

Air ionisation variability in coastal and mountainous areas. Case studies from Romania

Adrian-Călin Ciuciu¹, Tudor Caciora^{1*} and Grigore Vasile Herman¹

¹ Department of Geography, Tourism and Territorial Planning, Faculty of Geography, Tourism and Sport, University of Oradea, Romania

*Correspondence: tudor.caciora@yahoo.com; Tel.: 0740 94 11 44 (C.T.)

Keywords: air ionization; positive ions; negative ions; tourist resorts; sanogenetic effect; bioclimatology

Abstract: Air ionisation is an important indicator of air quality, influenced by meteorological, geological, and topoclimatic factors, and may have implications for human health. The present study analyses the air ionisation regime in six resorts in Romania: four on the Black Sea coast and two in the Carpathian Mountains, during summer conditions characterised by anticyclonic atmospheric conditions. The measurements were aimed at determining the concentrations of negative (n^-) and positive (n^+) ions, along with meteorological parameters (temperature, humidity, wind speed and atmospheric pressure). The final goal of the study was to determine the levels of air ionisation by components in mountain and coastal resorts, the differences between the two relief types in terms of air ionisation, and how weather and relief influence these levels. The results obtained highlight significant spatial differences between the coast and the mountains, with higher n^+ values in mountainous areas and lower air ionisation in coastal resorts. In all six resorts, positive ions predominate over negative ions, with the unipolarity coefficient superunitary, and all n^- values are below the threshold of 1000 ions/cm³ considered optimal by studies in the field. In coastal areas, ion concentrations are influenced by sea breeze dynamics and processes specific to the coastal environment, whereas in mountainous areas, differences are associated with geological peculiarities and altitude. From a health genetic perspective, the analysed environments present a moderately favourable character, falling into the clean air category for aeroionization, but without reaching optimal levels of negative ionisation associated with the maximum beneficial effects on well-being.

1. Introduction

Air ionisation is the physical process by which neutral molecules or atoms in the air acquire an electrical charge by losing or gaining an electron, in the formation of air ions, which are electrically charged atmospheric particles, permanently resulting in the Earth's atmosphere (Enache, 2017; Jiang et al., 2018). Air ions are particles formed when gaseous compounds, mainly nitrogen and oxygen, receive sufficient energy from natural radiation (e.g. cosmic or gamma) or other ionisation mechanisms and undergo changes in the electron-proton balance, which gives them either a positive or negative charge. Specifically, negative ions (n^-) are formed when air molecules capture one or more electrons, while positive ions (n^+) result from the loss of an electron from a gaseous molecule or atom, causing a charge imbalance in the air, an essential phenomenon in the electrical dynamics of the atmosphere (Golubenko et al., 2020). Typical concentrations of atmospheric air ionisation naturally vary from a few hundred to a few thousand ions per cm³, depending on local conditions, ionisation sources, and weather (Koch, 1962; Ewing et al., 2023).

In addition to natural radiation, air ionisation is generated by radioactive substances in the soil, the most important of which is radon (^{222}Rn), a product of the disintegration of radium in the soil (Chen and Kerminen, 2016). Recent studies show that air ionisation results from complex interactions among terrestrial gamma radiation, radon, and cosmic particles, which act simultaneously in the lower atmosphere (Chen and Kerminen, 2016; Baldoncini et al., 2017). Radium and thorium also contribute significantly to air ionisation, and local and temporal variations in air ionisation are closely correlated with the content and mobility of these elements in soil and rocks. Among these, radon plays an essential role due to its high concentration and 3.8-day half-life, which allow it to diffuse from the soil into the lower atmosphere, where it contributes significantly to ion density (Frimescu and Crețeanu, 1964; Golubenko and Rozanov, 2020). The radioactive content of the soil varies depending on the geological nature, with the highest values recorded in areas with igneous rocks (granite, gneiss) and the lowest in regions with sedimentary rocks (limestones and dolomites) (Frimescu and Crețeanu, 1964; Teodoreanu et al., 1984). This radioactive background determines diurnal and seasonal variations in air ionisation, which are influenced by local meteorological parameters, in particular temperature (T), pressure, and soil moisture. It has been shown that during periods of low pressure and high temperatures, radon exhalation is more intense, increasing the ion density in the lower atmosphere (Reiter, 1960; Israel, 1957; Frimescu and Crețeanu, 1964; Luts and Parts, 2002). Also, spatial variations in the atmospheric electric field and radon transport through vegetation and evapotranspiration processes can locally amplify ionisation, especially in forest ecosystems (Jayaratne and Ling, 2011).

At low altitudes, terrestrial radiation and radioactive emanations from the soil are the main source of ionisation, contributing approximately 4 ionisation units (I) out of an average total of 11 I per 1 m above the ground (Deleanu et al., 1988), while at high altitudes and over the oceans, cosmic radiation predominates in the main atmosphere. Also, near the coast, the phenomenon known as the "Lenard effect" explains the appearance of n^+ around breaking water droplets, which causes predominantly positive air ionisation.

