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Statistical evidence of an association between Balkan temperature variability and the weakening of the Atlantic Meridional Overturning Circulation

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Abstract

The Balkan Peninsula is a climate change hotspot, yet its temperature variability in relation to the Atlantic Meridional Overturning Circulation (AMOC) remains insufficiently investigated. Using $0.1^\circ \times 0.1^\circ$ ERA5-Land data from 7,262 grid cells, this study examines seasonal and annual air-temperature variability during 1950–2024 and its statistical relationship with AMOC variability during 1993–2023. ERA5-Land temperatures show close agreement with observations from 10 meteorological stations in Montenegro ($r = 0.92\text{--}0.98$). The Balkans exhibit significant warming, while the AMOC shows significant weakening, with an annual trend of -1.61 Sv/decade. The strongest negative temperature–AMOC relationships occur in autumn and annually, reaching -0.79 in Montenegro and ranging from -0.49 to -0.80 across the Balkans ($p < 0.01$). Significant negative relationships are also widespread in summer, more localized in spring, and largely absent in winter. AMOC variability is significantly associated with atmospheric CO_2 and AGGI ($r = -0.76$ and -0.77), as well as PDO, AMO, EA, and EAWR. Overall, the findings provide statistical evidence of a strong, seasonally heterogeneous relationship between AMOC variability and Balkan temperatures, likely mediated by large-scale atmospheric circulation and associated with anthropogenic greenhouse forcing.

Introduction

The influence of variability in the physico-chemical properties of the World Ocean on contemporary climate change is an important research topic. The role of the Gulf Stream in shaping the climate of Western and Northwestern Europe has long been recognized. Westerly winds crossing the mid-latitudes of the Atlantic, warmed and enriched with water vapor over the Gulf Stream, transport heat and moisture across Europe to the Ural Mountains. This highlights the importance of ocean–atmosphere interactions in regulating climate, as well as in the transport and exchange of nutrients, dissolved gases, plankton, and other microorganisms.

Contemporary global warming is well established, and the Copernicus Climate Change Service (C3S) and the World Meteorological Organization (WMO) reported that 2024 was the warmest year globally and across most continents since the beginning of the instrumental record in 1850, except Australia and Antarctica (C3S and WMO 2025). The Mediterranean is warming faster than the global average and is recognized as a climate change hotspot (Giorgi and Lionello 2008; Lionello and Scarascia 2018; Tuel and Eltahir 2020; Cos et al. 2022; Ali et al. 2022; Lazoglou et al. 2024; Burić 2026). During the past two to three decades, increasing temperature extremes, including both maximum and minimum temperatures, have been particularly pronounced over the Balkan Peninsula (Malinovic–Milicevic et al. 2016; Milošević et al. 2017; Popov et al. 2018; Burić and Doderović 2022).

Because many parts of the Balkans remain poorly covered by meteorological station networks, reanalysis datasets provide an important alternative source of spatially consistent climate information. Among the most widely used are the fifth-generation ERA5 and ERA5-Land datasets developed by the European Centre for Medium-Range Weather Forecasts (ECMWF) in collaboration with C3S, with spatial resolutions of 31 km and 9 km, respectively (Muñoz-Sabater et al. 2021; Hersbach et al. 2023). ERA5-Land generally provides more accurate temperature and precipitation estimates than ERA5 and has proven particularly useful in regions with sparse observations, including Piedmont (Italy) and Slovenia (Alexopoulos et al. 2023; Botto et al. 2025).

Although there is scientific consensus that contemporary global warming is predominantly driven by anthropogenic greenhouse gas emissions (Giorgi 2002; IPCC 2023; Ritchie et al. 2024), the role of large-

scale atmospheric and oceanic variability, should also be considered. The effects of the North Atlantic Oscillation (NAO), Atlantic Multidecadal Oscillation (AMO), Arctic Oscillation (AO), and other large-scale patterns on the hydroclimate of Montenegro, the Balkan Peninsula, and other regions have been extensively documented (Burić 2014; Deser et al. 2017; Semenov and Cherenkova 2018; Burić and Stanojević 2020; Luong 2021; Burić and Penjišević 2023; Burić et al. 2025; Mpheshea et al. 2025; Mitevski et al. 2025; Halifa–Marín et al. 2025). However, the relationship between the Atlantic Meridional Overturning Circulation (AMOC) and temperature or precipitation variability over the Balkans remains insufficiently investigated.

The AMOC is one of the most important components of the global ocean circulation and a major mechanism of large-scale heat redistribution. It transports warm surface waters northward across the Atlantic, where they cool and sink before returning southward as cold deep waters. According to the National Oceanography Centre (NOC, UK), the AMOC transports approximately 17 million m³/s of water northward and has an associated heat transport of about 1.2 petawatts (PW), approximately 100 times greater than the total global energy generated from terrestrial sources (NOC 2025). Changes in ocean–atmosphere conditions can therefore affect AMOC strength. Anthropogenic warming has increased ocean temperatures, evaporation, and freshwater input into the subpolar North Atlantic through enhanced precipitation and accelerated melting of Greenland and Arctic ice. Increased freshwater input reduces seawater density and stratification can inhibit deep-water formation, thereby weakening the AMOC and contributing to regional cooling in the North Atlantic. A weaker AMOC may also reduce the transfer of atmospheric carbon dioxide into the deep ocean, potentially contributing to higher atmospheric greenhouse gas concentrations (IPCC 2023). The AMOC forms part of the thermohaline circulation of the World Ocean, while the surface Gulf Stream represents only one component of this broader circulation system.

Reconstructions extending back to 400 CE indicate that AMOC weakening began during the 19th century after a long period of relative stability and accelerated from the mid-20th century onward (Caesar et al. 2021). Sea-surface-temperature-based estimates suggest a weakening of 3 ± 1 Sverdrup since 1950 (Caesar et al. 2018), while longer-term reconstructions indicate that present-day AMOC strength may be the lowest in more than a millennium (Caesar et al. 2021). Nevertheless, reanalysis-based evidence suggests substantial variability and indicates that a complete AMOC shutdown is unlikely in the near future (van Westen et al. 2024). Continued weakening could nevertheless have important climatic consequences, including changes in temperature, precipitation, atmospheric and oceanic circulation, storm tracks, and extreme weather events across Europe and the North Atlantic. AMOC variability may also contribute to regional sea-level changes; during the short-term slowdown in 2009–2010, sea level along the New York coast increased by 13 cm. Beyond its climatic significance, the AMOC is fundamental to nutrient transport, ocean mixing, and the redistribution of heat and energy within the climate system (NOC 2025).

