Climate Variation and Climate Change Projection for Bulgaria

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CLIMATE VARIATION AND CLIMATE CHANGE PROJECTION FOR BULGARIA

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CLIMATE VARIATION AND CLIMATE CHANGE PROJECTION FOR BULGARIA

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INTRODUCTION

The everyday common understanding of climate change is that it describes global warming and its effects on the climate system. In fact, the global warming is only one aspect of climate change during the Holocene, the modern geologic epoch that began about 12 000 years ago. But it is also undeniable that since the Industrial Revolution (1750–1850), many areas of the Earth have warmed and the average temperatures have risen significantly, especially in the last 30–40 years. According to the World Meteorological Organization (WMO), the decade 2011–2020 was the warmest on a global scale, and since the 1980s, each subsequent decade has been warmer than the previous one. The measurements and analyses of the National Institute of Meteorology and Hydrology (NIMH), which is the official representative of Bulgaria with the WMO, show that these trends are also characteristic for our country.

Climate change is gradually being recognized as a major problem facing humanity. The World Health Organization (WHO) calls climate change the greatest threat to global health in the 21st century. Climate migration, with its severe consequences, can create more and more real prerequisites for military conflicts. The anthropogenic pressure on the climate system associated with increased emissions of greenhouse gases, aerosols and particulate matter in the atmosphere, deforestation, aggressive land use, large-scale construction, etc., is now seen not as potential but as a very likely cause of global warming. The changes in the cryosphere, as well as the more frequent and more extreme weather and climate events with severe socio-economic consequences, are also attributed to human activities. These negative effects on the climate cannot and should not be ignored, but it is of utmost importance that global trends are correctly assessed at a regional level, separately for each country, because climate change has different manifestations in different parts of the globe.

NIMH's active participation in many projects funded by European programs to assess the impact of climate change on the environment, agriculture, water resources, etc., as well as in the development of mitigation and adaptation strategies, is an indicator of the level of scientific and applied activities carried by our staff (http://www.meteo.bg/bg/projects, https://hydro.bg, https://cris.nacid.bg/public/organization-preview/130).

In the 133-year history of NIMH, climate research has always had a special role due to its indisputable scientific and applied importance both for the development of climatology itself in Bulgaria and for the application of a physically based approach in preparing climate analyses and assessments for various economic sectors. A precise review of the scientific publications over the years is made in the monograph "History of climate research at the National Institute of Meteorology and Hydrology" (Branzov, ed., 2020).

The main purpose of the overview analysis presented here is to contribute to a clearer understanding of climate changes in Bulgaria. It introduces readers to the results of climate assessments and research by NIMH scientists and specialists, published over the last 10–15 years in refereed national and international journals and conference proceedings. We have summarized these results in the context of the main directions of scientific and applied activity of NIMH – meteorology, hydrology and agrometeorology. This edition is based mainly on the results of the analyses summarized in the book "The changing climate of Bulgaria – data and analyses" (Marinova and Bocheva, eds., 2023). The book presents the current climate trends (1961–2020) and the projected future climate of the country under various climate change scenarios until the end of the 21st century.

Climatic changes also have many aspects of local manifestation, which are the subject of scientific research and scientific-applied developments of NIMH in the field of atmospheric pollution, forecasting extreme events, marine meteorology, hydrogeology, etc. Results of climate analyses for specific meteorological and hydrological events, for which no future climate projections have been made at the moment, are also briefly presented here. They complement the understanding of Bulgaria's changing climate and give an idea of the diversity of climate research conducted at NIMH.

In most NIMH studies conducted after 2021, as well as in our monthly and annual hydro-meteorological bulletins, available at https://bulletins.cfd.meteo.bg, we use climate normals for the last WMO reference period (1991–2020). The main reference period used in the climate assessments presented here is 1961–1990. This does not change the trends and conclusions of the study itself. We explicitly state the specific reference period used for each analysis.

I. PAST AND PRESENT CLIMATE

I.1. Global and regional characteristics

Fluctuations in the surface temperature of the Earth occur naturally in the climate system but can be induced (forced) by natural as well as anthropogenic factors. Distinguishing them is essential for assessing the range of unforced variability and the sensitivity of the climate system to different forcing factors. Reconstructions of global mean temperature (GMT) of the planet's surface use global collections of temperature-sensitive paleoclimate "records" in corals, pollen, ice cores, tree rings, cave formations, sediments, etc. Knowledge of GMT fluctuations in past epochs is critical to understanding future climate change. Instrumental observations cover a historical period that is too short, which increases the uncertainty of estimating the relative contribution of different forcing factors and the ability of climate models to simulate the observed climate phenomena with sufficient accuracy. Although most global temperature reconstructions confirm the extraordinary rate and magnitude of warming in recent decades, there are significant discrepancies between them in terms of the magnitude and partly in the dating of past temperature fluctuations. The Past Global Changes (PAGES) project uses seven different statistical methods to reconstruct GMT over the past 2000 years (1–2000 AD) and the improved version of HadCRUT4 (Cowtan&Way, 2014) as a reference data set.

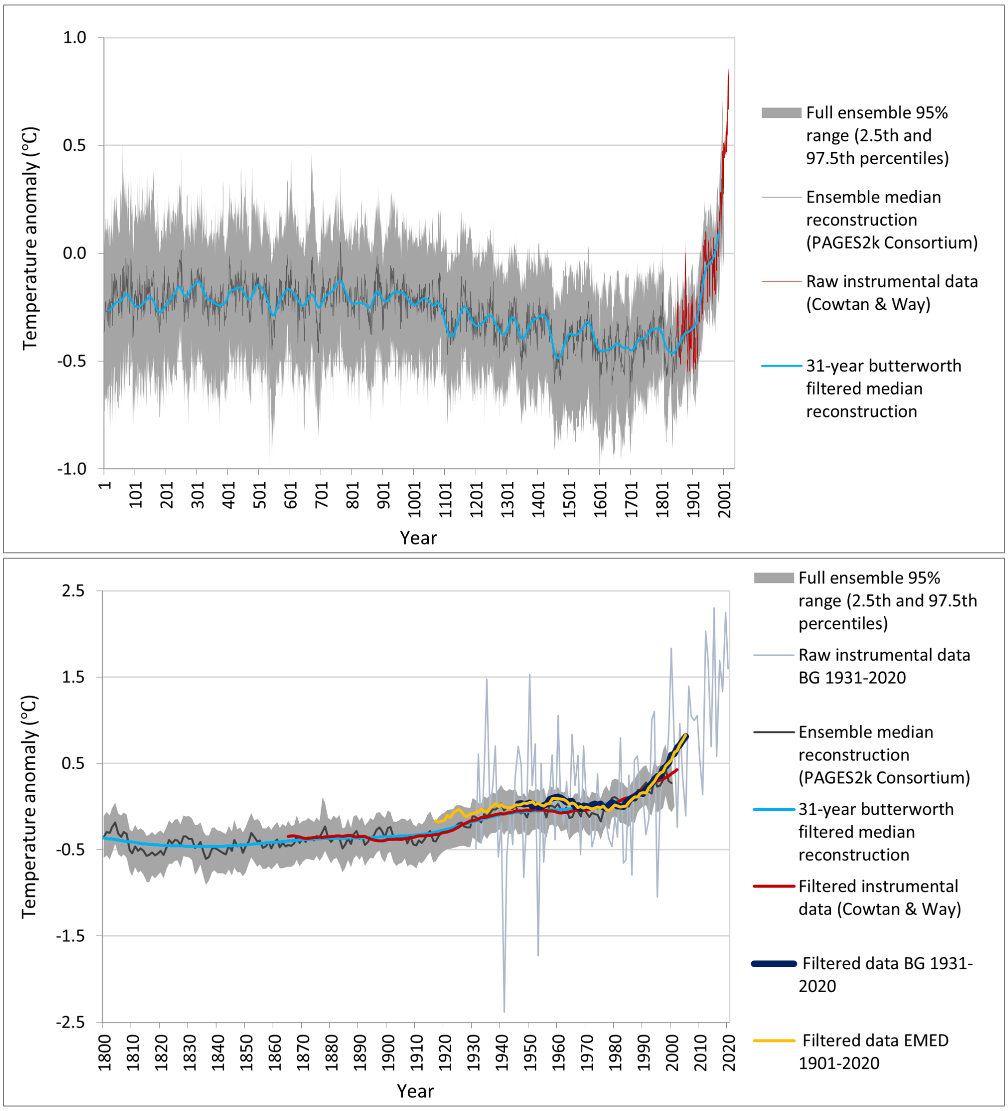


Fig. I.1-1. Top: annual GMT anomaly in the New Era (1–2020 AD) relative to the norm for the period 1961–1990. Bottom: annual anomaly of the mean air temperature for Bulgaria in the period 1931–2020 (BG 1931-2020), the mean for EMED temperature in the period 1901–2020 (EMED 1901-2020) and GMT in the period 1800–2020 compared to 1961–1990 norm; the mean annual temperature is calculated for the period May-April (for example, for 2020 it was calculated from May 2020 to April 2021); median and 95% range (between 2.5th and 97.5th percentile) of GMT is calculated on the full ensemble of reconstructions across all PAGES data and methods (source: www.ncdc.noaa.gov/paleo/study/21171); data are filtered with a 31-year moving average unless otherwise stated.

Global and regional long-term temperature variability is generally underestimated or overestimated by CMIP5 models in climate simulations of the recent past, according to the PAGES 2k Consortium (2019) analysis. The evolution of the GMT shows that the first millennium was warmer than the second, except for the 20th century (Fig. I.1-1). All reconstructions show a significant cooling trend in the second millennium before 1850, followed by rapid warming during the industrial era. The warmest 10-, 30- and 50-year period of the last two millennia falls in the second half of the 20th century. In particular, the long-term trend within the 20th century includes two distinct periods. The first reflects warming at the turn of the century, which has been shown to be due to a combination of forcing factors (including anthropogenic) and the natural multidecadal variability of the climate system. The second is the modern period of strong warming, which has lasted from the mid-1970s to the present day. Temperature trends during these two periods are outside the range of pre-industrial variability. Warm anomalies around 1320, 1420, 1560, and 1780, cold anomalies around 1260, 1450, and 1820, and periods of reduced variability during the cold 17th century and relatively warm 11th century are captured by both the reconstructions and the simulations. These similarities between reconstructions and models suggest a dominant influence of external forcing on the multidecadal variability of the GMT. The correlation of CMIP5 with the data is particularly strong between 1300 and 1800. The weaker agreement before 1300 can be explained mainly by the underestimated influence of volcanic activity (e.g., the 1109 eruption, followed by a distinct decrease in GMT, missing from the model datasets). The discrepancies in the 19th century are likely due to the simulations overestimating the response to the 1809 and 1815 eruptions. The relationship between solar forcing and GMT is weaker, suggesting that solar variability (as currently reconstructed) cannot explain temperature variation during the New Era, although it was found on multidecadal time scales at the regional level, as well as on multi-century time scales in the Northern hemisphere.

Fig. I.1-1 (bottom) presents a more detailed picture of temperature anomalies after 1800. For Bulgaria, the mean temperature in the period 1931–2020 (BG 1931-2020) was calculated from observational data, while the average regional temperature in the period 1901–2020 (EMED 1901-2020) was calculated on the CRU TS4.07 dataset (http://badc.nerc.ac.uk/data/cru). Here, EMED denotes the western part of the Eastern Mediterranean region (35° N – 50° N; 15° E – 35° E), in which the Balkan Peninsula falls. What is noteworthy is the strong correlation between instrumental and reconstructed data and a significant increase in the warming rate in the Eastern Mediterranean in recent decades. The presented results confirm that the observed temperature changes in Bulgaria follow the regional trends.

The fluctuations of the mean annual air temperature in Bulgaria in the period 1931–2020 compared to the climatic norm 1961–1990 show an increasing, statistically significant trend of 0.14 °C/10 years. Until the mid-1980s of the last century, the deviations from the norm vary from -1.6 °C (1942) to +1.0 °C (1934), with alternating periods of cooling and warming. However, since the beginning of the present century, there have been practically no negative deviations from the norm (except for 2005), and after 2011 there are none below 1 °C. The temperature anomaly of +2 °C for 2019 is a record in the considered 90-year period (Fig. I.1-2). Long-term temperature change is consistent with the observed global trend (IPCC, 2014; 2021a). Warming is established in all seasons.

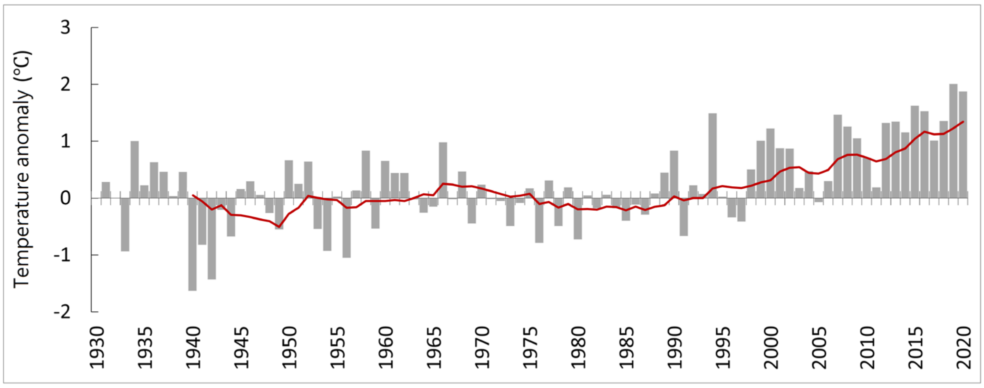


Fig. I.1-2. Deviations in the mean annual air temperature for Bulgaria for the 1931–2020 relative to the 1961–1990 norm. The red line shows the 10-year moving average.

Fluctuations in the mean annual precipitation sums in the period 1931–2020, relative to the norm (1961–1990), do not show a statistically significant trend. The longest periods of drought were recorded in the 1940s and the last two decades of the 20th century (Fig. I.1-3). The driest years were 1945 and 2000, and the wettest were 2005 and 2014 (50–60% above the national average).

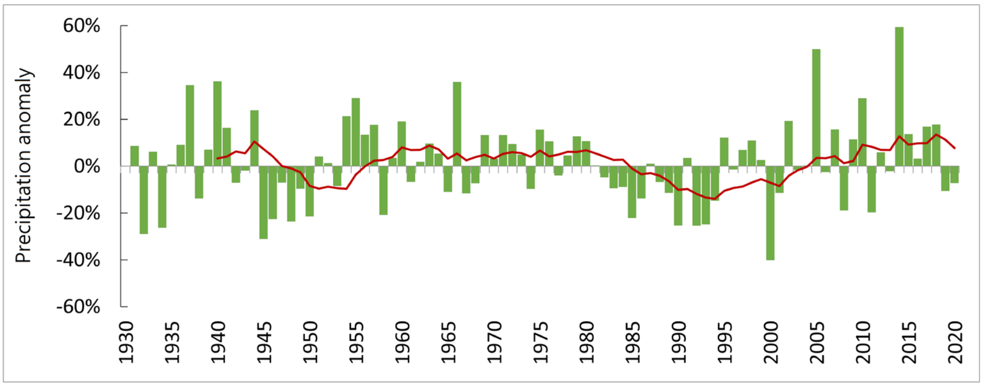


Fig. I.1-3. Deviations in the mean annual precipitation sums for Bulgaria for the period 1931–2020 relative to the 1961–1990 norm. The red line shows the 10-year moving average.

The combined plot of mean annual temperature and total annual precipitation anomalies for the period 1931–2023 relative to the norms for the period 1991–2020 confirms the general warming trend, as well as the lack of a clear signal of change in precipitation (Fig. I.1-4). The norms for the current period 1991–2020 are higher than those for the period 1961–1990, both for temperature (by about +0.8 °C) and for precipitation (about +8%). Most of the years since the beginning of the 21st century have mean annual temperatures above normal, with 2023 being the warmest year in Bulgaria since 1930, followed by 2019 and 2020.

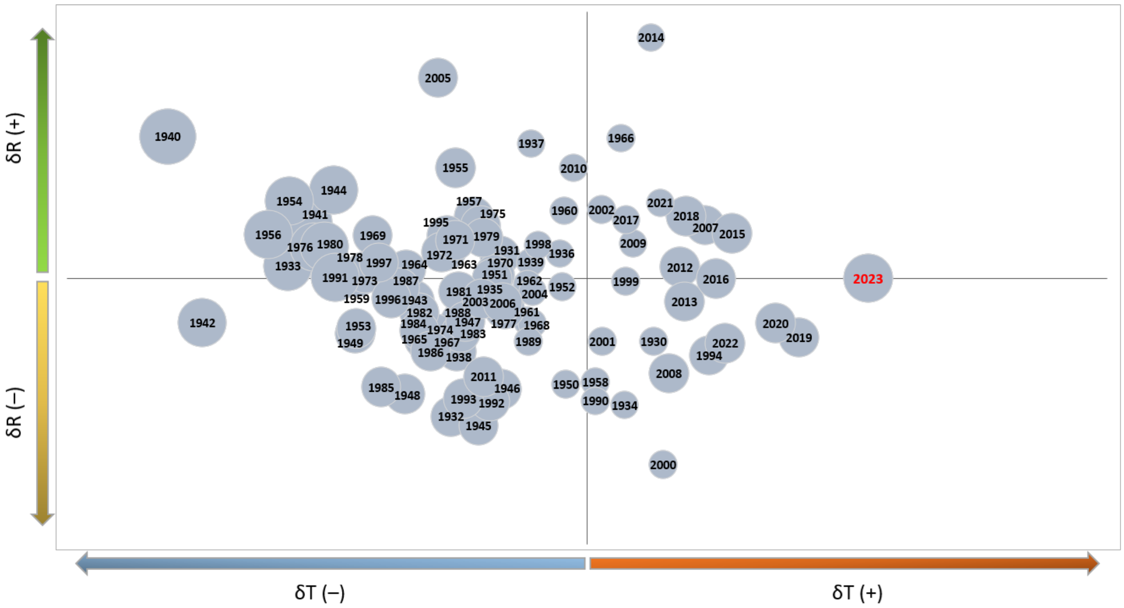


Fig. I.1-4. Combined diagram of the deviations of the national mean annual temperature and annual total precipitation (1931–2023) from the norms for the period 1991–2020. The size of the bubbles is proportional to the absolute magnitude of the temperature anomaly.

I.2. Present climate in Bulgaria

Bulgaria features unusually various climate conditions due to the influence of the strongly different continental and Mediterranean climates and the diverse landscapes. The climate is temperate, with four distinct seasons and a few altitudinal zones. According to the climate classification accepted in NIMH, the territory of Bulgaria is divided into two climatic areas (European-Continental and Continental-Mediterranean), four climatic subareas (Moderate-Continental, Transition-Continental, South-Bulgarian and Black-Sea), and twenty-five climatic regions, which include the corresponding coastal and mountainous zones.

As a major climatic factor, the latitude determines the levels of heat balance and, thence, the affiliation of the country to the regions with warmer climates in Europe. The intra-annual course of insolation has a well-pronounced seasonality. Because of the distance from the ocean, the Atlantic air masses reach the country chilled during the cold half-year and overheated in the warm half-year. A comparatively large and compact area of the Balkan Peninsula advantages the formation of local, continental air masses, which during the summer become almost like tropical air, and during the winter – like cold continental air. The short distance to the Mediterranean Sea enhances the climate differences between North and South Bulgaria. Despite the immediate proximity to the Black Sea, the influence of the sea is limited to the formation of marine climate in a narrow coastal area (20–40 km) and some peculiarities of atmospheric circulation patterns, mainly in the cold half-year. High mountains serve as barriers for the air masses transfer, thus determining the distribution of precipitation.

In the context of a changing climate, the Köppen-Geiger classification algorithm has proven to be an effective tool for assessing the extent and trends of climate change, thanks to the development of the global system for collecting, processing and providing climate data, as well as methods for spatio-temporal analysis. According to the climate classification of Köppen-Geiger, three main types of climate are distinguished in Bulgaria (Fig. I.2-1): 1) temperate (C), which can be without a dry season, with hot (Cfa) or warm (Cfb) summer, or Mediterranean-type – with dry and hot (Csa) or warm (Csb) summer; 2) boreal (D, boreal), continental type without dry season – with warm summer (Dfb) or cool summer (Dfc); 3) polar (E, polar) – alpine tundra type (ET). The temperature of the coldest month defines the boundary between temperate and boreal climates, which is -3 °C in the classical Köppen-Geiger classification scheme.

The predominant climate type during the period 1961–1990 was Cfb (61%), followed by Cfa (28.7%). In total, about 93% of the country's territory falls into the group of temperate climates. The Mediterranean influence is most pronounced in the southernmost regions – the type Csa (1%) predominates along the Eastern Rhodope rivers, and Csb (2.0%) is manifested mainly in the lower parts of the Eastern Rhodopes and Strandja, incl. the Strandja coast. Compared to earlier studies summarized in Stanev et al. (1991), in the period 1961–1990, steppe climate conditions did not appear. The relatively wetter types Cfa and Cfb replaced the Mediterranean Csa and Csb (characterized by a pronounced dry summer) to a large extent or entirely the Struma valley, the Black Sea coast, the Burgas lowland and some low-lying areas in South-East Bulgaria. In the low parts of the mountains (up to about 1000 m on the northern slopes and up to 1500 m on the southern slopes), as well as in some closed valley fields, the Dfb type (4.9%) is widespread. In the middle mountain belt, the Dfc type (1.8%) is prevalent, and above 2200 m – the alpine ET type (0.7%).

In the period 1991–2020, significant changes occurred in the distribution of the main subtypes. The transition from a colder to a warmer and/or drier climate has affected about 36% of the country's territory, and the relative change in the mountain climate subtypes shows a significant decrease (by 60–70%) in the alpine climate areas (Malcheva&Bocheva, 2023).

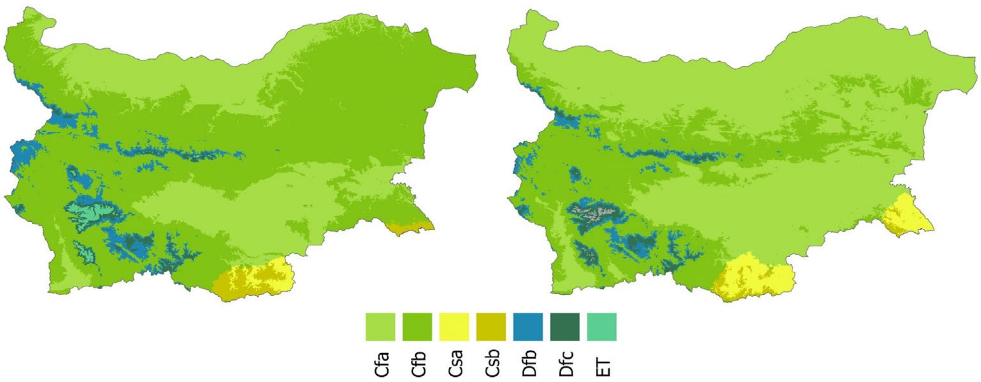


Fig. I.2-1. Köppen-Geiger climate classification (horizontal resolution: 30 arcsec) for the periods 1961–1990 (left panel) and 1991–2020 (right panel).

Circulation conditions in the first half of the 20th century, and their influence on the country's climate, are summarized in Stanev et al. (1991) based on a comprehensive analysis and classification of synoptic conditions over a relatively long period. The Mediterranean cyclones are most frequently observed from November to May/June; they significantly influence the weather and climate in South Bulgaria. The Atlantic cyclones rarely reach the central areas of the Balkan Peninsula, but they influence the weather and climate in North Bulgaria; their frequency is highest from February until June (with a maximum in May). The northwestern anticyclones appear most frequently from the middle of spring until the middle of summer and usually cause cold spells in late spring and early summer. The western anticyclones cause warm spells in the winter and cold spells in the summer. The southwestern anticyclones usually bring tropical air masses, the highest temperatures and droughty spells from July to September. The arctic anticyclones (moving from north/northeast towards southern continental areas) bring prolonged snowfalls and snowstorms in February and March. The formation of local anticyclones in the ridges of northeastern ones causes the lowest temperatures in Bulgaria.