Atmospheric ions, especially n^- ions, are a natural factor with significant effects on human health and general psychophysiological state. They form naturally in unpolluted environments rich in vegetation and water, such as mountain valleys, forests, and coastal areas, where processes of water droplet fragmentation, radiation, and photosynthesis generate a surplus of negative charges. In contrast, n^+ predominates in the atmosphere under polluted urban conditions, in closed spaces, or before storms, and is often associated with physiological discomfort. Experimental studies show that n^- influences the cardiovascular, respiratory, and central nervous systems, regulating vegetative tone, increasing blood micro-oxygenation and circulation, and reducing blood pressure (Wallner et al., 2015). Prolonged exposure to high concentrations of n^- (over 1000 ions/ cm^3) has been shown to be associated with reduced symptoms of depression and anxiety and increased cognitive and sleep functions, especially in cases of seasonal affective disorder (Perez et al., 2013; Della Vecchia et al., 2020). At the cellular level, n^- reduces oxidative stress and inflammatory processes, thereby stabilising cell membranes and activating endogenous antioxidant mechanisms (Xiao et al., 2023). They can also neutralise polluting particles and airborne microorganisms, thus improving the quality of the air we breathe and respiratory immunity (Zhou et al., 2018). In contrast, increased exposure to n^+ can cause headaches, insomnia, fatigue, irritability, and anxiety, and is correlated with activation of the sympathetic system and increased secretion of free serotonin, which explains the discomfort felt in certain atmospheric conditions (Terman and Terman, 2006). These effects of different types of ions on health and well-being are not manifested exclusively in open natural environments, but also in indoor spaces, where the ionic composition of the air is influenced by ventilation, artificial sources of ionization and the degree of pollution, causing similar changes in the physiological and psychological state of the individual (Caciora et al., 2025a, b).

Based on the above, the purpose of the present study is to analyse and compare the spatiotemporal variability of air ionisation in areas with contrasting topoclimatic conditions within coastal and mountain balneoclimatic resorts located at high altitudes in Romania. The study is based on the significant tourist and therapeutic importance of these resorts, visited annually by many tourists, many of whom choose these destinations for the curative effects of the climate. In this context, a central objective of the study is that the assessment regime for the aeroionization measures specific to these resorts contributes to their sanogenetic character and to their beneficial bioclimatic potential for human health. The novelty of the study lies in the comparative analysis of the aeroionization regime across two major types of natural bioclimatic environments, based on direct measurements correlated with local meteorological and geographical parameters. The scientific approach provides original data on the spatio-temporal distribution of atmospheric ions in Romania, a field that is less explored at the national and regional levels and contributes to evaluating the role of air ionisation in defining the health-promoting potential of coastal and mountain spa resorts.

2. Materials and Methods

2.1. Study area

The measurement campaign was carried out in six representative locations, selected according to different topoclimatic and altitudinal characteristics, four resorts on the Romanian Black Sea coast (Eforie Nord, Techirghiol, Costineşti and Olimp) and two mountain resorts located at high altitudes (Râncea – 1600 m and Babele chalet - 2292 m) (Figure 1).

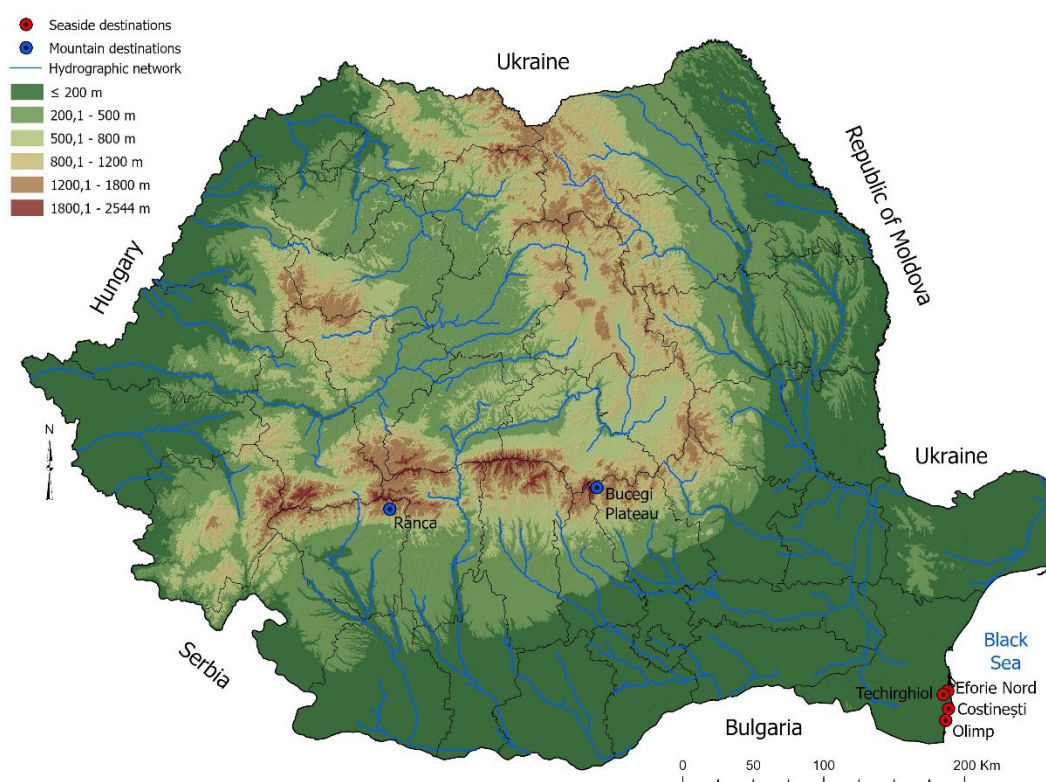


Figure 1. Geographic location of the stations where the aeroionometric measurements were carried out.

