



Short analysis of climate conditions till 2023 and future climate projections for Bulgaria

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Abstract: The paper presents a summary of the current and future climate of Bulgaria. The analyses show that the tendency in the long-term variations of the average annual air temperature is positive, while variations in the annual precipitation do not follow a clear trend, mainly due to the different signs of change in individual regions. The changes in the number of days with extreme weather phenomena, such as icy and hot days, hail and heavy rainfall days are also briefly commented. Projected changes in temperature and precipitation by the end of the century have been estimated under the four main socio-economic scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5) defined in the IPCC Sixth Assessment Report (AR6).

Keywords: Climate variation, Bulgaria, First Biennial Transparency Report under Article 13 of the Paris Agreement

1. INTRODUCTION

This paper briefly presents the current climate profile of Bulgaria, focusing on changes in temperatures and precipitation for the last two reference climate periods (1961-1990 and 1991-2020), as well as their long-term variation since 1930. Changes in the frequency of some extreme events are also commented on. The expected change in temperature and precipitation under four emission scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5) from the latest IPCC assessment report (AR6) is summarized for the territory of the country.

These analyses have been prepared in response to an official letter from the Ministry of Environment and Water dated 25.11.2024, requesting specific climate information on the current (including 1988-2023) and future climate of Bulgaria, as well as a brief description of the climate scenarios, necessary for the preparation of the First Biennial

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Transparency Report under Article 13 of the Paris Agreement. Strictly following the deadline pointed out in the letter, we submitted the required information on 09.12.2024. The report for Bulgaria (<https://unfccc.int/documents/645300>) was uploaded to the UN website on 02.01.2025, without any feedback to coordinate the final version of the prepared document with the authors of the materials. The compiled document made our analyses senseless and calls into question the competence of the scientists at NIMH and the relevance of their research. Particularly, it is a matter of complete disregard for the texts provided and the use of well-outdated information on the future climate of Bulgaria, provided again by NIMH, but in December 2017 for the preparation of the Seventh National Communication in connection with Article 12 of the UN Framework Convention on Climate Change (<https://www.moew.government.bg/bg/nacionalni-dokladi/>). Moreover, in Chapter 4.2. "Impacts, Risks and Vulnerabilities" of the document, there is a fairly large non-referenced text, which is copied from the brochure, prepared by NIMH for the 61st session of IPCC, held from July 27 to August 2024 in Sofia (Eds. Marinova&Bocheva, 2024).

Considering the above, we decided to publish in full text the material we prepared for the First Biennial Transparency Report under Article 13 of the Paris Agreement, as it was submitted to the Ministry of Environment and Water. Only the conclusions have been added as a summary of the information provided.

2. CLIMATE OF BULGARIA

The climate of Bulgaria is temperate continental with a transition towards the subtropical climate of the Mediterranean type and has four distinct seasons. Despite its small area, Bulgaria has unusually various climate conditions due to the combined influence of the strongly differing continental and Mediterranean climates and the diverse landscape. According to the accepted in the National Institute of Meteorology and Hydrology climate classification, 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.

The Balkan Mountains appear as a south boundary of the area in which continental air masses circulate freely. The Rhodope Mountains mark the northern border of the Mediterranean weather system influence. The intermediate area, which includes the Thracian Lowland, is affected by the interaction of the two systems, but the continental climate features predominate. So, the climate is generally more severe than that in other parts of Europe at the same latitude. The influence of the Black Sea mainly affects the climate in the immediate area along the coast and about 30-40 km inland; the strong winds and storms are frequent during the cold half-year. Mountains and valleys act as barriers or channels for air masses, causing sharp contrasts in weather over relatively short distances.

The long-term annual mean air temperatures in Bulgaria vary from -2.3°C to 14.7°C , depending on the location and elevation. Air temperature normally reaches a minimum in January and a maximum in July. The monthly mean temperature varies from -10.0°C to 4.1°C in January and from 6.0°C to 25.9°C in July. During severe winters, minimum temperatures may drop below -20°C , even below -30°C . Winters are cold along the Danube River but almost as mild as in the Mediterranean region along the southern sheltered valleys. The heating season varies between 160 and 220 days for the different locations. The temperature inversions are typical for valleys in the cold half-year, resulting in increased air pollution and smog in the industrial and urban zones. In the spring, mean maximum temperatures range from 15°C to 25°C , gradually increasing from March to May. The typical summertime begins in the middle of June when temperatures can reach above $30-35^{\circ}\text{C}$. July and August are the hottest months, with maximum temperatures $35-38^{\circ}\text{C}$. During all summer months, maximum temperatures even above 40°C , although rare and in places, are no exception for the plain regions of Bulgaria. Summer usually ends in mid-September, when temperatures begin to drop gradually. Autumn is not as rainy as Europe's west and central parts, and the weather from the mid-September to the mid-October can be quite pleasant with maximum temperatures up to $20-25^{\circ}\text{C}$ or more.

Dobrudzha in the northeast, the Black Sea coastal area, and parts of the Thracian Lowlands, sometimes receive less than 500 mm of precipitation per year. The Thracian Lowlands is often affected by summer and autumn droughts. High-altitude areas receive the most precipitation in the country – over 900-1000 mm per year. The air humidity is between 66 and 85% in the different parts of the country. Average cloudiness is about 55-56 percent. The prevailing winds are from northwest and west. The average wind speed varies between 1.2 and 4.0 m/s in lowlands. In some mountainous regions and the northern coastal zone, the average wind speed is over 5 m/s.

