PROJECTED CHANGES IN THE ROMANIAN CARPATHIANS AND SUBCARPATHIANS UNDER THE SSP3-7.0 CLIMATE SCENARIO BASED ON THE GFDL-ESM4 MODEL

MARIUS-VICTOR BIRSAN [1†], LAURA LUPU [1], DIANA DOGARU [1],
LOREDANA-ELENA HAVRIȘ [1], DANIEL CIUPITU [1]

[1]) Institute of Geography, Romanian Academy. Dimitrie Racoviță 12, 023993 Bucharest, Romania.
[†] E-mail: marius.birsan@gmail.com

Received:

Abstract. This paper shows the projected climatic changes in the Romanian Carpathians under the SSP370 climate scenario for nine biometeorological indices, at fine spatial resolution, over two horizons: 2041-2070 and 2071-2100. The projections are based on the GFDL-ESM4 model developped by the National Oceanic and Atmospheric Administration, USA. The following indices (computed from daily data) were extracted from the CHELSA database: mean annual air temperature, mean diurnal air temperature range, isothermality, mean daily minimum air temperature of the coldest month, annual range of air temperature, annual precipitation amount, growing season length, accumulated precipitation amount within the growing season, mean temperature of the growing season. The results show tiny increases in mean annual air temperature (compared to the reference period 1981-2010) for both near and distant future. The isothermality (defined as the ratio between the average daily and annual air temperature variation) is also very stable. The annual amount of precipitation shows very small deviations, with negative values in the southwest and positive in the northeast. The growing season length is projected to increase in most areas until the end of the century.

Key words: Climate projections; mountain region; Socio-Eonomic Pathways; SSP3 scenario; biometeorological indices; Romania; Eastern Europe.

DOI:

1. INTRODUCTION

Mountain regions represent a key environment for the well being of communities, providing a plethora of ecosystem services, like biodiversity, food and water supply, protection and tourism. The Romanian Carpathians (also known as Southeastern Carpathians) cover 54% of the length of the entire Carpathian range, and occupy an area of 66 303 km² over the Romanian territory. They constitute the highest and most rugged relief step, with an average altitude of 840 m.a.s.l. and are made up of three large relief units: the Eastern (55%), the Southern (21%) and the Western Carpathians (24%) [1].

The Eastern Carpathians extend over about 3° latitude and over an area of 34 549 km², of which 25% are represented by depressions, which reflects the attenuation of their massiveness; the average elevation is 1025 m.a.s.l., and the maximum is 2303 m.a.s.l. They include three subdivisions: the Carpathians of Maramureș and Bucovina (Northern group), the Moldavian-Transylvanian Carpathians (Central group) and the Curvature Carpathians (Southern group) [2].

The Southern Carpathians extend along about 4° longitude, from East to West for ~250 km and from north to south for 50-70 km, covering an area of 14 040 km². They represent the most imposing southern branch of the Carpathian arc, with an average elevation of 1136 m.a.s.l. and maximums of over 2500 m.a.s.l. [2].

The Western Carpathians span around 3° in latitude and ~370 km long between the Danube Valley and the Someș Valley and includes the Apuseni Mountains and the Banat Mountains. They cover an area of 17 714 km² and have an average altitude of only 654 m.a.s.l. The Apuseni Mountains represent the largest division, with an area of 11 645 km² and the highest peak of 1849 m.a.s.l. The Banat Mountains are located in the southwestern extremity of the Carpathian arc and have a maximum elevation of 1446 m.a.s.l. [2].

The Subcarpathians, located outside the Carpathian arc, have a pronounced geographical complexity and are characterized by mean elevations of 500-700 m.a.s.l. and maximums of over 1000 m.a.s.l. They are divided in three units: the Getic, the Curvature and the Moldavian Subcarpathians [2].

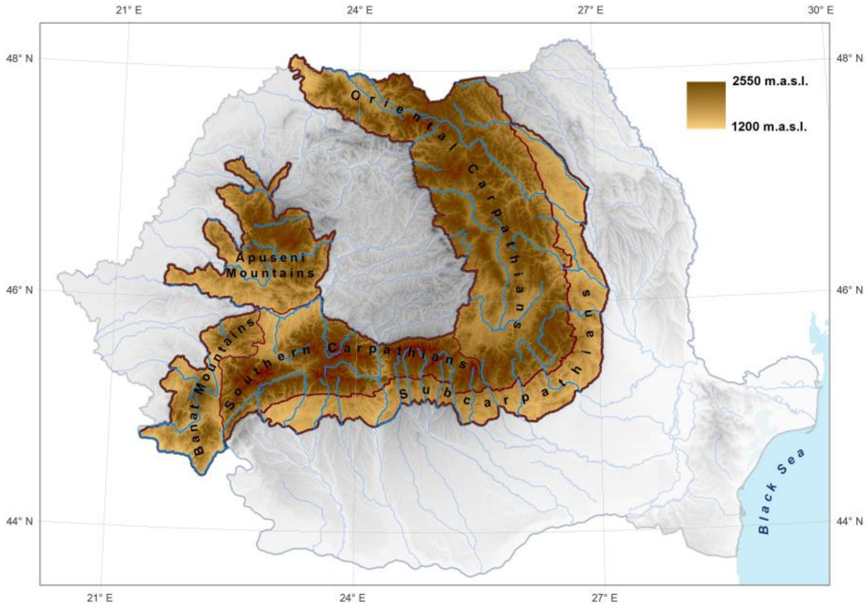

Fig. 1 — The area of study with its major subdivisions.