The coastal resorts were selected for the statistical study for their bioclimatic and touristic relevance, as well as for evaluating the influence of the marine environment on the aeroionization process. These are major tourist destinations of the Romanian Black

Sea coast, visited annually by a very large number of visitors, both for recreation and for balneoclimatic treatment. These resorts are characterised by a set of common climatic and touristic features that integrate them into a unitary bioclimatic ensemble: warm summers, specific wind circulation, and the presence of saline aerosols in the air. These factors contribute to the configuration of an environment with high sanogenetic potential, favourable to climatic comfort and general well-being.

The Râncă resort and the Bucegi Plateau were chosen, along with other specific high-altitude locations that provide an ideal setting for analysing the influence of atmospheric factors on air ionisation. These resorts are representative of the mountainous area in Romania, located at over 1,500 m altitude, where significant differences are manifested compared to the plain or coastal environment in terms of atmospheric pressure, T, solar and cosmic radiation.

Both Râncă and the Bucegi Plateau are notable for their spectacular landscapes, clean air, and tonic climate, beneficial for health, and are important tourist destinations, frequented year-round for recreational activities and balneal cures. In terms of altitude, health-promoting potential, and tourist appeal, these two locations are representative landmarks of Romanian mountain tourism, offering optimal conditions for studying the aeroionization regime in high-altitude environments.

2.2. Data collection methodology

The methodological flow of the study is schematically presented in Figure 2 and reflects the sequence of stages of collection, organisation, and analysis of data on air ionisation and the main meteorological elements. A comparable methodology, combining air-ion measurements with meteorological parameters and similar equipment, has been applied in previous studies. In Romania, Mihăilă et al. (2023) investigated positive and negative air ionisation in several tourist resorts and the Cacica salt mine, while Roşu et al. (2024) used a similar approach in two Carpathian tourist resorts. Internationally, comparable field measurements and analyses of the relationship between air-ion concentrations and meteorological or environmental parameters were conducted by Yue et al. (2020), Wright et al. (2014), and Chen et al. (2021).

The measurements were made in 2024, during the summer, when the number of tourists visiting the analysed resorts is very high. Thus, in Râncă, the measurements were made on July 23, in Eforie Nord on July 26, in Techirghiol on July 29, in Olimp on July 30, in Costineşti on July 31 and on the Bucegi plateau on August 2. The weather at the time of the determination was stable, in an anticyclonic regime, characterised by high atmospheric pressure, clear skies and weak atmospheric circulation. These atmospheric conditions ensured the stability of the lower atmosphere, allowing a representative assessment of the aeroionization regime in the absence of major meteorological disturbances.

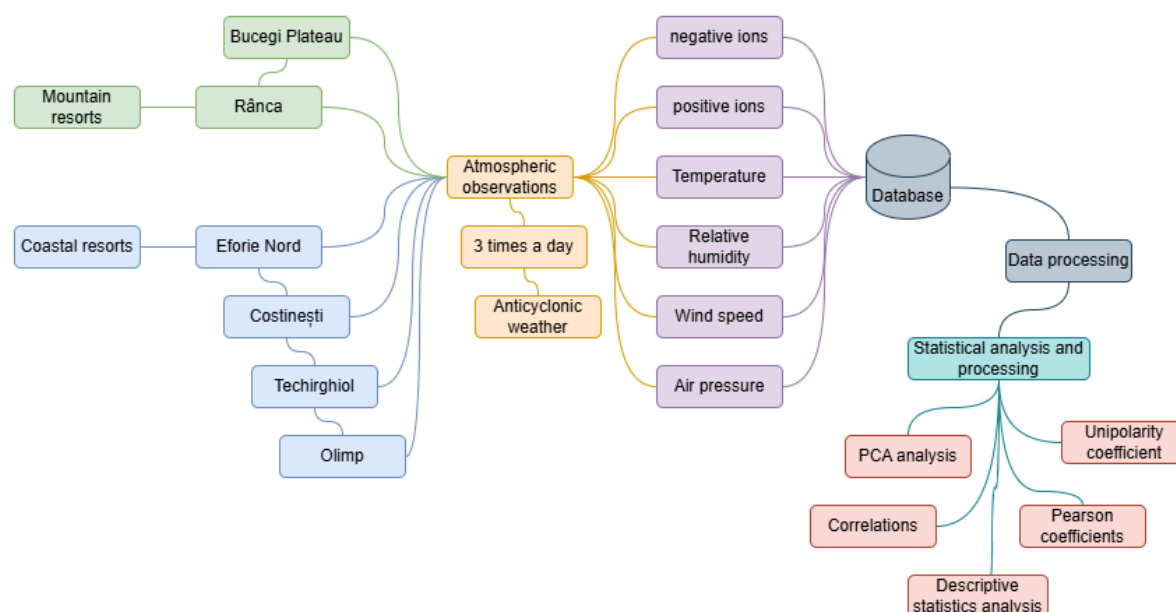


Figure 2. Conceptual diagram of experimental design and statistical analysis steps.

The measurement campaign carried out at the stations concerned consisted of making observations at each site. The determinations were made at three characteristic times of day: in the morning (08:00–09:00), at noon (13:00–14:00), and in the evening (18:00–19:00), with each session lasting approximately 1 hour. Within this interval, the concentrations of n^+ and n^- in the air were measured, along with T , relative humidity (RH), wind speed (WS) and total cloudiness, essential elements for characterising local meteorological conditions and correlating them with atmospheric ionisation processes.

