INFLUENCE OF LARGE-SCALE ATMOSPHERIC CIRCULATION ON ROMANIAN SNOWPACK DURATION

MARIUS-VICTOR BIRSAN [1], ION-ANDREI NITA [2], VLAD-ALEXANDRU AMIHĂESEI [3,4]

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

[2]) VisualFlow. Aurel Vlaicu 140, 020099 Bucharest, Romania.

[3]) Doctoral School of Geosciences, Alexandru Ioan Cuza University of Iași. 700506 Iași, Romania

[4]) National Meteorological Administration. Şos. București-Ploiești 97, 013686 Bucharest, Romania.

Received:

Abstract. Daily data of snow depth from 104 meteorological stations across Romania were used to study the variability of snowpack for the period 1961-2010. The weather stations are fairly distributed over Romania (both spatially and with respect to elevation). Trend analysis was conducted with the Mann-Kendall nonparametric test, while the magnitude of the linear trend was estimated with the Theil-Sen method. The results show that the maximum snowpack duration is decreasing in the intra-Carpathian region of Romania, showing a clear spatial pattern. The signal is consistent and statistically significant. The influence of large-scale atmospheric circulation on continuous maximum snowpack duration in Romania was investigated using several teleconnection indices. We found statistically-significant negative corelations between winter East Atlantic and North Atlantic Oscillation patterns and the maximum continuous snowpack duration. Our findings are in agreement with recent studies on snow variability in the region, which point to a diminished snow / rain ratio since 1961.

Key words: snow depth; trend analysis; nonparametric test; teleconnections; North Atlantic Oscillation (NAO); East Atlantic (EA); East Atlantic / West Russia (EAWR); Atlantic Multidecadal Oscillation (AMO); climate change; Eastern Europe.

DOI:

1. INTRODUCTION

Analysing long-term changes in the snowpack duration is essential for the assessment of the impacts of climate variability of a region. Snow cover represents a major storage of water and greatly influences the surface albedo and energy balance. The snow pack strongly affects the overlying air and the underlying ground, as well as the atmosphere downstream [1]. Snowpack duration has major effects on the growing season of the vegetation – in particular at high elevations [2]. A shortening snow season would enhance soil warming due to increased solar absorption [3].

Brown [4] and Dye [5] studied the snow variability and their spatial patterns at hemispheric scale, demonstrating the snow cover decrease as an effect of to recent climatic warming.

Being the largest country in southeastern Europe, Romania covers an area of 238,391 km², and the terrain is fairy equally distributed between mountains, hills, and lowland regions. The elevation ranges from 0 to 2544 m.a.s.l. The country has a transitional climate between temperate and continental, with four distinct seasons, and with several climatic influences: oceanic in the western part; Mediterranean in southwestern areas, semi-arid in the East, and Pontic (Black Sea) in the southeastern region.

Several countrywide hydroclimatic studies have been conducted in Romania within the last decade. Long-term changes in precipitation point to increases in rain shower frequency since 1961 [6,7]. Air temperature shows rising trends in all seasons except autumn [8], and warm-related thermal extremes also present increasing trends [9-11], which led to a decrease in snow depth [12,13]. Both mean and maximum wind speed shows overwhelmingly decreasing trends at monthly, seasonal and annual scales [14,15].

Clearly, these changes had affected the natural streamflow regime [16,17], as well at the meteorological droughts [18] – hence the agricultural yield [19], wine productivity [20], or forest ecosystems [21-23]. They also play an impact on human health – through heat and cold waves [24], air pollution [25,26] or pollen spreading [27]. Other effects regard the changes in precipitation chemistry [28-30].

This paper presents a 50-year analysis of changes in snowpack duration in Romania from observational weather station data.

2. DATA AND PERIOD OF STUDY

The data used in this study belongs to Meteo Romania, the National Meteorological Administration. The time series consist in quality-controlled, daily snow depth data from 104 weather stations, with continuous records over the 50-year study period (1961-2010).

No reconstructed records – like extensions or missing values filled using computational algorithms – were involved in the study. For all stations, all years that were taken into account have full daily records. In the few cases when a station had missing values during the cold season (October – April), the respective year was excluded from the analysis.