To classify the atmospheric circulation over the country in the period 1961–2020, the Jenkinson-Collison objective method is used (Jones et al., 1993). Circulation conditions on a daily basis are represented by 11 main types, which characterize the type of surface airflow – two rotational, cyclonic and anticyclonic (denoted by C and A, respectively), eight advective (on the octahedron scale for the wind direction: N, NE, E, SE, S, SW, W and NW) and one class covering weak- and no-gradient synoptic situations (LF). Fig. I.2-2 presents the relative seasonal frequencies for each circulation type (Malcheva et al., 2023). In general, the seasonal distributions agree well with the results in Stanev et al. (1991). The greatest in all seasons and annually is the recurrence of the anticyclonic type. The repeatability of the LF type has a distinct seasonal course: a minimum in winter and a maximum in summer. In autumn and spring, as well as annually, the frequency of LF is comparable to that of the cyclonic type. The frequency of advective types, in general, is about 40%. In summer and autumn it is lower (30–35%), and in spring and winter it reaches 45–50%. The frequency of the cyclonic type circulation decreased in all seasons in the period 1991–2020 (compared to 1961–1990) except autumn, with the most significant decrease in spring (by 3–4%). This result agrees well with some regional studies, e.g. Lionello et al. (2016), who found significant negative trends in winter and spring over the northeastern part of the Mediterranean region (including South-Eastern Europe). The largest absolute value difference between the two periods (~6%) is the reduction of the anticyclonic circulation in autumn, and the largest relative differences (up to ±36%) are mainly associated with advective types. These changes are generally in sync with the results of the extensive study by Kučerová et al. (2017), in which the trends in the frequency of circulation types were analyzed based on the methodology and data of COST733 Action "Harmonization and applications of classifications of meteorological types for European regions". Significant trends dominate in winter and for types with a relatively small share (usually < 20%), with the decrease being most often associated with the southern and western sectors and the increase – with the northern and eastern sectors.

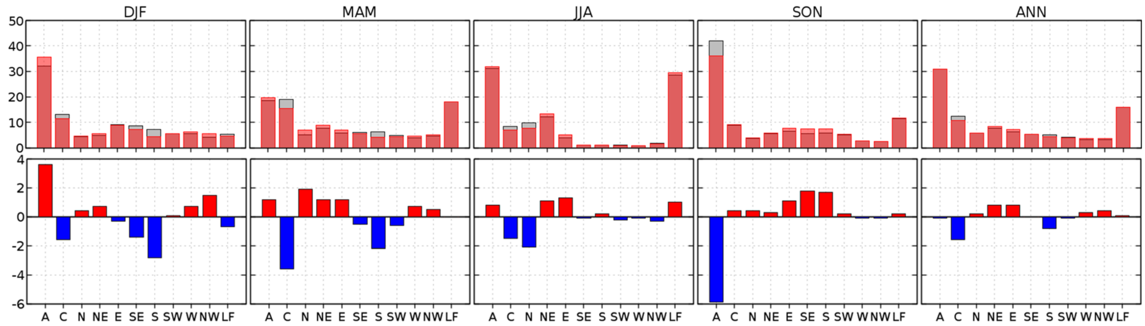


Fig. I.2-2. First row: multi-year seasonal and mean annual recurrence (in %) of the 11 circulation types for the periods 1961–1990 (in gray) and 1991–2020 (in red). Second row: absolute difference between repetitions of the second period compared to the first.

A number of studies in recent years have examined changes in the temperature and precipitation regime in the context of changing circulation conditions over Europe. Otero et al. (2017) associated the increase in the frequency of E and LF types in summer with higher temperatures in South Europe, while in winter, the easterly transfer leads to negative temperature anomalies. The authors predict an increase in the frequency of easterly component types and low-gradient flow situations in summer until the end of the century, i.e. more warm days can be expected. According to Herrera-Lormendez et al. (2023), the increase in the frequency of A, NE, E and SE types in summer favors the occurrence of more dry days. An increase in LF-dominated days is also predicted, which will also intensify droughts over South Europe in the coming decades.

I.2.1. Mean air temperature and precipitation

In a large part of the country, seasonal temperatures and rainfall have changed significantly since the middle of the 20th century. Temperature changes include both an increase in average seasonal temperatures and more frequent temperature extremes. In the precipitation regime, changes are observed both in the seasonal amounts and in the distribution of light, moderate and heavy precipitation.

Fig. I.2.1-1 and Fig. I.2.1-2 present the spatial distribution of the annual and seasonal norms of the average air temperature for the periods 1961–1990 and 1991–2020, as well as the absolute difference between them. Temperature conditions in the period 1961–1990 are close to those of the first half of the 20th century. The coldest are the mountain areas with mean annual temperatures of -3 °C to +8 °C, followed by the high fields in West Bulgaria (9–10 °C) and the areas exposed to the more intense invasion of continental air masses in winter, mountainous and hilly regions (10–11 °C). Areas with a more pronounced Mediterranean influence are well defined with annual temperatures above 12–13 °C.

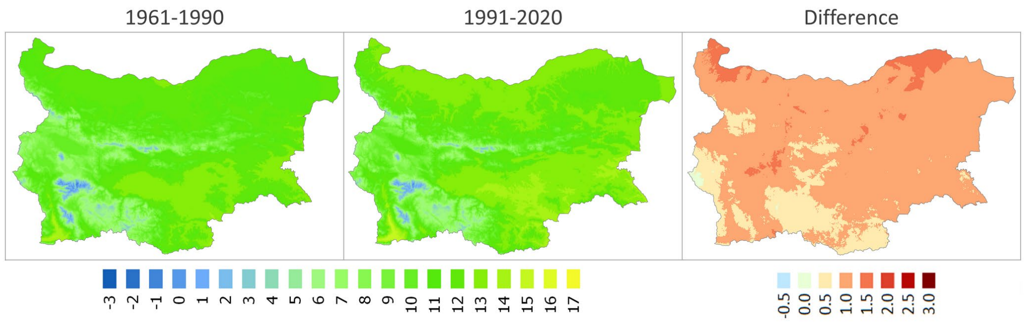


Fig. I.2.1-1. Spatial distribution of the average annual temperature for the time periods 1961–1990 and 1991–2020, along with the temperature difference (°C) between them.

Winter is colder in regions with a continental climate. The average temperature in January is negative in the Danube plain and in the high fields of West Bulgaria (from -2.3 °C to about -1 °C), but is positive in the Upper Thracian Lowland (0–1.5 °C) and the Southern Black Sea (above 3 C). In the mountains, the temperature decreases with altitude by 0.3–0.4 °C/100 m. In spring, the temperature differences between the northern and southern parts of the country decrease, except for the southernmost parts. The average temperature in April is 10–13 °C (below 10 °C in the valleys and above 13 °C in the southernmost areas). In mountainous regions, the temperature drops by an average of 0.6–0.7 °C/100 m. In summer, the temperatures in the north and south of the Balkan Mountains are almost the same. The average temperature for July is around 21–24 °C in the plain areas (up to 24–25 °C along the Struma valley) and significantly lower in the high fields of West Bulgaria (19–20 °C). The temperature along the Black Sea is about 22 °C, and in the mountains, it decreases with altitude by about 0.7 °C/100 m. The average temperature in October is the lowest in the Danube Plain and the high fields of West Bulgaria (10–12 °C). Autumn is warmer in the Upper Thracian Lowland (12–13 °C), along the Black Sea and in the southernmost regions (13–14 °C). In mountainous regions, the temperature drops by 0.5 °C/100 m.

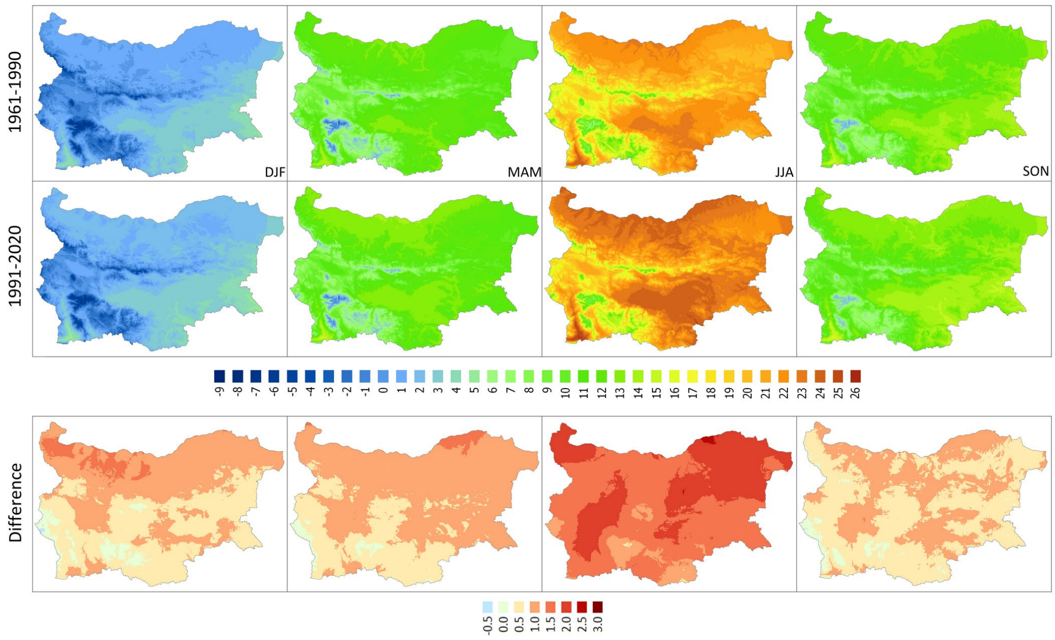


Fig. I.2.1-2. Spatial distribution of average seasonal temperatures for the periods 1961–1990 and 1991–2020, along with the temperature difference (°C).

In the period 1991–2020, the average annual temperature in Bulgaria increased by 0.8 ºC compared to the period 1961–1990. Warming in the mountains is generally weaker, while in some high fields, the Danube regions and places along the river valleys (mainly in North Bulgaria), the difference is over 1.0 °C. The increase in winter temperatures is more significant in North-West and Central-North Bulgaria (by more than 1 °C). In the rest of the northern part of the country, the high fields in West Bulgaria (without the Pernik field) and some places along the valleys of the larger rivers in South Bulgaria, temperatures increased by 0.5–1 °C. The increase in spring temperatures in the second period is about 0.7 °C on average for the country. Compared to winter, moderate warming (0.5–1 °C) also covers South-East Bulgaria, and more significant warming (over

1.0 °C) is found only in separate areas around the Danube River. Summer is the season with the most significant differences between the two periods – 1.5 °C on average for the country (in places, mainly in North Bulgaria, over 2 °C). Autumn is the season with relatively the smallest differences. The increase in temperatures is in the range of 0.1–0.5 °C almost in the whole country (only in some places it exceeds 1 °C). In all seasons, except for summer, minor negative anomalies are registered in some mountainside and mountain areas, mainly in the southern part of the country.

Fig. I.2.1-3 and Fig. I.2.1-4 present the spatial distribution of the annual and seasonal precipitation climate norms for the periods 1961–1990 and 1991–2020. The precipitation regime in the first period did not change significantly compared to the first half of the 20th century. Average precipitation varies significantly – from 400–500 mm along the Black Sea (except for its southernmost part), some areas in the northeastern and central parts of the Danube Plain and the Upper Thracian Lowland, to over 1100–1200 mm in the mountains. The annual amount of precipitation increases with altitude up to about 2000 m. The vertical gradient mainly depends on the exposure of the mountain slopes and the orographic features (the average for the country is 20–40 mm/100 m).

In the Moderate-Continental climate subarea, winter precipitation is the smallest (18–20% of the annual amount). It varies from 100–110 mm in the lowlands up to 190–200 mm in the mountains. In the Continental-Mediterranean climate area, the winter precipitation is the largest – around and over 30% of the annual amount (150–300 mm). In spring, rainfall in areas with a continental regime increases to 25–27% of the annual amount, while in areas with a Mediterranean rainfall regime, it decreases to about 23–25%. In the Moderate-Continental climate subarea, summer rainfall is about 30–35% of the annual amount. The increase in precipitation with altitude is pronounced, especially in the Balkan Mountains, Rila and Vitosha. In the regions with a Continental-Mediterranean climate, the summer precipitation is the smallest – about 20% of the annual amount. In autumn, in the Continental-Mediterranean climate area, precipitation is about 25% of the annual amount, and in regions with a continental regime, it is less compared to the summer and spring ones.

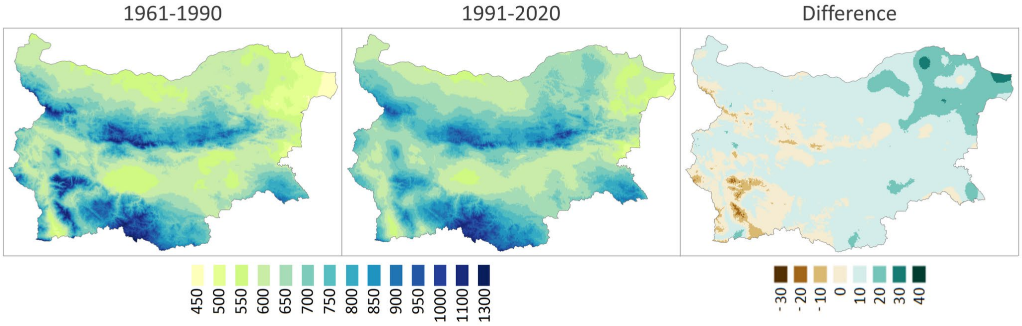


Fig. I.2.1-3. Spatial distribution of the annual precipitation amounts (mm) for the periods 1961–1990 and 1991–2020, along with the relative difference between the second and first periods in %.

In contrast to the mean annual air temperature, no significant change was observed in the annual amount of precipitation during the period 1991–2020 for the country as a whole due to the different signs of change in individual regions. Precipitation decreases significantly in the high parts of the mountains (up to 30%), while in North-East Bulgaria, the increase in precipitation reaches up to 40% in some places. However, after 1990, there were changes in the precipitation regime and a tendency to increase the contribution of heavy, potentially dangerous precipitation (≥ 30 mm/24 h) to the total annual precipitation, while the contribution of weak (≤ 5 mm/24 h) and moderate (5–15 mm/24 h) precipitation decreases. The increase in torrential potentially dangerous rainfall (≥ 60 mm/24 h) is statistically significant for North-East and Central-South Bulgaria.

Regarding the seasonal precipitation sums, excluding autumn, the differences between the two periods for most parts of the country are about ±10%. In winter, precipitation decreases in the high parts of Rila, Pirin and the Balkan Mountains, and in South-West Bulgaria by over 20% (-40% on peak Cherni Vrah), but in North-East Bulgaria and along the Black Sea, it increases by about 10–20%. In the second period, summer precipitation increased by more than 25% in the northeasternmost regions, while in the high parts of the mountains, it decreased by 10–15% and more. Autumn is the season with the largest increase in precipitation for the period 1991–2020 for almost the whole country (over 15% on average), except for the higher parts of the mountains. The most significant is the increase in autumn precipitation in North-East Bulgaria – between 25 and 40% (in some places up to 50–60%).

A suspected reason for the decrease in seasonal precipitation in winter, spring, and summer is the reduced frequency of cyclonic-type circulation that favors precipitation. The significant decrease in the anticyclonic type in autumn can be associated with increased seasonal precipitation.

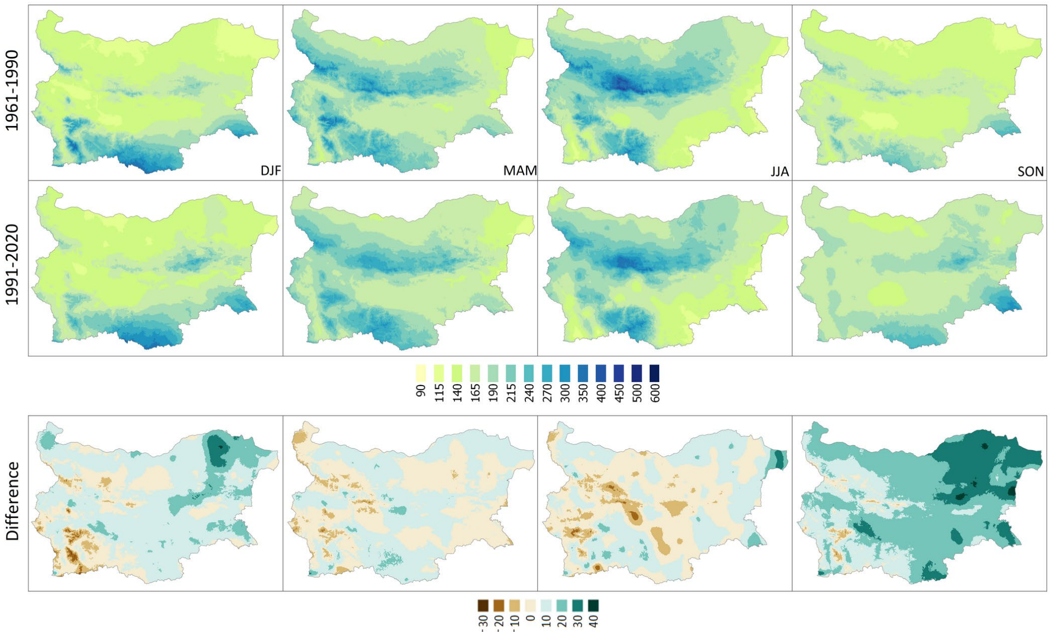


Fig. I.2.1-4. Spatial distribution of the seasonal precipitation amounts (mm) for the periods 1961–1990 and 1991–2020, along with the relative difference between the second and first periods in %.

I.2.2. Agrometeorological studies

Studies on the fluctuations and changes of the main meteorological elements are decisive for the development of agriculture by changing the technologies in our country and around the world. The assessment of environmental conditions and their influence on the growth, development and productivity of agricultural crops is carried out in relation to their biological requirements for the main factors – light, heat and water. Agroclimatic indicators are used for this purpose. They represent a quantitative expression of the dependence between the growth and development of plants and climatic factors. The requirements of plants to the environmental conditions change during their biological cycle. Therefore, the indicators are determined both for the entire vegetation period and for separate interphase periods. Dormant conditions are also an important part of characterizing agrometeorological conditions. To determine them, parallel data from annual, continuous observations on the growth and development of plants and accompanying meteorological conditions are used (WMO, 2010).

I.2.2.1. Changes in thermal conditions and precipitation during the growing season

The heat and humidity regime of the environment is one of the most important factors in the complex meteorological conditions that determine the types of plants that can reach full maturity in a given territory and the rates of their development. Thermal conditions determine the duration of the growing season, which affects the growth, development, and productivity of agricultural crops, as well as the possibility of obtaining a larger yield from one crop. The growing season for each crop is limited between the spring and autumn sustained passage of the mean diurnal air temperature through the biological minimum.

Thermal conditions are characterized by the average monthly air temperatures during the growing season, the average dates of permanent transition of the average daily air temperatures above and below the biological thresholds for the different groups of agricultural crops, the temperature sums during the period between these dates and the duration of the frost-free period. Moisture conditions are characterized by the amounts of precipitation during the individual stages of the development of agricultural crops, the total water consumption, the relative humidity of the soil, as well as by complex indicators.

The results presented refer to the period 1986–2015. The reference period used in the analysis is 1961–1990. The results are summarized according to the Bulgaria territorial dividing at the NUT2 level of Eurostat.

Three biological minimums, according to requirements for temperature conditions of agricultural crops in Bulgaria, have been adopted: 5 °C for low-sensitive ones (wheat and barley, oats, peas, lentils, etc.), 10 °C for moderate ones (sunflower, maize, bean, and soybean) and 15 °C for heat-loving crops (cotton and other heat-loving crops). Research shows that the actual biological minimum of each crop is different. Adopting common values by groups of crops allows an agroclimatic assessment for each group.

The dates of permanent transition of air temperature across 5 °C in spring and autumn determine the duration of the growing season for wintering cereals. During the period 1986–2015, they occurred earlier with 3–9 days in North Bulgaria and 3 days in South Bulgaria. Deviations in the autumn permanent transition through 5 °C vary between -4 and +4 days.

The period with temperatures above 5 °C in the agricultural regions of the country is 235–300 days on average. This period is shortest in the western part of the Pre-Balkan and in the Sofia Valley. It is the longest in South Bulgaria, except the western part of the Upper Thracian Lowland. The deviation from the reference period shows an increase of 9 days, with the exception of some parts in South-East Bulgaria, where a decrease up to 5 days is observed.

The period with temperatures higher than 10 °C varies between 191 and 263 days. Its duration in North-West and North-East Bulgaria is between 200 and 220 days, and in the southern parts of the country – between 230 and 240 days. Deviations from the reference period indicate an extension of the actual growing season by one week. Results show that the extension of the growing season is associated with the earlier transition of air temperature through biological thresholds in spring.

The heat resources are assessed quantitatively by the sum of the average daily air temperatures during the growing season. In the period 1986–2015, an increase in temperature totals by 200–420 °C was observed mainly in the north and southwestern parts of the country (Fig. I.2.2-1).

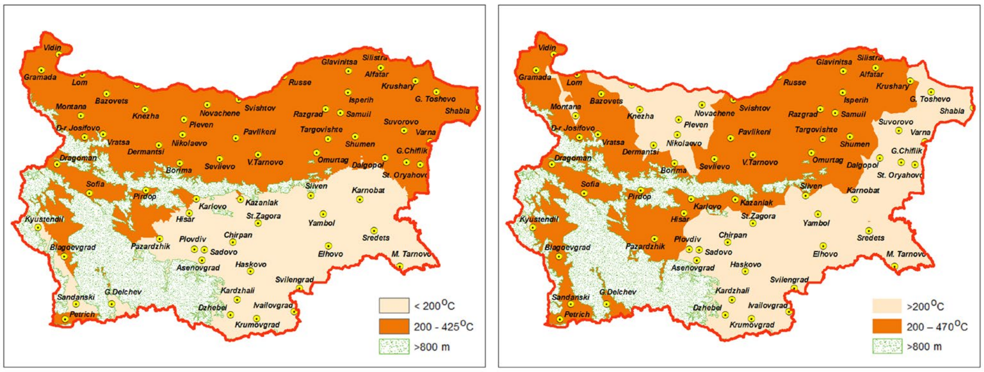


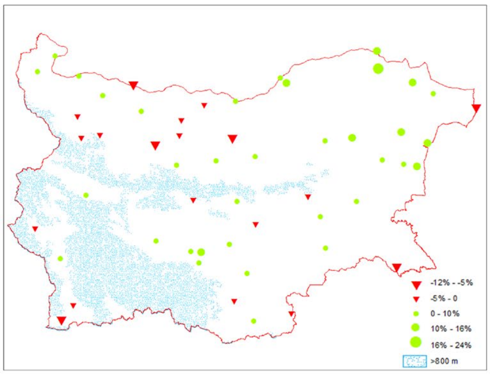
Fig. I.2.2-1. Deviations of active temperatures sum during the period with temperatures higher than 5 °C (left panel) and 10 °C (right panel)

Deviations in monthly rainfall totals during the growing season for the study period show a significant increase in September and October and a decrease in April, May and June. Predominantly negative deviations in the monthly precipitation totals and positive deviations in the average monthly temperatures deteriorate the agrometeorological conditions in four of the six regions, except North-West and Central-South Bulgaria.