To perform air ionisation measurements, we used a high-precision air ion counter, model COM-3200 PRO II (Com-System Inc., Japan), which complies with Japanese Industrial Standards (JIS B 9929). Further technical specifications and information about the instrument are available on the manufacturer/distributor's website: <https://world.n-ion.com/e/product/ion-counter/com-3200-pro-ii.html>. The device was connected to a computer, enabling automatic data recording and digital processing, ensuring continuous, precise monitoring of air ion concentrations. The counter operates on the principle of the Gerdien condenser, following the well-established method for determining the concentrations of n^+ and n^- in the atmosphere, widely used in atmospheric physics research. The instrument's measuring range spans three successive ranges, from 0 to 2,000,000 ions/cm³, enabling precise measurements under both low- and high-concentration conditions. The device is also equipped with internal sensors for determining air T with an accuracy of $\pm 1^\circ\text{C}$ and RH with an accuracy of $\pm 5\%$, parameters that were subsequently used to analyse correlations between meteorological conditions and the air ionisation regime at each study location. At all three times of the day, measurements were carried out in successive series, of which 30 minutes were allocated to the determination of n^+ , and another 30 minutes to the measurement of n^- , resulting in between 960 and 1010 values for each indicator and for each state. This procedure was imposed by the technical limitations of the equipment used, which do not allow simultaneous recording of n^+ and n^- concentrations, but only separate measurements in distinct time intervals.

To determine WS, a digital anemometer, Windboss 2 (Canel Handelsges. mbH, Hamburg, Germany), was used, which records absolute values and the average airspeed with an accuracy of $\pm 4\%$. Cloudiness was visually assessed using the standardised methodology for meteorological observations and expressed in tenths of the celestial vault. The determination of these parameters was essential for characterising local meteorological conditions, as several studies have highlighted a direct correlation

between these meteorological elements and the intensity of air ionisation processes, which influence both ion concentration and the spatial and temporal distribution of ions. Atmospheric pressure and altitude were determined using the Barometer and Altimeter mobile application (Peter Breitling, Stephanskirchen, Germany), installed on a smartphone equipped with a calibrated barometric sensor. The pressure values were used to characterise the local atmospheric regime, and altitude was determined using the standard barometric relationship specified in the application.

The values obtained from the measurements were processed and analysed using specialised statistical software, such as MATLAB R2025b (The MathWorks, Inc., Natick, Massachusetts, USA), enabling evaluation of the descriptive and comparative parameters established for each location and time of day. For each station, the hourly values of the ionisation parameters were determined: a minimum, an average, and a maximum for the determination interval, both for n^- and for n^+ . To these data sets, the recorded values for air T, RH, degree of cloudiness, and the average and maximum WS were added to analyse the correlations between meteorological conditions and the aeroionization regime.

3. Results

3.1. Determination of concentrations and n^+ and n^- values of meteorological elements

During the observation period in the six analysed resorts, meteorological conditions were characterised by stable, warm, and predominantly sunny weather, typical of an anticyclonic regime, except in the Râncă resorts, where showers occurred at noon.

T recorded lower values in the morning and evening in the mountain resorts (14–16°C) and higher at noon (18–21°C). In Râncă, the diurnal variation of T was more uniform, as a result of the showers produced during the lunch period. In the coastal resorts, the diurnal variation in T was 25–26°C in the morning, 28–31°C at noon, and 25–28°C in the evening.

RH varied between 58–83% in the morning and evening, and between 50–99% at noon, with the maximum value recorded in Râncă during atmospheric instability. In the coastal resorts, RH ranged from 70–80% in the morning, 60–70% at noon, and 42–95% in the evening. The average RH was 89.5% in Râncă, 54.8% on the Bucegi Plateau, 82.5% in Eforie Nord, 64.3% in Techirghiol, 58.1% in Olimp and 72.3% in Costinești.

WS recorded average values of 2–3 m/s on the Bucegi Plateau, 0.5 m/s in Râncă, 3 m/s in Eforie Nord, 0.4 m/s in Techirghiol, 2.8 m/s in Olimp and 2.8 m/s in Costinești. Maximum WS values reached 7 m/s on the Bucegi Plateau, 2.8 m/s in Râncă, 5.9 m/s in Eforie Nord, 3.7 m/s in Techirghiol, 5.5 m/s in Olimp and 5.7 m/s in Costinești (Table 1; Figure 3).

Table 1. Minimum, average and maximum values of air ionisation and meteorological parameters measured in the four seaside resorts on the Black Sea coast.