The daily snow depth is measured at 6 a.m. (in a consistent and robust manner that excludes instrument malfunctions) and is considered to be the value of the previous day. Here, snowpack duration is defined as the maximum number of consecutive days with snow depth ≥ 1 cm within the November-April interval.

In order to examine eventual correlations with large-scale atmospheric circulation, we used four teleconnection indices, as follows:

(1) North Atlantic Oscillation (NAO) Index as defined by Hurrel [31] for the meteorological winter season (DJF), retrieved from cpc.ncep.noaa.gov.

(2) East Atlantic (EA) pattern [32], retrieved from cpc.ncep.noaa.gov. EA is the second prominent mode of low-frequency variability over the North Atlantic, appearing as a leading mode in all months. The EA pattern consists of a north-south dipole of anomaly centres spanning the North Atlantic from east to west, structurally similar to the NAO.

(3) East Atlantic / West Russia (EAWR) Index – also known as the Eurasia-2 pattern [32], retrieved from cpc.ncep.noaa.gov. EAWR consists of four main anomaly centres, and is one of the three prominent teleconnection patterns that affects Eurasia throughout the year.

(4) Atlantic Multidecadal Oscillation (AMO) Index [33], unsmoothed, retrieved from esrl.noaa.gov.

3. METHODOLOGY

The statistical significance of trends was analysed with the nonparametric Mann-Kendall (MK) test [34,35] for the annual and seasonal mean wind speed. The MK test is a rank-based procedure, especially suitable for non-normally distributed data, data containing outliers and non-linear trends [36].

The null and the alternative hypothesis of the MK test for trend in the random variable *x* are as follows:

$$\begin{cases} H_0: Pr(x_j > x_i) = 0.5\,, & j > i \\ H_A: Pr(x_j < x_i) \neq 0.5\,, & \text{(two-sided test)} \end{cases} \tag{1}$$

The MK statistic S is calculated as

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(x_j - x_k) \tag{2}$$

where x_j and x_k are the data values in years *j* and *k*, respectively, with *j*>*k*, *n* is the total number of years and sgn() is the sign function:

$$sgn(x_j - x_k) = \begin{cases} 1\,, & \text{if } x_j - x_k > 0 \\ 0\,, & \text{if } x_j - x_k = 0 \\ -1\,, & \text{if } x_j - x_k < 0 \end{cases} \tag{3}$$

For large *n*, the distribution of *S* can be well approximated by a normal distribution with mean zero and standard deviation given by:

$$\sigma_S = \sqrt{\frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(i)(i-1)(2i+5)}{18}} \tag{4}$$

Equation (4) gives the standard deviation of S with the correction for ties in data, with t_i denoting the number of ties of extent i. The standard normal variate Z_S is then used for hypothesis testing.

$$Z_S = \begin{cases} \dfrac{S-1}{\sigma_S} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \dfrac{S+1}{\sigma_S} & \text{if } S < 0 \end{cases} \tag{5}$$

The null hypothesis is rejected at significance level a if $|Z| > Z_{\alpha/2}$ (two-tail test), where $Z_{\alpha/2}$ is the value of the standard normal distribution with an exceedance probability $a/2$. In the present study, the significance level was fixed at 10%, i.e., p-value < 0.1 (two-tail test).

For trend magnitude, we used the nonparametric Sen's slope estimator (also known as Kendall-Theil robust line), a robust method for estimating quasi-linear trends. This estimator is less affected by non-normal data and outliers [36]. The slope is computed between all pairs i of the variable x:

$$\beta_i = \frac{x_j - x_k}{j - k} \tag{6}$$

with $j > k$; $j = 2,...,n$; $k = 1,...,n-1$, $i = 1,...,N$.

For n values in the time series x, this will result in $N = n(n-1)/2$ values of β. The slope estimate b is the median of β_i, $i = 1,...,N$.