The high-mountain areas remain snow-covered until the late spring. In the lowlands, the snow cover persists for about 30-40 days per year. Abundant snowfalls may occur throughout the country from December to the end of March, especially in mountainous areas. The snow covers in Bulgaria are distinguished by a large variability. In the lower parts of the country, it forms and disappears several times per season (the average depth is about 10-15 cm per season). Although rarely, in the Danube Plain, the snow cover depth reached 80-100 cm. In mountainous areas, the accumulation of snow cover shifts with altitude. In the hilly parts (500-800 m), the accumulation begins in December and for altitudes above 1500 m – even in November. The average snow cover depth in the lower parts of the mountains is 25-30 cm in January and February. The values can reach 200 cm or more in the high-mountain areas in March and April when the maximum snow cover accumulation occurs.

The barrier effect of the Balkan Mountains is felt distinctly till the late 1990s – on an annual basis, Northern Bulgaria is cooler at about 1°C and receives about 192 mm more precipitation than Southern Bulgaria. Since the beginning of the 21st century, temperatures are rising (see Figure 1). The northern part of the country is warming faster than the southern one, equalizing the average annual temperature on both sides of the

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Balkan Mountains. In the period 1991–2020, the average annual temperature increased by 0.8 °C compared to the previous 30-year period (Figure 1). In general, warming in the mountains is weaker, but in individual regions of the non-mountainous part of the country, the temperature increase exceeds 1 °C. Winter warming is more pronounced in Northern Bulgaria, while in the southern part of the country, an increase in winter temperatures by 0.5-1 °C is recorded in the high fields of Western Bulgaria and individual places along the valleys of the larger rivers. In spring, warming also covers South-eastern Bulgaria. The increase in summer temperatures is 1.5 °C on average for the country (by over 2 °C in places, mainly in Northern Bulgaria), while in autumn in a large part of the country, the temperature increase is in the range of 0.1-0.5 °C. During winter and transitional seasons, negative anomalies are detected in some sub-mountainous and mountainous areas, mainly in the southern part of the country.

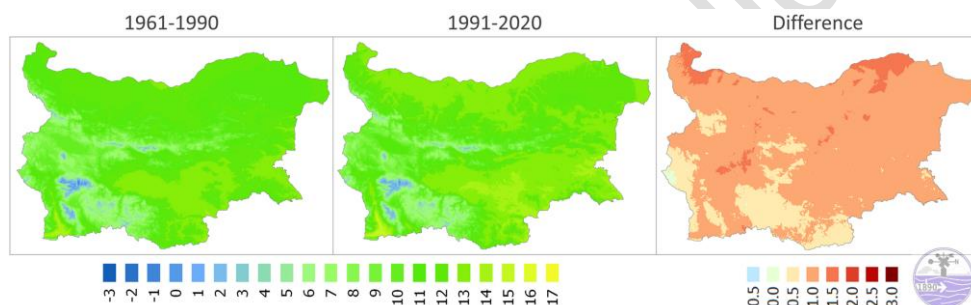


Fig. 1. Spatial distribution of the average annual temperature for the periods 1961–1990 and 1991–2020 and the absolute difference between the second and first periods (°C).

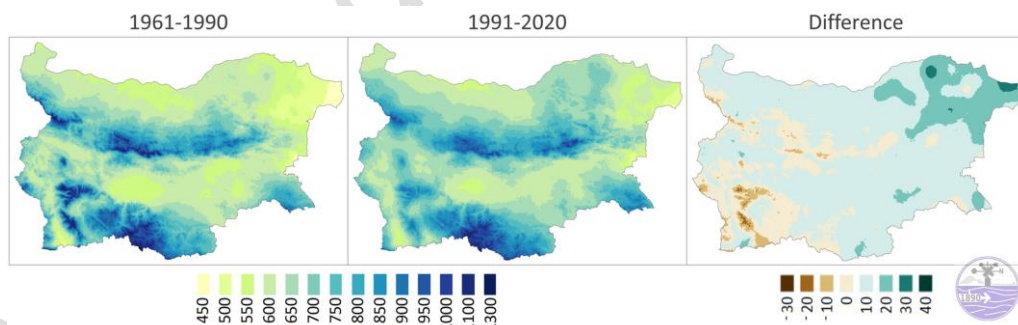


Fig. 2. Spatial distribution of annual precipitation (mm) for the periods 1961–1990 and 1991–2020 and the relative difference between the second and first periods in %.

The variations in the annual precipitation amount do not follow a clear trend in the period 1931–2020, mainly due to the different signs of change in individual regions. The fluctuations in seasonal precipitation suggest that it is very likely that their change by the end of the century will follow different patterns.

In a large part of the country, the precipitation regime changed after the middle of the 20th century – after a significant decrease in summer precipitation in the last two decades of the previous century, since the beginning of the 21st century, a significant increasing trend occurs in autumn precipitation. In the period 1991–2020, the change in seasonal precipitation amounts is within $\pm 10\%$ compared to the period 1961–1990 for a large part of the country (Figure 2).

In the period 1988–2023 (Source: NIMH), the average annual air temperature in the country ranges between 9.8 °C and 12.9 °C. The tendency in the long-term variations of the average annual air temperature is positive. Temperature anomalies for 21 years after 1988, as well as for all years after 2011, are positive compared to the 1991–2020 climate norm. Against this background, 2023 (with an average annual temperature of 12.9 °C) is the hottest year (followed by 2020 and 2019) in the observed period 1988–2023, but it is also the warmest one since 1930 in Bulgaria (Figure 3).