Romania has a transitional climate between temperate and continental, with four distinct seasons, and with several climatic influences: oceanic in the western part; Mediterranean in the South-West, semi-arid in the East, and Pontic (Black Sea) in the South-East. The Romanian Carpathians strongly affects the air circulation in the region [3-5]. Climate change studies on th eregion point to increases in the severity of heat waves [6-8] and droughts [9-11], and to decreasing wind speed [12,13]. which significantly influence the plant phenology [14-19], the natural streamflow regime [20], as well as the human comfort [21]. Increases in warm thermal extremes over the last decades clearly represent the most striking change [22-25]. The influence of large-scale circulation patterns on air temperature and precipitation regimes had also been demonstrated, in particular North Atlantic Oscillation and the East Atlantic pattern [26-29].

This paper presents the projected changes in the Romanian Carpathians and Subcarpathians – according to the SSP370 climate scenario – for nine climate indices, computed at fine spatial resolution, over two time horizons, namely 2041-2070 and 2071-2100. The projections are based on the GFDL-ESM4 model developped by the National Oceanic and Atmospheric Administration, USA [30].

2. DATA AND METHODS

2.1. CHELSA database and selected climatic indicators

The CHELSA (*Climatologies at high resolution for the Earth's land surface areas*) database [31-34] consists of downscaled model output of temperature and precipitation estimates at a horizontal resolution of 30 arcsec, which corresponds to 0.62-0.66 km over the area of study. The temperature algorithm is mainly based on statistical downscaling of atmospheric temperatures, while the precipitation algorithm incorporates orographic predictors including wind fields, valley exposition, and boundary layer height, with a subsequent bias correction. The selected biometeorological variables are shown in Table 1.

Table 1

Selected biometeorological indicators used in the study.

Acronym	Name	Unit	Scale	Description
Bio1	Mean annual air temperature	°C	0.1	Daily mean air temperatures averaged over one year
Bio2	Mean diurnal air temperature range	°C	0.1	Mean diurnal range of temperatures averaged over 1 year
Bio3	Isothermality	°C	0.1	Ratio of diurnal variation to annual variation in temperatures

Acronym	Name	Unit	Scale	Description
Bio6	Mean daily minimum air temperature of the coldest month	°C	0.1	The lowest temperature of any monthly daily mean maximum temperature
Bio7	Annual range of air temperature	°C	0.1	The difference between the maximum temperature of warmest month and the minimum temperature of coldest month
Bio12	Annual precipitation amount	mm / year	0.1	Accumulated precipitation amount over one year
GSL	Growing season length (TREELIM)	number of days	–	Length of the growing season according to TREELIM [35]
GSP	Precipitation amount during the growing season	mm	0.1	Accumulated precipitation amount over the growing season based on TREELIM [35]
GST	Mean temperature of the growing season	°C	0.1	Mean temperature of all growing season days based on TREELIM [35]

The GFDL-ESM4 model outputs [30] were selected from the CHELSA database, based on the performance assessment of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) [36]

2.2. The SSP3-7.0 climate scenario

The Shared Socioeconomic Pathways (SSPs) are the latest climate scenarios, build for the purpose of enabling integrated analyses of future climate vulnerabilities, impacts, adaptation, and mitigation.

SSP3-7.0 represents the second-highest scenario and has recently garnered attention as an alternative high-end scenario that provides another option for climate change risk assessment and adaptation planning [37]. It combines SSP3 (Shared Socio-economic Pathway 3) – which outlines the socio-economic trends underlying the scenario from one of the five global socio-economic narratives – with the projected radiative forcing of 7.0 W/m² for the year 2100, of the Representative Concentration Pathway 7.0 (RCP 7.0).

SSP3 contains both narrative and quantitative information, which are used to develop the SSP baseline and mitigation scenarios [38]. It describes a world dominated by regional rivalry: policies increasingly focus on national and regional security; investments in education and technological development are decreasing; some regions suffer drastic environmental damage. In this socio-economic context, a low international priority for environmental issues results in severe degradation in certain regions and hinders progress toward development goals [39]. In general, SSP3 has high mitigation costs, namely carbon price, GDP loss, and consumption loss, while technological development is slower than in the other SSPs. Slow energy and carbon intensity improvement rates and a lower yield growth rate also reflects this aspect. The high level of air pollutant emissions in the SSP3 baseline scenario would interest the atmospheric chemistry modeling community [40]. With a radiative forcing of 7.0 W/m² by the year 2100, SSP3-7.0 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.