Linkages with large-scale teleconnection patterns were done with Spearman’s *rho* correlation coefficient, which is a nonparametric, rank-based method used for estimating the monotone association between two random variables. Spearman’s *rho* is computed from the difference d between the ranks of independently sorted variables x and y [36]:

$$\rho = 1 - \frac{6\sum_{i=1}^{n} d_i^2}{n(n^2-1)} \tag{7}$$

Under the null hypothesis of no correlation between x and y, the distribution of ρ is approximated by a normal distribution with mean μ_ρ and variance σ_ρ^2:

$$\begin{cases} \mu_\rho = 0 \\ \sigma_\rho^2 = 1/(n-1) \end{cases} \tag{8}$$

The random variables x and y are considered correlated at the significance level α if $|\rho| > Z_{\alpha/2} / \sqrt{n-1}$ for a two-tailed test.

4. RESULTS AND DISCUSSION

The Mann-Kendall trend test applied to annual data series revealed substantial changes, with one third of the stations presenting decreasing trends in the maximum snowpack duration. All significant trends are downward, pointing to a robust climatic signal.

A clear spatial pattern of decreasing snowpack is observed in the intra-Carpathian area of the country, while the extra-Carpathian region does not seem to be affected by long-term changes in snowpack (Fig. 1). It is noticeable that the continental temperate climate of Romania is strongly influenced by orography, with the Carpathian Mountains significantly affecting the air circulation [37].

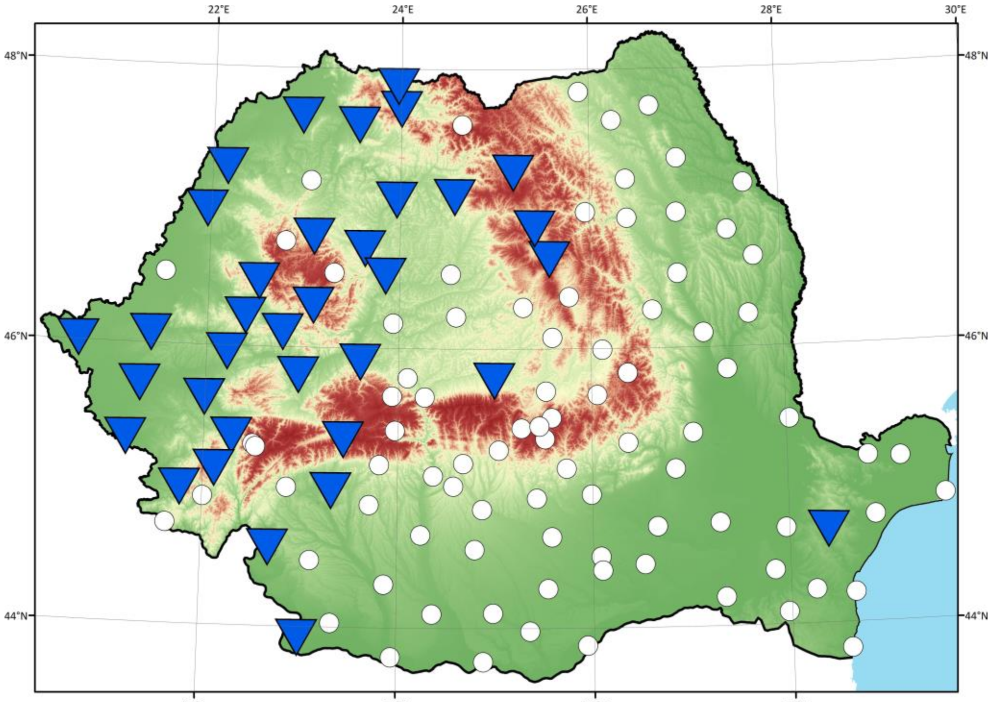


Fig. 1 – Trends in maximum continuous snowpack duration (1961-2010). Statistically-significant decreasing trends at 10% level (two-tail) are marked with downward triangles; circles represent stations with no trend.

Obviously, the snowpack duration shows a strong correlation with elevation (p-value < 0.001), as shown in Fig. 2.