Time	Statistical functions	Eforie Nord					Costești				
		n ⁺ (no/cm ³)	n ⁻ no/cm ³)	T °C (avg)	RH % (avg)	WS m/s (avg-max)	n ⁺ (no/cm ³)	n ⁻ no/cm ³)	T °C (avg)	RH % (avg)	WS m/s (avg-max)
Morning	min (n ^x)	330	140				260	90			
	avg (n ^x)	544	243	26.7	81	3.0-5.8	405	202	25.8	71	2.8-5.1
	max (n ^x)	730	370				550	330			
Midday	min (n ^x)	400	140				310	20			
	avg (n ^x)	575	320	28.5	74	2.6-5.9	515	302	27.8	71	3.6-5.7
	max (n ^x)	740	480				820	660			
Evening	min (n ^x)	370	120				280	30			
	avg (n ^x)	551	288	25.6	94	3.5-5.4	419	161	27.6	75	2.3-3.8
	max (n ^x)	770	440				620	270			
Time	Statistical functions	Techirghiol					Olimp				
		n ⁺ (no/cm ³)	n ⁻ no/cm ³)	T °C (avg)	RH % (avg)	WS m/s (avg-max)	n ⁺ (no/cm ³)	n ⁻ no/cm ³)	T °C (avg)	RH % (avg)	WS m/s (avg-max)
Morning	min (n ^x)	250	140				450	40			
	avg (n ^x)	763	546	25.5	64	0.3-1.9	627	241	26.8	68	4.2-6.3
	max (n ^x)	1130	1010				830	390			
Midday	min (n ^x)	450	330				500	70			
	avg (n ^x)	761	572	30.4	61	0.8-3.6	692	323	27.7	68	2.9-5.1
	max (n ^x)	960	730				940	520			
Evening	min (n ^x)	390	250				140	10			
	avg (n ^x)	662	397	29.7	69	0.9-2.4	472	257	30.6	40	1.4-3.4
	max (n ^x)	830	610				790	560			

Table 2. Minimum, average and maximum values of air ionisation and meteorological parameters measured in the two mountain resorts in the Carpathian Mountains.

Time	Statistical functions	Rânca					Bucegi Plateau				
		n^+ (no/cm ³)	n^- no/cm ³	T °C (avg)	RH % (avg)	WS m/s (avg-max)	n^+ (no/cm ³)	n^- no/cm ³	T °C (avg)	RH % (avg)	WS m/s (avg-max)
Morning	min (n^x)	940	650				260	0			
	avg (n^x)	1136	772	17.6	87	0.2-0.8	392	237	19.8	57	1.3-2.8
	max(n^x)	1400	1150				620	520			
Midday	min (n^x)	330	40				670	0			
	avg (n^x)	438	165	18.7	99	1.1-3.6	884	226	20	56	2.5-6.2
	max(n^x)	820	250				1070	520			
Evening	min (n^x)	520	0				380	40			
	avg (n^x)	1045	476	18.8	81	0.4-2.2	585	158	21.3	52	3.4-6.4
	max(n^x)	1470	920				890	380			

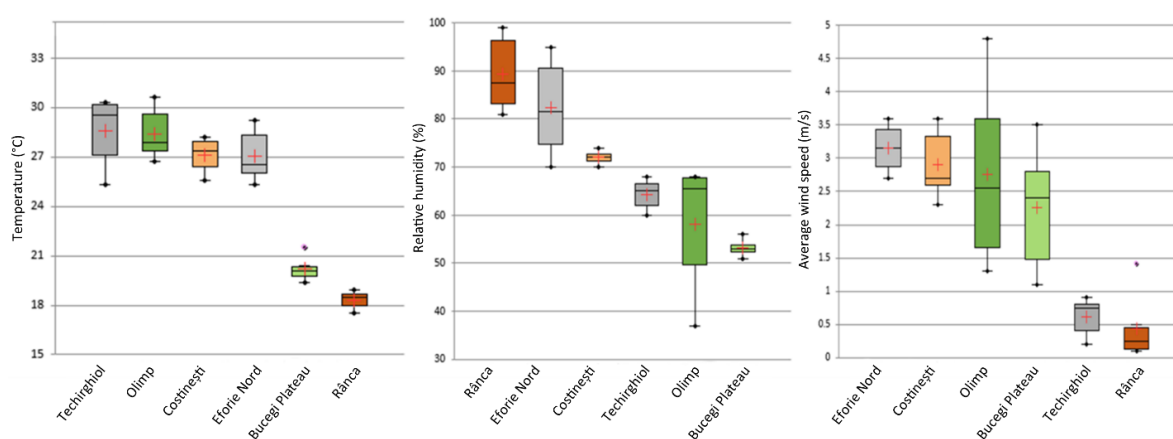


Figure 3. Distribution of meteorological parameter values determined within the six analysed stations.

On the Black Sea coast, the highest average air ionisation was recorded at Techirghiol, where the average concentrations were 505 n^-/cm^3 and 728 n^+/cm^3 , yielding a total average of 1233 n/cm^3 . The absolute maximum values were 1130 n^+/cm^3 and 1010 n^-/cm^3 . In terms of diurnal variation, the highest average values of n^+ were recorded in the morning (763 n/cm^3), while for n^- the maximum occurred at noon (572 n/cm^3).

At Eforie Nord, the total average air ionisation was 420 n/cm^3 , with n^+ (557 n/cm^3) predominating over n^- (283 n/cm^3), and the absolute values reached 770 n^+/cm^3 and 480 n^-/cm^3 . In this resort, the average maximum of air ionisation was recorded in the morning (575 n^+/cm^3 and 320 n^-/cm^3).

In the Olimp resort, the average values were 435 n/cm^3 , with the predominance of n^+ (597 n/cm^3) over n^- (274 n/cm^3), and the absolute maximum values were 940 n^+/cm^3 and 560 n^-/cm^3 . The lowest average values on the coast were recorded at Costinești (667 n/cm^3), of which 221 n^-/cm^3 and 446 n^+/cm^3 , with absolute maximums of 940 n^+/cm^3 and 560 n^-/cm^3 ; in this location, the highest average values were recorded at noon (692 n^+/cm^3 and 323 n^-/cm^3).