The fact that recent studies found that future emissions are unlikely to follow the highest-emisions scenario (SSP5-8.5) has determined the second highest scenario (SSP3-7.0) to receive increased attention. While the distinctiveness of SSP3-7.0 has not been acknowledged enough [37], this scenario was conceived in order to increase the socio-economic scenario diversity, therefore to present different characteristics than the other scenarios. Due to the assumption of a lenient air quality policy, aerosol emissions increase or change little in SSP3-7.0, while they decrease in the other SSPs and in all RCPs [41]. Decreases in forest area are substantial in SSP3-7.0 – unlike in the other scenarios –, allowing the investigation of the influences of strong land-cover changes on climate [42,43], while the high-aerosol-emission scheme from SSP3-7.0 enables climate modellers to evaluate the consequences of continuous high-level aerosol emissions on climate [44].

2.3. The GFDL-ESM4 model

GFDL-ESM4 represents the latest generation of the Earth System Models (ESMs) developed by NOAA's Geophysical Fluid Dynamics Laboratory (https://www.gfdl.noaa.gov/earth-system-model/). It is a global climate model build to include advanced modules to simulate the bio-physical processes at the intersection of atmosphere and terrestrial and aquatic ecosystems, thus capturing the interactions of the Earth's bio-geochemical cycles, including human actions, with the climate system. Hence, the model represents a simulation tool based on an atmospheric circulation model coupled with an oceanic circulation model, which also embeds land, sea ice and iceberg dynamics, as well as comprehensive land-atmosphere-ocean cycling of CO_2.

The model is based on numerous parameters of atmospheric, land and oceanic components, being able to mimic ecosystems' terrestrial and oceanic chemistry, including ecological and chemical tracers which control nutrient limitation, plant biomass, productivity, and functional composition. It is able to capture variations in land surface albedo (due to vegetation changes or land use) and aerosol chemistry. For instance, the atmospheric component includes physical features of natural and anthropogenic aerosols, cloud physics, and precipitation. The land component includes terrestrial hydrology and ecology to simulate dynamic reservoir of surface snow and carbon pools as well as soil temperature, liquid and frozen water, and carbon and runoff through streams, lakes, and rivers. The ice-oceanic component includes features such water fluxes, currents, vertical and lateral mixing, marine biogeochemistry and ecology, etc. Compared to previous versions, the ESM4 model features a considerable improved representation of climate patterns and variability, as well as comprehensive couplings for chemistry, carbon, and aerosols [45].

The development of GFDL-ESM4 model contributed reliable results to the sixth phase of the Coupled Model Intercomparison Project (CMIP6) multi-model ensemble used in the 6th Assessment Report of IPCC. GFDL-ESM4 is a high-resolution model, displaying 1° and 0.5° horizontal resolution of atmosphere and ocean, respectively. In this respect, the GFDL model is superior to other global climate models considered in the ISIMIP3b protocol for model priority [36,46]. Over the years, GFDL has increased its horizontal resolution of both atmosphere and ocean, and has improved the dynamical and physical parametrizations of the atmosphere, ocean, sea ice, land, and overall coupling [45].

3. RESULTS AND DISCUSSION

The results show very small increases in the average annual air temperature compared to the period 1981-2010: up to 0.03°C and 0.04°C for the intervals 2041-2070 and 1971-2100, respectively, with more pronounced increases in the eastern part (Fig. 2a).

The deviation of the daily air temperature difference (annual average) is similar for the aforementioned intervals and ranges between 0.01°C and 0.03°C (Fig. 2b).

The isothermality (the ratio between the average daily and annual air temperature variation) is very stable, with deviation values below 0.01°C and presenting a latitudinal gradient, more visible in the distant period (Fig. 2c).

The deviation of the minimum air temperature in the coldest month (monthly average) shows increases of up to 0.35°C in both periods (Fig. 3a), with higher values in the northern area.

The deviation of the annual air temperature difference compared to the period 1981-2010 also shows some negative values in the northwestern part of the Eastern Carpathians in the interval 2041-2070, but the warming signal clearly prevails – in all areas below latitude 47°N – with values of up to 0.3°C. These deviations are larger and exclusively positive in the distant future (Fig. 3b).

Regarding the annual amount of precipitation (Fig. 3c), the intervals 2041-2070 and 2071-2100 show very small deviations, with negative values in the southwest and positive in the northeast.

For both near and distant future, the growing season length also shows decreases of up to 39 days in the interval 2041-2070, and 30 days for the period 2071-2100, respectively (Fig. 4a). However, the predominant signal clearly shows a clear lengthening of the growing season in both intervals. This is likely due to the increase in the amount of precipitation during the vegetation growing season (Fig. 4b), as well as the stability of air temperature throughout the season (Fig. 4c), with relatively symmetrical positive/negative deviations. A summary of the projected changes at sub-regional level is shown in Table 2.