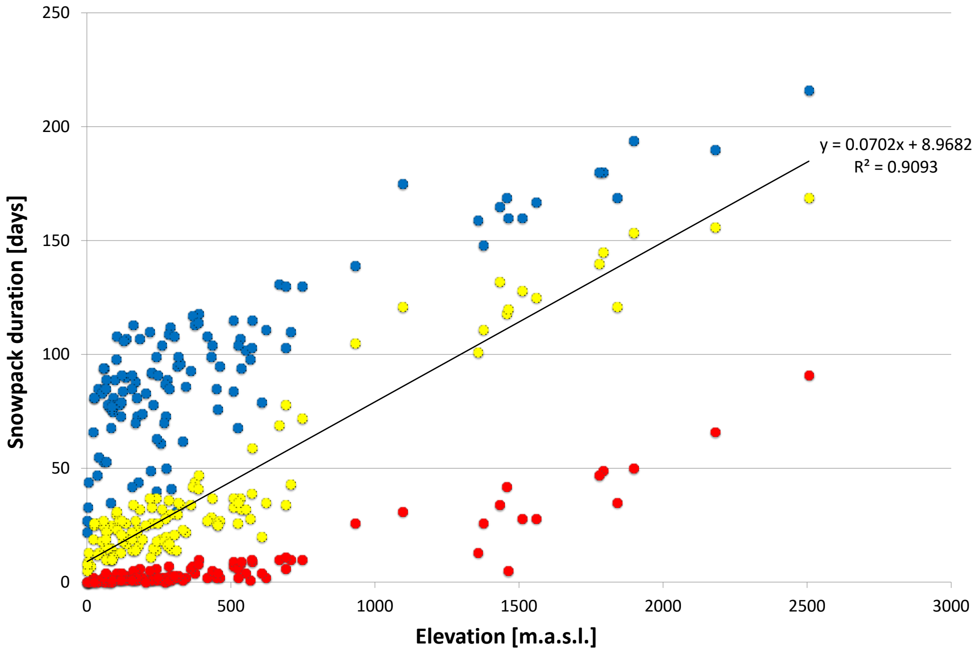
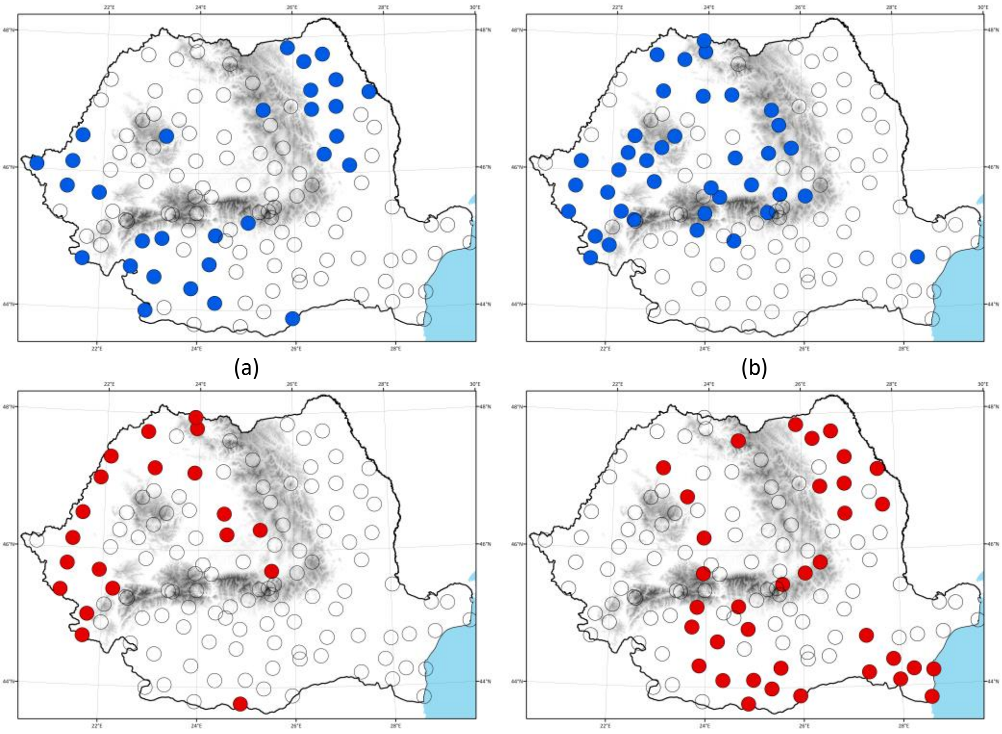


Fig. 2 – Relationship between snowpack duration (Nov.–Apr.) and elevation (1961-2010) for maximum (blue), median (yellow) and minimum (red) snowpack duration.