Figures 4a–b present additional statistical information on the variability and degree of constancy over time of the n^+ and n^- levels of the air at the six observation points. For the mean negative ionisation, higher variability is observed in the Rânca resort (mountain area), whereas in the coastal area it is low. Also, clearly higher levels of positive air ionisation and a higher variability are observed.

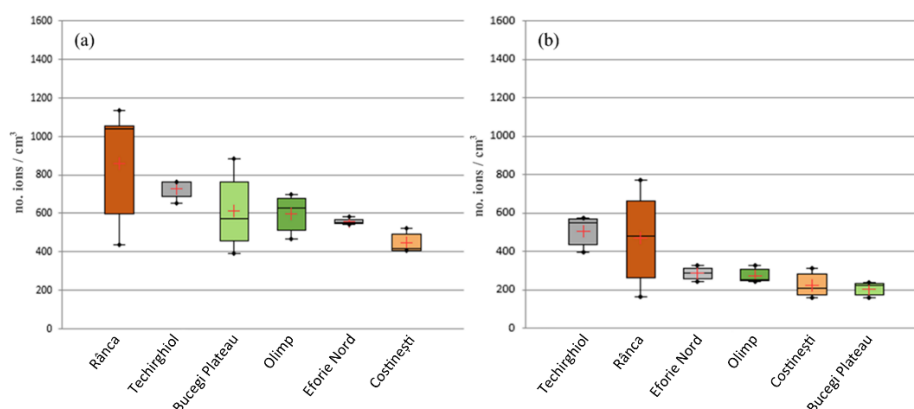


Figure 4. Distribution of air ionisation values determined within the six analysed stations (a – n^+ ; b – n^-)

In the mountainous area, the highest average aeroionisation values were recorded at the Rânca resort, where the average concentrations were 471 n^-/cm^3 and 873 n^+/cm^3 , corresponding to a total ionisation of 1344 n/cm^3 . The absolute maximum values reached 1470 n^+/cm^3 and 1150 n^-/cm^3 . In terms of diurnal variation, the highest average values were recorded in the morning, respectively 1136 n^+/cm^3 and 772 n^-/cm^3 .

On the Bucegi Plateau, the average air ionisation was significantly lower than at Rânca, both for n^- (207 n/cm^3) and for n^+ (620.3 n/cm^3), resulting in a total ionisation of 827.3 n/cm^3 . The absolute maximum values reached 1070 n^+/cm^3 and 520 n^-/cm^3 . Regarding the diurnal distribution, the maximum average values for n^+ were recorded in the afternoon (884 n/cm^3), and for n^- in the morning (237 n/cm^3).

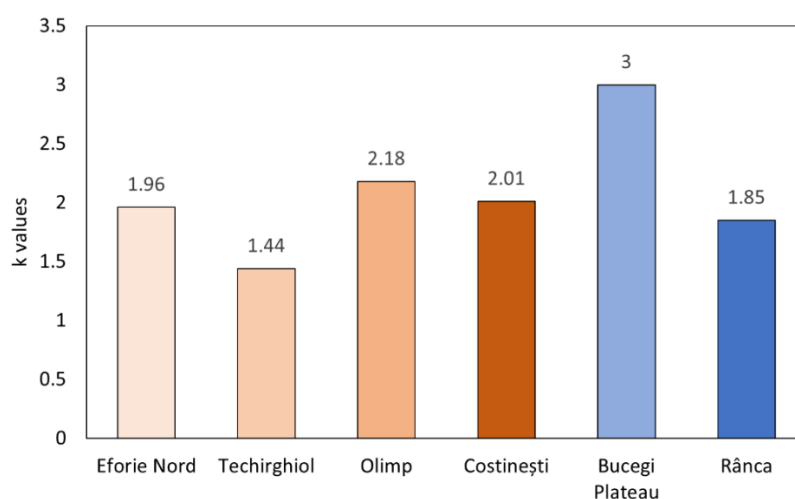


Figure 5. The value of the k index, which takes into account the ratio between n^+ and n^- within the six analysed stations.

In the coastal area, the coefficient k remains constantly above the value of 1, indicating a predominance of n^+ in all the resorts analysed. The recorded values range from 1.44 at Techirghiol to 2.18 at Olimp; the other coastal resorts show intermediate values (1.96 at Eforie Nord and 2.01 at Costinești).

In the mountainous area, the differences are more evident. At Rânca, the k coefficient (1.85) indicates a moderate positive predominance, close to the coastal values. On the Bucegi Plateau, the exchange coefficient reaches a maximum ($k = 3$), indicating the greatest dominance of n^+ over n^- among all locations analysed (Figure 5).

3.2. The influence of weather on air ionisation

Principal Component Analysis (PCA) highlights consistent relationships between air ionisation levels and meteorological parameters, differentiated by the type of environment analysed (coastal or mountainous), confirming the complex, multifactorial nature of the air ionisation process (Figure 6).

Analysing the relationships between air ionisation and meteorological elements for each coastal location, it is observed that WS is positively associated with n^- concentrations. This relationship can be explained by the intensification of mechanical fragmentation of water at the sea surface (the Lenard effect), which leads to the generation and dispersion of ions, as well as by the increase in local turbulence, which favours their transport in the lower atmosphere. Thus, the wind contributes to the dynamization of air–surface exchanges and the spatial redistribution of electrically charged particles.