Given the importance of the AMOC in large-scale ocean–atmosphere interactions, this study examines the relationship between AMOC variability and air temperature over the Balkan Peninsula. For 1950–2024, temperature trends were analyzed using ERA5-Land data at 0.1° horizontal resolution, followed by an assessment of the statistical relationship between AMOC variability and Balkan air temperatures. The reliability of ERA5-Land was evaluated by comparing reanalysis temperatures with in situ observations from 10 meteorological stations in Montenegro and the corresponding grid cells. Because AMOC variability is closely linked to large-scale atmospheric and oceanic patterns, its relationship with temperature over the Balkans was further examined through 14 teleconnection indices and two indicators of anthropogenic greenhouse forcing.

Materials and Methods

Research area

The Balkan Peninsula covers approximately 550,000 km² and is predominantly characterized by mountainous and valley terrain, with limited lowland areas mainly along its northern and coastal margins. Its northern physical boundary is generally defined by the Sava and Danube river valleys. The broader study domain extends from 36° to 46°N and approximately 13° to 30°E, encompassing the Balkan Peninsula as well as southern Romania and the southeasternmost parts of Moldova and Ukraine. The total analyzed area is approximately 650,000 km² (Fig. 1). Within the study domain (36°–46°N and approximately 13°–30°E), the 0.1° × 0.1° grid contains approximately 13,000 points. Because ERA5-Land

is available only over land, and after excluding surrounding seas, parts of Italy, and the Asian part of Turkey, the final study area comprises 7,262 land grid cells, including the major Balkan islands.

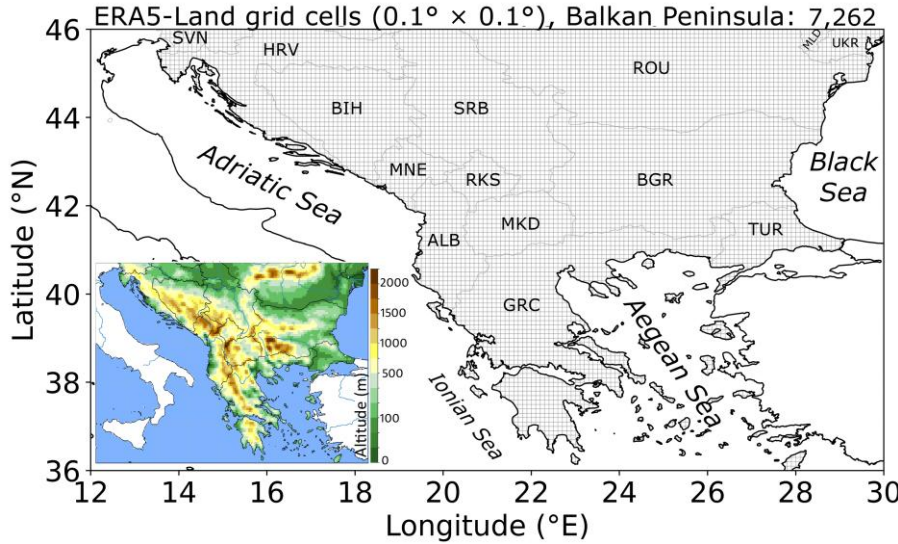


Fig. 1 ERA5-Land grid representation of the Balkan Peninsula at a spatial resolution of $0.1^\circ \times 0.1^\circ$ (latitude–longitude)

The peninsula spans approximately 10° of latitude in the meridional direction, while its complex relief, with Musala in the Rila Mountains reaching 2,925 m, and the prevailing cyclonic and anticyclonic activity strongly influence its climate. Major synoptic systems include Genoa and Icelandic cyclones, the Azores anticyclone, and summer blocking patterns. Similar to Montenegro, the Balkans lie at the intersection of temperate and subtropical (Mediterranean) climatic influences. According to the Köppen classification, the dominant climate types are Cs, Cf, Df, and Dw (Kottek et al. 2006; Burić et al. 2014). Previous studies have also identified variability and cyclicity in these influences. Peneva et al. (2023) identified an approximately 20-year climatic cycle and suggested that Mediterranean (synoptic) influences are likely to dominate across the Balkan Peninsula during 2020–2030.

Data and Methods

This study used monthly mean 2 m air temperature from the latest ERA5-Land reanalysis for 1950–2024, produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) within the Copernicus Climate Change Service (C3S). The data have a spatial resolution of $0.1^\circ \times 0.1^\circ$ (native resolution ~ 9 km). ERA5-Land is a global land-surface reanalysis that combines model output with station, satellite, and radiosonde observations to provide spatially and temporally consistent long-term climate information (Muñoz Sabater 2019; Muñoz-Sabater et al. 2021; Hersbach et al. 2023; ECMWF 2025). Temperature data for 7,262 grid cells, listed in Kelvin (K), converted to degrees Celsius ($^\circ\text{C}$). Seasonal and annual means were calculated from monthly data. Winter comprises December of the previous year and January–February of the following year; spring, summer, and autumn comprise March–May, June–August, and September–November, respectively.

For validation, monthly mean air temperature observations from 10 meteorological stations (MS) in Montenegro were obtained from the Institute of Hydrometeorological and Seismological of Montenegro (IHMSM 2025) for 1950–2024. MS Žabljak has a shorter record (1958–2024). Observations were compared with ERA5-Land values from the corresponding grid cells.

AMOC data were obtained from the Copernicus Marine Environment Monitoring Service (CMEMS) and represent meridional volume transport at 26.5°N in the Atlantic for 1993–2023, expressed in m^3/s (CMEMS 2024). Values were converted to Sverdrups ($1 \text{ Sv} = 10^6 \text{ m}^3/\text{s}$). Four AMOC series were analyzed: amoc_cglo (CGLO model), amoc_glor (GLORYS model), amoc_oras (ORAS model), and amoc_mean (ensemble mean).

Data from C3S–ECMWF and CMEMS were retrieved and processed in Python using pandas and the pymannkendall package (version 3.12.9–01); data acquisition was performed through Python-based cdsapi scripts from the Copernicus platform. Trends were assessed using Sen’s slope estimator and the Mann–Kendall test (Kendall 1975; Hirsch and Slack 1984; Salmi et al. 2002), with significance levels of $p < 0.05$ and $p < 0.01$. Pearson’s correlation coefficient (r) was used to examine relationships between temperature and AMOC, as well as between the AMOC and atmospheric CO₂ concentrations, the annual greenhouse gas index (AGGI), and teleconnection (patterns of atmospheric and oceanic oscillations). Correlation significance was evaluated using the t-test at the 95% ($p < 0.05$) and 99% ($p < 0.01$) confidence levels.