The results are in agreement with the recent studies on climatic changes in the region [38,39], which report significant warming, hence decreasing snow depth [40], and changes in the precipitation form, i.e., less snowfall and more rain [41, 42]. Another aspect regards the country-wide decrease in the number of snowfall days for the same period [13], which means that – in some regions – the same amount of snow would fall within a shorter interval, leading to more extreme events, sometime associated with blizzards [43].

The relationship between NAO (which affects the strength of westerly flow and weather patterns in Europe during winter) and the Romanian climate is well known. Positive thermal anomalies and negative precipitation anomalies over Romania are associated with a high NAO index. Previous studies found negative correlations between the DJF NAO index and the winter cumulated precipitation, mean snow depth, number of snowfall days [13,42] or streamflow [17]. Studies on the influence of solar activity on atmospheric circulation revealed a strengthening of the North Atlantic Oscillation [44,45], which (overall) is the most influential large-scale circulation pattern over Romania during winter – the influence of solar activity on climatic variables being higher during the cold season [46]. Also, increases in air circulation types associated with high-pressure centres over Central and Northern Europe led to a decrease in cloud cover in Eastern Europe [47]. The teleconnections results, namely the monotonic correlations between atmospheric circulation indices and the maximum continuous snowpack duration are shown in Fig. 3.



(a) (b)

(c) (d)

Fig. 3 – Correlation between winter (DJF) large-scale circulation patterns and the maximum continuous snowpack duration over Romania: (a) NAO; (b) EA; (c) EAWR; (d) AMO. Statistically-significant positive / negative correlations are marked in red / blue; unfilled circles denote no correlation.

NAO shows statistically-significant negative corelations (*p*-value<0.05) at 24% of the stations from eastern, western and southwestern regions, while EA correlates well with 32% of the stations, the vast majority of them being located in the intra-Carpathian region. The EA pattern is the second-most prominent mode of low-frequency variability over the North Atlantic, appearing as a leading mode in all months. It consists of a North-South dipole of anomaly centres spanning the North Atlantic from East to West, having a similar structure with NAO. EA's positive phase is associated with above-average surface temperatures in Europe in all months, and with below-average precipitation across southern Europe. EAWR is another prominent teleconnection pattern that affects Eurasia, consisting of four main anomaly centres. Precipitation anomalies associated with the positive phase of the EAWR pattern reflect generally below-average precipitation across central Europe. However, EAWR shows significant positive correlations with only 16.3% of the stations, most of them situated at lower elevations within the intra-Carpathian region. Finally, AMO (defined as the detrended Sea Surface Temperature anomalies over the North Atlantic from 0°N to 70°N), shows positive correlations at 29% of the stations, mostly in eastern and southern Romania. AMO was found to influence the summer temperature as well [48].

5. CONCLUSIONS

We presented an analysis of changes in continuous snowpack duration in Romania using daily observational data of snow depth from 104 meteorological stations, by means of non-parametric methods, over the period 1961–2010.

Our results show that the maximum continuous snowpack duration is decreasing in the intra-Carpathian region of Romania – showing a coherent spatial pattern – and suggesting a lessening of the snow/rain ratio since 1961.

The influence of large-scale atmospheric circulation seems to be the driving factor on the snowpack regime in Romania, especially EA and NAO.

Acknowledgements. We acknowledge the good quality of snow depth time series extracted from the National Meteorological Administration database.

REFERENCES

1. S. Vavrus, *The role of terrestrial snow cover in the climate system*. Clim. Dynam. **29**, 73-88 (2007); https://doi.org/10.1007/s00382-007-0226-0
2. F. Keller, S. Goyette, M. Beniston, *Sensitivity analysis of snow cover to climate change scenarios and their impact on plant habitats in alpine terrain*. Clim. Change **72**, 299-319 (2005); https://doi.org/10.1007/s10584-005-5360-2
3. A. Manea, et al., *Comparative Analysis of Land and Air Temperature in Romania since A.D. 1961*. Land **13**, 596 (2024); https://doi.org/10.3390/land13050596
4. R.D. Brown, *Northern Hemisphere snow cover variability and change 1915-97*. J. Climate **13**, 2339-2355 (2000); https://doi.org/10.1175/1520-0442(2000)013<2339:NHSCVA>2.0.CO;2
5. D.G. Dye, *Variability and trends in the annual snow-cover cycle in Northern Hemisphere land areas, 1972-2000*. Hydrol. Process. **16**(15), 3065-3077 (2000); https://doi.org/10.1002/hyp.1089
6. A. Busuioc, 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**(4), 2015–2034 (2016). https://doi.org/10.1002/joc.4477
7. A. Manea, et al., *Changes in the type of precipitation and associated cloud types in Eastern Romania (1961-2008).* Atmos. Res. **169**, 357–365 (2016). https://doi.org/10.1016/j.atmosres.2015.10.020