The amount of air shows a more obvious association with positive ionisation. Increasing T can enhance ion mobility and shift the balance between ionisation and recombination processes, favouring the predominance of n^+ under intense active-surface heating. As for RH, it suggests that its high value can drive ionic neutralisation and recombination. Atmospheric humidity favours the formation of hydrated clusters and increases the probability of aerosol–air interactions, which can reduce free n^- concentrations in the air.

At the two locations in the mountainous area, PCA indicates a significant positive correlation between atmospheric ion concentrations and parameters such as air T and WS. At higher altitudes, the increase in T and the intensification of air circulation may favour the mobility of ions and their redistribution in the lower atmospheric layer. The turbulence specific to the mountainous environment enhances vertical air mixing, thereby influencing the balance between ion generation and recombination.

A strong negative correlation is also highlighted between n^+ and parameters such as cloudiness and atmospheric humidity. The presence of clouds and high humidity favours the attachment of ions to water particles or aerosols, thereby reducing the concentration of free ions in the atmosphere.

In most of the analysed locations, a significant positive correlation is observed between atmospheric pressure and ionisation levels. This relationship can be associated with atmospheric stability conditions specific to the anticyclonic regime, which can favour the accumulation of ions in the lower atmosphere and indirectly influence radon exhalation from the geological substratum.

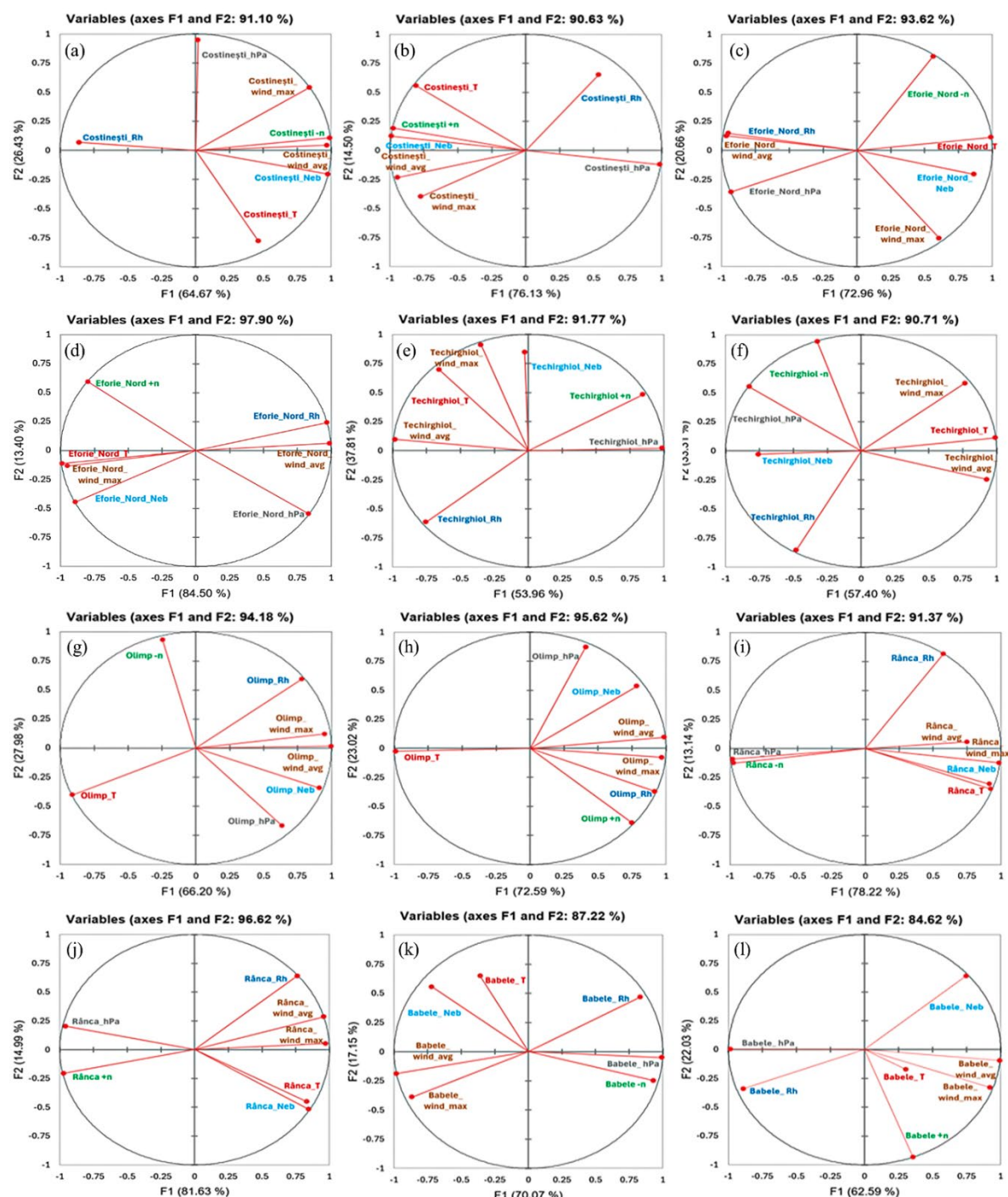


Figure 6. Principal Component Analysis (PCA) between air ionization levels (n+ and n-) and meteorological parameters determined in the six tourist resorts (a – n+ determined in Costinești; b – n- determined in Costinești; c – n+ determined in Eforie Nord; d – n- determined in Eforie Nord; e – determined in Eforie; f – determined in Techirghiol; g – n+ determined in Olimp; h – n- determined in Olimp; i – n+ determined in Râncă; j – n- determined in Râncă; k – n+ determined in Babele; l – n- determined in Babele).