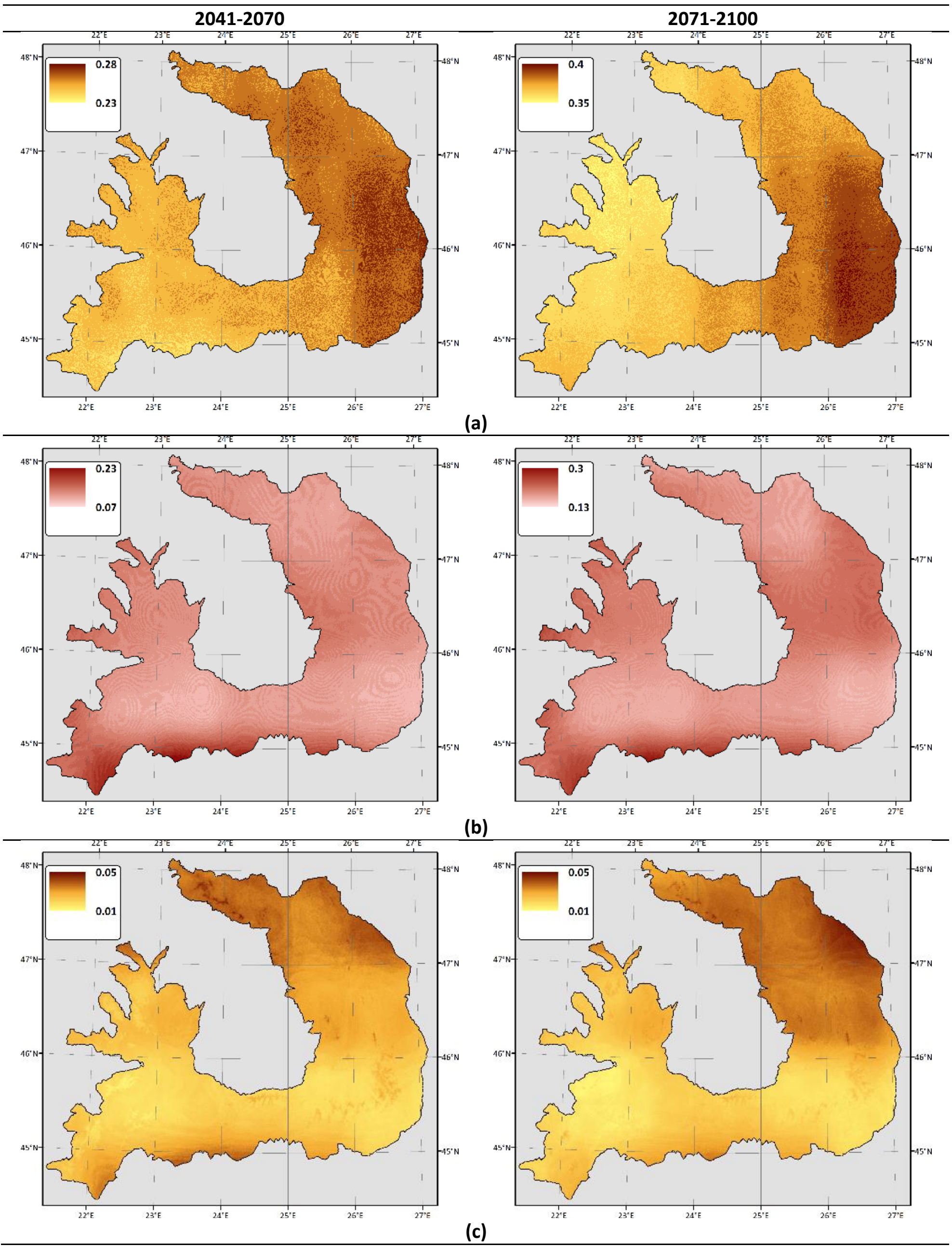

Fig. 2 — Projected anomalies according to SSP370 scenario / GFDL-ESM4 model for the 2041–2070 (left) and 2071–2100 (right) time intervals, compared to the 1981–2010 period, for: (a) mean air temperature (in 0.1°C); (b) mean diurnal temperature range (in 0.1°C); (c) isothermality (in 0.1°C).