8. D.M. Micu, et al., *Temperature changes and elevation-warming relationships in the Carpathian Mountains*. Int. J. Climatol. **41**, 2154–2172 (2021); https://doi.org/10.1002/joc.6952
9. L. Sfîcă, et al., *The extent and intensity of the urban heat island in Iași city, Romania*. Theor. Appl. Climatol. **134,** 777–791 (2018); https://doi.org/10.1007/s00704-017-2305-4
10. M.V. Birsan, et al., *Spatio-temporal changes in annual temperature extremes over Romania (1961-2013).* Rom. J. Phys. **64** (7–8), 816 (2019).
11. M.V. Birsan, A. Dumitrescu, D.M. Micu, S. Cheval, *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
12. D. Micu, *Snow pack in the Romanian Carpathians under changing climatic conditions*. Meteorol. Atmos. Phys. **105**, *1-2*, 1-16 (2009). https://doi.org/10.1007/s00703-009-0035-6
13. M.V. Birsan, A. Dumitrescu, *Snow variability in Romania in connection to large-scale atmospheric circulation*. Int. J. Climatol. **34**, 134-144 (2014). https://doi.org/10.1002/joc.3671
14. M.V. Birsan, L. Marin, A. Dumitrescu, *Seasonal changes in wind speed in Romania*. Rom. Rep. Phys. **65**(4): 1479-1484 (2013).
15. M.V. Birsan, et al., *Observed changes in mean and maximum monthly wind speed over Romania since AD 1961*. Rom. Rep. Phys. **72**, 702 (2020).
16. M.V. Birsan, L. Zaharia, V. Chendes, E. Branescu, *Recent trends in streamflow in Romania (1976-2005)*. Rom. Rep. Phys., **64**, *1,* 275–280 (2012).
17. M.V. Birsan MV (2015) *Trends in Monthly Natural Streamflow in Romania and Linkages to Atmospheric Circulation in the North Atlantic*. Water Resour. Manage. **29**(9), 3305-3313. https://doi.org/10.1007/s11269-015-0999-6
18. S. Cheval, 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
19. R. Prăvălie et al., *The impact of climate change on agricultural productivity in Romania. A country-scale assessment based on the relationship between climatic water balance and maize yields in recent decades*, Agr. Syst. **179**, 102767 (2020). https://doi.org/10.1016/j.agsy.2019.102767
20. L.M. Irimia, C.V. Patriche, H. Quenol, L. Sfîcă, C. Foss, *Shifts in climate suitability for wine production as a result of climate change in a temperate climate wine region of Romania*. Theor. Appl. Climatol. **131**, 1069–1081 (2018). https://doi.org/10.1007/s00704-017-2033-9
21. G. Mihai, 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
22. G. Mihai, et al., *Climate Change in the Provenance Regions of Romania over the Last 70 Years: Implications for Forest Management*, Forests **13**, 1203 (2022). https://doi.org/10.3390/f13081203
23. G. Mihai, 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
24. A. Dobrinescu, 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
25. M.M. Micheu, et al., *From air pollution to cardiovascular diseases: the emerging role of epigenetics*. Mol. Biol. Rep. (2020) https://doi.org/10.1007/s11033-020-05570-9
26. L. Sfîcă, et al., *The influence of weather conditions and local climate on particulate matter (PM10) concentration in Metropolitan Area of Iasi, Romania*, Present Environment and Sustainable Development **12**(2), 12, 47-69 (2018); https://doi.org/10.2478/pesd-2018-0029
27. N. Ianovici, M.V. Birsan, *The influence of meteorological factors on the dynamic of Ambrosia artemisiifolia pollen in an invaded area*. Not. Bot. Horti Agrobo. **48**(2): 752-769 (2020). https://doi.org/10.15835/nbha48211862
28. Á. Keresztesi, 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

