an internal mass nature, not so much related to the fronts of the barric systems. In the autumn and winter, barric troughs and their associated fronts more easily reach Bulgaria's latitude from the north and have a greater influence on precipitation. In contrast, in the high 500 hPa level troughs to the east of the country, the relations is negative and their presence is associated with drier weather, with the correlation coefficient having the highest absolute value in summer, meaning that in this season it is least likely to have precipitation in Sofia when they occur.

At Fig. 82 are shown the 11-year moving averages of the annual number of days with troughs west of Bulgaria and the annual rainfall amounts in Sofia. Moving averages are used to better graphically represent and visualize trends and manifestations of periodicity in circulation types and, in this case, the rainfall. However, the calculations of the correlation coefficients and trends are made with the true, not the smoothed values of the two parameters that are compared.

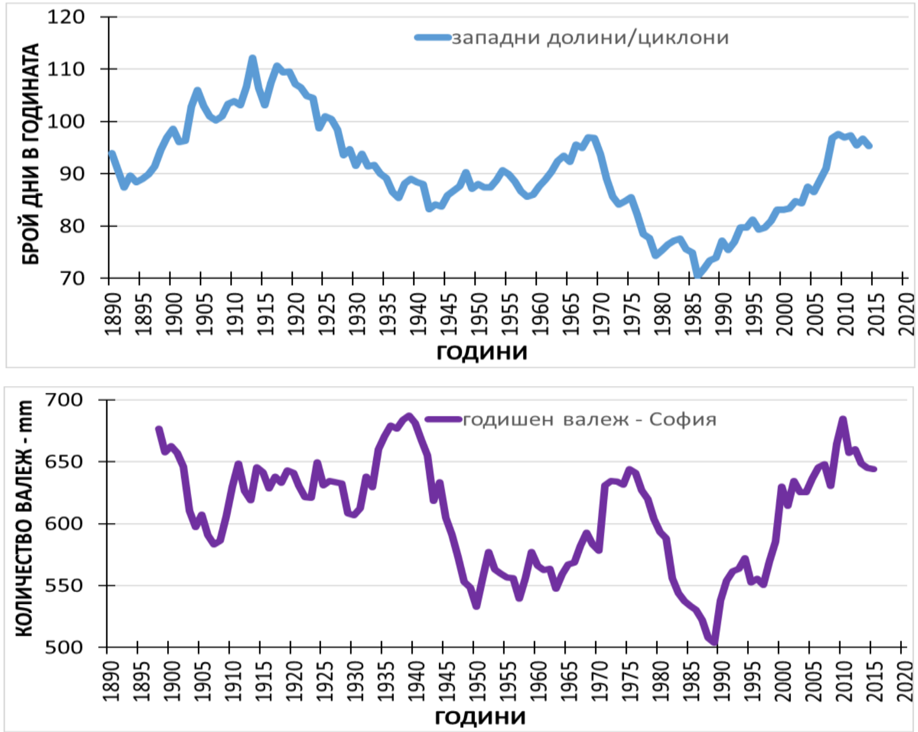


Figure 82. Number of days per year with troughs/cyclones west of Bulgaria and annual rainfall totals in Sofia (11 year moving averages)

The minimum in the number of high western troughs coincides with the minimum in rainfall in the late 1980s and early 1990s. Their maxima around the sixties and seventies of the twentieth century and since the beginning of the 21st century also coincide with the regime of annual rainfall amounts at least in Sofia. Since in the 120+ year period considered in this case, and as seen in (Fig. 70) also in the last 150 years, there is a statistically significant decrease in the frequency of the western 500 hPa troughs/cyclones, it can be assumed that this cycle with a periodicity of 50, 60 years is a part of some longer-periodic regime whose trend is, however, negative at least in this time period. In the present years we are still in the maximum of the high western valleys, and in a period of relatively higher rainfall, but in the next 20, 30 years it should generally decrease.

CHAPTER FOUR

RELATION OF THE CIRCULATION TYPES WITH SOME BASIC LARGE-SCALE CIRCULATION PROCESSES

Large-scale circulation processes play, to a greater or lesser extent, a major climate-forming role at all points on the globe. They cover huge areas and thus have a major climatological influence not only in the areas in which they are formed, but in some cases over a large distances of thousands of kilometres. In most of them they are related to the temperature of the ocean water, which has a large accumulating effect, and consequently these influences could exceed the time scale of a month, a season, or even more than an year. There are large-scale circulation processes such as the NAO (North Atlantic Oscillation) that are also related to atmospheric pressure. All large-scale circulation processes are given their physical and mathematical expression by the respective indices introduced for each of them. For the purpose of this work the possible interconnections between the large-scale circulation processes in the Atlantic, Pacific, Indian and Arctic Oceans with the circulation types of the developed classification of atmospheric circulation for the region of Bulgaria are investigated and analysed.