To assess the relationship between AMOC variability and large-scale oceanic and atmospheric circulation, correlations were also examined with 14 teleconnection indices: El Niño–Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), Atlantic Multidecadal Oscillation (AMO), Atlantic Meridional Mode (AMM), North Atlantic Oscillation at sea level (NAO–SLP), Summer North Atlantic Oscillation (SNAO), Arctic Oscillation (AO), Mediterranean Oscillation (MO), Western Mediterranean Oscillation (WeMO), East Atlantic Oscillation (EA), East Atlantic–West Russian Oscillation (EAWR), Scandinavian Oscillation (SCAND), Polar–Eurasian Oscillation (POLEUR), and North Atlantic Oscillation at 500 hPa (NAO–500 hPa) (Table 1).

Table 1 Table 1 List of variables used, including measurement units and data sources

Index	Source	Unit
Temperature		
ERA5-Land	https://cds.climate.copernicus.eu/datasets/reanalysis-era5-land-monthly-means?tab=overview	°C
IHMSM	https://www.meteo.co.me/page.php?keyword=reports	°C
Greenhouse Gases		
CO ₂	https://gml.noaa.gov/webdata/ccgg/trends/co2/co2_mm_mlo.txt	ppm
AGGI	https://gml.noaa.gov/aggi/aggi.html	1990 = 1
Oceanic Oscillations		
AMOC	https://data.marine.copernicus.eu/product/GLOBAL_OMI_NATLANTIC_amoc_max26N_timeseries/services	Sv (10 ⁶ m ³ /s)
AMM	https://psl.noaa.gov/data/timeseries/month/data/amm.data	°C
PDO	https://www.ncei.noaa.gov/pub/data/cmb/ersst/v5/index/ersst.v5.pdo.dat	°C
AMO	https://psl.noaa.gov/data/correlation/amon.us.data	°C
ENSO-NINO3.4	https://www.cpc.ncep.noaa.gov/data/indices/sstoi.indices	°C
Atmospheric Oscillations		
NAO-SLP	https://crudata.uea.ac.uk/cru/data/nao/nao.dat	hPa
SNAO	https://climexp.knmi.nl/data/isnao_ncepncar.dat	hPa
AO	https://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/monthly.ao.index.b50.current.ascii.table	hPa
MO	https://crudata.uea.ac.uk/cru/data/moi/moi1.output.dat	hPa
WeMO	http://www.ub.edu/gc/documents/Web_WeMOi-2020.txt	hPa
EA	https://ftp.cpc.ncep.noaa.gov/wd52dg/data/indices/ea_index.tim	gpm
EAWR	https://ftp.cpc.ncep.noaa.gov/wd52dg/data/indices/eawr_index.tim	gpm
SCAND	https://ftp.cpc.ncep.NOAA.gov/wd52dg/data/indices/scand_index.tim	gpm
POLEUR	https://ftp.cpc.ncep.noaa.gov/wd52dg/data/indices/poleur_index.tim	gpm
NAO-500hPa	https://ftp.cpc.ncep.NOAA.gov/wd52dg/data/indices/NAO_index.tim	gpm

Results

Overview of ERA5-Land Temperature Evaluation

ERA5-Land generally provides reliable temperature estimates, although local biases may occur depending on season, elevation, or regional climatic conditions, particularly in areas with complex topography (Muñoz-Sabater et al. 2021; Zhao and He 2022; Mihalevich et al. 2022; Satyapragyan et al. 2026). To assess its performance over the Balkans, mean seasonal and annual temperatures from 10 meteorological stations in Montenegro were compared with ERA5-Land data from the corresponding 0.1° grid cells. The comparison showed strong agreement between in situ and reanalysis temperatures, with correlation coefficients of 0.90–0.96 in winter, 0.91–0.96 in spring, 0.91–0.98 in summer, 0.90–0.97 in autumn, and 0.91–0.97 annually (Fig. 2).

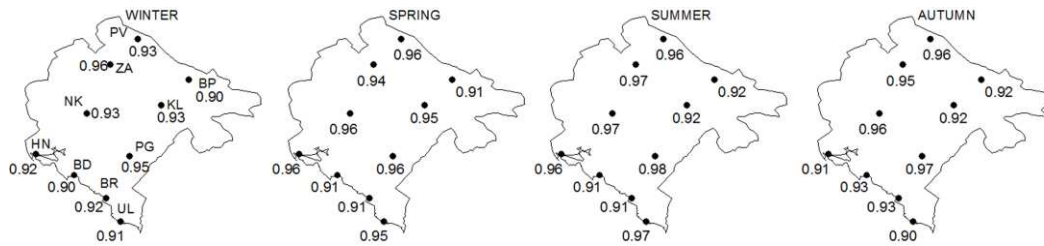


Fig. 2 Correlation coefficients between mean seasonal temperatures derived from ERA5-Land reanalysis ($0.1^\circ \times 0.1^\circ$ resolution) and in situ observations from ten meteorological stations in Montenegro (MNE) for the period 1950–2024 (UL—Ulcinj, BR—Bar, BD—Budva, HN—Herceg Novi, PG—Podgorica, NK—Nikšić, KL—Kolašin, ZA—Žabljak [1958–2024], BP—Bijelo Polje, and PV—Pljevlja)

A graphical comparison was additionally performed for Podgorica and Žabljak, representing lowland and mountainous environments, respectively. Seasonal and annual correlations ranged from 0.92 to 0.98 (Fig. 3). Small systematic differences were observed between the two datasets: ERA5-Land temperatures were slightly lower than in situ values in Podgorica, whereas they were slightly higher in Žabljak. These differences are consistent with the representation of local topography in the model. Podgorica is located at 44 m above sea level, compared with 58 m in the ECMWF model, while Žabljak is situated at 1,450 m, compared with 1,434 m in the model. In areas with sparse observations, reanalysis values may be strongly influenced by the Integrated Forecasting System (IFS), particularly over complex terrain (Lang et al. 2023).