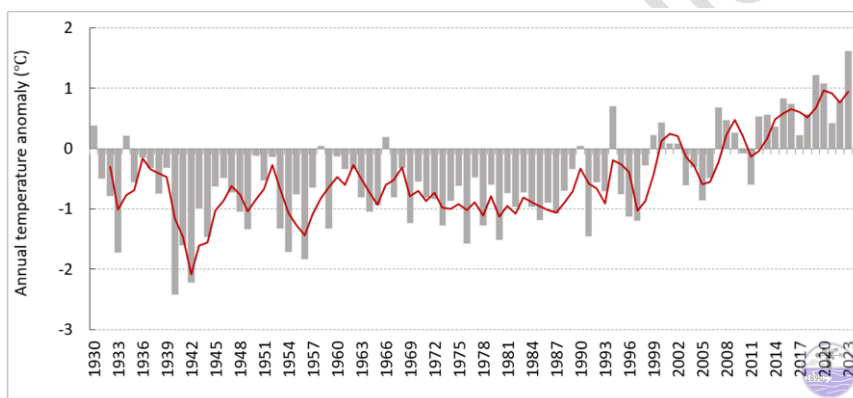


Fig. 3. Annual temperature anomaly for the period 1930–2023 (reference period 1991–2020). The 5-year moving average is also shown (in red).

The average amount of precipitation in 2023 is 636 mm, which is around the climate norm (Figure 4). 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 (Figure 5). 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.

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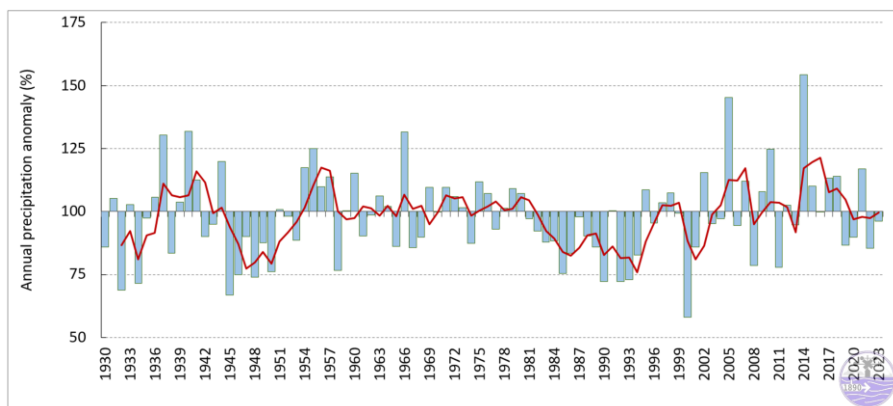


Figure 4. Annual precipitation anomaly for the period 1930–2023 (reference period 1991–2020). The 5-year moving average is also shown (in red).

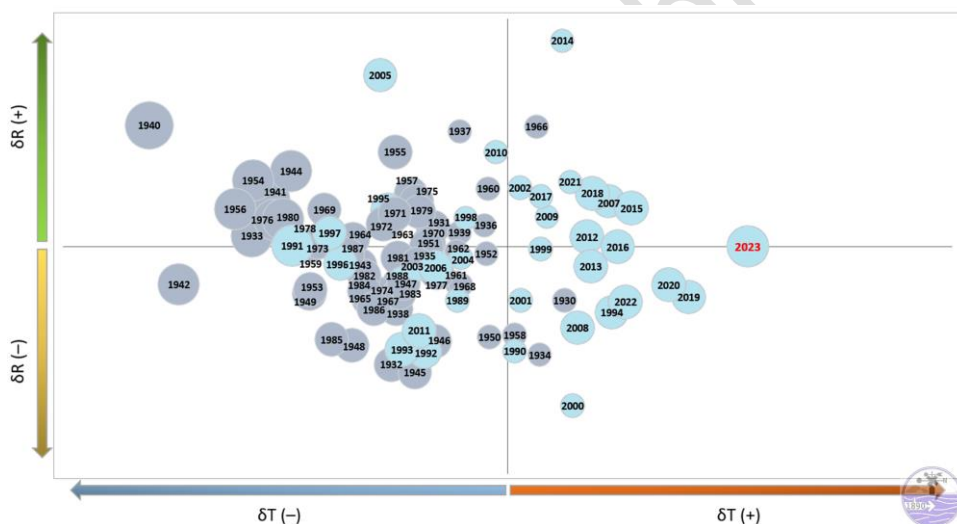


Fig. 5. Combined diagram of the annual temperature anomaly (δT) and the annual precipitation anomaly (δR) in the period 1930–2023. The distance from the center of the diagram horizontally corresponds to the temperature anomaly and vertically – to the precipitation anomaly. The size of the circles corresponds to the temperature anomaly magnitude. The reference period is 1991–2020. Light blue-colored circles mark the period 1988–2023.

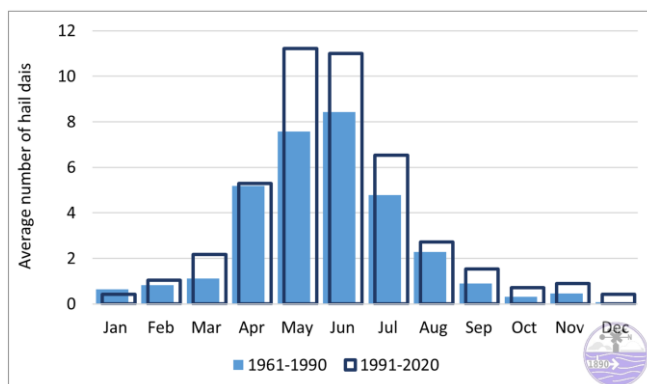


Fig. 6. Country average number of hail days by month for the periods 1961–1990 and 1991–2020.