4.1. Relations of the circulation types to the Atlantic Multidecadal Oscillation (AMO)

The observed large-scale multidecadal fluctuations in water surface temperature in the North Atlantic Ocean, from 0 to about 60-70 degrees north latitude, are called the Atlantic Multidecadal Oscillation (AMO) (Kerr, 2000). A cycles with periods of 60-80 year of AMO have been identified. The NOAA resource (Extended Reconstructed Sea Surface Temperature - ERSST, Version 5) for North Atlantic seawater temperature was used to calculate the AMO index and look for a connection between AMO and the circulation types. In (Fig. 86), the AMO index is represented by its monthly values in blue, and the 11-year (131 monthly) moving averages in brown. Two positive and two negative phases can be observed in the 19th and 20th centuries, as well as a strong positive phase that started at the end of the last century and has continued until the present time in the 21st century.

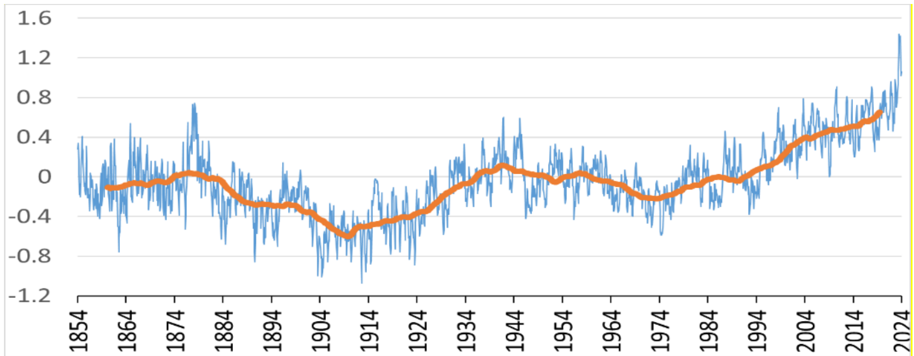


Figure 86. AMO – monthly values 1854–2024 (ERSST, Version 5)

The correlation coefficients of AMO and circulation types were calculated by their annual values, using Pearson's formula. In Table 29 the coefficients of the 500 hPa baric level types are presented using the original data series. The interpretation of the results shows statistically significant and negative correlation coefficients of AMO with anticyclonic types A1, A2 and A5 as well as with cyclonic Cnw. This means that their appearance is more frequent when the water temperature of the North Atlantic Ocean is lower. The correlation of types A4 and Cn is positive and statistically significant, i.e. their more frequent occurrence is associated with higher water temperatures in the North AtlanticSummary, western (Cnw+Cw+Csw) and eastern (Cne+Cse) troughs or cyclones at 500 hPa barric level are not statistically significantly correlated with AMO.

Table 29. Correlation of AMO with circulation types at 500 hPa, and summary of western (Cnw+Cw+Csw) and eastern (Cne+Cse) troughs

A1	A2	A3	A4	A5
-0.21	**-0.26**	**-0.02**	**0.22**	**-0.21**
Cnw	Cw	Csw	Cn	C
-0.16	**0.14**	**-0.07**	**0.23**	**0.00**
Cs	Cne	Cse	Западни	Източни
-0.13	**0.15**	**0.02**	**-0.11**	**0.14**

The correlations of AMO with sea-level circulation types are shown in Table 30. Statistically significant negative correlations are observed for anticyclonic types A2 and Mt2. Their more frequent appearance over Bulgaria during lower ocean temperatures is reasonable, since at high temperatures the cyclonic circulation over the Atlantic Ocean is more active and this prevents the development of ridges from the Siberian and eastern European anticyclone in a westward direction. The Mb1 and C types also have a statistically significant negative correlation. Positive and significant are the correlations of southern anticyclones A4 and A5, which means higher ocean water temperature, more frequent occurrence of these types and, respectively, higher air temperature over Bulgaria.

Table 30. Correlation of AMO with sea-level circulation types and sum of northern and Mediterranean cyclones.

A1	A2	A3	A4	A5
0.01	**-0.44**	**0.13**	**0.56**	**0.32**
Mt2		Mb1	Mb2	
-0.16		**-0.27**	**0.19**	
Cw	C	Csw	Cs	Cse
0.04	**-0.23**	**-0.07**	**0.25**	**0.13**
Cnw	Cn	Cne	Северни Ц.	Средиз.Ц.
0.00	**0.38**	**0.36**	**0.32**	**0.03**

The correlation with cyclonic types Cn, Cne and Cs is also positive and statistically significant. In general, northern cyclones (Cnw+Cn+Cne) are positively correlated with AMO, i.e. their more frequent occurrence is associated with warmer ocean temperatures, but overall Mediterranean cyclones (Cw+C+Csw+Cs+Cse) show no correlation with AMO.

4.2. Relations of the circulation types to the North Atlantic Oscillation (NAO)

The North Atlantic Oscillation (NAO) is a meteorological phenomenon over the North Atlantic Ocean of fluctuations in the difference in atmospheric pressure aligned to sea level (SLP) between the Icelandic cyclonic region of low atmospheric pressure and the Azores anticyclonic region of high atmospheric pressure. Through the fluctuations in the intensity of these two barric areas, the strength and direction of westerly winds and the location and tracks of the cyclones and storms across the North Atlantic are controlled (Hurrell et. al, 2003). A great difference in atmospheric pressure at the two stations (a high index year, denoted NAO+) results in more pronounced and stronger westerly winds and, therefore, cool summers and mild and wet winters in central and western parts of Europe. In contrast, if the index is low (NAO-), westerly winds are suppressed, in northern European regions winters are cold and dry, while the cyclonic activity is pushed south towards the Mediterranean.