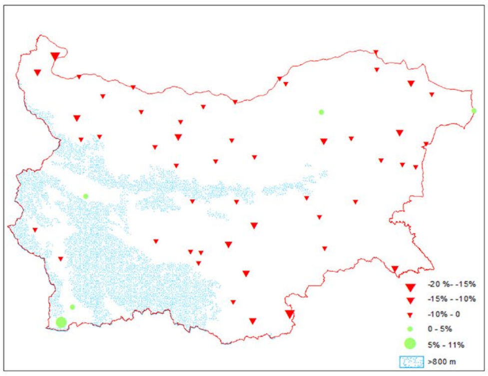
From the point of view of agrometeorology, the moisture conditions are characterized by the sums of precipitation in three periods: October-March, April-June and June-August. The first period is the autumn-winter period of moisture accumulation in the soil. These water supplies provide the soil water reserves for the growth and development of the plants after the restoration of the spring vegetation. The second period, April-June, characterizes the water assurance for the formation of yield from wintering crops. The precipitation amounts during the third period, June-August, characterize the soil moisture conditions during the final yields' formation from spring crops.

An increase of more than 10% in the precipitation totals during the period October-March in North-East Bulgaria was found. This is favorable because, during the last century, the region was characterized by lower rainfall and higher soil moisture deficit during the period of moisture accumulation. A decrease in precipitation totals is observed in Central-North, East and South-West Bulgaria. Previous studies for the period 1971–2000 showed that at the end of the period of soil water accumulation in the central part of the Danube Plain, full saturation was reached in the root zone. A 5–12% decrease in precipitation can lead to a 5–7% decrease in soil water reserves (Fig. I.2.2-2).

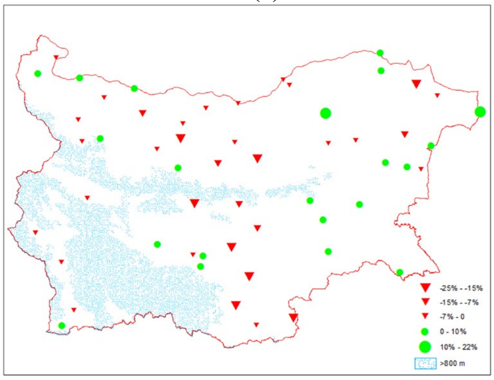
In the second period, April-June, the deviations of the precipitation totals are mostly negative, reaching 10–15% in Central and North-East Bulgaria. The biggest decline was observed in the northwesternmost regions (Vidin, 16%) and the southernmost regions (Ivaylovgrad, 20%).



(a)



(b)



(c)

Fig. I.2.2-2. Precipitation deviations during the periods: (a) October-March; (b) April-June; (c) June-August

The third period, June-August, is characterized by a significant decrease in precipitation in Central-South Bulgaria and part of the Danube Plain. The deviation varies between 7 and 25%. An increase of more than 10% in the amount of precipitation is observed in individual stations in North-East Bulgaria.

I.2.2.2. Changes in soil moisture and evapotranspiration

Chernozems and smolnitsa soil types occupy little more than 26% of Bulgaria's arable land. The chernozem zone is located in the Danube Plain, and the smolnitsa is a specific soil type for South Bulgaria. In the study of soil moisture reserves in representative stations of the chernozem and smolnitsa zone during the period 1981–2010 and their comparison with the period 1951–1980, made for three soil layers 0–20 cm, 0–50 cm and 0–100 cm, a decrease of up to 12% was found in the amount of soil moisture reserves. This decrease is clearly expressed in the agrometeorological stations in both parts of the country – South and North Bulgaria. The decrease is greatest in January and February, which leads to a deficit of moisture reserves at the beginning of the growing season in spring.

Based on data from 60 meteorological stations representative of the agricultural area of the country, the monthly values of reference evapotranspiration were calculated according to the FAO Penman-Monteith formula for the period 1971–2010. The analysis by stations using the Mann-Kendall test (Kendall, 1938; Mann, 1945) proves the existence of a tendency to increase the values of evapotranspiration (at the level of statistical significance α=0.001) both for the period July-August and for the potential vegetation period April-September.

The multi-year average values of reference evapotranspiration for the period 1981–2010 are distributed over the territory of the country as follows: in a dry year (75%) – from 560 to 890 mm, in a normal year (50%) – from 590 to 860 mm, and in a wet year (25%) – from 590 to 830 mm. There is a trend of increasing evapotranspiration from north to south and decreasing from west to east, with the lowest values of evapotranspiration along the Black Sea coast (Kazandjiev et al., 2022).

Reference evapotranspiration is highest in regions with a transitional-Mediterranean climate, followed by regions with a transitional-continental and temperate-continental climate. Similar trends are registered at potential evapotranspiration ETp. The evaporative capacity of the atmosphere increased during the period 1991–2010 compared to 1971–1990. A slight decrease was observed only in limited areas of North Bulgaria. A statistically significant increase in ETp (at significance level α=0.001 and α=0.01) was observed in the period July-August in all studied stations.

I.2.3. Hydrological studies

I.2.3.1. Change in the surface water resource

Bulgaria's water resources are not among the largest in Europe, but almost all of them are formed on Bulgarian territory, which makes the country independent in this aspect. The river runoff is characterized by multi-annual and intra-annual variability, determined mainly by climatic factors and anthropogenic impacts. The seasonal distribution of precipitation and the duration of snow cover largely determine the runoff regime of surface water such as rain and rain-snow types: maximum in spring (due to the significant amount of precipitation in this season and snowmelt) and a minimum in summer, which is mostly in the August-September period. Human activity related to the use of water resources and the building of hydrotechnical structures significantly disrupts the natural regime of water sources. Changes in the river runoff on the territory of the country were established after the 1960s with the development of large hydro-technical constructions.

The development of methods and technology for the quantitative assessment of freshwater resources for the territory of the country is an important task related to the assessment and effective management of water resources. Investigating the spatial homogeneity, uniformity and repeatability of hydrological and meteorological data series is essential for obtaining robust and robust statistical estimates. The distributions of the ranks of the average annual water quantities, the base for resource estimates, are of special interest (Gerasimov&Bojilova, 2004; Rankova&Kroumova, 2017).

Spatial homogeneity is an indicator of the synchronicity with which the temporal fluctuations of the river runoff are realized in individual river basins and for the country as a whole. The classification of the years as dry, medium and wet is related to water management practice. This classification is made by setting thresholds (33% and 66% empirical quantiles) for the range of annual resource estimates against which each subsequent year is classified. Another important feature is the stability of the classification of extremely dry and wet years, which confirms that for relatively long periods, such as a year or more, extreme phenomena cannot be local. Instead, they cover entire regions or the entire country.

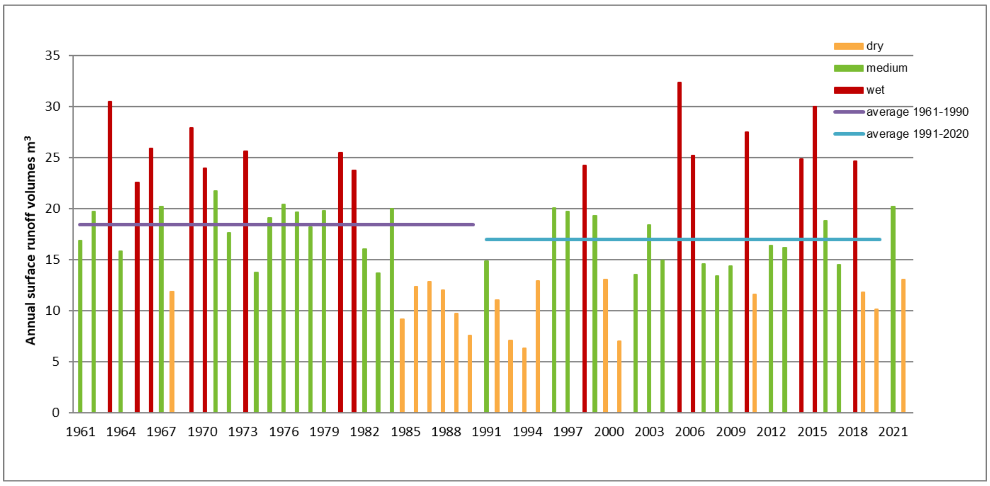


Fig. I.2.3-1. Chronological order of annual surface runoff volumes compared for two climate period averages, 1961–1990 and 1991–2020, defining dry, average, and wet years.

The annual values of the surface water resource in Bulgaria vary in a very large range – from 6.41x10^9 m^3 in 1994 to 32.37x10^9 m^3 in 2005 (Fig. I.2.3-1). The average multi-annual river runoff for the period 1961–2022 is 17.67x10^9 m^3. The established norms are 18.46x10^9 m^3 (1961–1990) and 16.96x10^9 m^3 (1991–2020), respectively. In the study, the period after 1961 was selected when regular observations of the river discharge were established and an optimal density of the network of hydrometric stations was reached. The division of the hydrological series by characteristic types of years makes it possible to determine runoff parameters during wet, medium and dry periods. To assess the resource change, a comparison was made with the norms for the periods 1961–1990 and 1991–2020. As seen in Fig. I.2.3-1, the medium and very wet years predominated in the period 1961–1984, which was followed by a prolonged drought until 1994. In the following period very wet (1998, 2005, 2006, 2010, 2014, 2015, 2018), medium and dry (2000, 2001, 2011, 2019, 2020, 2022) years were observed.

In Fig. I.2.3-2, the change in outflow during the 1961–2020 period is represented by the cumulative curve of the integral differences. The annual resource increased until 1981 and then decreased until 1995, thereafter it increased slowly, with significant fluctuations. The drought period 1982–1994 is analyzed in detail in

Gerasimov et al. (2004). Methodical approaches and developed technologies at NIMH are applied in the assessment of water resources in both annual and multi-annual contexts using real hydrological measurements of river runoff, statistical methods for regionalization, GIS technologies, etc. (Ninov et al., 2017). The method of hydrological regionalization is applied to all main watersheds in the country to determine regional regression dependencies between the average multi-annual river runoff and the area of the watershed in the homogeneous hydrological regions. The reliability of the obtained results is confirmed by the significant correlation coefficients (over 0.98).

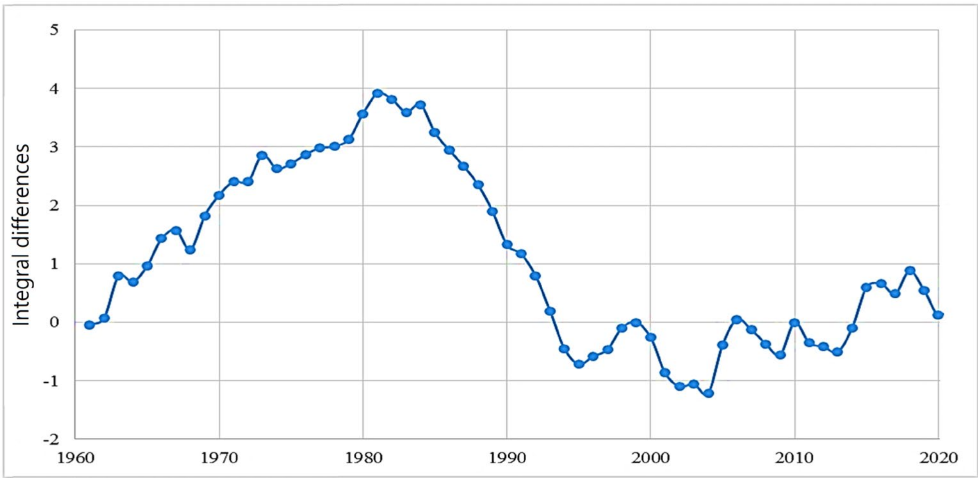


Fig. I.2.3-2. Cumulative curve of the integral differences of the modulus coefficients of the annual resource for the period 1961–2020.

The concept of determining the annual resource includes the determination of the annual volumes of river water using the observations at the hydrological stations along the main rivers located the closest to their confluence with the water (Danube River and the Black Sea) or land border of Bulgaria (Fig. I.2.3-3). The results are used by the Ministry of Environment and Water, National Statistical Institute and European institutions for a general assessment of Bulgaria's yearly resources. The use of recorded river runoff information at hydrometric stations provides certainty for avoiding errors that are possible in rainfall-runoff modeling. The obtained estimates enable the managing body to administer the remaining water resource under the existing anthropogenic load.

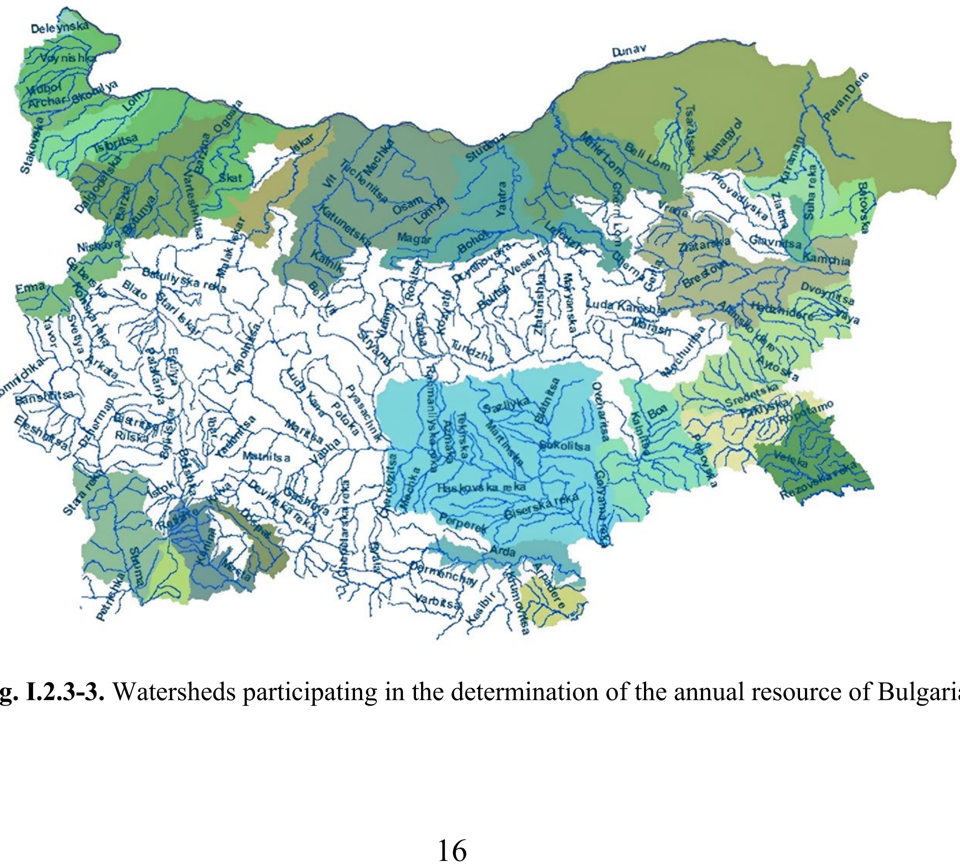


Fig. I.2.3-3. Watersheds participating in the determination of the annual resource of Bulgaria.

In the analysis of the empirical distributions of the series with annual river runoff, a connection with the probability distribution of the annual precipitation amounts is searched. The spatial stability of the classification of river runoff into dry, medium, and wet year categories is investigated, as well as the correlation of river runoff ranks and resource estimates. A reasoned conclusion is sought for the spatial quasi-homogeneity of the annual runoff and determination of the relative share of individual watersheds when forming estimates for geographic and administrative regions. The annual hydrographs are examined through cluster analysis and a substantiated hypothesis is needed for the formation of the annual river discharge as a result of the prevailing climatic influence in the regions. These studies provide answers to some questions about the statistical variability and homogeneity of the annual river runoff. However, the search for a relationship between the realizations of the annual runoff and the indices of the prevailing atmospheric circulation should be continued.

I.2.3.2. Status of groundwater in recent decades

Fresh groundwater in Bulgaria is widespread throughout the country and is of fundamental importance for the formation of water resources. The different types of groundwater are located in various basins and are generally divided into karst, fractured, and porous types. To consolidate all aquifers in Bulgaria, "administrative" boundaries for these aquifers were established in 2000, resulting in the formation of 169 groundwater bodies across the country (Fig. I.2.3-4).

A summary analysis of the deviations of the average annual values of water levels and discharges relative to the norms for 2023 by groundwater bodies (GWB) is presented in Fig. I.2.3-4. During the past year, great spatial variety and a well-expressed negative trend in the change of water resources in these bodies were found. The trend was recorded in more than 66% of the monitored groundwater bodies, by the Groundwater Monitoring Operational Network. A decrease in the average annual values of levels and discharge compared to the norms for 2023 was observed in 41 GWB and an increase – in 19 GWB.

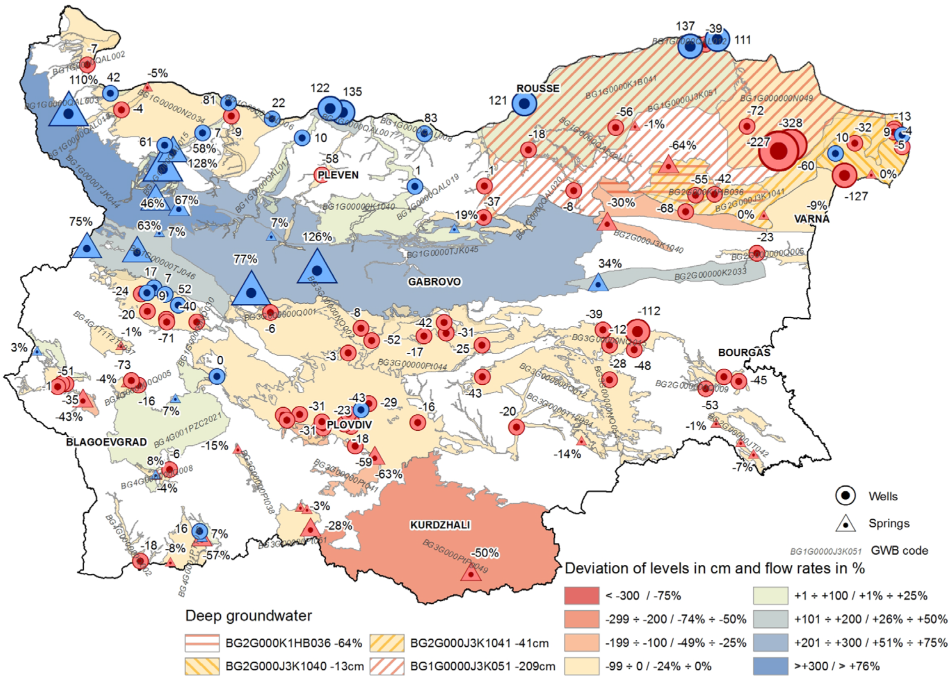


Fig. I.2.3-4. Deviations of the average annual values of water levels and flow rates compared to the norms for 2023.

A short analysis of groundwater changes was made for 2013/2014 to 2022. Two main drinking source aquifers in North-East Bulgaria (Dobrudzha) were investigated – the Sarmatian shallow karst aquifer and the Valanjinian deep karst aquifer. The area depends mainly on groundwater for all water needs. In the East, where the population has low density, the groundwater tables are aroused. Near the Black Sea coast (Shabla), where saltwater intrusion exists (Ivanov&Damyanova, 2024), there are no changes in groundwater tables. In the top shallow aquifer (Fig. I.2.3-5, left), 24 groundwater monitoring observation points were used, where in 10 wells a groundwater level declined with magnitude from -10 m till -0.2 m and average negative change of -3.42 m. In 9 wells, there are no significant changes or trends are observed, while in 5 observation points, the water levels are raised from 1.5 to 3.5 m, with an average rise of 2.1 m. If we compare all monitoring points, the mean changes are negative (-0.99 m).

The main groundwater table depression is observed near Dobrich town. A similar situation is seen in the southeast near Balchik, but in Kavarna, it is expected but not observed due to the absence of observation boreholes. In the same region, there exists another permeable aquifer that is deeper and more confined than the top aquifer (Fig. I.2.3-5, right). Here, we see an even more depleted area in the south of Dobrich.

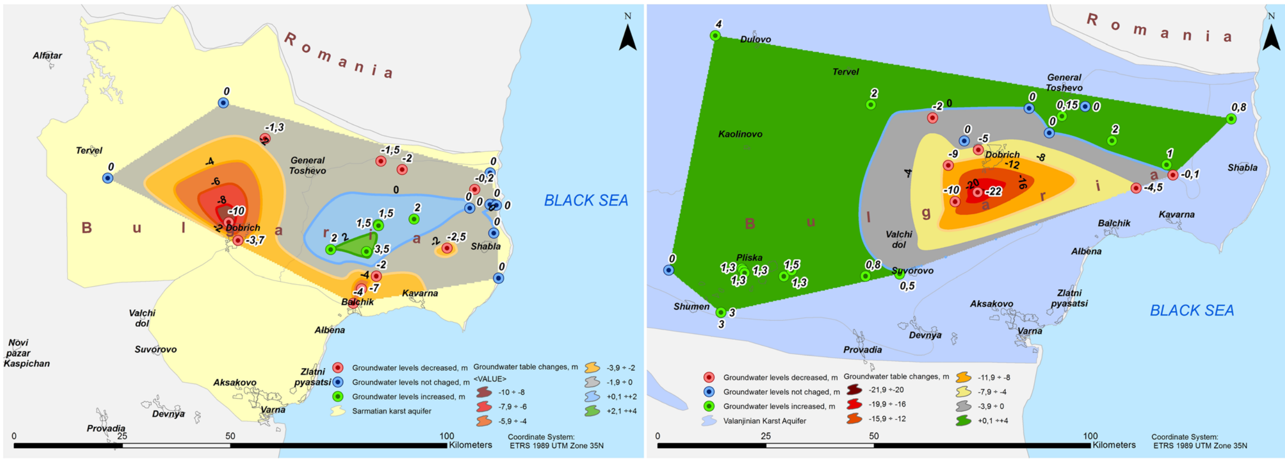


Fig. I.2.3-5. Groundwater levels change in the National groundwater monitoring network in Dobrudzha from 2013/14 to 2022 in the Sarmatian shallow karst aquifer (left panel); in the Valanjinian deep karst aquifer (right panel)

The groundwater depression is proved by 5 monitoring points. The maximum drawdown East of Dobrich is 22 m. In the analyzed area, a similar number of monitoring points (27) were used for the deep Valanjinian aquifer. The mean changes from all points are close to the shallow aquifer of 1.06 m. The water levels decrease at 7 monitoring points and rise at 15 water tables. The mean rise is 1.6 m, while the mean decline is 7.5 m.

I.2.3.3. Marine climatology for the Black Sea

The climatology of the severe storms affecting the Western Black Sea coast is based on numerical modeling of the waves and storm surges. The reason to use modelling is the lack of measurements of the wave parameters for a long enough period. The atmospheric input data for the numerical models was obtained from the reanalyses ERA-Clim for the period 1900–2010 (110 years long hindcast) (Galabov&Chervenkov, 2018a, b) and ERA5 for the period 1950–2020 (70 years period) (Galabov, 2020a, b). Various wave parameters (maximal annual wave height, wave energy (as defined in Galabov, 2013), annual duration of the storms, the number of the storms above a threshold maximal wave height, and storm power index have been used (Fig. I.2.3-6). Another approach is the use of dynamical downscaling of reanalysis data in order to reconstruct notable historical storms (Galabov et al., 2015; Bresson et al., 2018). For the storm surges, the studied parameters are the maximal annual surge for selected locations, the number of surges above a threshold, and an index analogous to the storm power index but based on surge parameters (Galabov, 2020b).