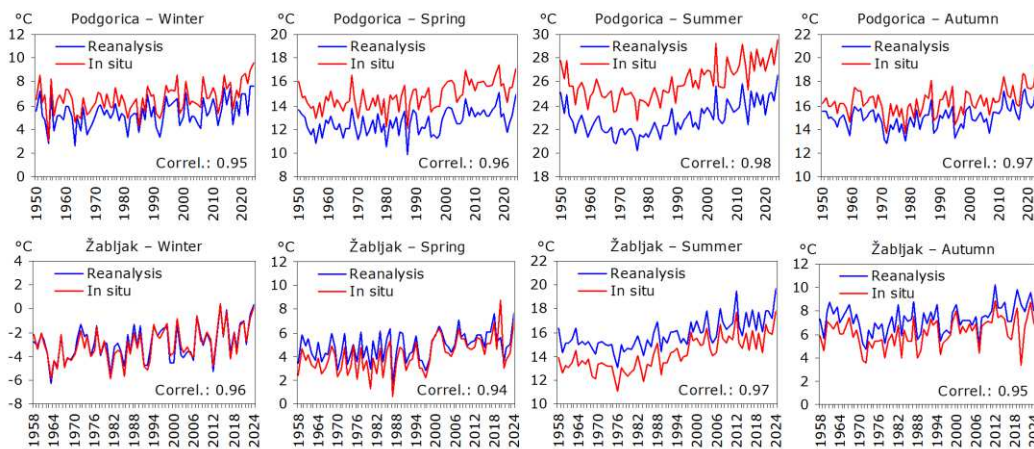


Fig. 3 Correlation between seasonal mean reanalysis temperatures and in situ observations at the Podgorica (44 m) and Žabljak (1450 m) stations in Montenegro for the periods 1950–2024 and 1958–2024, respectively

Previous studies reported significant warming of mean monthly, seasonal, and annual air temperatures in Montenegro during 1960–2020 (Burić et al. 2024; Burić 2024). For the 1950–2024 period examined here, in situ observations from the 10 stations indicate the strongest seasonal warming in summer (0.30 – $0.60^\circ\text{C}/\text{decade}$) and the weakest in winter (0.01 – $0.31^\circ\text{C}/\text{decade}$). Annual warming ranges from $0.15^\circ\text{C}/\text{decade}$ along the coast to $0.39^\circ\text{C}/\text{decade}$ in northern Montenegro, with trends significant at $p < 0.001$ at all stations. At both seasonal and annual scales, warming generally increases from southern to northern Montenegro.

The consistency between station observations and ERA5-Land is further illustrated by the Podgorica station. In situ trends for winter, spring, summer, autumn, and annual temperature were 0.21 , 0.27 , 0.40 , 0.19 , and $0.27^\circ\text{C}/\text{decade}$, respectively, compared with 0.18 , 0.21 , 0.33 , 0.17 , and $0.23^\circ\text{C}/\text{decade}$ from the corresponding ERA5-Land grid cell. Differences ranged from $0.02^\circ\text{C}/\text{decade}$ in autumn to $0.07^\circ\text{C}/\text{decade}$ in winter. Similar agreement was obtained for the remaining nine stations, supporting the reliability of ERA5-Land temperature data for Montenegro and their applicability to the broader Balkan region.

Trends in mean seasonal and annual temperatures in the Balkans

The Balkan Peninsula is situated at the crossroads of subtropical (Mediterranean) and temperate climate influences. Its relief is highly fragmented, with numerous valleys, basins, and mountain ranges, whose peaks reach elevations of nearly 3000 meters. Owing to these and other factors, the Balkans represent a true climatic mosaic. According to the ERA5-Land dataset for the period 1950–2024, the mean annual air temperature on the Balkan Peninsula ranges from 3.0°C in the high-altitude areas of the Rila Mountains to 19.2°C on the island of Rhodes (Fig. 4). This island is the warmest in winter, with an average temperature of approximately 13.6°C. In winter, the coldest areas are the high mountain regions, generally characterized by negative temperatures, with the lowest mean values in this season recorded in the highest parts of the Southern Carpathians in Romania (around -6.0°C). The high-altitude areas of the Rila Mountains in Bulgaria are, on average, the coldest in spring and summer (1.4°C and 11.6°C, respectively), while spring and summer are warmest in Rhodes and the interior of the Peloponnese, respectively (16.7°C and 27.3°C). The Rila Mountains are also the coldest in autumn, where some areas record temperatures of around 4.3°C. The highest mean autumn temperatures are recorded in parts of Rhodes (21.2°C).

Average Annual Temperature (ERA5-Land, 0.1°, N=7,262)

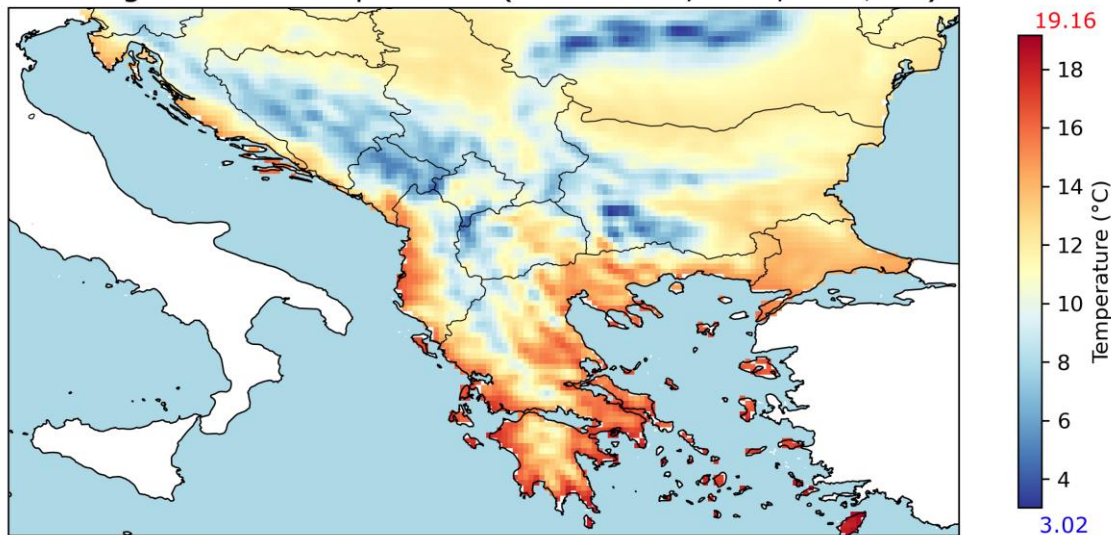


Fig. 4 Mean annual air temperatures on the Balkan Peninsula based on ERA5-Land data (1950–2024)

The higher the elevation, the lower the mean temperature; consequently, mountain systems represent the coldest climatic zones of the Balkans, particularly the Rila Mountains, the Southern Carpathians, the Balkan Mountains, and the Dinaric Alps. It can also be concluded that temperatures increase toward the south and closer to the sea, with the exception of enclosed basins that experience extreme summer warming, such as the inland areas of southern Greece and southern Albania, the Vardar River valley in North Macedonia, and the area surrounding the capital of Montenegro (Podgorica). Thus, the influence of latitude, the sea, and the region's relief characteristics on air temperature across the Balkans is clearly evident.