Figure 90 shows the annual NAO averages from 1950–2023 and the 11-year moving averages. It can be noticed that in the last two decades of the 20th century the averaged values of the index are relatively higher, which can be associated with the relatively lower amounts of precipitation in this period in the region of Bulgaria, despite the relatively weak negative correlation with precipitationAlso, at the beginning of the 21st century and around the 1960s, NAO values were more often negative, which corresponds with the relatively higher amounts of precipitation in Bulgaria during these periods.

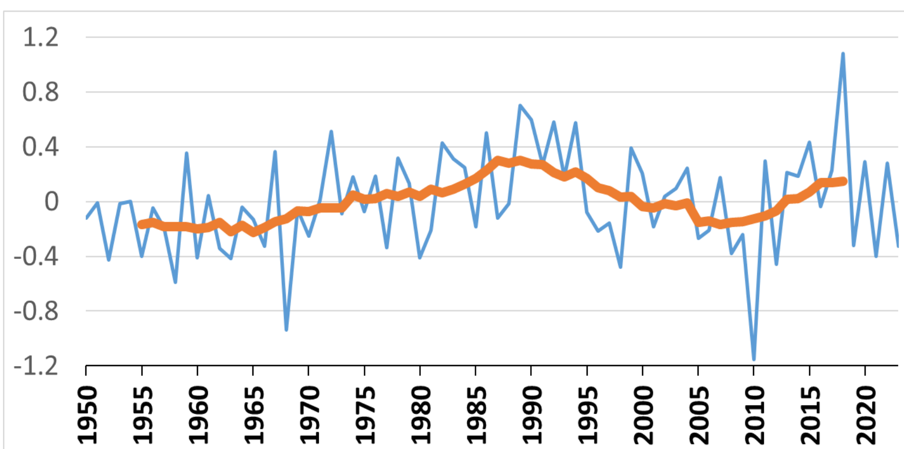


Figure 90. NAO – average annual values 1950–2023 (NOAA/NCEP)

Tables 31 and 32 present the calculated correlation coefficients between the NAO index and the circulation types. Because the study period is significantly shorter than that of AMO, the threshold above which the correlation coefficients are significant (at the chosen significance level $\alpha = 0.05$) is higher and is almost 0.24It is remarkable that the number of circulation types that are significantly correlated with the NAO is significantly smaller than for the AMO, which could generally mean that the NAO index is relatively less correlated with the barric formations over Bulgaria, and hence with the most important meteorological elements temperature and amount of precipitation. At the 500 hPa barric level, the NAO has a positive and statistically significant relationship only with anticyclones located to the northwest of Bulgaria and over Bulgaria (types A1 and A3) (Table 31).

Table 31. Correlation of NAO with circulation types at 500 hPa, and summary of western (Cnw+Cw+Csw) and eastern (Cne+Cse) troughs.

A1	A2	A3	A4	A5
0.24	**0.03**	**0.24**	**0.19**	**-0.14**
Cnw	Cw	Csw	Cn	C
-0.44	**0.03**	**0.02**	**-0.13**	**-0.01**
Cs	Cne	Cse	Западни	Източни
0.02	**0.18**	**0.16**	**-0.34**	**0.23**

The negative and statistically significant NAO correlation is summed for the westward-located types Cnw, Cw, and Csw; however, considered separately, it is statistically significant only with type Cnw. Concerning the eastern circulation types Cne and Cse, the relation is positive but not sufficient to be statistically significant. At the sea-level circulation types (Table 32), there is a statistically significant, negative correlation only with the cyclonic types located west and southwest of the country (Cw and Csw), which, however, is sufficiently for the Mediterranean cyclones in general to be negatively and statistically significantly correlated with the NAO. About the cyclones to the north of the country, separately the signal is negative with the types to the northwest and north of Bulgaria and weakly positive with the type to the northeast of it, resulting in almost zero correlation in total for them as a whole.The anticyclonic SLP types A1, A3, A4 and A5, the connection is positive but not statistically significant. These results are consistent with the positive correlation between NAO and atmospheric pressure at the sea level.

Table 32. The correlation of NAO with sea-level circulation types, and summary of northern and Mediterranean cyclones.