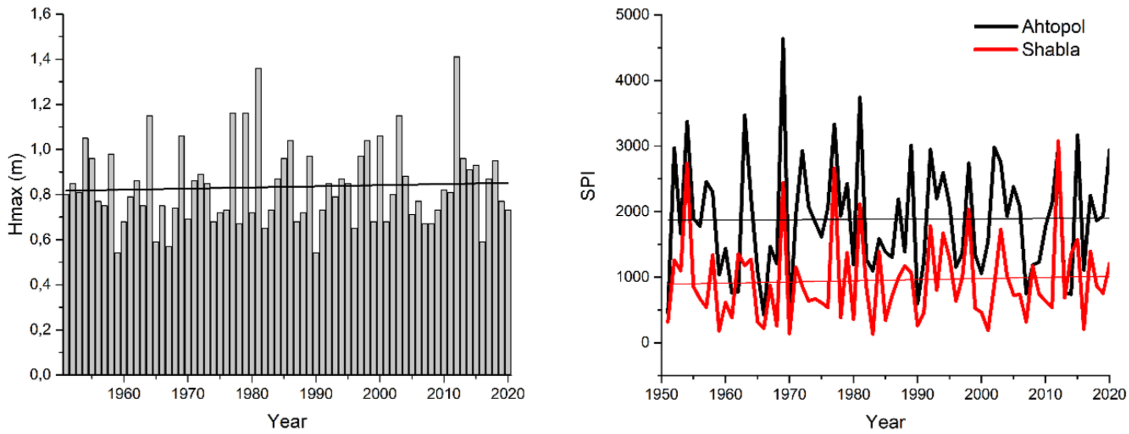


Fig. I.2.3-6. Left: The annual maximum surge for the Bay of Burgas; Right: The storm power index (SPI) for two locations: near Cape Shabla on the northern Bulgarian coast and Ahtopol – on the southern Bulgarian coast. Both figures are for the period 1950–2020 (hindcasts based on ERA5 data).

The conclusions are that during the last 110 years (70 years respectively), there have been no statistically significant trends in any of the mentioned wave and surge parameters, but there is evidence of cycles of increase and decrease in storminess. We also studied the cyclones causing the most severe storms in the Western Black Sea and found that the most severe storms are caused by explosive cyclones originating from the North Sahara/Sidra Bay (Galabov&Chervenkov, 2020b). Finally, it is important to stress that in the future, even without changes in the storms intensity and frequency, the consequences may be more severe due to the eminent increase of the Black Sea level. The reconstruction of the Western Black Sea wave climate based on a numerical hindcast using the SWAN wave model and ERA5 input data is also investigated (Galabov, 2020a). The study is focused on the storminess affecting the Bulgarian coast. The storminess in the recent decade (2010–2019) was found to be the highest compared to the previous 3 decades covered by the reanalysis, whereas the previous decade (2000–2009) had the lowest storminess. However, the trends in the storm proxies used in the study are not statistically significant. This confirms the conclusions of other studies that the wave climate of the Western Black Sea is steady.

I.2.4. Extreme weather events - analyses and trends

I.2.4.1. Climate indices

The most widely used indices in climate change monitoring are developed by the two WMO expert groups: ETCCDI (http://etccdi.pacificclimate.org/list_27_indices.shtml) and ET-SCI (https://climpact-sci.org/indices). Climate indices can generally be grouped into five categories (Alexander et al., 2006). Here, we have used several threshold indices (defined as the number of days in which a given climate variable is above/below a fixed threshold value) to diagnose significant, but not extreme, changes in the temperature and precipitation regime.

Although threshold indices have some obvious drawbacks, they can be successfully used to assess both extreme climate events and long-term changes that are not "extreme" per se. Moreover, changes in the regime of threshold indices can serve as an indicator of the critical impacts of climate change on the environment and human health (Tye et al., 2022). The presented analysis considered four temperature-based and two precipitation-based indices calculated on a yearly/seasonal basis like the number of days: frost days (FD) – days with minimum temperature below 0 °C, ice days (ID) – days with maximum temperature below 0 °C, summer days (SU) – days with maximum temperature above 25 °C, tropical night (TR) – days with minimum temperature above 20 °C; R05mm – days with precipitation sum above 5 mm, and R10mm – days with precipitation sum above 10 mm. The number of frost and ice days is sensitive to long-term seasonal changes in the distribution of temperatures towards low values, and the number of summer days and tropical nights is sensitive to changes towards high values. Daily rainfall amounts of 5 and 10 mm have been adopted as threshold values for distinguishing 'light', 'moderate' and 'heavy' rainfall (IPCC, 2021a, b).

The multi-year average values of selected climate indices for the two periods, 1961–1990 and 1991–2020, were calculated based on data from ERA5 Land (Muñoz-Sabater et al., 2021) and measurements at climate stations.

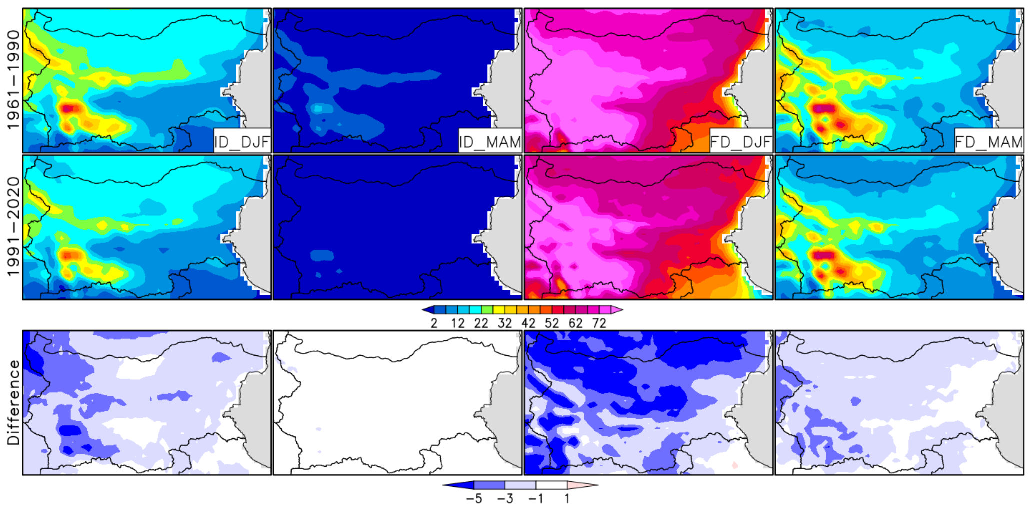


Fig. I.2.4-1. Multi-year mean values of ID and FD for the winter (DJF) and spring (MAM) based on ERA5 Land data. The differences of the second period relative to the first are shown in the third row. Units: number of days.

Figure I.2.4-1 presents a comparison of the indices of the ice days and frost days (ID and FD), which are typical for the cold half-year. Their spatial distribution is dominated by a well-defined vertical gradient. The values of both indices are significantly greater in winter than in spring.

Ice days in winter vary from 1–2 to 20–28 in lowlands to approximately twice as many in the mountainous part of the country (over 70–80 days on the mountain peaks). For frost days, the corresponding averages are 60 and above 80. Area-averaged values during the transition seasons, and especially in autumn, are very small, even in the mountainous regions. In the period 1991–2020, the ID index decreased in winter on average by 2 days in the lowlands and by 4 days in the mountains. In 54% of climate stations, the reduction is by more than 1 day (up to 9–11 days in some places in North-West Bulgaria). The change is insignificant in spring. Regarding frost days in winter, we have both a significant decrease (at 64% of stations) and an increase (at 17% of stations). The FD index decreased during the period 1991–2020 on average by 4 days in the lowlands and by 2 days in the mountains. In some places in North Bulgaria, the difference exceeds 5 days. In spring, on average, the change in frost days (FD) in the non-mountainous part was insignificant, whereas in the mountains, there was a decrease of 3 days. In autumn, FD decreased on average by 2 days in the non-mountainous part of the country and by 5 days in the mountains.

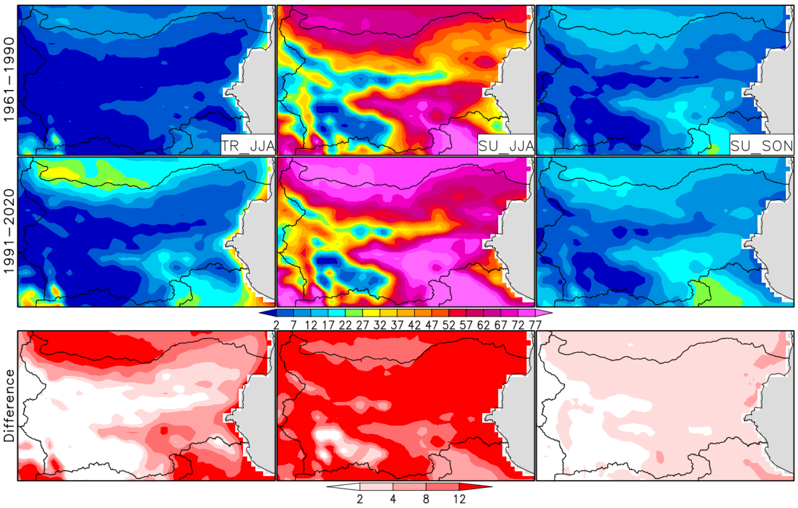


Fig. I.2.4-2. Multi-year mean values of TR for the summer (JJA) and SU for the summer (JJA) and autumn (SON) derived from ERA5 Land data. The differences between the second and the first periods are shown in the third row. Units: number of days.

Figure I.2.4-2 illustrates the changes in the indices of tropical nights (TR) and summer days (SU) typical for the warm half of the year. Comparison between the two periods shows an increase in the TR index by 4–12 days in some areas (over 12 days along the Black Sea and the Struma River). The long-term mean summer SU is 60–75 days in the plains and less than 10 days in the mountains, decreasing significantly with altitude. In the period 1991–2020, the most significant increase in SU was in the summer – for a large part of the country it was over 12 days. In the autumn, the SU increases by more than 2 days only in the non-mountainous part (more than 8 days in some places). The differences between the two periods are significant for both indices.

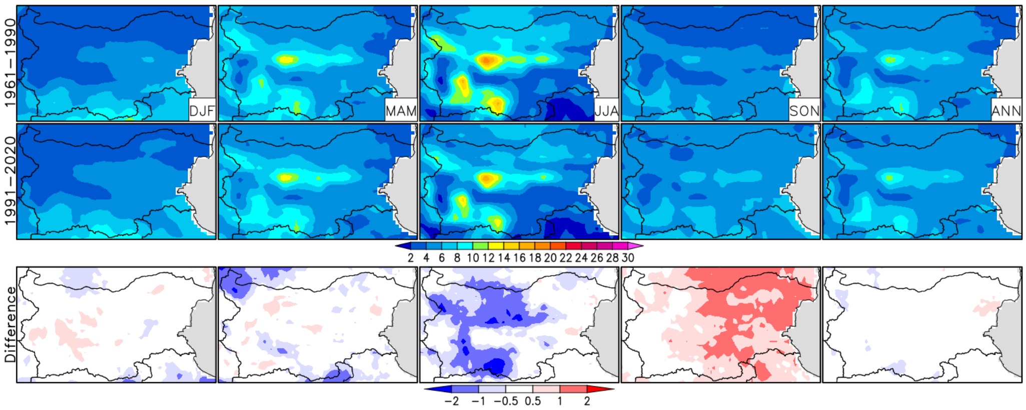


Fig. I.2.4-3. The multi-year mean values of R10mm for the winter, spring, summer and autumn seasons from ERA5 Land data, as well as on an annual basis (ANN). The differences of the second period compared to the first are shown in the third row. Units: number of days.

A distinctive feature of precipitation-based indices is their spatial inhomogeneity. The vertical gradient is well expressed in the spring and summer when convective precipitation is decisive in the formation of seasonal sums. The multi-year average number of days with precipitation over 10 mm (R10mm) is about 2–4 days in the flat part of Bulgaria and over 8 days in the mountains (Fig. I.2.4-3). In general, no significant differences are observed between the two periods on an annual basis due to the different signs of change in individual regions. In the autumn, the occurrence of moderate and heavy rainfall increases, mainly in the eastern part of the country (by more than 1 day). In summer, especially in the sub-mountainous and mountainous regions, the contribution of moderate and heavy precipitation to the seasonal total decreases.

I.2.4.2. Heat waves

Prolonged heat in Bulgaria is most often associated with the advection of tropical air masses over the Balkan Peninsula and additional radiation overheating due to a low-gradient surface baric field. Maximum temperatures above 42–43 °C in our country are relatively rare but possible temperature extremes. In accordance with the obtained statistical estimates of the high temperatures characteristic of the climate of the low part of the country during the warm half-year, extreme heat events are defined as periods with a daily maximum air temperature ≥ 32, 34, 36, 38 and 40 °C and duration of at least 6, 5, 4, 3 and 2 consecutive days, respectively. This climate indicator well describes the severity of heat waves at a country and regional level (SE Europe) as a combined assessment of its intensity and duration (Malcheva et al., 2021; 2022).

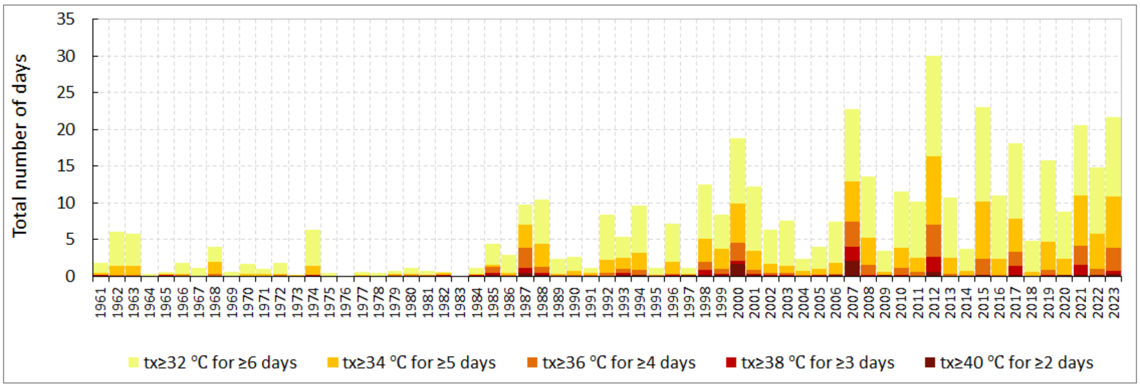


Fig. I.2.4-4. Multi-year variation of the hot spells duration indicator (country averaged) in the period 1961–2023.

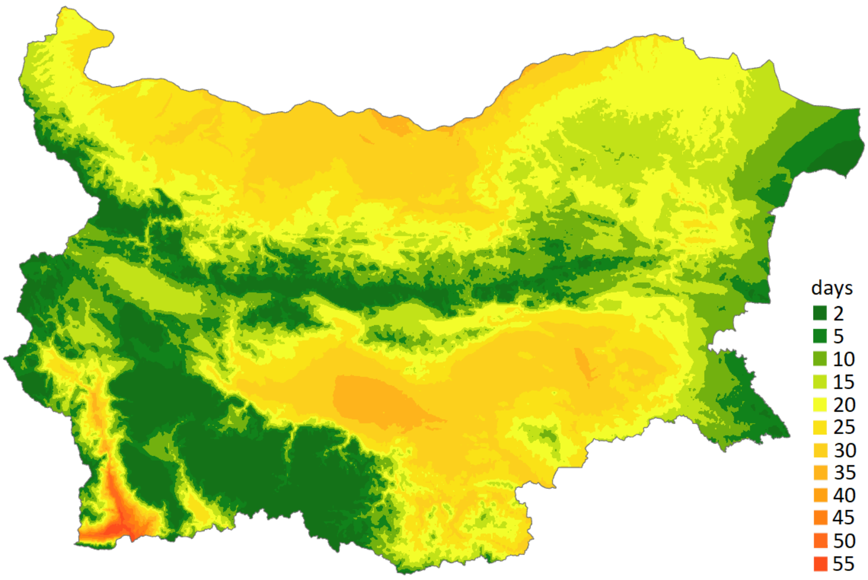


Fig. I.2.4-5. Spatial distribution of the average multi-year number of hot days for the period 1961–2020.

There has been an apparent increase in the frequency of hot periods in recent decades (Fig. I.2.4-4). All extremely hot periods with maximum temperatures ≥ 38 °C and ≥ 40 °C and about 90% of hot periods at threshold values of 32, 34 and 36 °C occurred after the mid-1980s. In some areas of East Bulgaria and the high fields of West Bulgaria, almost all hot periods were recorded after 1985. The phenomenon is characteristic for July and August, but its relative frequency in June and September increased after 1985, reaching 5–8% of total cases. The hottest place in the country is the Struma Valley, next to the Kresna Gorge, where the indicator reaches maxima at all temperature thresholds. In some years, extreme heat is observed here, with temperatures ≥ 40 °C on 6–8 consecutive days.

Analyses for the period 1961–2020 show that the average multi-year number of hot days (with maximum temperatures > 32 °C) reaches 40–55 in the Struma River valley (Fig. I.2.4-5), while in the mountain areas and some separate coastal areas (especially along the Northern Black Sea coast) hot days are from 0 to 2–3 per year.

I.2.4.3. Extreme precipitation

The maximum 24-hour precipitation, calculated on a monthly or annual basis, is included in the core group of 27 ETCCDI indices for climate change assessment and is one of the main features of extreme rainfall often used in flood risk analysis. Since the beginning of the century, a significant number of extreme 24-hour precipitation events (especially in 2005 and 2014) have been recorded in Bulgaria, leading to significant damages and human casualties. In general, the annual course of the maximum 24-hour precipitation follows the peculiarities of the precipitation regime in the country. In regions with a continental climate, the number of rainy days as well as the occurrence of heavy precipitation, increases significantly in the second half of spring, with a distinct peak in early summer. In the second half of autumn, precipitation is mainly frontal. In areas more strongly influenced by the Mediterranean climate, 24-hour precipitation reaches maximum values in the second half of autumn and the beginning of winter. Although the amount and intensity of precipitation decreases in spring, a secondary maximum is observed in early summer. On the Black Sea coast, the rainiest season is autumn.

Annual maximum 24-hour precipitation is determined based on daily precipitation measurements in the NIMH weather network at 7:30 a.m. local time. The assessment of the multi-year variation of the country's average annual maximum 24-hour precipitation for the period 1961–2020 shows almost equal values for the northern and southern parts of the country (47–48 mm), but the variation of this indicator in North Bulgaria is about 1.5 times larger (https://bulletins.cfd.meteo.bg/bull/Godishen_buletin_NIMH_2020.pdf). Since the mid-1990s, an increasing trend (~3 mm/10 years) has been observed, which is not statistically significant. In individual stations and regions, however, significant changes in the regime of the annual maximum 24-hour precipitation are found. In more than 9% of the stations (mainly in the Eastern Rhodopes, the Eastern Upper Thracian Lowland and North-East Bulgaria) the trend is increasing, and in about 5% of the stations – decreasing (mainly in South-West Bulgaria and the high parts of the mountains).

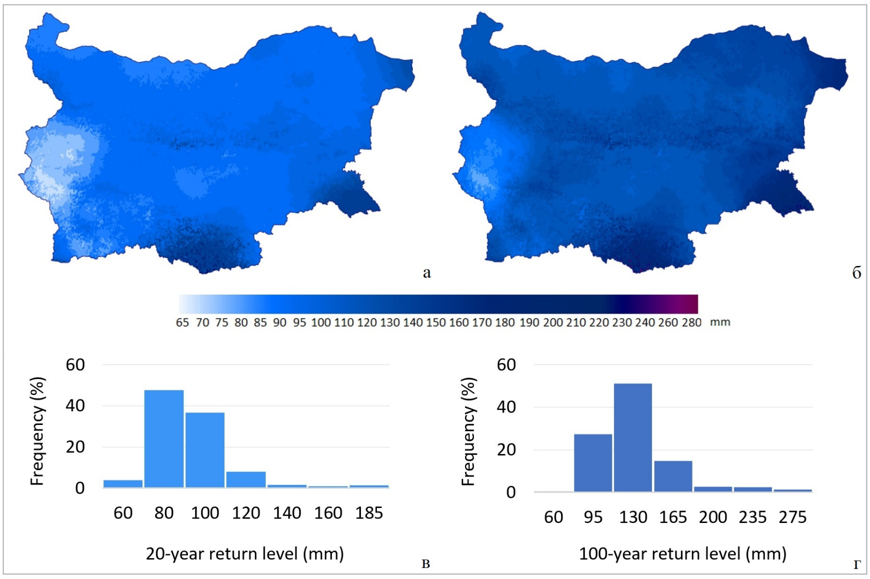


Fig. I.2.4-6. Distribution of the characteristic values of the maximum 24-hour precipitation with a return period once in 20 years (a, c) and once in 100 years (b, d).

The peculiarities in the spatial distribution of the maximum 24-hour precipitation are determined both by the large-scale processes of atmospheric circulation over Europe and the Balkan Peninsula and by local processes often associated with extreme precipitation. The analysis of the annual maxima time series (for the entire observation period of each station) shows that at 87% of the stations, the 90^{th} percentile values fall into the category of potentially dangerous precipitation (≥ 60 mm/24 h). At about 5% of the stations, the 50th percentile values also fall into this category. The median of the recorded maximum precipitation is 111.5 mm. The lowest maximum values (60–80 mm) are found in the central parts of West Bulgaria and along the upper reaches of the Struma River, while the highest values (over 200 mm) are observed in the Eastern Rhodopes, Strandzha, the eastern part of the Danube plain, and the northern Black Sea coast.

Figure I.2.4-6 presents the spatial distribution of the characteristic values (return levels) of the maximum 24-hour rainfall with a probability of exceedance 5% and 1%, i.e. with return periods of 20 and 100 years. The country averaged values are 79.5 mm and 109.3 mm, respectively. The lower values prevail in the central part of West Bulgaria and the upper part of the Struma Valley. The larger values (in some areas even over 200 mm) are characteristic for the southern parts for the Rhodopes, Strandzha, the central part of the Balkan Mountains, the most northern and southern part of the Black Sea coast (Malcheva et al., 2020).

Although there is no clear tendency for changes in the annual amount of precipitation in the country, in some areas of Central-South Bulgaria (mainly the Rhodopes) and North-East Bulgaria, a statistically significant increase in the contribution of the potentially hazardous precipitation (≥ 60 mm/24 h) to the annual total is found (Bocheva, 2015). In general, the spatial distribution of these extreme events coincides with the presented in Fig. I.2.4-6 distribution of 24-hour precipitation with large return periods. To a great extent it also follows the distribution of annual precipitation (the greater the amount of precipitation, the greater the frequency of potentially hazardous precipitation). The biggest difference is observed in North-East Bulgaria, where the frequency of extreme precipitation is relatively high, while the average multi-year precipitation is one of the lowest in the country (Bocheva&Malcheva, 2020).

I.2.4.4. Floods

Extreme hydrological events such as floods have been and still are one of the major natural hazards causing loss of lives and economic losses. It is a challenge to link floods to climate change, as both meteorological and anthropogenic factors can influence flood occurrence. Insufficient data on the amplitude and recurrence frequency of past extreme hydrological events in Bulgaria hinders accurate estimation of the potential scale and frequency of future extreme hydrological events. In 2016, an archive of registered extreme events (floods) in Bulgaria was created and managed at the NIMH (Balabanova et al., 2019).