For the observed 75-year period (1950–2024), trend calculations indicate that the entire Balkan Peninsula is experiencing warming across all seasons and on an annual basis. In winter, the interior of the Peloponnese exhibits the lowest increase in mean temperature (0.06°C/decade), whereas the most pronounced warming occurs in northern Bosnia and Herzegovina (up to 0.49°C/decade), near the border with Croatia. During spring, the trend in mean temperature ranges from 0.08°C/decade in the Thessalian Plain in Greece to 0.33°C/decade in the area around Bucharest in Romania. In summer, the distribution of trends varies from 0.10°C/decade in the southeastern Balkans (Cyclades Islands) to 0.45°C/decade in western Croatia. Autumn shows the lowest trend values, ranging from 0.04°C/decade in southeastern Serbia to 0.23°C/decade in northwestern Croatia (Fig. 5). The annual mean temperature trend ranges from 0.09°C/decade in the interior of the Peloponnese to 0.37°C/decade in the northwestern Balkans (parts of Croatia and Bosnia and Herzegovina).

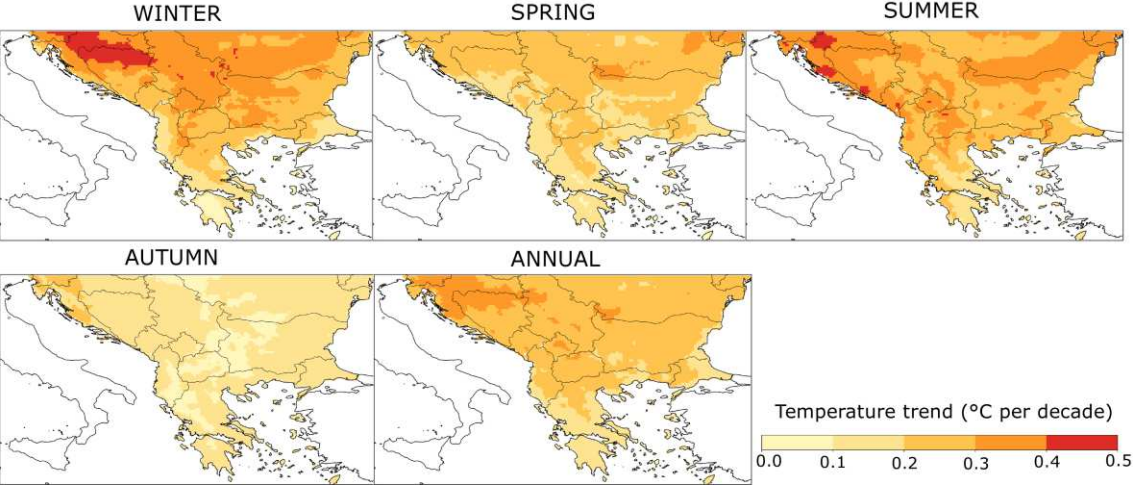


Fig. 5 Spatial distribution of mean seasonal and annual air temperature trends on the Balkan Peninsula (1950–2024)

In most cases, positive trends in mean seasonal and annual temperatures are statistically significant. The Mann–Kendall test indicates that, during summer and on an annual basis, the entire Balkan Peninsula is undergoing significant warming. In this context, the positive trend in mean annual and summer temperatures is significant at the highest level ($p < 0.001$) in all 7,262 and 7,200 grid cells, respectively. Warming is significant in 7,097 grid cells in winter and in 4,161 grid cells in autumn (Table 2). In other words, out of 7,262 grid cells covering the Balkan Peninsula, warming is statistically significant in 100.0% of cases in summer and on an annual basis, in 99.6% of cases in spring, in 97.7% of cases in winter, and in 57.3% of grid cells in the autumn season.

Table 2 Number of ERA5-Land grid cells ($0.1^\circ \times 0.1^\circ$) showing positive/negative and statistically significant/non-significant trends in mean seasonal and annual temperatures on the Balkan Peninsula (1950–2024)

		Number of grid cells	Significant		Significant (%)	Not significant
			$p < 0.05$	$p < 0.01$		
Winter	Positive trend	7,262	373	6,724	7,097 (97.7%)	165
	Negative trend	0	0	0	0	0
	Total	7,262	373	6,724	7,097	165
Spring	Positive trend	7,262	272	6,961	7,233 (99.6%)	29
	Negative trend	0	0	0	0	0
	Total	7,262	272	6,961	7,233	29
Summer	Positive trend	7,262	62	7,200	7,262 (100%)	0
	Negative trend	0	0	0	0	0
	Total	7,262	62	7,200	7262	0
Autumn	Positive trend	7,262	2,478	1,683	4,161 (57.3%)	3,101
	Negative trend	0	0	0	0	0
	Total	7,262	2,478	1,683	4161	3,101
Annual	Positive trend	7,262	0	7,262	7,262 (100%)	0
	Negative trend	0	0	0	0	0
	Total	7,262	0	7,262	7,262	0

3.3 Correlation between AMOC and in situ temperature in Montenegro

The relationship between in situ air temperature in Montenegro and the four AMOC datasets (CGLO, GLOR, ORAS, and ensemble mean) was assessed for 1993–2023. The results show the strongest negative associations between AMOC variability and air temperature during autumn and at the annual scale (Table 3). This pattern is consistent across all four AMOC datasets, with correlations predominantly significant at $p < 0.01$. During summer, the correlation coefficient between in situ mean air temperature and the ORAS AMOC dataset reaches -0.69 , while the corresponding values for autumn and annual temperature reach

–0.71 and –0.78, respectively. The ensemble mean shows the strongest associations with autumn and annual temperatures, with correlation coefficients reaching –0.77 and –0.79, respectively. During spring and summer, the strongest relationships are observed for the ORAS dataset and the ensemble mean.