A1	A2	A3	A4	A5
0.19	**-0.01**	**0.18**	**0.08**	**0.15**
Mt2		Mb1	Mb2	
-0.04		**-0.03**	**-0.06**	
Cw	C	Csw	Cs	Cse
-0.32	**-0.13**	**-0.31**	**0.01**	**-0.03**
Cnw	Cn	Cne	Северни Ц.	Средиз.Ц.
-0.17	**-0.12**	**0.11**	**-0.03**	**-0.35**

4.3. Relations of the circulation types to the Arctic Oscilation (AO)

The Arctic Oscillation is based on the sea level atmospheric pressure anomalies in the Arctic on the one side, and the pressure anomalies but with the opposite sign in the area between 37 and 45 degrees north latitude. During the positive phase of the AO, zonal transport of the air masses predominates. During the negative (cold) phase, a higher atmospheric pressure prevails in the Arctic region, causing westerly winds to weaken in the upper atmospheric layers. As a consequence, cold Arctic air reaches more southerly latitudes in North America, Europe and Asia. Lower than normal atmospheric pressure in the central Atlantic and weaker westerly winds in northern Europe contribute to the development of cyclonic activity in the Mediterranean region. During the negative phase, meridional air circulation prevails in most of the northern hemisphere mid-latitude regions. At (Fig. 95) are illustrated the annual mean AO values from 1950-2023 and the 11-year moving averages. It is noticeable the similarity of the curves with those of the NAO index from (Fig. 90).

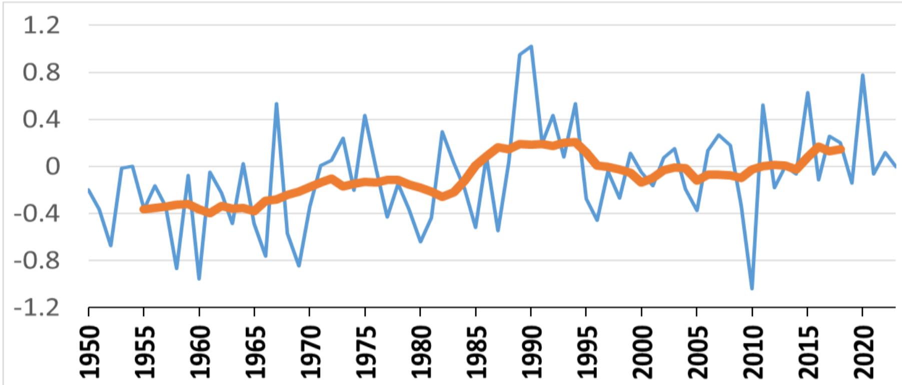


Figure 95. AO – average annual values 1950–2023 (NOAA/NCEP)

Tables 33 and 34 present the calculated correlation coefficients between the AO index and circulation types, again with positive and negative statistically significant values shown respectively in red and blue colors. At both 500 hPa barric level and at sea level, the correlation coefficients are similar in value, but for almost all types, are higher than the NAO indexThis indicates that, in general, the AO index has a stronger relation to the circulation types from the current atmospheric circulation classification, as its spatial characteristics probably better describe barric formations concretely in the Balkan Peninsula region. At 500 hPa barric level (Table 33), there are three circulation types with statistically significant correlations with AO (as with the NAO index) - A4, A5 and Cnw. The relation is positive only for A4, i.e. during high positive values of AO and the presence of zonal circulation over Europe, there are good conditions for the existence of this type and its warming climatic influence on Bulgaria.

Table 33. Correlation of AO with circulation types at 500 hPa, and sum of western (Cnw+Cw+Csw) and eastern (Cne+Cse) troughs.

A1	A2	A3	A4	A5
0.22	**-0.04**	**0.21**	**0.39**	**-0.30**
Cnw	Cw	Csw	Cn	C
-0.53	**0.05**	**-0.01**	**-0.09**	**-0.08**
Cs	Cne	Cse	Западни	Източни
0.15	**0.23**	**0.09**	**-0.42**	**0.25**

Type A5, as well as the troughs/cyclones to the northwest of the country (type Cnw) have a negative correlation with the AO, which means that their more frequent appearances are more related to the presence of meridional atmospheric circulation. The presence of type A5 at 500 hPa barric level south of the country means that a high barric trough has settled over the central Mediterranean and probably over central Europe, which in itself suggests a meridional circulation over the European continent. In summary, troughs located west of the country have a negative statistically significant correlation with the AO, while those located east of it are generally positively correlated with the index.