29. Á. Keresztesi, et al., *Assessing the variations in the chemical composition of rainwater and air masses using the zonal and meridional index*. Atmos. Res. **237**; 104846; https://doi.org/10.1016/j.atmosres.2020.104846
30. S. Ţîmpu, et al. *Tropospheric Dust and Associated Atmospheric Circulations over the Mediterranean Region with Focus on Romania's Territory*. Atmosphere **11**(4):349 (2020). https://doi.org/10.3390/atmos11040349
31. J.W. Hurrell, *Decadal trends in the North Atlantic Oscillation: Regional temperatures and precipitation*. Science 269:676-679 (1995).
32. A.G. Barnston, R.E. Livezey, *Classification, seasonality and persistence of low-frequency atmospheric circulation patterns*. Mon. Wea. Rev. **115**:1083-1126 (1987).
33. D.B. Enfield, et al., The Atlantic Multidecadal Oscillation and its relationship to rainfall and river flows in the continental US. Geophys. Res. Lett. 28:2077-2080 (2001).
34. H.B. Mann, *Non-parametric tests against trend*. Econometrica **13**: 245–259 (1945).
35. M.G. Kendall, *Rank Correlation Methods*, fourth ed. Charles Griffin, London (1975).
36. D.R. Helsel, et al., *Statistical methods in water resources*. U.S. Geological Survey Techniques and Methods, book 4, chapter A3, 458 p. (2020). https://doi.org/10.3133/tm4a3
37. D. Bălteanu, V. Chendeş, M. Sima, P. Enciu. *A country-wide spatial assessment of landslide susceptibility in Romania*. Geomorphology **124**, 102–112 (2010). https://doi.org/10.1016/j.geomorph.2010.03.005
38. C. Necula, 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
39. A. Busuioc, et al., *Spatial and temporal variability of climate extremes in Romania and associated large-scale mechanisms*. Int. J. Climatol. **35**(7), 1278-1300 (2015). https://doi.org/10.1002/joc.4054
40. S. Cheval, et al., *Climate variability in the Carpathian Mountains Region over 1961–2010*. Global Planet. Change **118**: 85–96 (2014). https://doi.org/10.1016/j.gloplacha.2014.04.005
41. M.V. Birsan, L. Zaharia, V. Chendes, E. Branescu, *Seasonal trends in Romanian streamflow*. Hydrol Process. **28**(15): 4496–4505 (2014). https://doi.org/10.1002/hyp.9961
42. V.A. Amihăesei, 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
43. L. Niacsu, L. Sfica, A. Ursu, P. Ichim, D.E. Bobric, I.G. Breaban, *Wind erosion on arable lands, associated with extreme blizzard conditions within the hilly area of Eastern Romania*, Environ. Res. **169**, 86-101 (2019) https://doi.org/10.1016/j.envres.2018.11.008
44. L. Sfîcă, M. Voiculescu, R. Huth, *The influence of solar activity on action centres of atmospheric circulation in North Atlantic*, Ann. Geophys. **33**, 207–215 (2015). https://doi.org/10.5194/angeo-33-207-2015
45. L. Sfîcă, M. Voiculescu, *Possible effects of atmospheric teleconnections and solar variability on tropospheric and stratospheric temperatures in the Northern Hemisphere*. J. Atmos. Sol.-Terr. Phy. **109**, 7-14 (2014). https://doi.org/10.1016/j.jastp.2013.12.021
46. L. Sfîcă, I. Iordache, M. Voiculescu, *Solar signal on regional scale: A study of possible solar impact upon Romania's climate*, J. Atmos. Sol.-Terr. Phy. **177**, 257-265 (2018). https://doi.org/10.1016/j.jastp.2017.09.015
47. L. Sfîcă, 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
48. M. Ionita, et al., *Multidecadal variability of summer temperature over Romania and its relation with Atlantic Multidecadal Oscillation*. Theor. Appl. Climatol. **113**,305–315 (2013).