Table 3 Correlation of temperature in Montenegro with AMOC values from three models and the ensemble model (1993–2023)

MS	MODEL											
	CGLO	GLOR	ORAS	ENSEM.	CGLO	GLOR	ORAS	ENSEM.	CGLO	GLOR	ORAS	ENSEM.
	WINTER				SPRING				SUMMER			
Ulcinj	-0.04	-0.06	0.25	0.11	0.00	-0.16	-0.30	-0.20	-0.23	-0.09	-0.42 ⁺	-0.34
Bar	-0.15	-0.10	-0.22	-0.20	-0.02	-0.27	-0.64 [*]	-0.41 ⁺	-0.28	-0.14	-0.69 [*]	-0.52 [*]
Budva	-0.11	-0.12	-0.09	-0.11	-0.13	-0.32	-0.55 [*]	-0.43 ⁺	-0.34	-0.19	-0.55 [*]	-0.48 [*]
H.Novi	0.03	0.00	0.20	0.12	0.03	-0.24	-0.48 [*]	-0.31	-0.21	-0.15	-0.52 [*]	-0.40 ⁺
Podgorica	-0.19	-0.12	-0.15	-0.17	-0.11	-0.31	-0.56 [*]	-0.42 ⁺	-0.28	-0.12	-0.38 ⁺	-0.34
Nikšić	-0.13	0.00	0.01	-0.04	-0.09	-0.26	-0.48 [*]	-0.35 ⁺	-0.24	-0.13	-0.35 ⁺	-0.31
Žabljak	-0.12	-0.03	0.00	-0.05	0.00	-0.20	-0.43 ⁺	-0.28	-0.22	-0.21	-0.46 [*]	-0.39 ⁺
Kolšin	-0.10	0.01	0.04	-0.01	-0.06	-0.29	-0.50 [*]	-0.36 ⁺	-0.44 ⁺	-0.28	-0.61 [*]	-0.58 [*]
B.Polje	-0.20	-0.10	-0.22	-0.21	-0.20	-0.44 ⁺	-0.67 [*]	-0.55 [*]	-0.45 ⁺	-0.24	-0.65 [*]	-0.59 [*]
Pljevlja	-0.11	-0.04	-0.01	-0.05	-0.05	-0.28	-0.39 ⁺	-0.30	-0.19	-0.14	-0.36 ⁺	-0.31
	AUTUMN				YEAR							
Ulcinj	-0.40 ⁺	-0.63 [*]	-0.25	-0.43 ⁺	-0.35 ⁺	-0.47 [*]	-0.21	-0.34				
Bar	-0.64 [*]	-0.62 [*]	-0.71 [*]	-0.76 [*]	-0.50 [*]	-0.43 ⁺	-0.78 [*]	-0.72 [*]				
Budva	-0.69 [*]	-0.64 [*]	-0.69 [*]	-0.77 [*]	-0.61 [*]	-0.52 [*]	-0.67 [*]	-0.71 [*]				
H.Novi	-0.48 [*]	-0.59 [*]	-0.45 [*]	-0.55 [*]	-0.39 [*]	-0.45 [*]	-0.54 [*]	-0.54 [*]				
Podgorica	-0.61 [*]	-0.62	-0.62 [*]	-0.70 [*]	-0.61 [*]	-0.50 [*]	-0.67 [*]	-0.70 [*]				
Nikšić	-0.64 [*]	-0.59 [*]	-0.62 [*]	-0.70 [*]	-0.63 [*]	-0.50 [*]	-0.63 [*]	-0.68 [*]				
Žabljak	-0.48 [*]	-0.49 [*]	-0.47 [*]	-0.54 [*]	-0.60	-0.59 [*]	-0.68 [*]	-0.72 [*]				
Kolšin	-0.63 [*]	-0.56 [*]	-0.57 [*]	-0.66 [*]	-0.69 [*]	-0.56 [*]	-0.66 [*]	-0.73 [*]				
B.Polje	-0.70 [*]	-0.54 [*]	-0.69 [*]	-0.75 [*]	-0.73 [*]	-0.54 [*]	-0.74 [*]	-0.79 [*]				
Pljevlja	-0.50 [*]	-0.47 [*]	-0.43 ⁺	-0.52 [*]	-0.62 [*]	-0.57 [*]	-0.56 [*]	-0.65 [*]				

Signific.level:
+ $p < 0.05$
* $p < 0.01$

3.4 Correlation between AMOC and ERA5-Land temperatures in the Balkans

For 1993–2023, the AMOC ensemble mean shows a significant decreasing trend in mean seasonal and annual transport at 26.5°N (Fig. 6). The strongest decline occurs in autumn (–1.80 Sv/decade), while the weakest is observed in winter (–1.36 Sv/decade). The annual trend is –1.61 Sv/decade over the 31-year period. The relationship between AMOC variability and ERA5-Land air temperature was therefore examined using the ensemble mean at seasonal and annual scales.

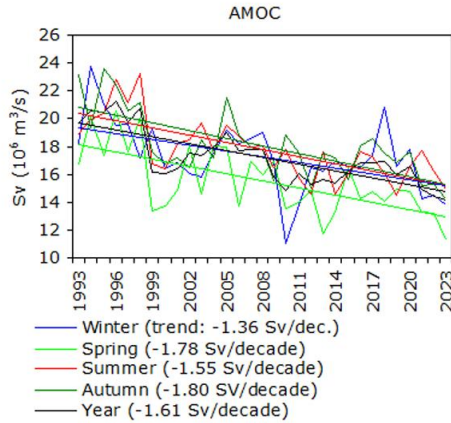


Fig. 6 Trends in mean seasonal and annual AMOC transport at 26.5°N in the Atlantic (1993–2023)

In winter, correlation coefficients range from –0.37 to –0.05. Of the 7,262 grid cells, 6,235 (85.9%) show negative correlations and 1,027 (14.1%) positive correlations. However, only three cells (0.04%), located on the Aegean Sea islands, exhibit statistically significant negative correlations ($p < 0.05$). In spring, correlation coefficients range from –0.08 to –0.52, with the strongest relationships in the southeastern Balkans. Significant correlations occur in 1,971 grid cells (27.1%), including 56 cells at $p < 0.01$ and 1,915 at $p < 0.05$. In summer, the strongest negative relationships occur in the northeastern Balkans, where correlation coefficients reach –0.66. Overall, correlations are predominantly negative, with statistically significant associations in 6,230 grid cells (85.8%), including 2,282 cells at $p < 0.01$ and 3,948

at $p < 0.05$. In autumn and at the annual scale, all 7,262 grid cells show statistically significant negative correlations at $p < 0.01$. Autumn coefficients range from -0.50 to -0.77 , while annual values range from -0.49 to -0.80 . The strongest absolute correlations occur in the Lower Danube region (Wallachian Plain) and the Peloponnese (Table 4).