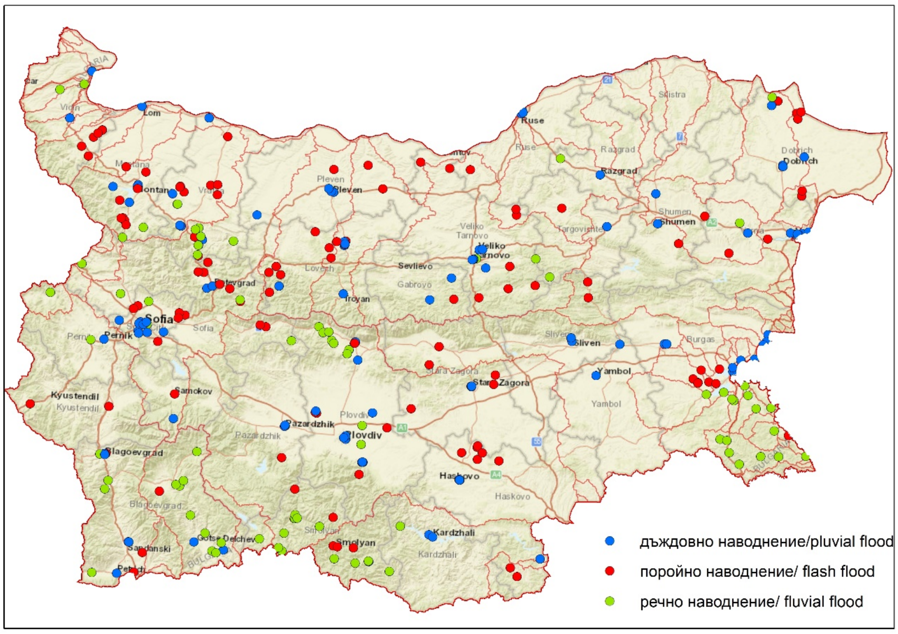


Fig. I.2.4-7. Registered floods 2016–2023 – part of the GeoDatabase managed by NIMH.

The historical archive contains important information for identifying and characterizing floods in chronological order. It includes synoptic, meteorological and hydrological information and, if available, information about the floods impact. The archive is an important tool for estimating the possible magnitude and frequency of flood occurrence and better analyzing and understanding the factors leading to such extreme events in Bulgaria.

According to NIMH's archive, intensive rainfalls that lead to flash and pluvial floods are the cause for 78% of the floods registered in the period 2016–2023 (Fig. I.2.4-7). The rest of the floods are fluvial. Nowadays, higher temperatures in winter, together with earlier snowmelt, are the reason for the typical spring high water and flash flood risk shifting towards winter months – in December and January. On the other hand, intensive and convective rainfalls are typical during the summer season. Together with the depletion of summer soil moisture, these conditions may act as precursors for flash flood occurrences.

I.2.4.5. Precipitation chemistry

The atmosphere is an important environment in which different gaseous and aerosol species are transported. Precipitations play an important role in removing particles and dissolving gaseous pollutants from the atmosphere. They also scavenge sulphur dioxide (SO_2), nitrogen oxides (NO_x), and other atmospheric pollutants, which can affect their acidity and chemical composition and cause ecological damage to ecosystems (Seinfeld&Pandis, 2006). The chemical composition of precipitation depends on pollutants emitted by sources of anthropogenic and natural origin, the dynamical processes in the atmosphere and the chemical reactions that occur during both local and long-range transport. Nitrates (NO_3^-), sulphates (SO_4^{2-}) and other ions such as ammonium (NH_4^+), chloride (Cl), magnesium (Mg), calcium (Ca), potassium (K), and sodium (Na) are commonly present in the aqueous phase. Some of these species originate from natural sources such as sea spray, soils and forest fires. Other species, such as ammonium, come from anthropogenic activities, including agricultural fertilizers and biomass burning (Hůnová et al., 2017). The presence of all these ions and elements determines the final value of precipitation pH.

The NIMH network for monitoring precipitation chemistry (established and maintained since 1998) consists of 35 stations, co-located with the synoptic stations. Bulk precipitation samples are collected every 6 hours in the main synoptic terms – 00, 06, 12, 18 UTC, and pH is measured on site after sampling. The scale for the acid-alkali composition of the precipitations is evaluated as follows: pH < 5 (acid), 5 ÷ 5.6 (slightly acid), pH = 5.6 (neutral), pH > 5.6 (slightly alkaline), pH > 6 (alkaline). The frequency analysis of precipitation pH in Bulgaria for the period of 10 years is illustrated in Fig. I.2.4-8.

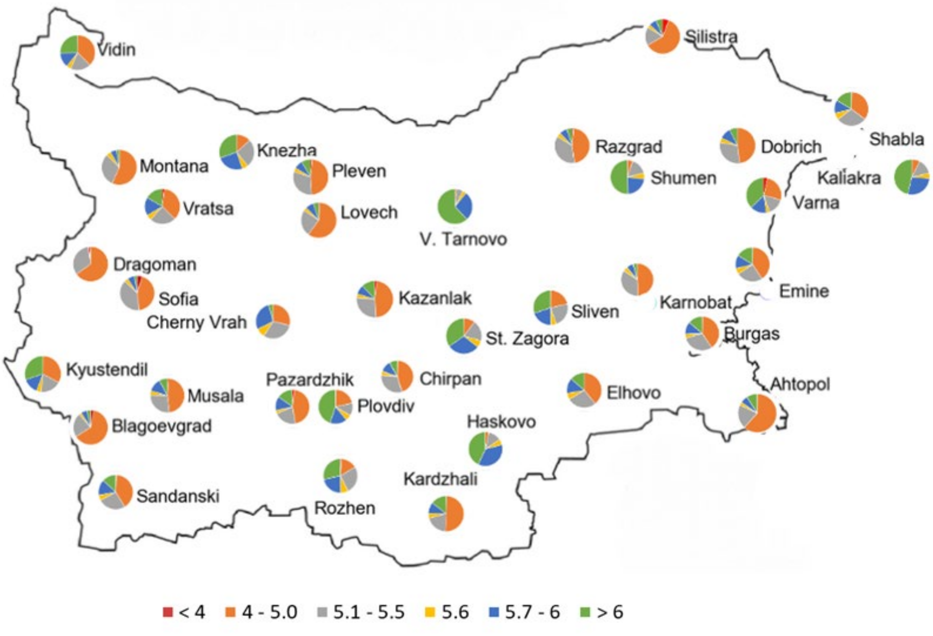


Fig. I.2.4-8. Frequency distribution of precipitation pH for the period 2011–2020.

This analysis shows that in 13 stations, more than 50% of the measured pH values are in the acidic range. For the other stations, the percentage of the acidic pH values varies from 7 to 48%. The percentage of pH values in the neutral range varied for different stations from 0.4 to 9%. At only two stations (Veliko Tarnovo and Shumen), 50% of the pH values are in the alkaline range. In order to understand the reason for the high percentage of acid precipitation on the territory of Bulgaria, it is necessary to perform regular chemical analyses for the main acidifying substances. Therefore, in recent years, NIMH has been conducting research activities on atmospheric depositions in Bulgaria, including both numerical simulations and observational campaigns (Georgieva et al., 2018; Hristova et al., 2016; Hristova&Veleva, 2015). The observational campaigns are organized in areas that could be adversely impacted by the depositions of acidifying and eutrophying compounds and, thus, be exposed to environmental risks (mountain and nature protected areas)

(Georgieva et al., 2022; Georgieva et al., 2021a, b; Hristova et al., 2021; Hristova, 2017; Valcheva&Hristova, 2021; Georgieva&Hristova, eds., 2022).

I.2.4.6. Lightning activity over Bulgaria

Lightning activity based on data from ATDnet (Anderson et al., 2014) over the territory of Bulgaria for the 10-year period between 2012 and 2021 is evaluated in Tsenova&Gospodinov (2022). Lightning data were considered as the number of detected flashes and number of days with at least one detected flash – thunderstorm days (TD). Results show that over the studied region, the mean number of detected flashes is around 600 000 (exactly 620 763) flashes per year, while the mean number of TD is 237 per year. During the considered period, 2018 is the year with the highest number of detected flashes (~8 000 000), and 2019 is the year with the highest number of TD (263) over Bulgaria. Figure I.2.4-9 shows the annual spatial distribution of flash density.

More than 95% of the flashes over Bulgaria and about 65% of TD were detected during the warm half-year (approximately 60% in June and July). More than 30% of detected flashes and most TD over Bulgaria were between 12 and 15 UTC. Detected flashes and TD are denser over mountainous regions and rarer over the sea. There is an increase in the number of detected flashes with the increase of the average terrain altitude up to 1800 m, followed by a slight decrease in the number of flashes at altitudes above 1800 m. The TD number increases with the increase of terrain altitude up to 1900 m and then decreases for altitudes above 1900 m. During the cold half-year in the studied region, thunderstorms formed mainly over the southern part of Rhodopes, North Greece and Turkey, while during the warm half-year – over mountainous regions (mainly in the western part of Bulgaria). The maximum flash density over the larger part of the country was reached between 12 and 18 UTC. Over a part of mountainous regions (Rila) and a part of the Black Sea, it was reached in the early morning, between 03 and 06 UTC. These results are in accordance with those obtained for other regions in Europe, such as the relationship between lightning activity and terrain topography (Bourscheidt et al., 2009) and the clear annual and diurnal cycles of lightning activity.

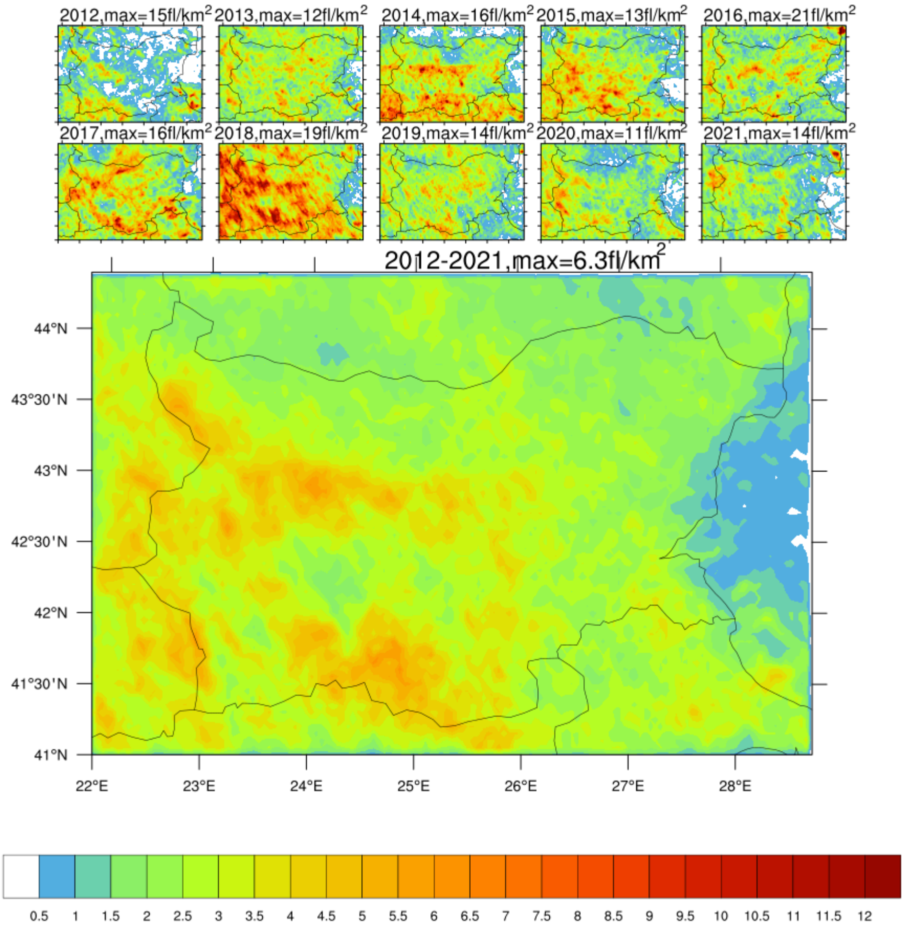


Fig. I.2.4-9. Annual spatial distribution (on a grid of 0.05×0.05 deg) of flash density (number of flashes per km^2 per year) according to ATDnet during each year of the period 2012–2021 and the yearly averaged for the whole period.

I.2.4.7. Saharan dust transport over the country

Sahara is the largest hot desert in the world that produces more aeolian soil dust than any other world desert. Saharan dust has an important impact on climate, biogeochemical and hydrological processes. Also, Saharan dust has a strong impact on air quality and affects human health. As a result, it is important to monitor the frequency and the trajectory of dust storms.

In Ilieva et al. (2024), an objective circulation classification is combined with the Dust product of the METEOSAT Second Generation satellites and synoptic charts to produce a quantitative analysis of the days with transport of Saharan dust towards Bulgaria for the period 2011–2020. For this period, there is a total of 365 days of Saharan dust transport over Bulgaria, with the number of days per year being between 16 (2017) and 53 (2013). A 10-year climatology shows that the transport of Saharan dust towards Bulgaria has a clear seasonality, with higher frequency from February to May (Fig. I.2.4-10, left). The rarest transport of Saharan dust over Bulgaria is observed during the period July-September.

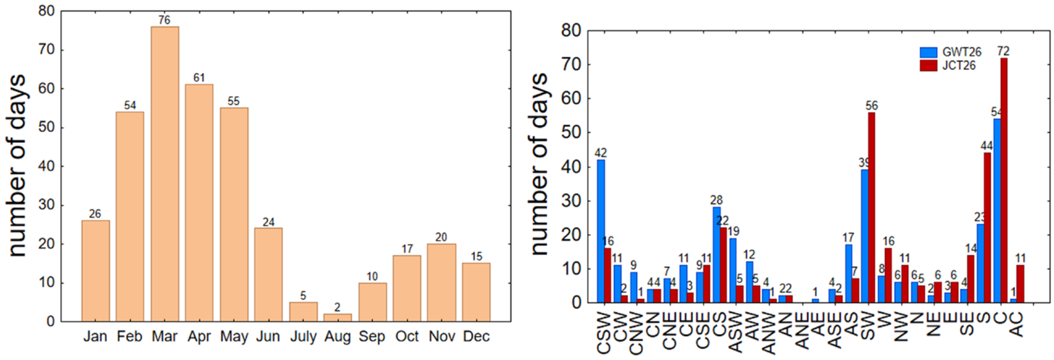


Fig. I.2.4-10. Saharan dust transport over Bulgaria: Monthly distribution of days for the period 2011–2020 (left panel); Objective circulation classifications with 26 types GWT26 (blue) and JCT26 (red) for the period 2011–2019 (right panel).

An objective classification of the atmospheric circulation on days with Saharan dust transport to Bulgaria is made for the period 2011–2019. Two objective circulation classifications with 26 types, GrossWetter Types (GWT) and Jenkinson-Collison Types (JCT), were used. According to the objective classification, the main circulation types associated with Saharan dust transport are linked to the development of Mediterranean cyclones and the transport of air masses from the south-southwest (Fig. I.2.4-10, right).

I.2.4.8. Drought

Drought is one of the most complex and large-scale climatic phenomena with a negative impact on people, the environment and the economy. The definition of drought adopted by the IPCC is: “A period of abnormally dry weather long enough to cause a hydrological imbalance”. According to the elements of the hydrological cycle affected by the drought, the following types of drought can be defined: meteorological, agrometeorological, hydrological and socio-economic drought. Drought is defined as a three-dimensional phenomenon characterized by its severity, duration and affected territory.

Hydrological drought typically exhibits phase shifts and lags behind the occurrence of meteorological and agro-meteorological droughts because it requires more time to manifest the lack of precipitation in the hydrological system (Yordanova et al., 2022). It can take days to months before a rainfall deficit results in reduced river runoff, declining groundwater levels, decreased inflows to dams, and water supply deficits. Hydrological drought is associated with a general reduction of natural water resources, and the restoration of their normal state after drought is slower. Drought impacts both socio-economic and natural systems, but the severity and consequences of drought also depend on the measures taken to mitigate its effects.

NIMH supports the implementation and use of drought indices in the operational practice of the Ministry of Environment and Water and the Basin Directorates by providing a monthly assessment of the spatial distribution of three drought indices (see http://hydro.bg/):

- Standardized Precipitation Index (SPI) after McKee et al. (1993).
- Soil Moisture Index (SMI) after Hunt et al. (2009)
- Standardized Runoff Index (SRI) after Shukla&Wood (2008).

The multi-year change in the country average values of the indices calculated from point data for the joint analysis period 2014–2020 is presented in Fig. I.2.4-11. The more significant hydrological drought in 2019–2020 is well reflected by the SRI. It results from accumulated rainfall deficit (meteorological drought identified by SPI) and subsequent soil drought identified by SMI. All watersheds are affected (except for the Ogosta River), and the duration varies from 1–2 to 11 months. The total annual volume of river runoff in the country in 2019 was 52% less than in 2018, and compared to the norms for the periods 1961–1990 and 1981–2010, the decrease is 36.1% and 24.3%, respectively. For 2020, the comparison with the norms for the same two periods shows a decrease in the total volume of the river runoff by 45.2% and 35.0%, respectively.

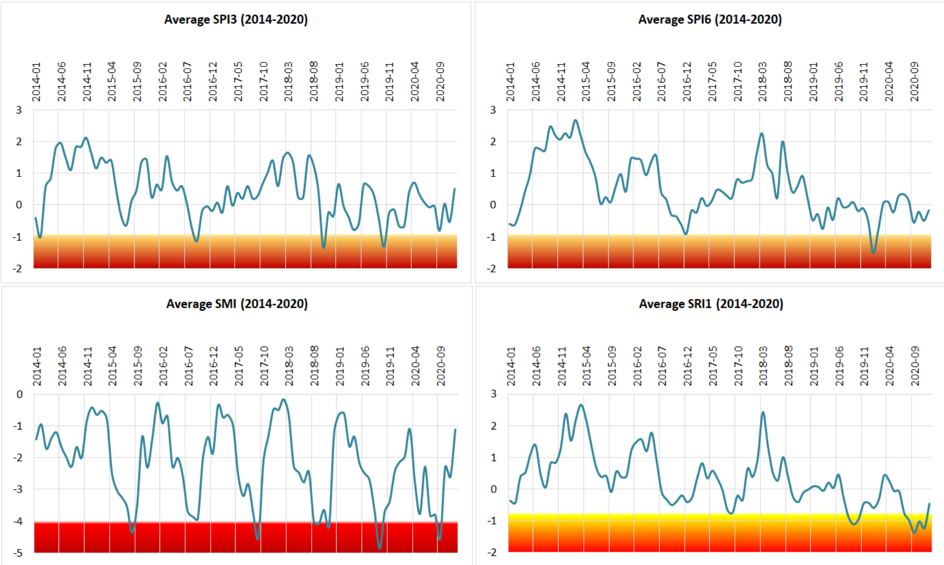


Fig. I.2.4-11. Multi-year change in the country average values of the indices calculated from point data for the period 2014–2020. The degree of drought is determined on a scale based on the threshold values that are reached.

The most significant is the decrease in runoff for the Black Sea region, followed by the West Aegean, East Aegean, and Danube River regions. During both dry years, groundwater reserves decreased, and in over 70% of the hydrogeological points across the entire country, a decrease in the levels and flow rates compared to the norms was recorded in individual months. In addition, in both years, there is a predominant tendency (over 80% of observed cases) for groundwater reserves to decrease during the autumn-winter period (Drumeva-Antonova et al., 2022). There are also water shortages and socio-economic impacts in the conditions of prolonged drought.

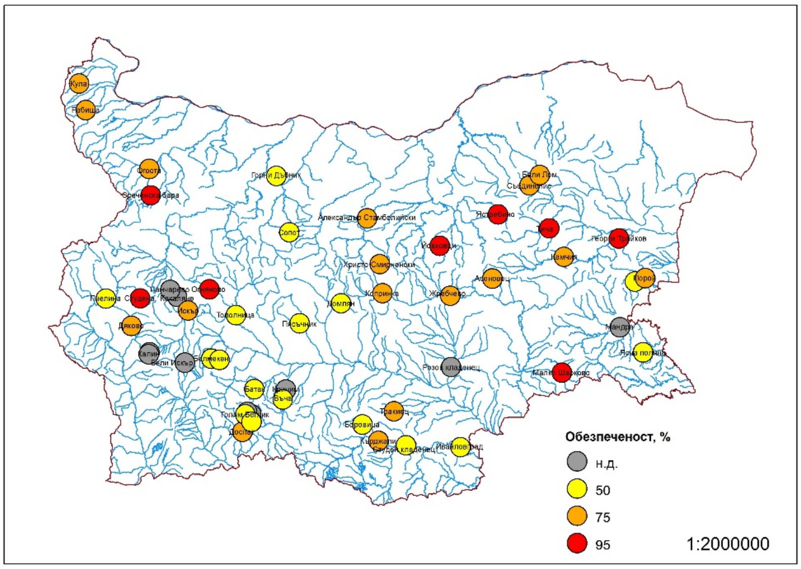


Fig. I.2.4-12. Total inflow to complex and significant dams, July 2019.

Through a joint analysis of hydrological, meteorological, and agrometeorological drought indicators, along with the indicators used by the MoEW, such as inflow and dam levels, it is possible to identify hotspots and critical areas. These include dams, watersheds, and river basins whose regulating capacities diminish during prolonged drought and are at risk (Ilcheva et al., 2022). In such a way, even before July 2019, the risky rivers, watersheds and dams were identified (Fig. I.2.4-12). Two consecutive dry years and the autumn-winter drought are critical.

The De Marton index (I_{DM}) and the dryness index (AI_{UNEP}) are most often used to determine the degree of drought in agrometeorology. A comparison of the monthly values of the De Marton index for two thirty-year periods, 1951–1980 and 1981–2010, shows that the climate in the second period has become drier compared to the previous one. The drought index (AI_{UNEP}) for the period 1981–2010 was obtained by applying the formula recommended by the JRC-Ispra in the Methodology for identifying areas with natural constraints (Terres et al., 2016). To designate an area as affected by the "drought" criterion, it must correspond to an AI value ≤ 0.5 in more than 20% of the years of the study period (in this case, 7 and more). The area of agricultural land affected by the "drought" criterion in each plot must be ≥ 60%.

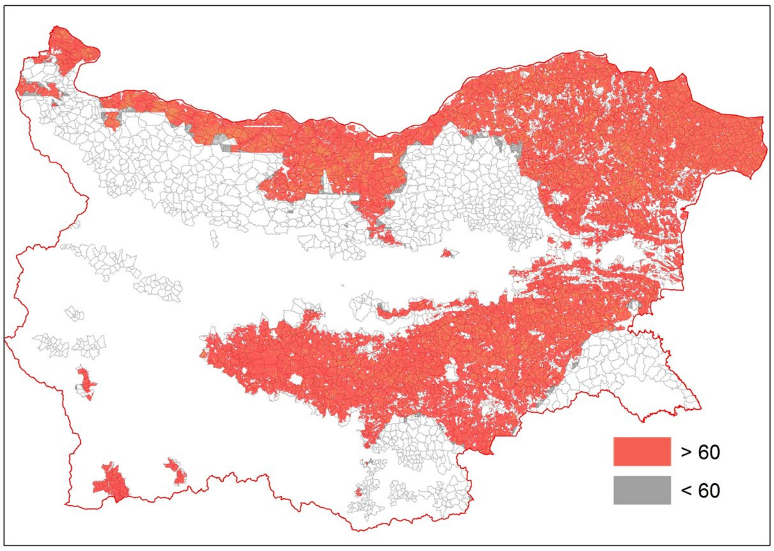


Fig. I.2.4-13. Agricultural lands with restrictions under the "drought" criterion for the period 1981–2010 by land area.

In a study for the period 1981–2010, the regions with natural constraints according to the "drought" criterion were identified by land location (Fig. I.2.4-13). They cover the regions along the Danube River, and in the central northern regions, they reach the Pre-Balkans. North-East Bulgaria, including Dobrudzha, is the most affected by the drought. In South Bulgaria, separate places in the valleys along the Struma River (around Blagoevgrad and the Petrich-Sandanski region) and the Mesta River are affected. The shortage of water will be felt more and more often in the Upper Thracian Lowland and some areas in the Yambol and Burgas regions. The results of this research were used as one of the criteria for determining the disadvantaged areas in Bulgaria in the preparation of Decree No. 25 of February 20, 2020, on the amendment and supplement of the Ordinance on determining the criteria for the disadvantaged areas and their territorial scope from 2008 (SN, 2008).