Since the beginning of the 21st century a significant increase (above 30%) in the average number of days with 24-hour precipitation above 100 mm has been observed. The snow cover persistence in the mountains decreases and the average snow cover depth shows a positive tendency towards thinning. Convective precipitation, which is typical for spring and summer become more frequent during the winter months. The country average annual number of hail days for the period 1991–2020 shows a statistically significant positive trend. The number of hail days increased significantly (almost doubled) in relatively cold months in spring and autumn (March, September, October and November) as seen in Figure 6. The number of hail days in June increased significantly in the central and western parts of Southern Bulgaria.

In line with the tendency of global warming, one of the basic indicators of winter severity – the number of ice days (daily maximum air temperature below 0 °C) – shows a clear decreasing trend since the end of the last century (Figure 7a). About 44% of the stations in Northern Bulgaria (NBG) and 18% of the stations in Southern Bulgaria (SBG) show a statistically significant decrease of ice days by 2.1-2.3 days per decade on average. According to the climatic conditions in Bulgaria, hot days are defined as days with a daily maximum air temperature above 32 °C. The number of hot days has increased over the last few decades, as seen in Figure. 7b. In over 90% of the stations, a statistically significant increasing trend by 3.5-3.6 days per decade on average is observed.

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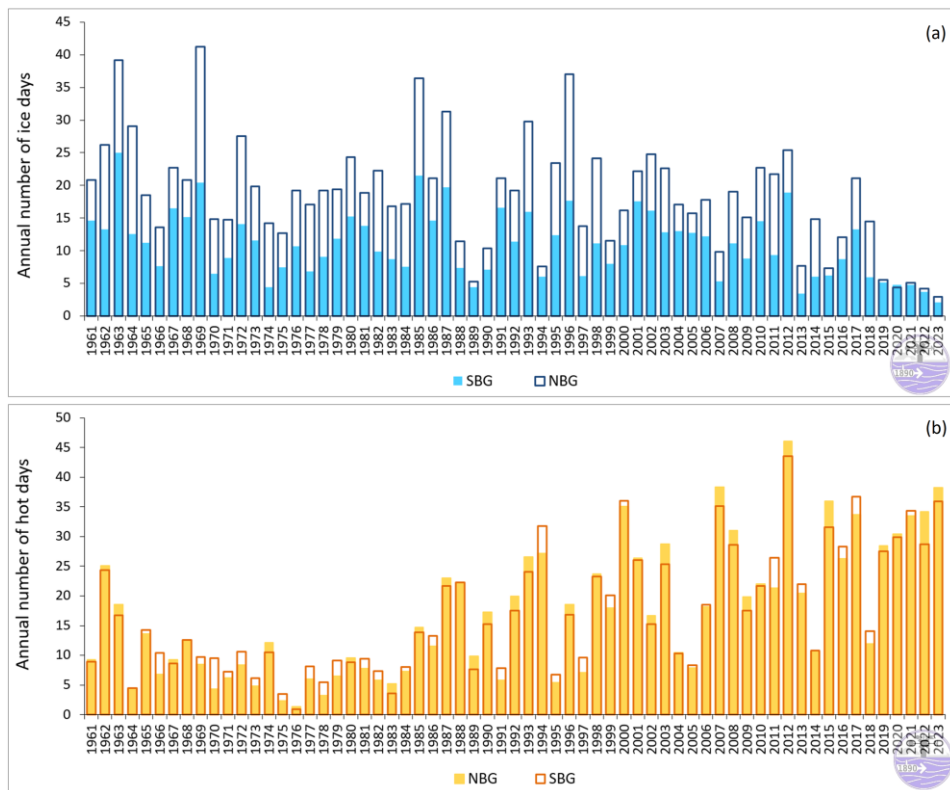


Fig. 7. Annual number of ice days (a) and annual number of hot days (b) in the period 1961–2023.

3. SCENARIOS FOR BULGARIA

3.1. Used data and methodology

The modern coupled atmosphere-ocean general circulation models (CAOGCMs), which simulate the physics, chemistry, and biology of the atmosphere as well as its interactions and feedback with the other geophysical spheres, are key (mathematically and physically consistent) tools to understand the climate change in the past and the future. The Coupled Model Intercomparison Project (CMIP, <https://www.wcrp-climate.org/wgcm-cmip>) provides a standard protocol for simulations and outputs of CAOGCMs used in the Intergovernmental Panel on Climate Change (IPCC) Assessment Reports (ARs). The IPCC AR6 (<https://www.ipcc.ch/assessment-report/ar6>) has featured state-of-the-art CMIP6 models with higher spatial resolution, incorporating new physical processes and biogeochemical cycles.

The latest version of the U.S. National Aeronautics and Space Administration

(NASA) Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) product comprises of statistically downscaled and spatially disaggregated climate scenarios for the globe that are derived from the runs of 35 models conducted under CMIP6 and across all four Tier 1 Shared Socioeconomic Pathway (SSP) scenarios (<https://www.nccs.nasa.gov/services/data-collections/land-based-products/nex-gddp-cmip6>). The dataset provides climate variables with high spatial ($0.25^{\circ} \times 0.25^{\circ}$) and temporal (daily) resolution for 1950–2100, including a historical period (1950–2014) and scenario-driven projections for 2015–2100. The used in the present report 25 models from NEX-GDDP-CMIP6 are shown in Table 1.

The observation-based daily gridded dataset E-OBS of the European Climate Assessment & Dataset project (<https://www.ecad.eu/download/ensembles/download.php>) is used as a reference dataset for the historical period.