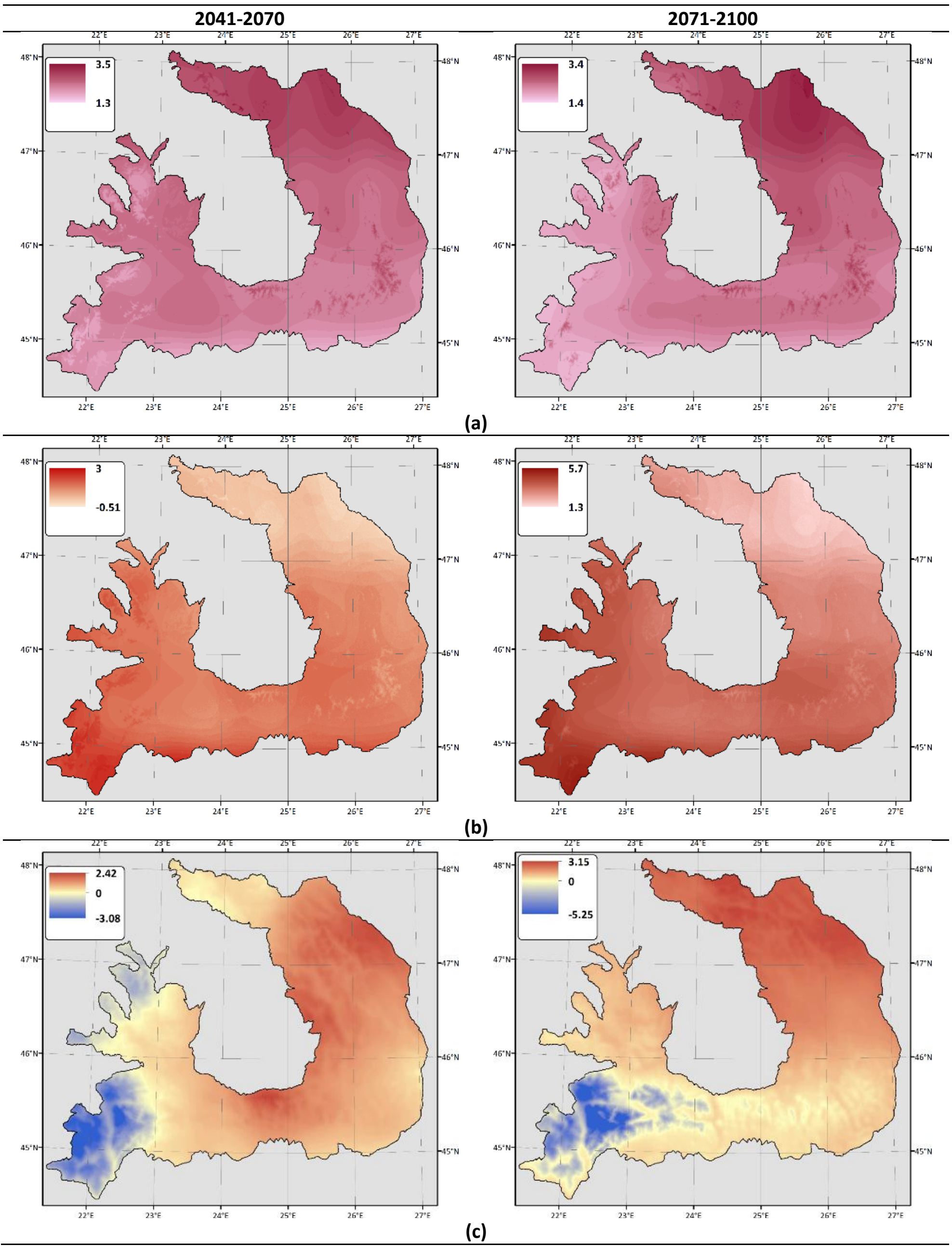

Fig. 3 — Same as Fig. 2 for: (a) mean daily minimum air temperature of the coldest month (in 0.1°C); (b) annual range of air temperature (in 0.1°C); (c) annual precipitation amount (in 0.1mm/year).