Table 4 Number of grid cells ($0.1^\circ \times 0.1^\circ$) showing statistically significant and non-significant correlation coefficients between AMOC and mean seasonal and annual temperatures on the Balkan Peninsula (1993–2023)

	Significant correlation		Significant (%)	Not significant (%)
	$p < 0.01$	$p < 0.05$		
Winter	0	3	0.04	99.96
Spring	56	1915	27.1	72.9
Summer	2282	3948	85.8	14.2
Autumn	7262	0	100.0	0.0
Annual	7262	0	100.0	0.0

Overall, correlation coefficients of approximately -0.35 to -0.44 correspond to $p < 0.05$, whereas values of -0.45 or lower generally correspond to $p < 0.01$ (Fig. 7). The results indicate a clear seasonal asymmetry in the statistical relationship between AMOC variability and Balkan temperatures, with the strongest and most spatially coherent associations occurring in autumn and at the annual scale, substantial negative associations in summer, more localized relationships in spring, and little evidence of a significant relationship in winter.

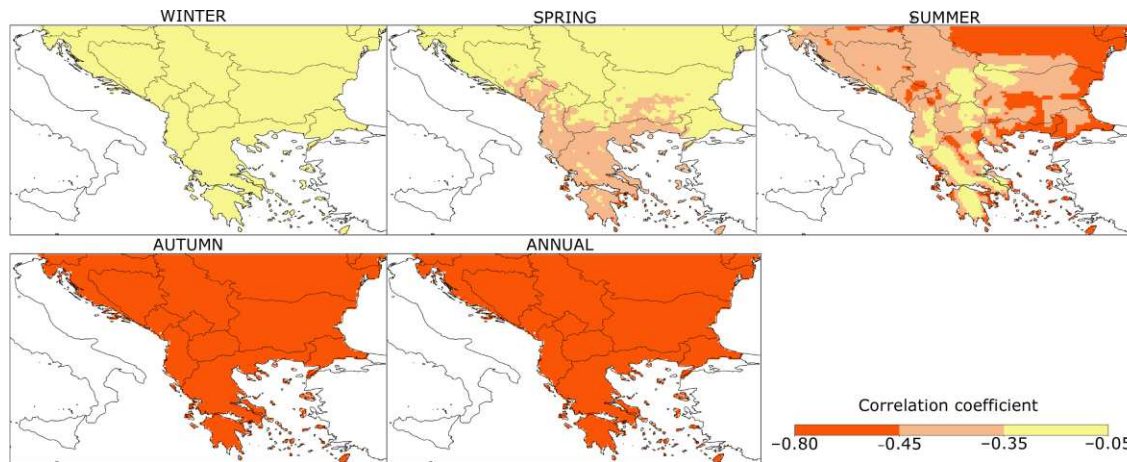


Fig. 7 Correlation coefficients between mean seasonal and annual AMOC values and air temperature over the Balkan Peninsula

4. Discussion

The results demonstrate significant warming across the Balkan Peninsula, including Montenegro, during 1950–2024, together with a significant weakening of the AMOC during 1993–2023. The annual AMOC trend at 26.5°N was -1.61 Sv/decade, with the strongest seasonal decline in autumn (-1.80 Sv/decade) and the weakest in winter (-1.36 Sv/decade). The statistical relationship between AMOC variability and Balkan temperatures was strongly season-dependent, with the most spatially coherent negative associations occurring in autumn and at the annual scale, substantial negative associations in summer, more localized relationships in spring, and little evidence of a significant relationship in winter. To our knowledge, this is the first study to examine the statistical relationship between AMOC variability and air temperature across the Balkan Peninsula. Previous studies have documented the effects of atmospheric and oceanic teleconnections on temperature and precipitation in individual Balkan countries (Luković et al. 2015; Burić et al. 2019).

The significant weakening of the AMOC was also associated with indicators of anthropogenic greenhouse forcing. For 1993–2023, correlations between AMOC strength and atmospheric CO₂ concentration and the Annual Greenhouse Gas Index (AGGI) were -0.76 and -0.77 , respectively. The AGGI, defined by NOAA (NOAA 2024), integrates the radiative forcing of major long-lived greenhouse gases, including CO₂, CH₄, N₂O, and several chlorofluorocarbons. These strong negative associations are consistent with the broader understanding that increasing greenhouse gas concentrations and associated warming can weaken the AMOC through changes in ocean temperature, freshwater input, and deep-water formation.

The relationship between AMOC variability and oceanic oscillations was selective. Among PDO, ENSO, AMO, and AMM, significant correlations were found with PDO (0.60) and AMO (-0.37). Previous research indicates that the AMOC–AMO relationship involves temporal lags and that AMOC weakening can contribute to a transition of the AMO from a positive to a negative phase (Kim et al. 2021). In the present analysis, the strongest AMOC–AMO relationship was obtained when AMOC variability was shifted by two years, reaching -0.60 . Among the 10 atmospheric indices examined, significant relationships were identified with the East Atlantic (EA; -0.48) and East Atlantic–West Russia (EAWR; 0.43) patterns. Although no significant contemporaneous correlation was detected between AMOC and the NAO, their interaction is known to be complex and potentially bidirectional (Kim et al. 2023). The significant relationships between AMOC, greenhouse-gas indicators, and the selected oceanic and atmospheric indices are summarized in Fig. 8.

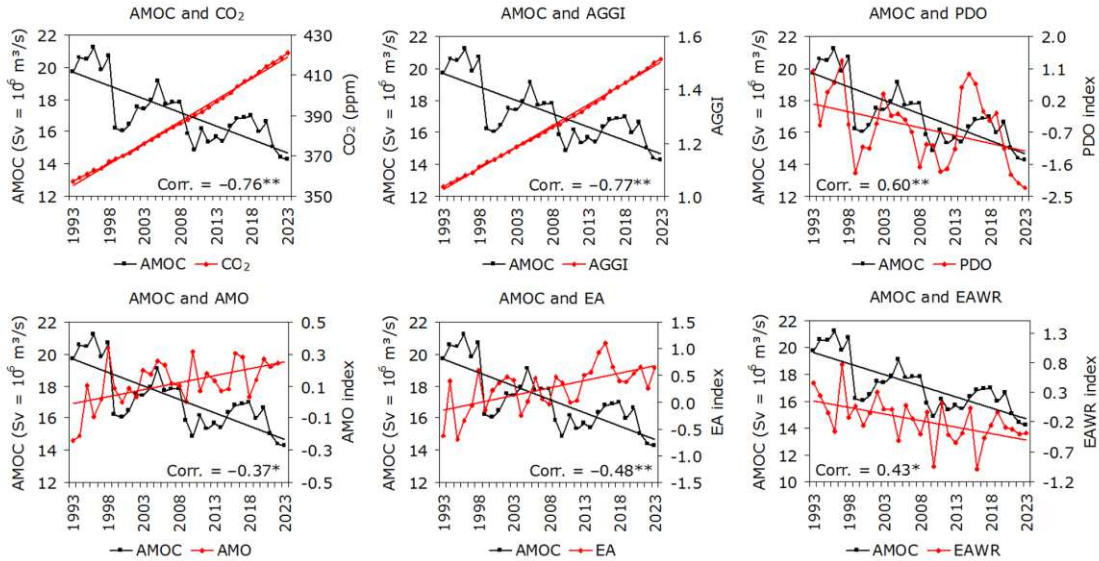


Fig. 8 Correlation between AMOC and GHG indicators (CO₂ and AGGI), oceanic oscillations (PDO and AMO), and atmospheric oscillations (EA and EAWR) for the period 1993–2023. (Significance: * $p < 0.05$; ** $p < 0.01$)