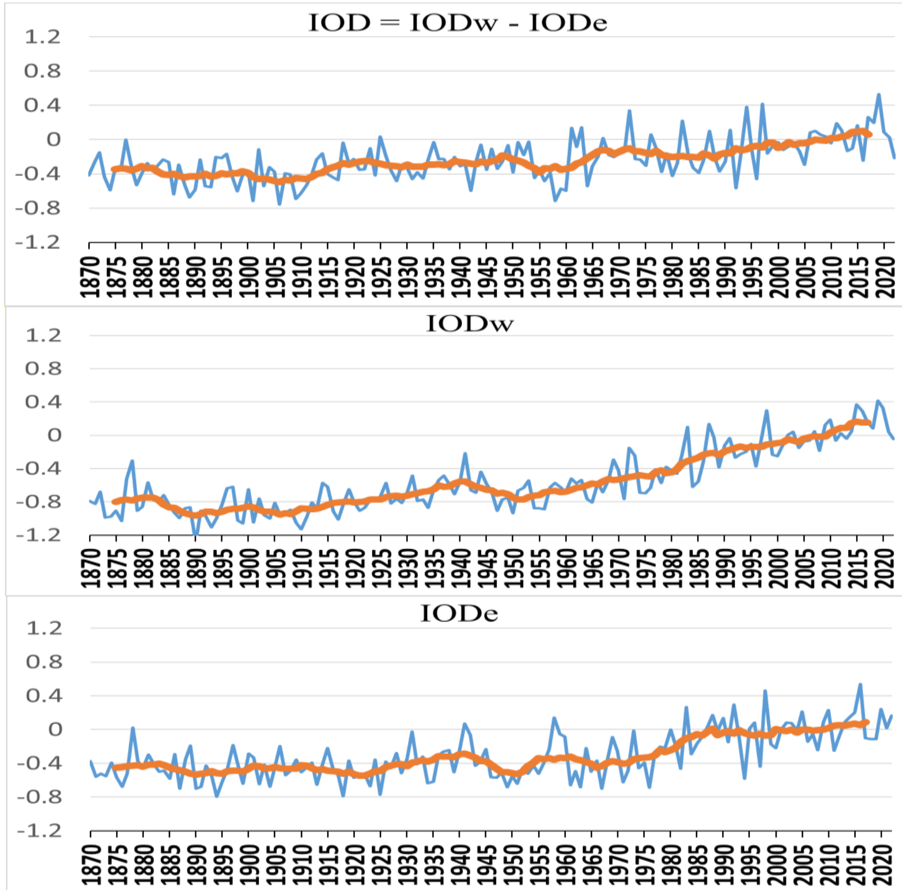
At the sea level, 7 types have a statistically significant correlation with AO - anticyclonic A2 (negative), A3 and A4 (positive) and all cyclones to the west and over Bulgaria. Mediterranean cyclones are negatively correlated with the AO, consistent with their favorable conditions for arising primarily under meridional circulation and cold air intrusion from the northern quarter of the horizon (Table 34).

Table 34. Correlation of AO with sea-level circulation types, and sum of northern and Mediterranean cyclones.

A1	A2	A3	A4	A5
0.21	**-0.28**	**0.24**	**0.28**	**0.17**
Mt2		Mb1	Mb2	
-0.07		**0.21**	**-0.06**	
Cw	C	Csw	Cs	Cse
-0.46	**-0.32**	**-0.29**	**0.08**	**-0.06**
Cnw	Cn	Cne	Северни Ц.	Средиз.Ц.
-0.28	**-0.06**	**0.20**	**0.00**	**-0.48**

4.4. Relations.of.the.circulation.types.to.Indian.Ocean.Dipole.(IOD)

IOD (Indian Ocean Dipole) is a natural phenomenon in the Indian Ocean discovered in 1999 (Webster et. al, 1999), (Saji et. al, 1999). It is represented as the difference in sea surface temperature anomalies between the western (50°E - 70°E and 10°S - 10°N) and eastern (90°E - 110°E and 10°S - 0°) parts, around its equatorial regionsThere are two phases of this oscillation - positive and negative (IOD+ and IOD-). During the positive phase (IOD+), water temperatures are higher than normal in the western Indian Ocean and lower than normal in the eastern Indian Ocean. The IOD index is calculated as the difference in temperature anomalies between the western and eastern domains, locked at the coordinates mentioned above. After calculating the correlation coefficients with the circulation types of the defined index, the coefficients were calculated separately for the western and eastern Indian Ocean regions. It was found that in absolute values they were highest for the western Indian Ocean area with few exceptions for some circulation types. The coefficients for the original index were the lowest, so it was decided to visualize just the correlation coefficients between water temperature only in the western and eastern regions. In (Fig. 100), the total IOD index, represented as the difference between the western and eastern domains, and the western IODw and eastern IODe indices are presented separately. The largest increase in water temperature is observed in the western Indian Ocean since the mid-20th century. According to the projections of the majority of climate models, it is the western Indian Ocean that will warm at the most accelerated rate due to climate change, resulting in greater periods of positive index values. This is very likely to lead to more intense rainfall in East Africa during the short rainfall period there (Chu et al., 2014), (Zheng et al., 2013), (Cai et al., 2018), (Kendon et al., 2019).



Фигура 100. IOD – средни годишни стойности 1870–2022 (HadISST1.1)

As mentioned above, it is this part of the Indian Ocean that has the greatest climatic influence on the barric formations of the Balkans. The index values are more often negative because they are calculated relative to their 1981-2010 averages, which are closer to contemporaneous and relatively warmer.

Tables 35 and 36 show the correlation coefficients of IODw, to the left of the slash, and IODe, to the right of the slash, with circulation types at 500 hPa barric level and at sea-level, respectivelyWith few exceptions, almost everywhere the correlation coefficients are higher for IODw. About the 500 hPa types, a statistically significant negative correlation was observed for the Cnw and A5 types for both indices, while statistically significant positive correlations were observed for A4 and Cse only for IODw (Table 35). In general, the western and eastern 500 hPa troughs are not statistically significantly related to Indian Ocean water surface temperatures.

Table 35. Correlation of IODw/IODe with circulation types at 500 hPa, and summary of western (Cnw+Cw+Csw) and eastern (Cne+Cse) troughs.