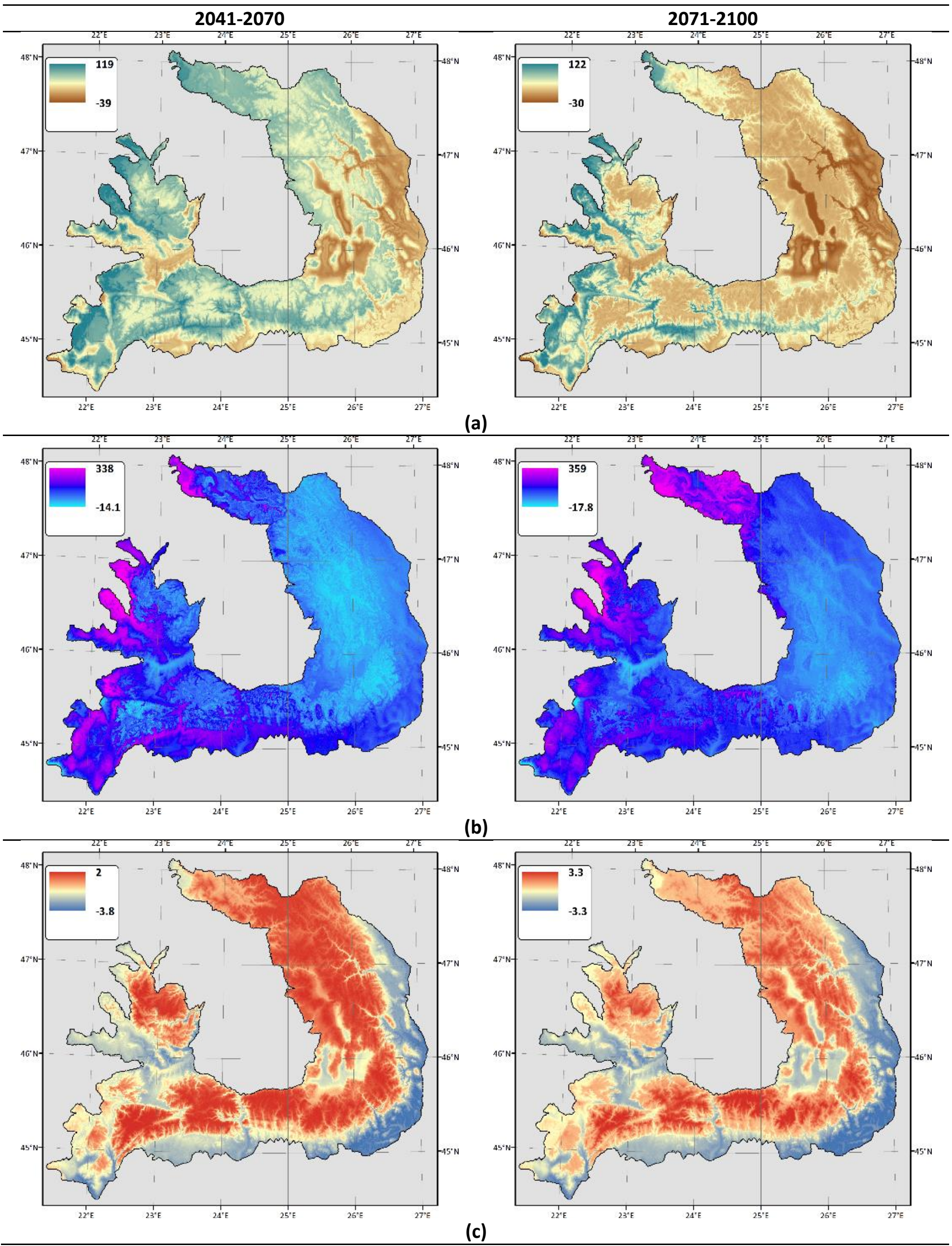

Fig. 4 — Same as Fig. 3 for: (a) growing season length (in days); (b) precipitation amount during the growing season (in 0.1mm/year); (c) mean air temperature of the growing season (in 0.1°C).

Table 2

Projected changes at sub-regional level for the growing season length (GSL), the precipitation amount during the growing season (GSP), and the mean air temperature of the growing season (GST). The numbers represent the difference between the projected values and the 1981-2010 period.

	GSL (days)		GSP (0.1·mm/year)		GST (0.1°C)	
	2041-2070	2071-2100	2041-2070	2071-2100	2041-2070	2071-2100
Oriental Carpathians	33.9	46.3	7.2	10.3	0.08	0.11
Southern Carpathians	46.7	58.2	10.7	11.6	0.05	0.12
Banat Mountains	74.6	68.2	14.7	13.7	-0.09	-0.01
Apuseni Mountains	62.6	62.7	14.1	14.9	-0.05	0.02
Subcarpathians	39.7	26.0	10.7	9.9	-0.19	–0.14
Entire area	44.5	48.6	10.1	11.4	-0.01	0.04

4. CONCLUSIONS

We presented an overview of projected climatic changes in the Romanian Carpathians and Subcarpathians, as simulated with NOAA's GFDL-ESM4 model under the latest SPS3-7.0 scenario. The main results are summarized below:

• The mean annual air temperature is projected to increase slightly for both near (2041-2070) and distant (2071-2100) future – compared to the reference period 1981-2010;

• The isothermality is projected to be stable over the region;

• The annual amount of precipitation shows very small deviations, with negative values in the southwestern areas and positive in the northeastern regions;

• The growing season length is projected to increase in most areas until the end of the century.

Acknowledgments. Part of this study was done within the framework of the project «Changes in climate suitability of Romanian vineyards» (CARVE), code PN-IV-P1-PCE-2023-1875, funded by UEFISCDI (the Executive Agency for Higher Education, Research, Development and Innovation Funding).

References

1. Micu, D.M., et al., *Temperature changes and elevation-warming relationships in the Carpathian Mountains*. Int. J. Climatol. **41**(3): 2154-2172 (2021). https://doi.org/10.1002/joc.6952
2. Velcea, V., Savu, A., *Geografia Carpaților și Subcarpaților Românești (Geography of the Romanian Carpathians and Subcarpathians)*, Editura Didactică şi Pedagogică, Bucureşti (1982).
3. Busuioc, A., et al., *Changes in the large-scale thermodynamic instability and connection with rain shower frequency over Romania. Verification of the Clausius–Clapeyron scaling*. Int. J. Climatol. **36**, 2015–2034 (2016). https://doi.org/10.1002/joc.4477
4. Manea, A., Birsan, M.V., Tudorache, G., Cărbunaru, F., *Changes in the type of precipitation and associated cloud types in Eastern Romania (1961-2008).* Atmos. Res. 2016, 169, 357–365 (2016). https://doi.org/10.1016/j.atmosres.2015.10.020