Table 1. Used in the present report CAOGCMs from NEX-GDDP-CMIP6

Model	Name	Institution/Country	Grid, Hor. Res. (lon $\times$ lat)
1	ACCESS-CM2	CSIRO-ARCCSS/Australia	192 $\times$ 144, 1.875 $^{\circ} \times 1.25^{\circ}$
2	ACCESS-ESM1-5	CSIRO/Australia	192 $\times$ 145, 1.875 $^{\circ} \times 1.25^{\circ}$
3	BCC-CSM2-MR	BCC/China	320 $\times$ 160, 1.125 $^{\circ} \times 1.125^{\circ}$
4	CanESM5	CCCma/Canada	128 $\times$ 64, 2.813 $^{\circ} \times 2.813^{\circ}$
5	CMCC-ESM2	CMCC/Italy	288 $\times$ 192, 1.25 $^{\circ} \times 0.94^{\circ}$
6	EC-Earth3	EC-Earth-Consortium/EC-Earth consortium	512 $\times$ 256, 0.703 $^{\circ} \times 0.703^{\circ}$
7	EC-Earth3-Veg-LR	EC-Earth-Consortium/EC-Earth consortium	512 $\times$ 256, 0.703 $^{\circ} \times 0.703^{\circ}$
8	FGOALS-g3	CAS/China	180 $\times$ 80, 2 $^{\circ} \times 2.025^{\circ}$
9	GFDL-ESM4	NOAA-GFDL/USA	288 $\times$ 180, 1.25 $^{\circ} \times 1^{\circ}$
10	INM-CM4-8	INM/Russia	180 $\times$ 120, 2 $^{\circ} \times 1.5^{\circ}$
11	INM-CM5-0	INM/Russia	180 $\times$ 120, 2 $^{\circ} \times 1.5^{\circ}$
12	IPSL-CM6A-LR	IPSL/France	144 $\times$ 143, 2.5 $^{\circ} \times 1.259^{\circ}$
13	KACE-1-0-G	NIMS-KMA/Republic of Korea	199 $\times$ 144, 1.875 $^{\circ} \times 1.25^{\circ}$
14	MIROC6	MIROC/Japan	256 $\times$ 128, 1.403 $^{\circ} \times 1.403^{\circ}$
15	MPI-ESM1-2-HR	MPI-M, DWD, DKRZ/Germany	384 $\times$ 192, 0.939 $^{\circ} \times 0.939^{\circ}$
16	MPI-ESM1-2-LR	MPI-M, AWI, DKRZ, DWD/Germany	192 $\times$ 96, 1.875 $^{\circ} \times 1.875^{\circ}$
17	MRI-ESM2-0	MRI/Japan	320 $\times$ 160, 1.125 $^{\circ} \times 1.125^{\circ}$
18	NorESM2-LM	NCC/Norway	144 $\times$ 96, 2.5 $^{\circ} \times 1.875^{\circ}$
19	NorESM2-MM	NCC/Norway	288 $\times$ 192, 1.25 $^{\circ} \times 0.94^{\circ}$
20	TaiESM1	AS-RCEC/Taiwan	288 $\times$ 192, 1.25 $^{\circ} \times 0.94^{\circ}$
21	CNRM-CM6-1	CNRM-CERFACS/France	128 $\times$ 64, 2.813 $^{\circ} \times 2.813^{\circ}$

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22	CNRM-ESM2-1	CNRM-CERFACS/France	256×128, 1.406°×1.406°
23	GISS-E2-1-G	NASA-GISS/USA	144×90, 2.5°×2°
24	MIROC-ES2L	MIROC/Japan	256×128, 1.406°×1.406°
25	UKESM1-0-LL	MOHC/UK	192×144, 1.875°×1.25°

The SSP scenario group Tier 1 consists of four climate change scenarios. Three of them (SSP1-2.6, SSP2-4.5, and SSP5-8.5) provide continuity with the AR5 representative concentration pathways (RCPs) by targeting a similar level of aggregated radiative forcing. The scenario SSP1-2.6 (also called 'Sustainability') with 2.6 W/m² by the year 2100 is a remake of the optimistic scenario RCP2.6 and was designed to simulate a development compatible with the below 2°C warming target. This scenario assumes climate protection measures are being taken. The intermediate scenario SSP2-4.5 ('Middle of the Road') could be regarded as an update to RCP4.5 (with 4.5 W/m² radiative forcing by the year 2100) and represents the medium pathway of future GHG emissions. This scenario also assumes that climate protection measures are being taken. With 7.0 W/m² radiative forcing by the year 2100, the scenario SSP3-7.0 ('Regional Rivalry') is in the upper-middle part of the full range of scenarios. It was newly introduced after the RCP scenarios, closing the gap between RCP6.0 and RCP8.5. SSP5-8.5 represents an upper boundary of the range of scenarios (i.e., extreme one, also called 'Fossil-fueled Development: Taking the Highway') in which no policies are applied regarding the emission of GHG resulting in a forcing pathway of 8.5 W/m² in 2100.

In the present report, the quantitative assessment of daily minimum, mean, and maximum air temperature and daily precipitation sum (*tn*, *tg*, *tx*, and *rr*, correspondingly) is based on the multimodel ensemble (MME, <https://archive.ipcc.ch/ipccreports/tar/wg1/347.htm>) methodology. The analysis is focused on multimodel statistics: the multimodel mean (MM) and the multimodel 25th, 50th, and 75th percentiles (X25, X50 and X75, respectively). Two time frames for the climate change projections are selected: 2021–2050 ('near future') and 2071–2100 ('far future'). The used reference period is 1981–2010.

3.2. Future air temperature projections

The long-term changes of the *tn*, *tg* and *tx* are quantified by comparing the multiyear means of the scenario-driven future with their counterparts for the reference period. The MME median of the models listed in Table 1 for all four scenarios for the near and far future is compared to the median of the reference period. The results are shown in Figures 8 and 9 using the same color legends, ensuring in such a manner better comparability.