I.2.4.9. Frosts

The appearance of frost is associated with an adverse effect on plants and damage to agricultural production. The most dangerous are late spring and first autumn frosts. In 15 of the first 23 years of this century, frost damage was observed on the territory of the country in March and April, mainly on the stone plantations of apricots, cherries and peaches, and during later frosts (April-May), also on apples and pears. Since 2015, frosts of very high intensity and huge losses have been recorded every subsequent year.

The most susceptible to frost damages are the fruit crops and especially the early flowering stone species as almond, apricot, peach, cherry and others. From the field crops, the mid-early and late crops are the most vulnerable (soybeans, maize, potatoes, cotton, rice, etc.). All vegetable crops are also sensitive to spring and early autumn frosts. The dates of the last spring and first autumn frosts limit the potential growing season to varying degrees. The potential vegetation period is related to the permanent increase in the average daily air temperature above 10 °C, when all crop plants, except heat-loving ones, are in active vegetation (Georgieva et al., 2023). The earliest dates of frost were observed in the northern Danube regions, Central-South Bulgaria and the southernmost regions, and the latest ones – in the far northeastern regions, Sofia Valley and part of the Pre-Balkans during the first ten days of April. In our research, we found the average spring frost dates appeared on average 8 days earlier. These results show the increase in the extreme character of weather and the increasing risk to agriculture.

II. PROJECTED CLIMATE CHANGES UP TO THE END OF THE CENTURY

II.1. Changes in the mean air temperature and the precipitation

The projected seasonal changes in the mean temperature and precipitation up to the end of the century are estimated under two main radiative scenarios (RCP4.5 and RCP8.5) based on results from the first simulation round of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP Fast Track), which includes data for over 20 climate indicators in a uniform grid with 0.5°×0.5° resolution from five CMIP5 global circulation models for the period 1950–2099. The reference period for long-term climate change assessment is 1981–2010 (https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-agroclimatic-indicators?tab=overview). The seasonal and annual values of the mean temperature and precipitation are calculated from the ensemble multimodel median of the ISIMIP Fast Track models available.

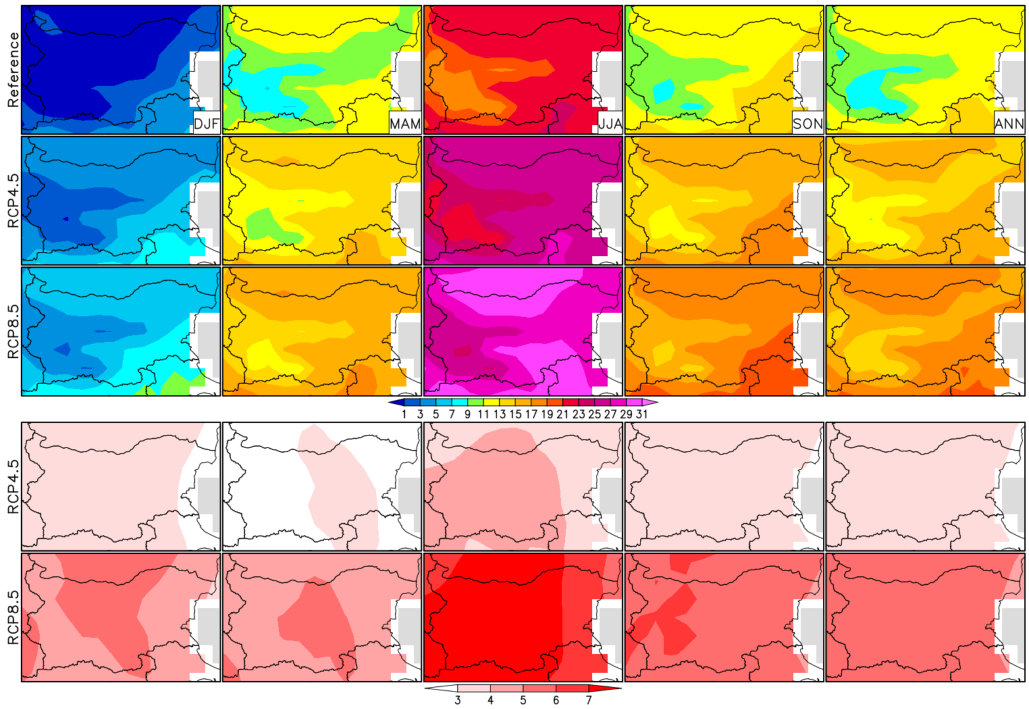


Fig. II.1-1. Multi-year mean values of the mean temperature for all seasons as well as an annual basis (ANN) for the reference (1981–2010) and far future (2070–2099) period according to the scenarios RCP4.5 and RCP8.5. The absolute differences between the second and the first period are shown in the fourth and fifth row for RCP4.5 and RCP8.5, respectively. Units are °C.

Fig. II.1-1 shows the distribution of the mean air temperature for the territory of Bulgaria by seasons and annually for the reference and future periods according to the data from the reanalysis and climate simulations with the two scenarios. The main and most distinct result is the dominance of the expected change – in both scenarios, for the territory of the entire country, the difference is positive. In all seasons and annually, the temperature increase is greater for the pessimistic than for the realistic scenario. It changes depending on the season, being most significant in summer (under RCP8.5, it exceeds 6 °C for almost all of Bulgaria). The expected increase in mean annual temperature (last column of Fig. II.1-1) is 3–4 °C for RCP4.5 and 5–6 °C for RCP8.5.

The change in the distribution of precipitation both in space and time, especially in the long term, is significantly more heterogeneous than that of temperature. The differences between the simulation results obtained by the individual models and the variance in the multi-model ensemble are relatively large. Fig. II.1-2 presents the distribution of the precipitation sum for the reference and the future period. Although the spatial resolution is relatively coarse for a local climate assessment, the seasonal features in the areal distribution of precipitation for the regions with different precipitation regimes – continental or Mediterranean type – are clearly apparent.

In general, a decrease in precipitation in the projected future climate is expected, strongly expressed in the pessimistic scenario in East Bulgaria. The change in the annual precipitation sum is from -5 to -25% under RCP4.5 and from -10 to -30% under RCP8.5. The reduction of seasonal precipitation reaches the greatest values in summer (30–35% on average for the country under RCP8.5). Simulations under the RCP4.5 scenario show no significant change in winter and spring precipitation; even in some areas, they increase by about 5–10%. These results agree well with established and projected long-term changes in temperature and precipitation at continental and regional scales (e.g., Georgoulias et al., 2022; Gadzhev et al., 2021).

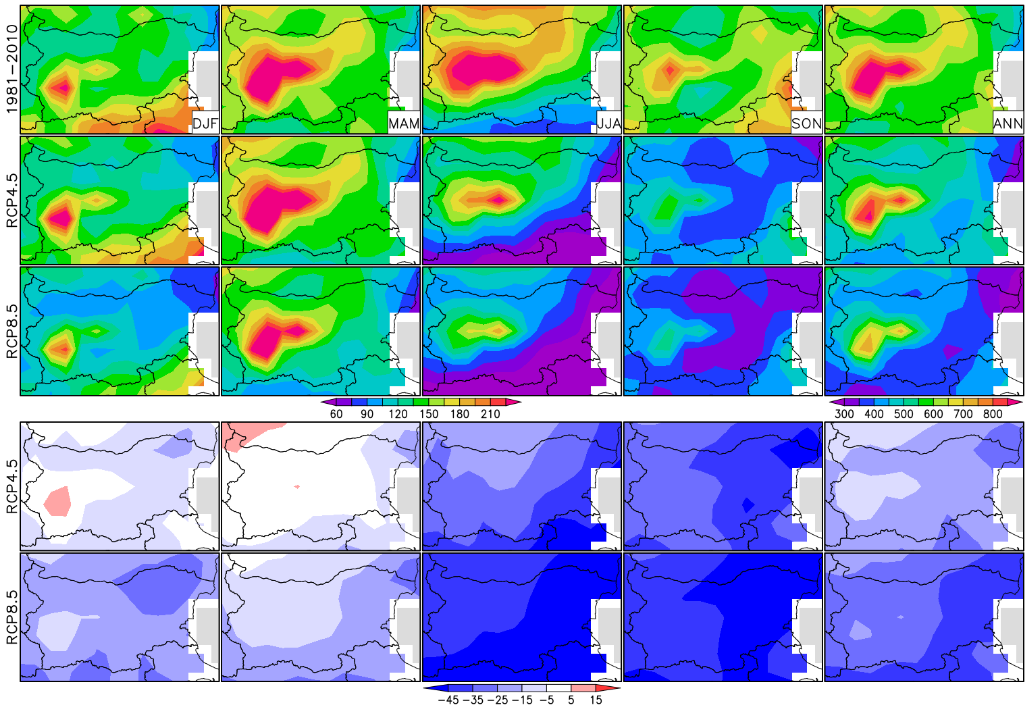


Fig. II.1-2. Multi-year mean values of the precipitation sum for all seasons as well as an annual basis (ANN) for the reference (1981–2010) and far future (2070–2099) period according to the scenarios RCP4.5 and RCP8.5. Units are mm. The relative (in %) differences between the second and the first period are shown in the fourth and fifth rows for RCP4.5 and RCP8.5, respectively.

Table II.1-1 summarizes the results of the analysis of projected changes in temperature and precipitation under both scenarios for the near (2021–2050) and far (2070–2099) future (Bocheva et al., 2023). Along with the annual mean values of the minimum, mean day-night and maximum temperature (denoted as TN, TG and TX), seven ETCCDI indices calculated on an annual basis were analyzed: absolute maximum temperature (TXx), absolute minimum temperature (TNn), maximum number of consecutive frost days (CFD), maximum number of consecutive summer days (CSU), total rainfall (RR), number of heavy rainfall days (RR10 mm) and maximum number of consecutive dry days (CDD).

Table II.1-1. Change of the climate indicators according to the RCP4.5 and RCP8.5 scenario for the near (2021–2050) and far (2070–2099) future

Period	*Scenarios*	*TN, °C*	*TG, °C*	*TX, °C*	*TNn, °C*	*TXx, °C*	*CFD, days*	*CSU, days*	*RR, %*	*RR10mm, days*	*CDD, days*
2021-2050	*RCP4.5*	+ 1–2	+ 1–3	+ 1–4	+ 2–3	< +2	- 7–14	+ 14–21	- 5–8	- 1–2	+ 4–6
	RCP8.5	+ 1–2	+ 1–3	+ 1–3	+ 3–4	+ 2–3	- 7–14	> + 21	- 5–8	- 2–3	+ 6–7
2070-2099	*RCP4.5*	+ 2–3	+ 3–4	+ 3–4	+ 3–5	+ 1–3	- 18–30	+ 42–54	- 10–15	- 2–5	+ 10–15
	RCP8.5	+ 4–5	+ 5–6	> + 6	+ 7–9	+ 5–7	- 18–30	> + 54	< -20%	- 4–8	> +15

The distinct warming expressed in the spatial patterns and temporal evolution of all considered temperature indicators is consistent with the trends of the daily mean and extreme temperatures. A “warming asymmetry” is also found (i.e., TNn increases faster than TXx, but the decrease in CFD is slower relative to the increase in CSU). In terms of rainfall-based indices, the results confirm the expected decrease in rainfall by the end of the century, but also reveal changes in the rainfall regime – less heavy rainfall and longer dry periods.

Changes in mean annual and seasonal temperatures and precipitation also were simulated using the regional climate model RegCM4, which has a horizontal resolution of 20 km (https://github.com/ICTP/RegCM) under the same scenarios (RCP4.5 and RCP8.5). These simulations were conducted for two future periods: 2021–2050 and 2071–2099, with the reference period 1975–2004 used for comparison (Valcheva&Spiridonov, 2021).

The results confirm that warming will continue across all seasons, with a pronounced increase during the summer. Under the RCP4.5 scenario, the annual average temperature in Bulgaria is projected to rise by 1.8–2.1 ºC in the period 2021–2050 and by 2.9–3.2 ºC in the period 2071–2099. During the first period, the greatest warming is expected in the summer, with an increase ranging from 2.6–3.2 ºC, while smaller increases of 1.5–1.9 ºC are anticipated in the other seasons. For the second period, the expected temperature rise varies by season: 2.2–2.4 ºC in winter, 4.0–4.4 ºC in summer, and 2.5–3.5 ºC in spring and autumn. Under the RCP8.5 scenario, the annual average temperature is projected to increase by 2.1–2.2 ºC during the first period and by 4.5–5.4 ºC during the second period. For 2021–2050, the most significant warming is expected again in the summer, increasing to 3.0–3.2 ºC. In the other seasons, the temperature increase is smaller – 1.6–2.4 ºC. During the period 2071–2099, seasonal temperatures are expected to rise by 3.5–4.5 ºC, except in summer, when the temperature increase could reach up to 6 ºC.

For precipitation, simulations using the RegCM4 model under the RCP4.5 scenario (Figs. II.1-3) show no significant changes in total annual precipitation for 2021–2050 compared to the reference period 1975–2004 (from -5% to +10%). Precipitation in winter is expected to increase by 10–15% in most of the country, and by similar amounts in spring, mainly in North Bulgaria. However, a significant decrease in summer precipitation is expected, especially in areas with a continental climate, with reductions of up to 30% in some places, except for a slight increase of +5% in the easternmost parts. For autumn, the changes in precipitation are within ±10%, with larger positive deviations mainly in the eastern and northwestern parts of the country and negative deviations in the southwestern part (Valcheva, 2021; Valcheva&Spiridonov, 2023). For the period 2071–2099, the change in annual precipitation remains within ±10%. Precipitation in winter is expected to increase by about 20% in North Bulgaria and up to 10% in spring in the northern and northwestern parts. In summer, precipitation increases by 20% in the easternmost parts of the country, while a decrease of about 10% is observed in autumn in the central and southern parts. In the western regions, summer rainfall is expected to decrease by up to 30%. Under the RCP8.5 scenario for the period 2021–2050, summer and autumn precipitation is expected to decrease by 10% to 20%, with the largest reductions in summer occurring in the northeastern parts of the country. In the second period (2071–2099), winter precipitation is expected to increase by 20% and spring precipitation by 10%, mainly in the northern parts of the country. Precipitation in the summer is expected to decrease by up to 30% in the central and southwestern parts, but to increase by 20% along the Black Sea. For autumn, a decrease in precipitation of up to 20% is expected in Central and South Bulgaria, and only rainfall on the Black Sea coast will increase by about 10%.

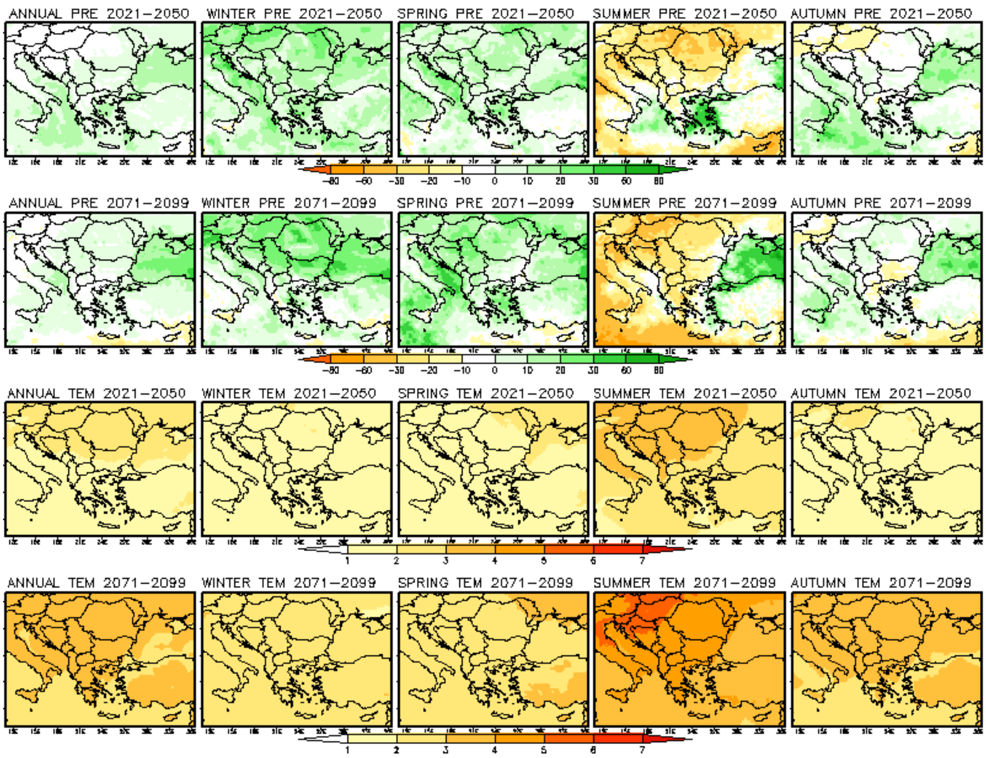


Fig. II.1-3. Simulated annual and seasonal changes in precipitation (in %) – the first two rows, and temperature (in °C) – the next two rows, using the regional climate model RegCM4 under the RCP4.5 scenario for the periods 2021–2050 and 2071–2099 compared to the reference period 1975–2004 (Valcheva, 2021).

II.2. Change in agroclimatic conditions in the near future

The future climatic conditions are important to assess their effects for agriculture, the development of plans and policies for the adaptation of the sector, as well as for reducing the contribution of agricultural activities to the anthropogenic forcing of climate change. This knowledge will provide a realistic insight into setting priorities and guidelines for improving and changing the Common Agricultural Policy (CAP).

To assess the impact of future climate changes and their impact on agroclimatic conditions, daily data obtained through simulations from the regional climate model ALADIN under the future climate scenario SRES A1B for the period 2021–2050 were used for 56 representative stations of the country's agricultural zone meteorological stations. The deviations of multi-year mean temperatures and precipitation for the period 2021–2050 relative to the period 1961–1990 were calculated (Kazandjiev et al., 2023).

The expected increase in winter temperatures worsens the dormancy conditions of wintering crops and especially fruit species. These trends will lead to an earlier start of the potential growing season. The increase in average monthly temperatures during the spring and summer months, when the growth, development and yield formation processes occur for most agricultural crops, orchards and vineyards, results in increasing the sums of active temperatures. They determine the plant development, as each growth phase is associated with reaching a certain, characteristic amount of active (effective) temperatures. The increase in the sums of active temperatures during the March-October period is from west to east and is in the range of 300–660 °C.

The increase in average daily temperatures is also associated with an increase in maximum temperatures. Maximum air temperatures higher than 32–34 °C cause heat stress in plants, slow down growth, adversely affect fertilization and pollination processes and reduce yields.

The distribution of the annual precipitation totals in the agricultural regions of the country is uneven and varies widely (from 360 to 770 mm). The amount of precipitation until 2050 is expected to decrease by an average of 10–25% compared to the reference period 1961–1990. This also affects the precipitation totals in the periods important for agriculture.

The increase in air temperatures during the April-June period leads to an increase in water consumption by plants. Over the next 30 years, spring and early summer precipitation is expected to decrease by up to 10% in the northeastern, southeastern, and central regions of the country. In some regions of East Bulgaria, the reduction will reach up to 15%, and in the extreme southwestern regions – up to 30%. At the same time, an increase in precipitation in the extreme northwestern regions by up to 30% is predicted.

The June-August period is characterized by the completion of vegetative development and transition to the reproductive stage of most spring crops. During this period, many varieties of cherries, apricots, pears, apples, peaches and dessert varieties of vines, watermelons and melons reach harvest maturity. This also applies to all varieties of mid-early field vegetable production – tomatoes, pepper, zucchini, eggplant, cucumbers, beans, okra, potatoes, carrots, etc. During the period of formation of yields from the mentioned crops, the water sonsumption is significant. When harvesting maturity is reached, it is recommended to harvest the produce in drier weather. The deviation of the precipitation totals in the summer months of the period 2021–2050 compared to the period 1961–1990 is projected to be +20 to -45%. In West and Central Bulgaria, up to 10% less precipitation is expected, and in the eastern regions – up to 20% less, as in some places, the decrease can reach 30–40%.

The trends in temperature and precipitation changes, along with their distribution in different agricultural regions, are also supported by indices used to assess agrometeorological conditions comprehensively. These include the De Martonne aridity index (I_{DM}), the Selyaninov hydrothermal coefficient (HTK – Selyaninov, 1937), and potential evapotranspiration values according to Thornthwaite (Thornthwaite, 1948). These indices are calculated on the data obtained from the ALADIN climate model under the SRES A1B scenario for both near-2050 and far-2070 future projections.

Bulgaria is located in a relatively dry area (I_{DM} values vary from 20 to 40). In such areas, it is necessary to compensate for the moisture deficiencies during certain seasons through irrigation.

The changing trends of all three studied indices for the period 1971–2010 are a good reason and prerequisite to predict warming and drought in Bulgaria for the future period (Eitzinger et al., 2008; Moteva et al., 2009). The comparison of the values of the indices and the trend of their change in the near and far future compared to the reference period (1971–2000) shows a deterioration of the hydrothermal conditions for the development of agriculture in our country (Table II.2-1).

If the soil water content in the period 1971–2000 is characterized as insufficient (HTC=1.0), the water deficit in the period 2021–2050 (HTC=0.5) will lead to a serious decline in yields and beginning degradation process of agro-ecosystems. Serious consequences for the soils are expected in the period 2051–2070, caused by their highly disturbed water balance (HTK=0.4). In some parts of the country, processes of soil degradation will be observed, which should be considered the beginning of desertification.

Table II.2-1. Indices – average values for the reference period (1971–2000), near (2021–2050) and far (2051–2070) future

Indices	1971–2000	2021–2050	2051–2070
I_{DM}, mm °C^{-1}	29.7	21.3	16.4
ET_P, mm	552	712	845
HTK, mm °C^{-1}	1.0	0.5	0.4

The monthly values of the I_{DM} decreased by an average of 34% from the first to the second period and by an average of 28% from the second to the third period. The biggest changes are expected to be registered in the months of July, August and September. Monthly Thornthwaite potential evapotranspiration (ETp) values increased by 47.4% from the first to the last period. During July and August, ETp values change from 105.0–108.5 mm (reference period) to 144.6–145.0 mm (near future) and 174.9–175.5 mm (far future). The difference between the values during the summer months of the individual periods is approximately equal to one monthly irrigation rate (Fig. II.2-1).

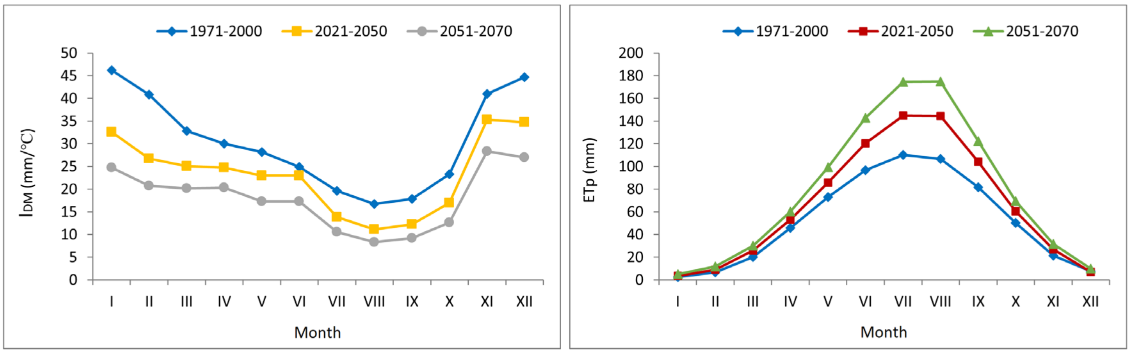


Fig. II.2-1. Monthly dynamics for different periods 1971–2000, 2021–2050 and 2051–2070 of the De Marton aridity index (left panel) and Thornthwaite potential evapotranspiration (right panel).