5. Keresztesi, Á., et al. *The risk of cross-border pollution and the influence of regional climate on the rainwater chemistry in the Southern Carpathians, Romania*. Environ. Sci. Pollut. Res. **27**, 9382–9402 (2020). https://doi.org/10.1007/s11356-019-07478-9
6. Croitoru, A.E., et al., *Changes in heat waves indices in Romania over the period 1961–2015*. Global Planet. Change **146**, 109–121 (2016). https://doi.org/10.1016/j.gloplacha.2016.08.016
7. Dobrinescu, A., et al., *Changes in thermal discomfort indices in Romania and responsible large-scale mechanisms*. Clim. Res., **64**(3), 213-226 (2015). https://doi.org/10.3354/cr01312
8. Papathoma-Koehle, M., et al. *A common methodology for risk assessment and mapping for Southeast Europe: an application for heat wave risk in Romania*. Nat. Hazards, **82** (Suppl. 1), 89-109 (2016). https://doi.org/10.1007/s11069-016-2291-3
9. Cheval, S., et al., *Spatiotemporal variability of meteorological drought in Romania using the standardized precipitation index (SPI)*. Clim. Res., **60**, 235-248 (2014). https://doi.org/10.3354/cr01245
10. Cheval, S., Dumitrescu, A., Birsan, M.V. *Variability of the aridity in the South-Eastern Europe over 1961-2050*. Catena, **151**, 74-86 (2017). https://doi.org/10.1016/j.catena.2016.11.029
11. Dascalu, S.I., et al. *Drought-related variables over the Bârlad basin (Eastern Romania) under climate change scenarios*. Catena, **141**, 92–99 (2016). https://doi.org/10.1016/j.catena.2016.02.018
12. Birsan MV, et al., *Observed changes in mean and maximum monthly wind speed over Romania since AD 1961*. Rom. Rep. Phys. 72:702 (2020).
13. Birsan, M.V., Marin, L, Dumitrescu, A. *Seasonal changes in wind speed in Romania*, Rom. Rep. Phys. 65(4), 1479-1484 (2013).
14. Mihai G, et al. *Adaptive genetic potential of European silver fir in Romania in the context of climate change*. Ann. of For. Res. 61(1): 95–108 (2018). https://doi.org/10.15287/afr.2018.1021
15. Pravalie R, et al. *Machine learning-based prediction and assessment of recent dynamics of forest net primary productivity in Romania*. J Env Manage, **334**, 117513 (2023). https://doi.org/10.1016/j.jenvman.2023.117513
16. Mihai, G., et al. *Impact of Climate Change and Adaptive Genetic Potential of Norway Spruce at the South–eastern Range of Species Distribution*. Agr. Forest Meteorol. **291**, 108040 (2020). https://doi.org/10.1016/j.agrformet.2020.108040
17. Mihai, G., et al., *Intraspecific Growth Response to Drought of Abies alba in the Southeastern Carpathians*. Forests 12(4):387 (2021). https://doi.org/10.3390/f12040387
18. Mihai, G., et al. *Growth and Adaptive Capacity of Douglas Fir Genetic Resources from Western Romania under Climate Change*. Forests 13(5): 805. https://doi.org/10.3390/f13050805 (2022)
19. Mihai, G., et al. *Climate Change in the Provenance Regions of Romania over the Last 70 Years: Implications for Forest Management*. Forests **13**(8), 1203 (2022). https://doi.org/10.3390/f13081203
20. Birsan, M.V., *Trends in Monthly Natural Streamflow in Romania and Linkages to Atmospheric Circulation in the North Atlantic*. Water Resour. Manag. **29**(9), 3305–3313 (2015). https://doi.org/10.1007/s11269-015-0999-6
21. Micheu, M.M., et al. *Influence of meteorological variables on people with cardiovascular diseases in Bucharest, Romania (2011-2012)*. Rom. Rep. Phys. **73**, 707 (2021).
22. Birsan, M.V., Dumitrescu, A., Micu, D.M., Cheval, S. *Changes in annual temperature extremes in the Carpathians since AD 1961*. Nat. Hazards **74**(3):1899–1910 (2014). https://doi.org/10.1007/s11069-014-1290-5
23. Birsan, M.V., Micu, D.M., Nita, A.I., Mateescu, E., Szép, R., Keresztesi, A., *Spatio-temporal changes in annual temperature extremes over Romania (1961-2013)*. Rom. J. Phys. **64**, 816 (2019).
24. Necula, C., et al., *Maximum winter temperature over Romania in connection to atmospheric circulation*, Theor. Appl. Climatol. **155**, 3861–3870 (2024). https://doi.org/10.1007/s00704-024-04854-5
25. Amihăesei, V-A., et al., *Changes in snow cover climatology and its elevation dependency over Romania (1961-2020),* J. Hydrol.: Reg. Stud., **51**, 101637 (2024). https://doi.org/10.1016/j.ejrh.2023.101637