A1	A2	A3	A4	A5
-0.13 / -0.16	**-0.15 / -0.12**	**0.10 / 0.11**	**0.23 / 0.12**	**-0.25 / -0.21**
Cnw	Cw	Csw	Cn	C
-0.22 / -0.16	**0.12 / 0.15**	**-0.01 / -0.04**	**0.10 / 0.10**	**0.18 / 0.12**
Cs	Cne	Cse	Западни	Източни
-0.14 / -0.12	**0.04 / 0.09**	**0.19 / 0.13**	**-0.15 / -0.10**	**0.12 / 0.14**

In Table 36, it is shown that at the sea level, most types have significant correlations with both IODw and IODe indices. There are some interesting patterns, such as the warm surface anticyclones A3, A4 and A5, as well as the cyclonic types north, south and east of Bulgaria, being statistically significantly positively correlated with Indian Ocean temperatures. At the same time, the cyclonic type over Bulgaria shows a statistically significant negative relationship with IODw. On the other hand, the A2 and Mt2 types, which especially in the cold half of the year could cause prolonged and even extreme cold weather, are strongly negatively correlated with Indian Ocean temperatures. This means that their longer persistence and corresponding longer cooling influence could take place at lower seawater temperatures in the Indian Ocean. The low-gradient type Mb1 in the weak cyclonic field is negatively correlated with IODw and IODe. This is probably indirectly related to the area of low pressure in summer over the Persian Gulf region, which with its northwestern periphery often also covers the Balkan Peninsula in the form of a low- gradient cyclonic field. The low-gradient circulation type Mb2 in a weak anticyclonic field is positively correlated with both indices, which is a logical result due to the fact that, by its nature, it is similar to the anticyclonic types A3, A4 and A5.

Table 36. Correlation of IODw/IODe with sea-level circulation types and summary of northern and Mediterranean cyclones.

A1	A2	A3	A4	A5
-0.01 / -0.11	**-0.58 / -0.46**	**0.24 / 0.18**	**0.54 / 0.42**	**0.30 / 0.27**
Mt2		Mb1	Mb2	
-0.38 / -0.24		**-0.31 / -0.33**	**0.37 / 0.27**	
Cw	C	Csw	Cs	Cse
-0.07 / 0.01	**-0.27 / -0.10**	**-0.14 / -0.11**	**0.22 / 0.21**	**0.39 / 0.29**
Cnw	Cn	Cne	Северни Ц.	Средиз.Ц.
0.10 / 0.23	**0.43 / 0.46**	**0.58 / 0.49**	**0.49 / 0.51**	**0.02 / 0.11**

The correlation coefficients of the PDO - Pacific Decadal Oscillation, SOI – Southern Pacific Oscilation index and the Mediterranean Oscillation (MOi), with the circulation types, are presented along with all the indices discussed above in Tables 44 and 45. The last two rows in Table 44 present the correlations summed over the western troughs (W.) and the eastern troughs (E.) at the 500 hPa levelThe positive and statistically significant correlation coefficients are marked in red throughout the tables, the statistically significant negative coefficients are marked in blue, and the coefficients with no statistical significance are marked in black. The correlation coefficients of the circulation types with the large-scale sea-level circulation indices are presented in (Table 45). (MC.) indicates the cumulative frequencies of Mediterranean cyclones, and (NC.) indicates cumulative frequencies of the cyclones centered northwest, north, and northeast of Bulgaria.

The Pacific Decadal Oscillation (PDO) is a persistent, recurring climate phenomenon in the land-atmosphere system over mid-latitudes in the North Pacific. During the warm or positive phase, the western parts of the Pacific become colder and the eastern parts near the coast of North America become warmer. The negative phase is characterized by the opposite regime, i.e., warmer waters in the western part of the ocean and cooler waters in the eastern part.

The South Pacific Oscillation Index (SOI) is a standardized index based on observed sea level pressure (SLP) differences between Tahiti and Darwin, Australia. SOI is an atmospheric index and is a measure of the large-scale fluctuations in atmospheric pressure occurring between the western and eastern tropical Pacific during El Niño and La Niña episodes.

The Mediterranean Oscillation (MOi) is described as the bipolar behaviour of the atmosphere between the western and eastern Mediterranean. The index measuring the dipole intensity is defined as the anomaly of the difference in geopotential height at 500 hPa between Algiers and Cairo (Conte et al., 1989), (Palutikof et al., 1996An alternative definition (Palutikof, 2003) estimates the (MOi) index as the difference in adjusted atmospheric pressure to sea level SLP between the northern boundary of the Strait of Gibraltar and Lod Airport in Israel.

CHAPTER FIVE

CONCLUSIONS

Conclusions on the classification of atmospheric circulation over Bulgaria:

- In the 150-year period of the study, an increase, although not statistically significant, in the cumulative frequency of anticyclonic circulation types at the 500 hPa barric level and a reciprocal decrease in the frequency of cyclonic types was observed over Bulgaria. High anticyclones are warm baryonic formations, and their more frequent occurrence is related to increasing temperatures both at altitude and at the land surface.
- At the sea level, there is a statistically significant cumulative decrease in anticyclonic circulation types and a statistically significant increase in cyclonic and low-gradient types. This is also related to the current warming because the warmer land surface initiates upward air circulation, which is the basis of sea-level cyclogenesis. The positive trend in low-gradient types can also be explained as a consequence of the climate warming, because the reduced temperature contrast between the equator and the poles leads to weaker barric gradients in moderatete latitudes.