The strong seasonal asymmetry over the Balkans is particularly noteworthy. Winter showed little evidence of a significant relationship, whereas summer, autumn, and the annual scale showed predominantly strong negative associations. This seasonal contrast may reflect the varying influence of large-scale atmospheric circulation, including westerlies, the NAO, Mediterranean Oscillation, and other synoptic patterns. The stronger autumn relationship coincides with the strongest seasonal AMOC decline identified here, while the weak winter relationship may be related to the more complex winter circulation regime and the southward displacement of the subtropical high-pressure belt. However, these mechanisms cannot be established from correlation analysis alone. The spatial distribution further supports an atmospheric mediation of the AMOC signal: significant negative correlations occurred in 85.8% of grid cells during summer, while all 7,262 grid cells were significant in autumn and at the annual scale. Spring relationships were concentrated mainly in the southeastern Balkans. He et al. (2022) similarly showed that atmospheric circulation, particularly increased westerly winds, may explain approximately 50% of the cooling trend in the northern subpolar Atlantic, or “warming hole. Because AMOC variability is closely

related to heat transport (Rahmstorf et al. 2015) and carbon uptake (Brown et al. 2021), its future evolution is relevant to both regional and global climate (Bellomo et al. 2021).

The future evolution of the AMOC remains uncertain. Ditlevsen and Ditlevsen (2023) suggested that continued greenhouse gas emissions could result in an AMOC collapse around the middle of the 21st century, whereas other studies indicate that a complete collapse is unlikely before 2100. Model projections indicate a 90–100% probability of AMOC weakening during the 21st century, while confidence in a complete shutdown before 2100 remains medium (Weijer et al. 2020; Whitt and Jansen 2020; IPCC 2023; van Westen et al. 2024). More recent results based on 34 models indicate that complete AMOC shutdown is unlikely even under extreme increases in greenhouse gas concentrations and North Atlantic freshwater input, owing to a compensating contribution from the Southern Ocean. Baker et al. (2025) further suggested that complete collapse would require the development of a compensating Pacific Meridional Overturning Circulation (PMOC), while the importance of the Southern Ocean in sustaining the northern AMOC has also been highlighted by Tuchen et al. (2022).

The regional climatic consequences of AMOC weakening may differ substantially. Yang et al. (2025) demonstrated contrasting oceanic responses, including subsurface cooling in the western Pacific and warming in the equatorial Atlantic, together with a Niño-like sea-surface-temperature response in both basins. Wang et al. (2023) showed that weakened and strengthened AMOC conditions correspond to large-scale cooling and warming, respectively, and suggested that AMOC-related signals can propagate through Rossby waves across the middle and high latitudes of the Northern Hemisphere. They also emphasized the close relationship between decadal AMOC variability and the AMO. Particularly relevant to the Balkans, Meccia et al. (2025) found that a weakened AMOC may reduce heat-wave frequency over much of Europe but increase it in Eastern Europe, including the Balkans, possibly through jet-stream changes and increased atmospheric blocking over the Urals. The exceptional North Atlantic cooling in 2015 and the concurrent Central European heat wave provide an illustrative example, with Ducheux et al. (2016) linking the two events through jet-stream circulation.

Overall, the results indicate that the relationship between AMOC variability and Balkan temperatures is embedded within a complex ocean–atmosphere system rather than representing a simple direct response. The particularly strong negative associations in autumn, summer, and at the annual scale, together with the localized spring response and weak winter relationship, suggest an important role of atmospheric circulation in mediating the regional expression of AMOC variability. The significant associations of AMOC with PDO, AMO, EA, EAWR, CO₂, and AGGI further indicate coupling with both natural climate variability and anthropogenic forcing. Further research combining AMOC observations, atmospheric circulation diagnostics, sea-level pressure fields, jet-stream characteristics, and high-resolution climate modelling is needed to clarify the mechanisms underlying the observed Balkan temperature response.

5. Conclusions

For 1950–2024, the Balkan Peninsula and Montenegro experienced significant warming at seasonal and annual scales, with the warming trend generally increasing from southeast to northwest. ERA5-Land temperatures showed close agreement with in situ observations in Montenegro ($r = 0.92$ – 0.98), supporting the reliability of the reanalysis for regional temperature analysis. During 1993–2023, the AMOC exhibited a significant weakening, with seasonal trends ranging from -1.36 Sv/decade in winter to -1.80 Sv/decade in autumn and an annual trend of -1.61 Sv/decade. The relationship between AMOC variability and temperature was strongly season-dependent. The strongest negative associations occurred in autumn and at the annual scale, reaching -0.79 in Montenegro and ranging from -0.49 to -0.80 across the Balkans ($p < 0.01$). Significant negative relationships were also widespread in summer, more localized in spring, and absent in winter. AMOC variability was significantly associated with atmospheric CO₂ and AGGI ($r = -0.76$ and -0.77), as well as PDO ($r = 0.60$), AMO ($r = -0.37$; -0.60 with a two-year lag), EA ($r = -0.48$), and EAWR ($r = 0.43$). Overall, the findings provide statistical evidence of a strong, seasonally heterogeneous relationship between AMOC variability and Balkan temperatures, likely mediated by large-scale atmospheric circulation and teleconnections. Further research is needed to clarify the physical mechanisms underlying these relationships.

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Data Availability In situ data supporting the findings of this study are publicly available on the website of the State Institute for Hydrometeorology and Seismology of Montenegro (<https://www.meteo.co.me/page.php?keyword=reports>). Reanalysis data for temperature and AMOC are available via the links provided in this paper (Copernicus Climate Change Service and Copernicus Marine Service Information: <https://doi.org/10.24381/cds.68d2bb30>; <https://doi.org/10.48670/moi-00232>).

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