The results for the period 1961–2050 presented in Kazandjiev et al. (2021) were obtained on the basis of observational data (for the periods 1961–1990 and 1971–2000) and numerical simulation with the ALADIN model (for the period 2021–2050 under the SRES A1B scenario) for 55 meteorological stations from the agricultural area of the country. The analysis shows that:

– the number of days with a maximum temperature below 0 °C for the period 1961–2000 does not change on average for the country but will decrease over time, and by the middle of this century, it is expected to decrease by 5–8 days in North Bulgaria, which will worsen the resting conditions of agricultural crops;

– the duration of the growing season for the last 30 years of the 20th century increased by only 8 days compared to 1961–1990, but this increase is expected to reach 31 days in 2021–2050;

– with visibly increasing values of the temperature indicators, the days with and without precipitation remain relatively constant.

Three main classes were determined according to the productivity and stability of yields for a total of 50 varieties of winter wheat grown in parallel in General Toshevo (North Bulgaria) and Sadovo (South Bulgaria). The obtained results should be accepted as indicators for North and South Bulgaria (Kazandjiev et al., 2023).

The analysis of the data on the relationship of the harvest with agrometeorological conditions by periods of development after the restoration of vegetation in the spring can be summarized as follows:

- Yields in the southern regions depend most strongly on the amount of precipitation during the period from resumption of vegetation to ripening and less on the sum of temperatures and the sum of precipitation from maturity to milk maturity;
- Analytical dependences between gluten and protein content depending on yields and agrometeorological conditions have been obtained. The trends of the expected yields by year until 2050 and by regions of the country with the current composition of the varieties have also been established;
- The obtained results confirm the necessity for precise assessment of agroclimatic conditions in the country over the next 30 years and regionalization of winter wheat production based on agro-industrial zones and the potential productivity of existing varieties.

II.3. Climate change impact on water resources

The hydrological system is very sensitive to climate change. The climate is the main natural driver of the water resources variability. Variations in precipitation totals, as well as in their spatial and temporal distribution, air temperature changes and changes in evapotranspiration have a direct effect on all the components of the hydrological cycle and on the hydrological regime. The water balance model is used to evaluate runoff. Infiltration and groundwater recharge of river flow are not considered for long-term periods. Reservoir retention capacity, water use in the watershed and transferred water are not taken into account in the model (Balabanova, 2010).

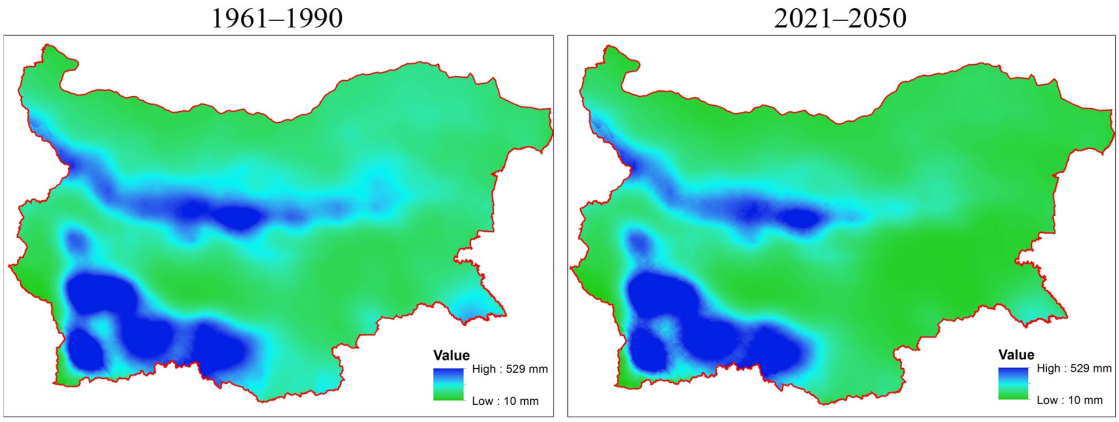


Fig. II.3-1. Annual runoff distribution for the periods 1961–1990 (left panel) and 2021–2050 (right panel).

Runoff is modelled based on precipitation and temperatures spatial distribution and calculated actual evapotranspiration for the referent period 1961–1990 and the simulations for the future period 2021–2050 from the regional climate model ALADIN (10 km resolution) using SRES A1B scenario.

Evapotranspiration is a major water balance component. With temperatures rising in the future, it is expected that evapotranspiration will rise as well. The analyses and conclusions regarding precipitation and actual evapotranspiration influence runoff results. Decreased precipitation and increased temperatures lead to a reduction in runoff, primarily due to lower water input and higher losses, such as evaporation. The relative decrease in runoff is more pronounced compared to that of precipitation (Fig. II.3-1).

For characterizing the climate change impact on moisture depletion degree and for identifying areas with insufficient water resources, De Martonne aridity index is applied (Fig. II.3-2). There is a distinct divergence between the mountainous areas and the rest of the country. During the simulated future period, De Martonne aridity index shows growing semi-arid areas while mountainous and foothill areas still remain in the humid level.

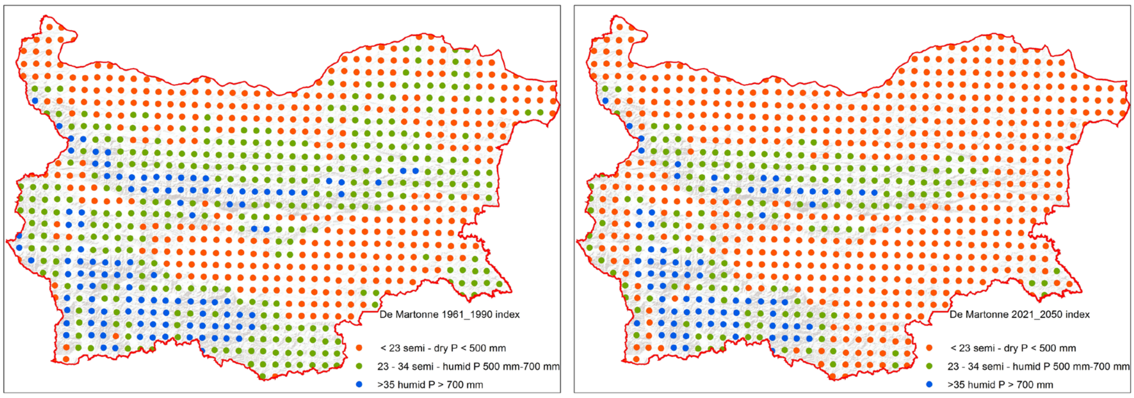


Fig. II.3-2. Distribution of the De Martonne aridity index for the periods 1961–1990 (left panel) and 2021–2050 (right panel).

The impact of expected climate changes in the 21st century on the annual cumulative river runoff in the four basin management areas according to the most commonly used climate scenarios, RCP 2.6, RCP 4.5 and RCP 8.5, was also assessed (Artinyan et al., 2021). Climate impact indicators and tools available through the European Copernicus Climate Change Service (C3S) project (ECMWF, 2017) were used. Appropriate combinations of global climate model + regional climate model + hydrological model were selected for which simulation results are available with the chosen RCP scenarios. Additionally, an appropriate reference period

(1971–2000) was selected, for which national runoff data are available for the four basin regions. Implicitly included in the national data are the amounts used for irrigation and inter-basin transfers, which can account for up to 7% and up to 4% of river runoff, respectively (Artinyan et al., 2008). The national data were calculated using measured runoff at NIMH hydrometric stations and extrapolated using a statistical-hydrological approach (Ninov&Karagyozova, 2015) to account for unobserved streamflow and runoff-free areas. Inflows from basins outside Bulgaria, mainly in the West-Aegean region, are included.

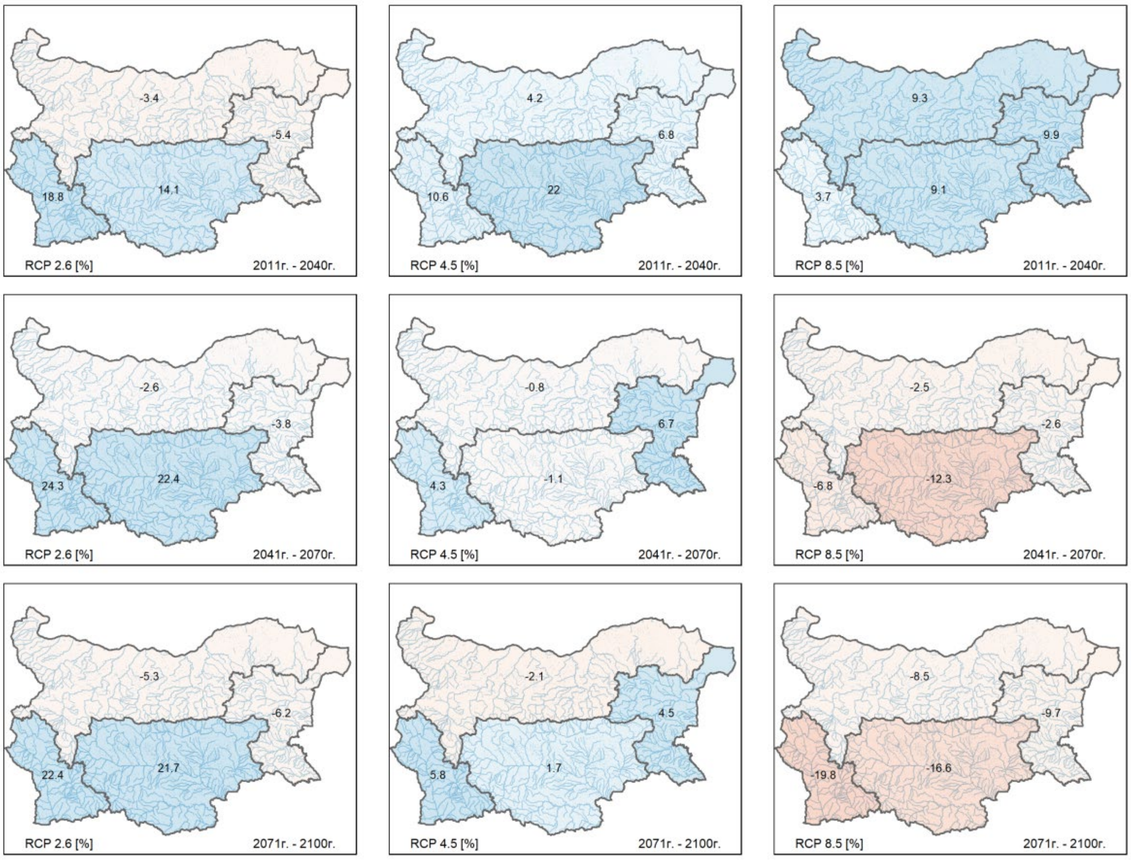


Fig. II.3-3. Relative change in multi-year average runoff (%) under the RCP 2.6 (left column), RCP 4.5 (middle column) and RCP 8.5 (right column) scenarios in the four Basin Management Areas for the three 30-year periods 2011–2040, 2041–2070 and 2071–2100 relative to the reference period 1971–2000.

Under the RCP 2.6 scenario, a relative increase in the annual runoff amount is projected for the Aegean Sea regions (14 to 24%) and a decrease for the Danube and Black Sea regions (-2.6 to -6.2%) by mid-century. In the other two scenarios, a relative increase is expected in the first period (2011–2040). More pronounced is the trend of a relative decrease in runoff for the period 2041–2070, but in the RCP 4.5 scenario, it remains weak (below -3%). For the period 2071–2100, the results under the RCP 4.5 scenario show a decrease in runoff in the Danube region and a slight increase for the Black Sea and Western Aegean Sea regions. Under RCP 8.5, there is a clear downward trend in runoff in the Aegean basin (up to -19.8%), while runoff in the Danube and Black Sea regions is reduced by up to -9% (Fig. II.3-3).

The projected results of the relative change of the annual runoff sum for the territory of the four water management basin districts in Bulgaria show noticeable but divergent differences. The most significant is the relative decrease in runoff for the Aegean Sea regions from 2041 to 2100 under the RCP 8.5 scenario. For the same period under all three scenarios, a relatively small reduction in the annual runoff amount is expected for the Danube region (from -0.8 to -8.5%).

II.4. Impact of climate change on the energy consumption and energy potential of some renewable sources

A large number of modern studies show that climate change has a direct and indirect impact on the energy sector. The relationship between air temperature and energy consumption for heating, ventilation and air conditioning of buildings can be quantitatively assessed by the indicators heating and cooling degree-days (HDDs and CDDs), denoted by ºD. The methodology of the UK Met Office, described in detail in Spinoni et al. (2018), was used for the calculation of HDDs and CDDs.

The necessary data for the daily minimum, mean, and maximum temperature for the considered reference period 1975–2004 and under projected future climate conditions (2070–2099) were obtained by simulations with RegCM4 under three climate scenarios – RCP2.6, RCP4.5, and RCP8.5. The multi-year mean values of HDDs and CDDs calculated for the reference and future periods are compared. Regarding the spatial distribution of the two indicators, a distinct altitudinal gradient is observed (Chervenkov et al., 2020).

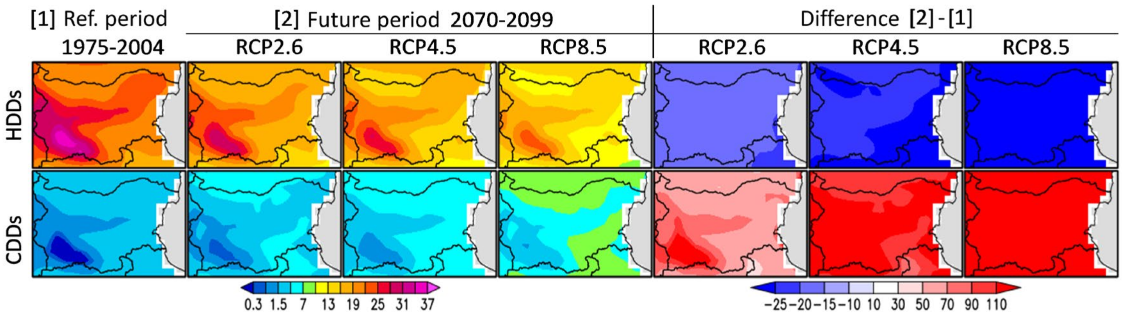


Fig. II.4-1. Multi-year mean values of the HDDs and CDDs for the reference period 1975–2004 and according to the scenarios RCP2.6, RCP4.5, and RCP8.5 for 2070–2099, as well as the relative (in %) differences between the second and the first period.

Over the whole of Bulgaria, the values of HDDs decreased, and CDDs increased in the second period compared to the first one, with the absolute value of the change increasing from RCP2.6 to RCP8.5 (i.e., proportionally to the radiative forcing). It is important to note that the relative change of CDDs compared to HDDs is significantly larger, and this is more pronounced under RCP4.5 and especially under RCP8.5 (Fig. II.4-1).

Table II.4-1 presents the area-averaged multi-year averages of HDDs and CDDs for the reference period and the far future under the RCP2.6, RCP4.5, and RCP8.5 scenarios. The differences in the relative change of the two indicators stand out especially clearly, with the change being many times greater for CDDs compared to HDDs. This confirms the aforementioned warming asymmetry and the expected change in seasonal temperatures (see Fig. II.1-1).

Table II.4-1. Area-averaged multi-year mean values of the HDDs and CDDs for the reference period and the far future according to the scenarios RCP2.6, RCP4.5 и RCP8.5. The relative differences (in %) between both periods are shown in brackets

Indicator	**1975–2004**	**2070–2099**		
		RCP2.6	RCP4.5	RCP8.5
CDDs, 100 ºD	2.05	3.28 (*60.1%*)	4.36 (*113%*)	6.64 (*224.6%*)
HDDs, 100 ºD	23.59	19.24 (*-18.4%*)	17.53 (*-25.7%*)	14.31 (*-39.3%*)

The long-term variation of these two indicators on a pan-European scale has been studied in depth by Spinoni et al. (2018). The key message is that under the projected future climate, a widespread increase in CDDs is expected, but in the Mediterranean region, it will be significant. At the same time, a prominent reduction in HDDs over South Europe is expected. Our results for South-East Europe, described in detail in Ivanov et al. (2020) and Chervenkov et al. (2021), are in principle agreement with the conclusions of other regional studies. The expected long-term changes in HDDs and CDDs show that climate change has the potential to exert a substantial and long-lasting impact on the structure and seasonality of energy consumption.

The use of wind and solar energy as renewable energy sources (RES) will increase in the medium term. The impact of expected climate changes in the near future on the energy potential of RES is analyzed in Valcheva (2019). To assess the change in wind energy potential, the nominal power was calculated for the reference (1961–1990) and future (2021–2050) periods at the height of 100 m. Fig. II.4-2 (left) presents the spatial distribution of the expected changes (in %) of the wind energy potential on an annual basis. The change varies from -12% to +14%, with the most significant increase in South-East Bulgaria (by about 8–14%).

The most significant drop can be expected in Central (8–12%) and South-West Bulgaria (4–6%). The reason for this is the lower efficiency due to the expected increase in wind speed along the ridges of the mountains. In the rest of the country, the change in wind power potential is within ±2%. The biggest reduction in wind potential is predicted in winter, mainly in mountainous areas and the coastal zone (up to -50%). In the rest of the country, a change within ±5% can be expected. Similar but weaker trends are expected in autumn. In summer, an increase in the wind potential is predicted (up to +50% in South-West Bulgaria and the coastal zone). In spring, the expected changes range from -5 to +30%, with the increase being greatest in South-East and South-West Bulgaria (up to 30%).

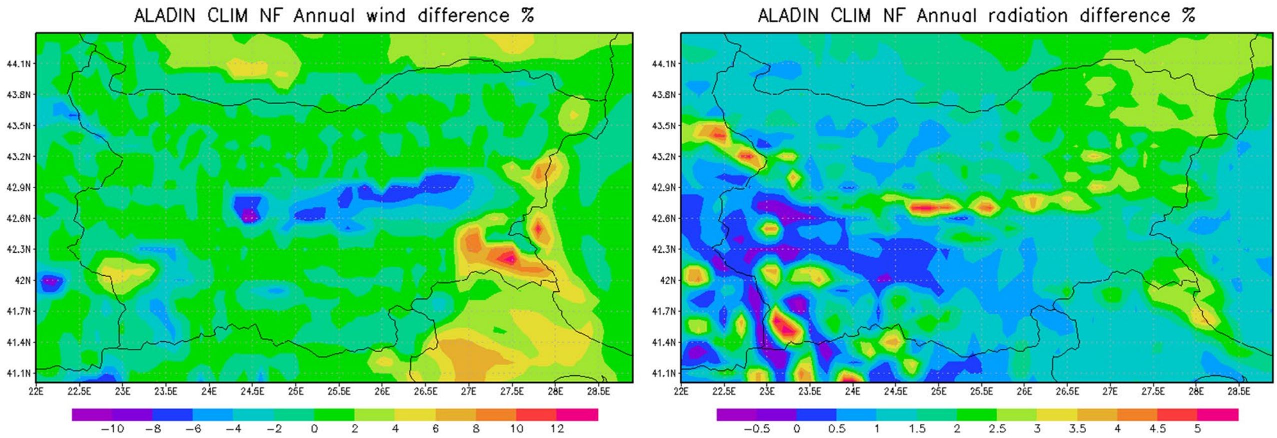


Fig. II.4-2. Expected changes (in %) in the annual wind energy potential (left panel) and the annual solar radiation energy potential (right panel) across Bulgaria for the period 2021–2050 compared to the reference period 1961–1990.

From the entire spectrum of sun radiation, shortwave radiation is the most important for the production of electricity. The change in the future compared to the reference period is calculated analogously to the wind energy potential. Fig. II.4-2 (right) presents a map of changes (in %) in the energy potential of solar radiation for the period 2021–2050 compared to the reference period 1961–1990 on an annual basis for the territory of Bulgaria. Projected changes in the energy potential of solar radiation are much less than those of wind and are between 1 and 6%. An increase can be expected mainly in North-East Bulgaria (2–3.5%) and in places on the high parts of the Balkan Mountains and Pirin (up to 6%). In the rest of the country, the change is between 0 and 2%. In winter, the change in the potential of solar energy is positive throughout the country, with the largest increase expected in Central and North-East Bulgaria (8–10%), as well as in the mountainous regions. In summer, an increase in solar radiation is expected in both the North (from 2 to 4%) and South Bulgaria (0–2%). In spring, the increase is greatest in North-East Bulgaria and the high mountains (2–4%). In autumn, solar energy decreases throughout the country, with the most significant decrease in the southern parts of the country (from -2 to -4%).

II.5. Estimation of the frequency of extreme climate events in the future

Although prolonged hot weather is a typical summer phenomenon in the Mediterranean and South-East Europe, the region is considered one of the most vulnerable on the continent and projected future summer warming is expected to exceed global levels by 40% (Cramer et al., 2018). Climate projections of floods and droughts in Europe under global warming of +2 °C relative to the pre-industrial period show increasing intensity and duration (Roudier et al., 2015). Intense rainfall is expected to increase significantly over the entire continent, including the Balkan Peninsula. Droughts in some areas will become more intense and longer, mainly due to less precipitation sum and higher evaporation. Changes in the hydrological cycle will lead to both increased droughts and more floods.

II.5.1. Heat waves

The quantitative assessment of the heat extremes in South-East Europe is performed by means of extreme heat events (EHEs) indicators computed from data from the NEX-GDDP CMIP5 dataset (NASA Earth Exchange Global Daily Downscaled Projections, https://www.nccs.nasa.gov/services/data-collections/land-based-products/nex-gddp), for the historical period 1950–2005 and for the future period 2071–2100 according to two climate scenarios – RCP4.5 and RCP8.5.

The annual number of hot days (nhd), the annual maximum number of consecutive hot days (chd), and the hot spells duration (hsd) at different thresholds were computed for each of the available 21 models in NEX-GDDP separately and the ensemble multi-model median is considered (Chervenkov&Malcheva, 2023).

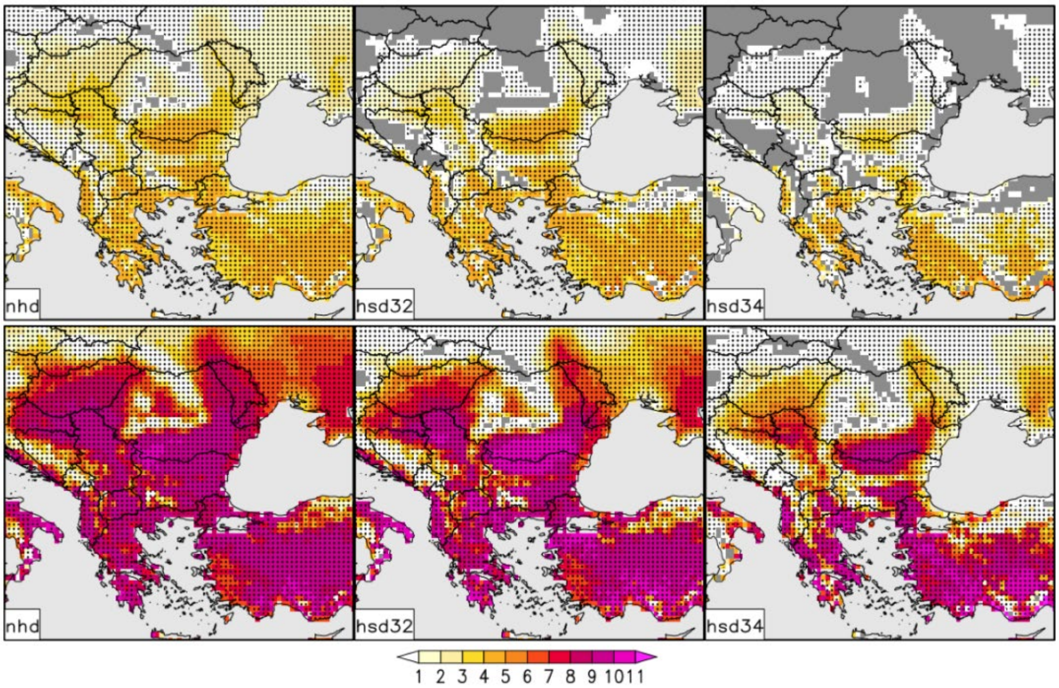


Fig. II.5-1. Trend magnitude (days/10 years) for the period 1950–2100 of extreme hot weather indicators: annual number of hot days (nhd), annual number of hot period days with maximum temperature ≥ 32 and 34 °C of respective duration of at least 6 and 5 consecutive days (hsd32 and hsd34). Stippling indicates grid cells with significant changes at the 5% significance level.