- The frequency of the troughs/cyclones at 500 hPa positioned west of Bulgaria are statistically significantly, positively correlated with annual precipitation amounts in Sofia, and this fact applies to most of the country. The annual frequencies of this group of troughs show a certain cyclicity with a period of about 50-60 years, and this can be used as a long-term forecast of the range of a few decades for the annual rainfall totals and possible longer dry periods. On this basis, the next 20-30 years could be expected to have lower average annual rainfall amounts than those of the early 21st century to the present.
- When studying the trends of the anticyclonic sea level circulation types and the correlations between their frequencies and seasonal temperatures in Sofia, it was found without exception that the frequencies of the types causing cooling are decreasing and vice versa - the frequencies of the types causing warming are increasing. This is evidence that atmospheric circulation, at least with regard to surface anticyclones, has changed in the direction of climate warming.
- Mediterranean surface cyclones impacting Bulgaria do not show an annual trend, their number decreases in autumn and winter, but increases in spring and summer.
- The cyclones north of Bulgaria are increasing statistically significantly on an annual basis, and this is the group of the circulation types with the most significant increase in the period 1871-2020. One of the possible reasons for the significant increase in cyclones located north of the country since the 1970s is related to the Arctic and Polar fronts, which have probably changed their mid-seasonal spatial position in a more northerly direction due to climate warming.

Conclusions on the relation of large-scale circulation processes to atmospheric circulation types:

- The more frequent ridges from the Azores anticyclone (type A4) and at 500 hPa and near the surface, bringing warmer weather over the Balkans, are favoured by warmer surface ocean waters in the Atlantic and Indian Oceans (positive AMO and IOD), by positive Arctic Oscillation (AO) values, which favours zonal circulation over Europe (lower than normal atmospheric pressure in northern Europe and higher in southern Europe), and also logically by higher atmospheric pressure in the western Mediterranean compared to the eastern, which is evident in the two MOi indices.

- The higher frequency of Cnw at 500 hPa over Bulgaria is caused by lower ocean water temperatures in both the Atlantic and Indian Oceans, and also at negative values of AO and NAO, i.e. at prevailing meridional circulation over Europe.
- The seasonal barric centre, most often a ridge of a Siberian or eastern European anticyclone (SLP type A2) is negatively correlated with Atlantic and Indian Ocean temperatures, higher water temperatures in recent decades result in lower frequencies of the circulation types associated with it.
- The Mediterranean surface cyclones affecting Bulgaria are related not so much to the ocean water temperature as to the zonality or meridionality of the atmospheric circulation expressed quantitatively by the indices AO and NAO and their negative relationship to these circulation types. I.e. a higher frequency of these cyclones can reasonably be expected in a meridional circulation over Europe.
- The frequency of the surface cyclones located north of Bulgaria are strongly positively correlated with Atlantic and Indian Ocean water temperatures and therefore their increasing frequency is also a result of global warming as a consequence of warmer temperatures not only of these water basins but also of the world ocean as a whole. This outcome once again proves the rather warming influence of these cyclones for the Central Balkan region, and Bulgaria in particular.

Dissertation Research Contributions

Scientific contribution

Statistically significant positive trends in the frequencies of some and negative trends in the frequencies of other circulation types are found and these changes are assessed in the context of climate change and global warming. The relation between circulation types and the two most important meteorological elements - air temperature and precipitation on the territory of Bulgaria - has been proven. The relation between a number of circulation types and some of the most widely used large-scale circulation processes and how they directly affect climate in Bulgaria through the influence of atmospheric circulation is also demonstrated.

Scientific and applied contributions

The result regarding the cyclicity found in the high troughs at the 500 hPa barric level and their significant relation with the annual rainfall could also be used as a long-term forecast in this important field with a perspective of certain policies on securing the needs and re-evaluation of the priorities in the use of water resources and prevention in the protection of the forest fund of the country.

Scientific-methodological contribution

Contribution to the classification of the atmospheric circulation for the region of Bulgaria is the compilation of a daily classification for a 150-year period (1871-2020), for the first time for two isobaric levels, with the separation of 13 circulation types at the barric level of 500 hPa and 16 types at the sea level using the subjective method of atmospheric circulation classification. The last classification of atmospheric circulation in Bulgaria was carried out back in 1960.