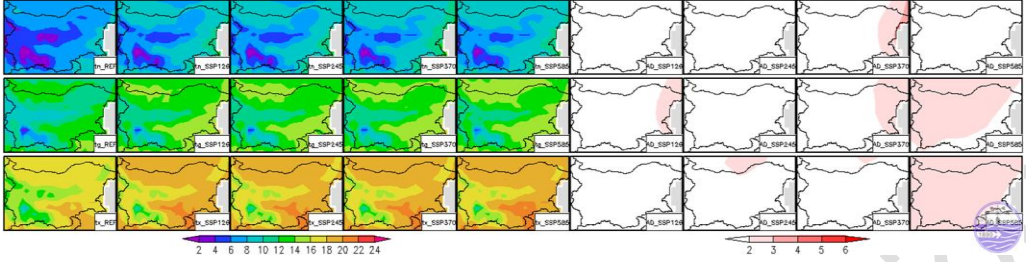


Fig. 8. Results for the near future 2021–2050: MME median of the multiyear means of t_n , t_g and t_x for the reference period ('REF') and for the Tier1 scenarios, as well as the absolute differences ('AD', i.e., scenario minus reference). The units are °C.

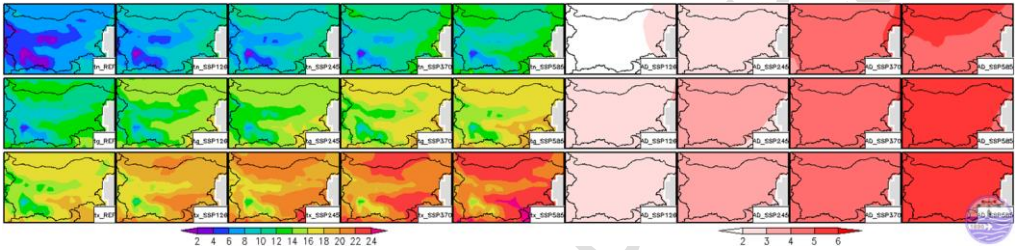


Fig. 9. Results for the far future 2071–2100: MME median of the multiyear means of t_n , t_g and t_x for the reference period ('REF') and for the Tier1 scenarios, as well as the absolute differences ('AD', i.e., scenario minus reference). The units are °C.

Although the horizontal resolution is too coarse for local climatological analysis, the vertical gradients are well emphasized – there is clear difference between the temperatures in the flat party of the country on the one hand and in the mountains in the other. Figures 8 and 9 show a gradual increase of the projected changes from SSP1.2-6 to RCP5.8-5, i.e., proportional to the radiative forcing. The changes are similar in magnitude for all variables for fixed scenario RCP2.6-RCP6.0 and do not have a clear spatial structure. As aspect, the magnitude of the warming in the far future is significantly bigger than in the near future, which can be generally explained with the longer cumulative effect of the radiative factors.

The long-term time evolution of the area-averaged values of t_n , t_g and t_x are shown in Figure 10.

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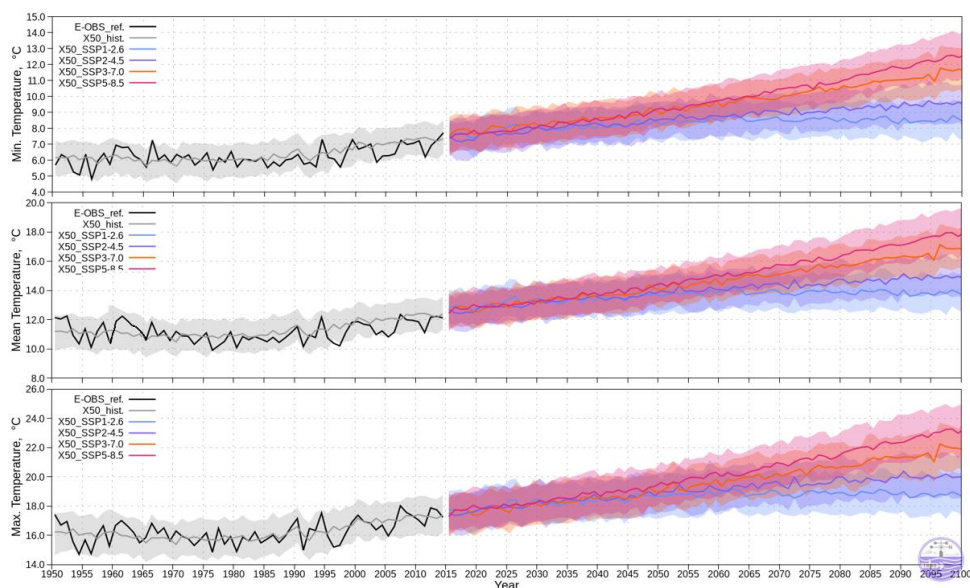


Fig. 10. Area-averaged t_n , t_g and t_x values in the upper, middle and lower pane correspondingly. Solid lines indicate the MME median and the shading indicates the interquartile ensemble spread (between the 25th and 75th percentile). The thick black line indicates the reference data.

Many conclusions could be drawn from Figure 10. First of all, the upward tendency is clearly recognizable. The reference data almost entirely fall into the interquartile band; the differences between the MME median and reference data are in the range of $\pm 1^\circ\text{C}$. Although simulations cannot reproduce the year-to-year variability of the reference data, there is no systematic under- or overestimation.

The projected evolution of the considered temperature variables shows practically overlapping trajectories up to the middle of the century, indicating minor scenario dependence in the near future. It is also worth emphasizing that up to this time horizon, the magnitude of the interquartile spread is larger than the differences between scenarios.

The difference between the 30-year running mean values of climate variables and the norms for the reference period is frequently used to measure climate signals. The time evolution of this measure for t_n , t_g and t_x is shown in Figure 11.