The duration and spatial extent of heat extremes are expected to increase significantly by the end of the century practically over the whole territory of Bulgaria. The regional average duration of hot periods with maximum temperature ≥ 32 and 34 °C will increase from almost zero during 1976–2005 to 60 and 45 days, respectively, by the end of the century under the pessimistic RCP8.5 scenario. In the projected future climate, the Balkan Peninsula will become more susceptible to extreme heat waves (Fig. II.5-1). Across most of the region, extreme hot weather increases by 2–5 days/10 years under the RCP4.5 scenario and 5–10 days/10 years under the RCP8.5 scenario.

II.5.2. Floods

Floods have been and still are one of the most important natural hazards causing loss of human life and economic losses in Bulgaria (Balabanova et al., 2015). Heavy rainfall does not certainly lead to flooding, however, it does increase the possibility of its occurrence. Even moderate amounts of rainfall may cause flooding, especially in urban areas. In areas where seasonal snowmelt significantly impacts runoff, higher temperatures may cause intensive snowmelt as well as more rainfall events on existing snowpack. This leads to faster and earlier snowmelt and the formation of significant runoff. Anthropogenic activities such as the construction and management of hydrotechnical facilities, land-use changes and urbanization (often with scales that do not correspond to urban drainage networks) increase the risk of flooding leading to severe consequences.

The expected changes in the frequency of intensive precipitation as a potential cause for floods for the period 2021–2050 are evaluated based on ALADIN model simulations for the SRES A1B scenario (Spiridonov&Balabanova, 2017). Increase by 5 and 10% of the cases with 6-hour precipitation over 10 mm compared to the period 1961–1990 are defined for 1088 subwatersheds in Bulgaria. The threshold of 10 mm/6 h is defined according to the thresholds used by Meteoalarm (http://www.meteoalarm.org/) and the hypothesis that a condition for precipitation above 10 mm/6 h is a 24-h precipitation of 25–35 mm corresponding to the yellow warning threshold. In Bulgaria such precipitation events are registered mostly in the warm period of the year. The watersheds with a sustainable increase of more than 5 and 10% in the number of cases with precipitation events over 10 mm/6 h are presented in Fig. II.5-2. The watersheds west of the Ogosta River, the upstream Ogosta River watershed, the middle and downstream Vit River watershed, Struma River up- and downstream tributaries, Mesta River middle- and downstream tributaries, Maritsa River up- and downstream tributaries and Arda River upstream tributaries are more vulnerable to flooding. The regions sustainably at risk of flooding are North-West and Central-North Bulgaria.

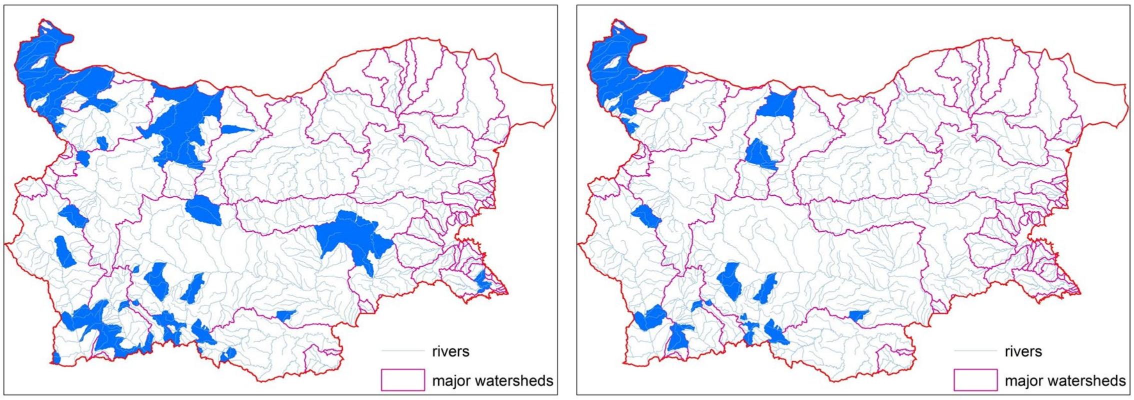


Fig. II.5-2. Watersheds with 5% (left panel) and 10% (right panel) sustained increases in intensive rainfalls over 10 mm/6 h for the period 2021–2050 compared to the reference period 1961–1990.

Flood forecasting in a changing climate is one of the major measures for mitigating flood risk and flood consequences (Balabanova et al., 2022). Floods do not recognize political and administrative borders but provoke international cooperation for flood risk management on a basin level (Bezak et al., 2021). The Danube region is the most international river basin in the world with major tributaries along 14 countries. Within the DAREFFORT project, a standardized international hydro-meteorological data exchange platform to improve the quality and efficiency of national forecast services is set up (http://hydro.bg/en/DAREFFORT).

II.5.3. Climate projections of hazardous events according to Meteoalarm codes

Changes in the frequency of intense convective precipitation and extreme wind events for the territory of Bulgaria (Valcheva&Spiridonov, 2021) and the Balkan Peninsula (Valcheva&Spiridonov, 2023) were studied for two future periods (2021–2050 and 2071–2099) under two climatic scenarios (RCP4.5 and RCP8.5). The regional climate model RegCM4 (with a horizontal resolution of 20 km) was used for these simulations. The reference period is 1975–2004, and the change in the number of cases of intense convective precipitation and extreme wind events is determined using the accepted thresholds for Bulgaria under Meteoalarm codes "yellow", "orange" and "red" (Table II.5-1). The most significant changes in the number of cases of extreme convective precipitation are expected in coastal and mountainous regions. Notably, an increase in the number of these events does not necessarily imply an increase in the total amount of precipitation in these regions. This can be attributed to the extension of the period during which such events can occur, driven by rising temperatures. For extreme wind events, significant increases in frequency are predicted for North and South-West Bulgaria, as well as coastal areas.

Table II.5-1. Accepted treshholds values for Bulgaria according to Meteoalarm codes

ELEMENT/CODE	YELLOW	ORANGE	RED
PRECIPITATION	15–35 mm/24 h or intense precipitation up to 30 mm/6 h	35–65 mm/24 h or intense precipitation > 30 mm/6 h	> 65 mm/24 h
WIND	**Strong wind:** speed of 14–19 m/s (50–69 km/h) and/or gusts up to 24 m/s (90 km/h)	**Stormy wind**: Speed of 20–29 m/s (70–100 km/h) and/or gusts up to 32 m/s (115 km/h)	**Hurricane wind**: Speed ≥ 30 m/s (>100 km/h)

Fig. II.5-3 presents the annual and seasonal change in the number of cases with convective precipitation above 35 mm/24 h (orange code). The annual number of heavy rains in both future periods and for both scenarios is expected to decrease in mountainous areas (by 20–40 events/30 years) and increase along the coast (by 40–60 events/30 years). Seasonal analysis shows an increase in extreme precipitation in autumn along the Black Sea by 20–30 cases for the period 2021–2050 and by 30–40 cases for the period 2070–2099. In mountainous regions, extreme precipitation decreases in spring and summer with 10–20 cases in 30 years.

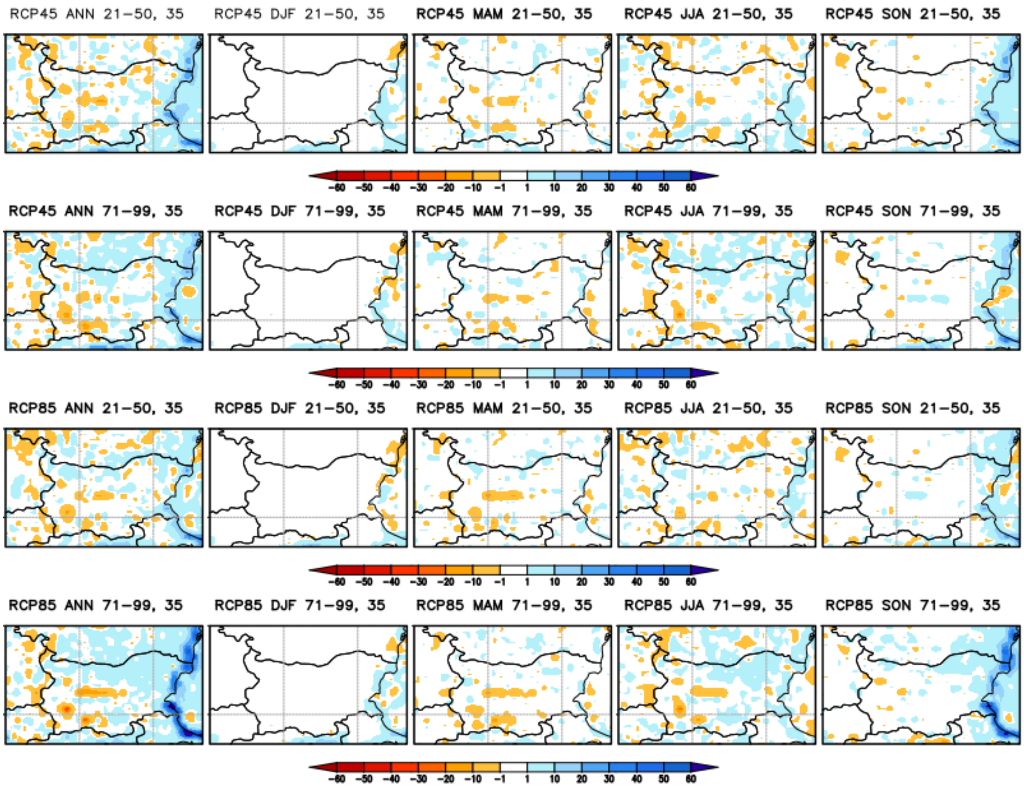


Fig. II.5-3. Simulated annual and seasonal changes in the number of cases of 24-hour convective precipitation exceeding the fixed threshold of 35 mm/24 h (orange code) for the periods 2021–2050 and 2071–2099 according to the RCP4.5 scenarios (first two rows) and RCP8.5 scenarios (last two rows).

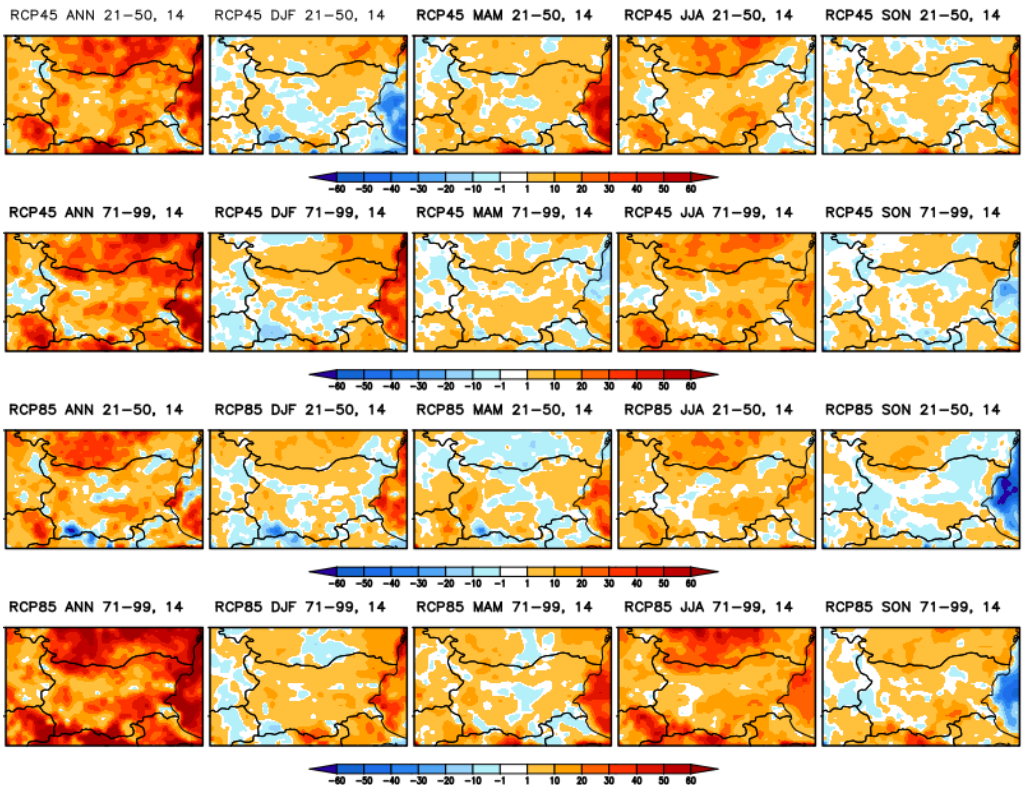


Fig. II.5-4. Simulated annual and seasonal changes in the number of occurrences of maximum wind speed above 14 m/s (code yellow) at 10 m above ground level for the periods 2021–2050 and 2071–2099 under the RCP4.5 scenarios (first two rows) and RCP8.5 scenarios (last two rows).

In the case of strong wind with a speed ≥ 14 m/s at 10 m above ground level, an increase in the annual number of events is expected for the period 2021–2050 under both scenarios with about 20 cases (Fig. II.5-4).

According to the RCP4.5 scenario for the period 2071–2099, an increase in cases of strong wind (up to 40–60) is expected over the Danube Plain, Dobrudzha, the Upper Thracian Lowland and the Black Sea coast, as well as in the southernmost regions of Rila and Pirin. According to the RCP8.5 scenario for the same period, the increase in the whole region is significant – with 40 cases in the northwestern regions, 40–80 cases along the Black Sea coast and up to 100 cases in Central and South Bulgaria. An increase in the number of strong wind events is expected in all seasons over most of the country, mainly in the plains and coastal areas.

II.5.4. Convection-permitting simulations for Bulgaria under the RCP8.5 scenario

Although regional climate models provide valuable information for climate change, there is a growing need for high-resolution simulations to assess local impacts more accurately. Recent advances in supercomputing power and the development of regional climate models have enabled simulations at kilometer-scale resolutions.

In Valcheva et al. (2024), the first 10-year-long simulations for both historical and future scenarios at a convection-permitting scale (3 km) for Bulgaria are presented. These simulations are conducted on the EuroHPC JU supercomputer, Discoverer, located in Sofia Tech Park, Sofia, Bulgaria (https://sofiatech.bg/en/petascale-supercomputer/). The study evaluates various precipitation metrics (Tab. II.5-2) and their projections under the RCP8.5 scenario. The downscaling process involves a two-step approach: the HadGEM2-ES global climate model is initially downscaled to a 15 km grid using the convection-parameterized non-hydrostatic regional climate model RegCM4.7.1 (Giorgi et al., 2012; Coppola et al., 2021); this 15 km resolution is further refined to a 3 km grid using a convection-permitting model (Coppola et al., 2021), which accurately resolves deep convective processes. The primary distinction between the two modeling approaches lies in their treatment of deep convective processes. The convection-parameterized model uses a cumulus convective scheme to approximate these processes, while the convection-permitting model explicitly resolves them, providing more detailed and accurate simulations at the kilometer scale.

Table II.5-2. Daily and hourly precipitation metrics

Indicators	Description	Units
Mean precipitation	Daily mean precipitation	mm/d
Frequency	Wet day and hour frequency is defined as a % of the number of wet days/hours per season	(%)
Intensity	Wet day and wet hour intensity	mm/d; mm/h
Heavy precipitation	Defined as the 99th percentile of all daily precipitation events (p99) and the 99.9th percentile of all hourly precipitation events (p99.9)	mm/d; mm/h
Bias	Model-observation	mm/d; mm/h; (%)
PDF	Probability density function of hourly/daily precipitation	

The evaluation of precipitation metrics (Valcheva et al., 2023) demonstrates that kilometer-scale simulations enhance the representation of various rainfall characteristics. These simulations improve the depiction of the intensity of hourly rainfall (over 1 mm/h) across all seasons. There is a better representation of the frequency of hourly rainfall during spring, autumn, and winter. The simulations more accurately capture extreme rainfall events (99.9th percentile) in winter and autumn.

Projected changes in rainfall patterns (Fig. II.5-5 and Fig. II.5-6) (Valcheva et al., 2024) suggest a decrease in average summer and autumn precipitation, except for the northwesternmost parts of the domain in autumn, and an increase in average spring and winter precipitation. During spring, both average and heavy rainfall are expected to increase and intensify by the end of the 21st century. In winter, the mean precipitation is projected to rise by 15–20% across the studied area, with a significant increase in heavy precipitation by 30–35% over Bulgaria, leading to more intense rainfall events. The kilometer-scale simulations indicate a positive projected change in wet-hour intensity across all seasons in Bulgaria, with increases of 13.86% in spring (MAM), 17.48% in summer (JJA), 1.97% in autumn (SON), and 17.43% in winter (DJF). Extreme precipitation (p99) is expected to increase in the winter and spring for both resolutions for the territory of Bulgaria by the end of the century. The frequency of wet-day and wet-hour precipitation is projected to decrease over Bulgaria, except in the winter, and the intensity increases. Heavy precipitation becomes more intense at both the hourly and daily time scales.

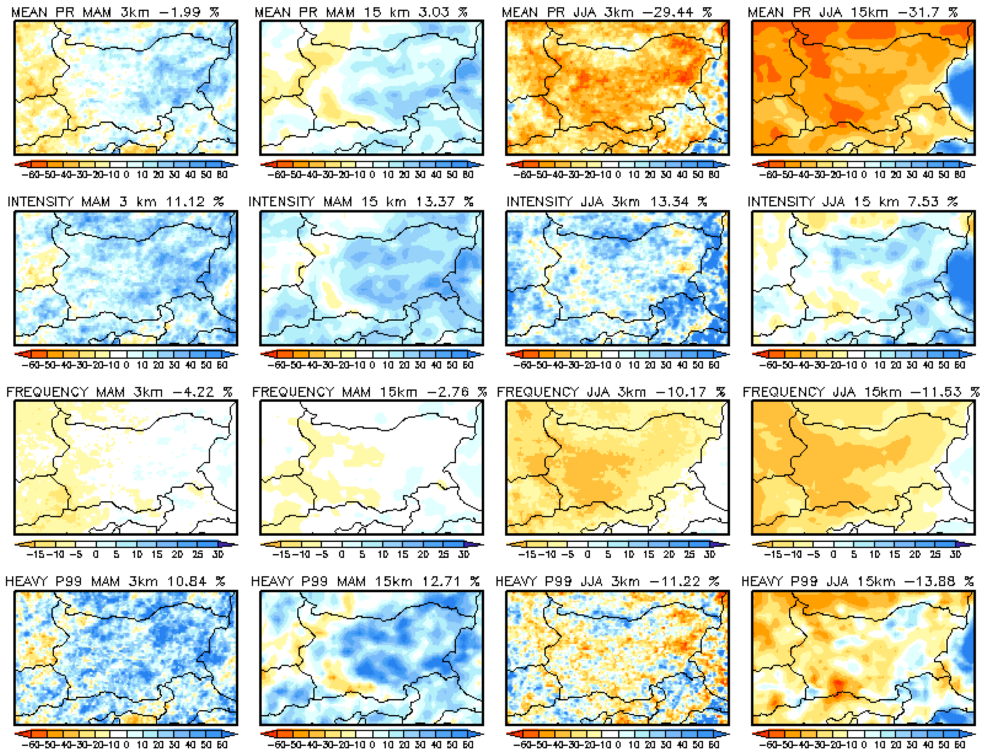


Fig. II.5-5. Expected changes in daily rainfall (first row), the intensity (second row) and frequency (third row) of wet days (> 1 mm/day), and extreme rainfall (99.9th percentile), defined as the 99.9th of all events – dry and wet (last row), simulated by the two models (3 km CPRCM and 15 km RCM) for spring – MAM (first two columns), and summer – JJA (last two columns), by the end of the century (2089–2099) under the RCP8.5 scenario, compared to the historical period (1995–2005) in percent (Valcheva et al., 2024; License CC BY 4.0; https://creativecommons.org/licenses/by/4.0/).

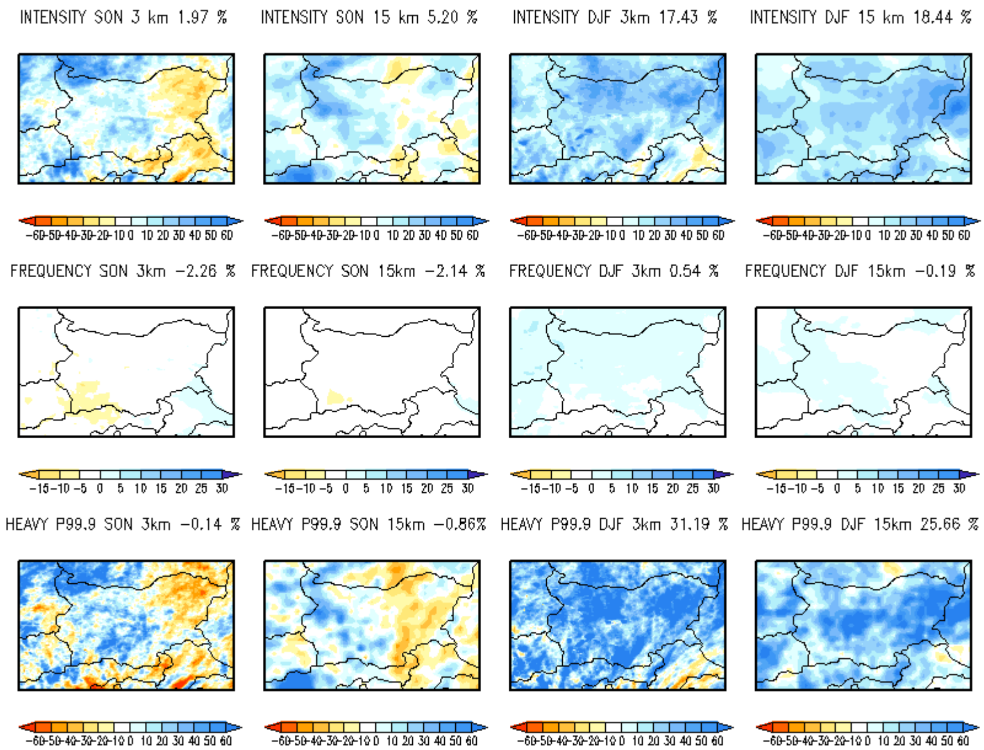


Fig. II.5-6. Expected changes in the intensity and frequency of hourly rainfall > 0.1 mm/h (first and second rows, respectively) and extreme hourly rainfall (99.9th percentile), defined as the 99.9th percentile of all events – dry and wet (last row), simulated by the two models (3 km CPRCM and 15 km RCM) for autumn (SON, first two columns) and winter (DJF, last two columns) by the end of the century (2089–2099) under the RCP8.5 scenario, compared to the historical period (1995–2005) in percent (Valcheva et al., 2024; License CC BY 4.0; https://creativecommons.org/licenses/by/4.0/).

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