ПУБЛИКАЦИИ ПО ДИСЕРТАЦИОННОТО ИЗСЛЕДВАНЕ

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Table 44. Correlation between circulation types and large-scale circulation indices at 500 hPa.

type	AMO	NAO	AO	IOD_w	IOD_e	PDO	SOI	MOi_{AC}	MOi_{GI}
A1	-0.21	0.24	0.22	-0.13	-0.16	0.05	-0.07	0.09	0.12
A2	-0.26	0.00	-0.04	-0.15	-0.12	0.09	-0.06	0.08	0.15
A3	-0.02	0.24	0.21	0.10	0.11	0.18	-0.18	0.13	0.16
A4	0.22	0.19	0.39	0.23	0.12	-0.07	-0.03	0.42	0.30
A5	-0.21	-0.14	-0.30	-0.25	-0.21	0.02	0.16	-0.19	-0.07
Cnw	-0.16	-0.44	-0.53	-0.22	-0.16	-0.05	0.11	-0.24	-0.36
Cw	0.14	0.03	0.05	0.12	0.15	-0.09	0.13	-0.19	-0.20
Csw	-0.07	0.02	-0.01	-0.01	-0.04	0.01	-0.12	0.10	0.04
Cn	0.23	-0.13	-0.09	0.10	0.10	-0.02	0.06	0.01	-0.04
C	0.00	-0.01	-0.08	0.18	0.12	0.05	-0.09	-0.11	-0.12
Cs	-0.13	0.02	0.15	-0.14	-0.12	0.01	0.03	0.12	0.06
Cne	0.15	0.18	0.23	0.04	0.09	0.05	-0.04	-0.08	-0.10
Cse	0.02	0.16	0.09	0.19	0.13	-0.03	-0.25	0.07	0.09
W.	-0.11	-0.34	-0.45	-0.15	-0.10	-0.06	0.10	-0.24	-0.21
E.	0.14	0.23	0.25	0.12	0.14	0.04	-0.13	-0.05	-0.06

Table 45. Correlation between circulation types and large-scale sea-level circulation indices.

type	AMO	NAO	AO	IOD_w	IOD_e	PDO	SOI	MOi_{AC}	MOi_{GI}
A1	0.01	0.19	0.21	-0.01	-0.11	-0.10	-0.05	0.12	0.01
A2	-0.44	-0.01	-0.28	-0.58	-0.46	0.03	0.11	-0.38	-0.20
A3	0.13	0.18	0.24	0.24	0.18	0.08	-0.17	0.41	0.36
A4	0.56	0.08	0.28	0.54	0.42	-0.04	-0.04	0.40	0.24
A5	0.32	0.15	0.17	0.30	0.27	0.07	0.08	-0.04	-0.04
Mt2	-0.16	-0.04	-0.07	-0.38	-0.24	0.00	-0.02	-0.03	0.03
Mb1	-0.27	-0.03	0.21	-0.31	-0.33	-0.23	0.17	0.07	0.08
Mb2	0.19	-0.06	-0.06	0.37	0.27	0.00	0.19	0.15	0.16
Cw	0.04	-0.32	-0.46	-0.07	0.01	0.03	-0.02	-0.40	-0.35
C	-0.23	-0.13	-0.32	-0.27	-0.10	0.06	0.03	-0.29	-0.25
Csw	-0.07	-0.31	-0.29	-0.14	-0.11	0.02	0.08	-0.08	-0.06
Cs	0.25	0.01	0.08	0.22	0.21	0.12	-0.03	-0.01	-0.11
Cse	0.13	-0.03	-0.06	0.39	0.29	0.05	-0.01	0.03	0.06
Cnw	0.00	-0.17	-0.28	0.10	0.23	0.07	-0.08	-0.27	-0.17
Cn	0.38	-0.12	-0.06	0.43	0.46	0.08	-0.15	0.06	-0.01
Cne	0.36	0.11	0.20	0.58	0.49	0.16	-0.23	-0.00	-0.07
MC.	0.03	-0.35	-0.48	0.02	0.11	0.13	-0.20	-0.34	-0.32
NC.	0.32	-0.03	0.00	0.49	0.51	0.12	0.02	-0.06	-0.09

Table 46. Number of significant correlation coefficients with respect to circulation indices.

Index	AMO	NAO	AO	IOD_w	IOD_e	PDO	SOI	MOi_{AC}	MOi_{GI}
Period	1871-2020	1950-2020	1950-2020	1871-2020	1871-2020	1871-2020	1951-2020	1948-2020	1948-2020
500 hPa	6	3	3	4	3	1	1	2	2
SLP	10	2	7	12	12	1	0	6	4

Table 47. Number of significant correlation coefficients with respect to circulation types.

type	Significant correlat. Coef. 500 hPa	+	-	Significant correlat. Coef. SLP	+	-
A1	3	2	1	0	0	0
A2	1	0	1	5	0	5
A3	2	2	0	5	5	0
A4	5	5	0	6	6	0
A5	4	0	4	3	3	0
Mt2				3	0	3
Mb1				4	0	4
Mb2				3	3	0
Cw	0	0	0	4	0	4
C	0	0	0	5	0	5
Csw	0	0	0	2	0	2
Cs	0	0	0	3	3	0
Cse	2	1	1	2	2	0
Cnw	7	0	7	3	1	2
Cn	1	1	0	3	3	0
Cne	0	0	0	3	3	0
W.	3	0	3			
E.	1	1	0			
MC.				4	0	4
NC.				3	3	0