Figure 11 confirms the fact that the magnitude of the change is practically proportional to the radiative forcing, i.e., it increases from SSP1.2-6 to RCP5.8-5. The changes follow a monotonically increasing, almost linear tendency for all scenarios, except the scenario with the weak forcing (SSP1.2-6), for which a ‘saturation’ of the change for all three temperature variables can be detected in the period 2061–2090. The change rate is the smallest for the t_n ; the rates of the t_g and t_x are practically identical. The projected changes are summarized also in Table 2.

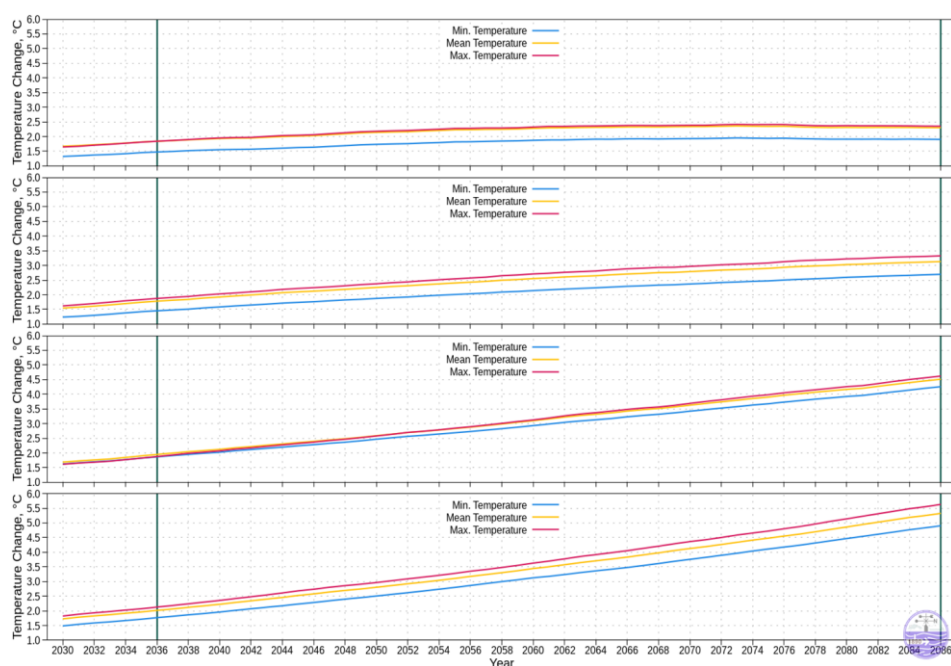


Fig. 11. Evolution of the difference between the centered 30-year running means for the 2015–2100 and the 1981–2010 norms of the temperature variables for SSP1.2-6 to RCP5.8-5 from upper to lower pane correspondingly. The years which corresponds to the middle year of the near and far future period are marked with dark green vertical bars. Note, that the Y-axis scale of all subplots is the same

Table 2. Magnitude of the generalized projected changes of the field mean minimum, mean and maximum temperature (unit: °C) for the near (2021–2050) and far future (2071–2100) periods

		2021–2050				2071–2100			
Scenario	Variable	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5
tn		[1.4 , 1.5]	[1.4 , 1.5]	[1.8 , 1.9]	[1.7 , 1.8]	1.9	[2.6 , 2.7]	[4.2 , 4.3]	[4.9 , 5.0]
tg		[1.8 , 1.9]	[1.7 , 1.8]	[1.9 , 2.0]	2.0	2.3	[3.1 , 3.2]	[4.5 , 4.6]	[5.3 , 5.4]
tx		1.8 – 1.9	[1.8 , 1.9]	[1.8 , 1.9]	[2.1 , 2.2]	[2.3 , 2.5]	[3.3 , 3.4]	[4.6 , 4.7]	[5.6 , 5.7]

3.3. Future projections of annual precipitation

Due to the complex nature of the precipitation processes, the spatial and temporal patterns of this climate variable are more unpredictable compared to the spatio-temporal

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variation of the temperature. As in many other places of the world, in contrast to the projected changes in temperatures, where there is a general agreement on the sign of long-term change independent of the region considered, changes in the annual precipitation over Bulgaria are less consistent.

Similarly, to Figures 8 and 9, Figure 12 compares the MME median of the models listed in Table 1 (for all four scenarios and the near- and far-future periods) to the median of the reference period.

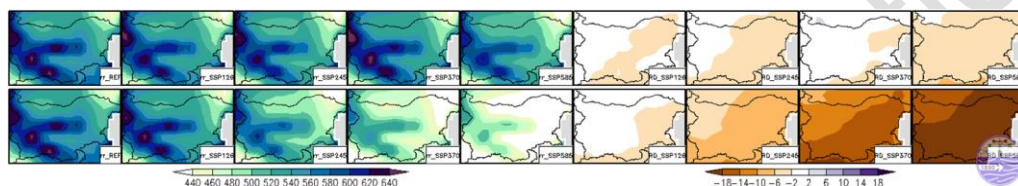


Fig. 12. MME median of the multiyear means of the annual precipitation sum for the reference period ('REF') and for the Tier1 scenarios as well as relative differences ('RD', i.e., the ratio of scenario to reference in %) for the near and far future in the upper and lower subplot correspondingly.

Figure 12 reveals the spatial distribution of annual precipitation, especially the local maximum over the mountainous part of the country. Although the total precipitation amount shows a clear downward tendency, particularly over the southern and eastern parts of the domain, there is no significant difference, both in magnitude and spatial distributions, in the relative changes in scenarios SSP1.2-6 – SSP3.7-0 for the near future shown in the upper subplot of Figure 5. As in the case of the temperature variables, the changes in the far future are essentially more prominent, reaching almost 20% for the scenario with the strongest forcing, SSP5.8-5.