26. Birsan, M.V., Nita, I.A., Amihăesei, V.A. *Influence of large-scale atmospheric circulation on Romanian snowpack duration*. Rom. Rep. Phys, **76**, 708 (2024). https://doi.org/10.59277/RomRepPhys.2024.76.708
27. Nita, I.A., Apostol, L., Patriche, C.V., Sfîcă, L., Bojariu, R., Birsan, M.V. *Frequency of Atmospheric Circulation Types over Romania According to Jenkinson-Collison Method Based on Two Long-Term Reanalysis Datasets*. Rom. J. Phys. **67**, 812 (2022)
28. Sfîcă L, et al. *Cloud cover changes driven by atmospheric circulation in Europe during the last decades*. Int. J. Climatol. **41** (Suppl. 1): E2211– E2230 (2021). https://doi.org/10.1002/joc.6841
29. Țîmpu, S., et al. *Tropospheric Dust and Associated Atmospheric Circulations over the Mediterranean Region with Focus on Romania's Territory*. Atmosphere **11**, 349 (2020). https://doi.org/10.3390/atmos11040349
30. Krasting, J.P., et al., *NOAA-GFDL GFDL-ESM4 model output prepared for CMIP6 CMIP*. Earth System Grid Federation (2018). https://doi.org/10.22033/ESGF/CMIP6.1407
31. Karger, D.N., et al., *Climatologies at high resolution for the Earth land surface areas*. Scientific Data. **4**, 170122 (2017). https://doi.org/10.1038/sdata.2017.122
32. Karger D.N., et al., *Data from: Climatologies at high resolution for the Earth's land surface areas*. EnviDat (2018). https://doi.org/10.16904/envidat.228.v2.1
33. Brun, P., et al. *Global climate-related predictors at kilometre resolution for the past and future*. Earth Syst. Sci. Data **14**, 5573–5603 (2022). https://doi.org/10.5194/essd-14-5573-2022
34. Brun, P., et al. *CHELSA-BIOCLIM+ A novel set of global climate-related predictors at kilometre-resolution*. EnviDat. (2022) https://www.doi.org/10.16904/envidat.332
35. Paulsen, J., Körner, C., *A climate-based model to predict potential treeline position around the globe*. Alp. Botany **124**, 1–12 (2014). https://doi.org/10.1007/s00035-014-0124-0
36. Frieler, K., et al. (2024): Scenario setup and forcing data for impact model evaluation and impact attribution within the third round of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP3a), Geosci. Model Dev., **17**, 1–51 (2024). https://doi.org/10.5194/gmd-17-1-2024
37. Shiogama, H., et al. Important distinctiveness of SSP3–7.0 for use in impact assessments. Nat. Clim. Chang. **13**, 1276–1278 (2023). https://doi.org/10.1038/s41558-023-01883-2
38. Welch, I., *The IPCC Shared Socioeconomic Pathways (SSPs): Explained, Evaluated, Replaced*. NBER Working Paper No. w32178, Available at: https://ssrn.com/abstract=4746788 (2024)
39. Riahi, K., et al. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Global Environ. Chang. **42**, 153-168. (2017) https://doi.org/10.1016/j.gloenvcha.2016.05.009
40. Fujimori A, et al. SSP3: AIM implementation of Shared Socioeconomic Pathways. Global Environmental Change **42**: 268-283. https://doi.org/10.1016/j.gloenvcha.2016.06.009 (2017)
41. Lund, M. T., Myhre, G., Samset, B. H., *Anthropogenic aerosol forcing under the Shared Socioeconomic Pathways*. Atmos. Chem. Phys **19**, 13827–13839 (2019).
42. Popp, A. et al. *Land-use futures in the shared socio-economic pathways.* Glob. Environ. Change **42**, 331–345 (2017). https://doi.org/10.1016/j.gloenvcha.2016.10.002
43. Lawrence, D. M. et al. *The Land Use Model Intercomparison Project (LUMIP) contribution to CMIP6: rationale and experimental design*. Geosci. Model Dev. **9**, 2973–2998 (2016)
44. Collins, W. J. et al. *AerChemMIP: quantifying the effects of chemistry and aerosols in CMIP6*. Geosci. Model Dev. **10**, 585–607 (2017). https://doi.org/10.5194/gmd-10-585-2017
45. Dunne, J.P., et al., *The GFDL Earth System Model Version 4.1 (GFDL-ESM 4.1): Overall coupled model description and simulation characteristics*. J. Adv. Model. Earth Sy., **12**, e2019MS002015 (2020). https://doi.org/10.1029/2019MS002015
46. Gutiérrez, J M., A.-M. Tréguier (eds.) *Annex II: Models*. In: Masson-Delmotte, V., et al. (Eds.): *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, pp. 2087–2138 (2023). https://doi.org/10.1017/9781009157896.016