Figure 13 shows the evolution of the area-averaged values of annual precipitation in the period 1950–2100. The interquartile spread, both for the historical and future periods, is more significant compared to the temperature variables. This fact reflects the essential variations between the particular models in the MME in this regard. Although the year-to-year changes in the reference data are significant, they fall into the MME interquartile range of the historical simulation, except for a couple of years. The general downward tendency in the future is distinguishable. There is, however, no apparent difference between the scenarios even after the middle of the century; their interquartile diapasons practically overlap almost up to the end of the considered period. Again, the magnitude of the interquartile spread is more significant than the scenario difference.

Figure 14 shows the relative difference between the annual precipitation sum averaged over consequent 30-year-long time frames (i.e., running mean) and the norm for the 30-year-long period 1981–2010. The magnitude of the changes is generally proportional to the level of radiative forcing. Specifically, the absolute value of changes increases from SSP1.2-6 to RCP5.8-5. The exception is the scenario with the weakest forcing, SSP1.2-6, where the relative change remains nearly constant at about -2%

throughout the period. In contrast, the other scenarios show a consistent decreasing trend in changes. A summary of the projected changes is also presented in Table 3.

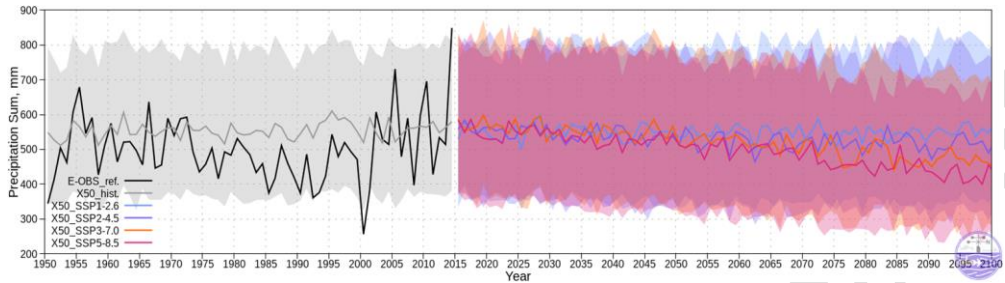


Fig. 13. Field mean value of the rr. Solid lines indicate the MME median and the shading indicate the interquartile ensemble spread (between 25th and 75th percentile). The thick black line indicates the observational reference.

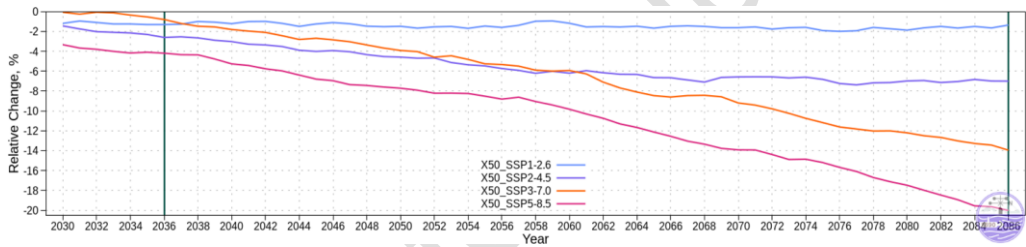


Fig. 14. Evolution of the relative difference between the centered 30-year running mean for the 2015–2100 and the 1981–2010 norm of the annual precipitation. The years corresponding to the middle year of the near- and far-future period are marked with the dark green vertical bars.

Table 3 Magnitude of the generalized projected relative changes (in %) of the field mean annual precipitation sum for the near (2021–2050) and far future (2071–2100) periods

		2021–2050				2071–2100			
Scenario	Variable	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5
rr		[-2 , -1]	[-2 , -3]	[-1 , 1]	[-5 , -4]	[-2 , -1]	[-8 , -7]	[-13, -14]	[-21 , -20]

4. CONCLUSIONS

The present study briefly summarizes the spatial and temporal changes of annual temperatures and precipitation during the current climate (including 1988–2023) and the expected changes by the end of the century according to four main socio-economic scenarios, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5. Fluctuations in annual mean

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air temperature since 1930 reveal a statistically significant warming trend, but no clear signal is detected for annual precipitation. The climate normals for 1991–2020 are higher than the previous period, 1961–1990, both for temperature (about +0.8 °C) and precipitation (about +8%). Most years after 2000 have annual temperatures above normal, with 2023 being the warmest from the beginning of meteorological instrumental measurements in Bulgaria.

The shift to a warmer (and drier in some areas) climate is consistent with both the observed long-term increase in global and regional average annual temperatures (IPCC, 2021) and changes in temperature-based climate indices (Alexander et al., 2006). A more pronounced decrease in ice days and an increase in hot days (over 2 and 3 days per decade, respectively) are found in both Northern and Southern Bulgaria for the period 1961–2023. In the conditions of a warming climate, an increase in the number of days with extreme rainfall (over 30%) is also observed, as well as a statistically significant increase in the number of hail days, especially in the cold half of the year.

The analysis of future climate projections reveals a distinct warming, expressed in the spatial patterns and time evolution of all considered temperature variables over the whole domain. The climate change signal intensifies gradually as radiative forcing increases in the examined scenarios. The "warming asymmetry" can be recognized in the evolution of temperature variables – the maximum temperature increases faster than the minimum temperature. Regarding annual precipitation, the results highlight the complexity and inherent uncertainty of the anticipated changes. The projected decrease in precipitation for the southern and southeastern parts of Bulgaria, especially under the worst-case scenario SSP5-8.5 in the far future, could exacerbate the adverse effects of the expected hotter climate.

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