The analysis of Pearson correlation coefficients presented in Table 3 reveals consistent statistical relationships between atmospheric ion concentrations (n+ and n-) and the analysed meteorological parameters, confirming the dependence of aeroionization processes on local meteorological conditions.

RH shows, in most locations, moderate to very strong positive correlations ($r > 0.6$) with ionic levels, especially with n+. This association is more pronounced in seaside resorts, where the increase in RH is related to the formation of hydroions and the

stabilisation of hydrated ionic clusters in the presence of marine aerosols. High RH values favour ion–particle attachment processes and reduce the rate of rapid recombination, thereby maintaining higher ion concentrations in the lower atmosphere. Under low RH conditions, ionic concentrations tend to decrease due to the increased efficiency of neutralisation processes (Table 3).

Table 3. The values of the Pearson correlation coefficients established between the average levels of n^- and n^+ and the average values of T, RH, N, atmospheric pressure (hPa) and the average and maximum values of WS

n^-	Eforie Nord	Costinești	Techirghiol	Olimp	Rânca	Bucegi Plateau
$n^- \div T$	0.73	0.12	-0.3	-0.11	-0.76	-0.98
$n^- \div Rh$	-0.37	-0.99	-0.32	0.33	-0.66	0.6
$n^- \div N$	0.81	0.95	0.61	-0.65	-0.91	-0.94
$n^- \div \text{average WS}$	-0.47	0.99	-0.37	-0.23	-0.22	-0.83
$n^- \div \text{maximum WS}$	-0.1	0.91	0.37	-0.2	-0.9	-0.51
$n^- \div \text{hPa}$	-0.81	-0.23	-0.65	-0.65	0.99	-0.94
n^+	Eforie Nord	Costinești	Techirghiol	Olimp	Rânca	Bucegi Plateau
$n^+ \div T$	0.63	0.83	-0.31	-0.86	-0.6	-0.12
$n^+ \div Rh$	-0.5	0.03	-0.99	0.95	-0.89	0.22
$n^+ \div N$	0.3	0.99	0.48	0.22	-0.68	-0.3
$n^+ \div \text{average WS}$	-0.65	0.77	-0.83	0.81	-0.99	0.38
$n^+ \div \text{maximum WS}$	0.55	0.6	0.19	0.83	-0.98	0.69
$n^+ \div \text{hPa}$	-0.97	-0.59	0.87	0.22	0.91	0.38
-0.19 ÷ 0 ; 0 ÷ 0.19	very weak correlation					
-0.2 ÷ -0.39 ; 0.2 ÷ 0.39	weak correlation					
-0.4 ÷ -0.59 ; 0.4 ÷ 0.59	moderate correlation					
-0.6 ÷ -0.79 ; 0.6 ÷ 0.79	strong correlation					
-0.8 ÷ -1 ; 0.8 ÷ 1	very strong correlation					

Atmospheric pressure shows strong and very strong positive correlations ($r > 0.8$) in most locations, suggesting that atmospheric stability associated with the anticyclonic regime favours the accumulation of ions in the lower atmosphere. In addition, pressure variations can indirectly influence radon flux from the geological substrate, thereby modifying the intensity of natural ionisation.

In the coastal area, the relationship between humidity and ionisation is more pronounced for n^+ , reflecting the specific influence of the marine environment and saline aerosols on the atmospheric ionic balance. In the mountainous area, although RH remains a relevant factor, a more pronounced contribution of T and atmospheric pressure is observed, suggesting a stronger control of radiative and geological factors on ionisation processes (Table 3).

Overall, the correlational results confirm that air ionisation variability is determined by the complex interaction between meteorological parameters and local physical-geographical particularities, with differences between coastal and mountainous environments reflecting distinct dominant mechanisms.

4. Discussion

Studies on aeroionization on the Romanian Black Sea coast and in various resorts have a tradition of almost a century, starting with the determinations made by Frimescu and Crețeanu (1964) and Enache (1977), and continuing with recent research (Enache, 1939; Enache, 2023). Historically reported values for the coast are generally between approximately 600 and 1200 n/cm^3 , with unipolarity coefficients above unity in most

cases. The results obtained in the present study fall within this historical range, with total values ranging between 667 n/cm³ (Costinești) and 1233 n/cm³ (Techirghiol), confirming the moderate nature of aeroionization in the coastal area. Furthermore, the predominance of positive ionisation ($k > 1$ in all resorts) is consistent with previous observations on the Black Sea coast. Thus, the values determined in this study fall within the range reported for unpolluted natural air (500–2000 n/cm³) in both mountain and maritime environments (Kolarž et al., 2012; Jiang et al., 2018).

A consistent difference is evident between the aeroionic regime on the coast and in the mountainous area (Harrison and Carslaw, 2003; Tammet et al., 2006). Under warm anticyclonic weather conditions, the predominance of n^+ was observed in all six locations, but the total values were generally higher in the mountainous environment (especially at Râncă – 1344 n/cm³) compared to most coastal resorts.

On the coast, the average values are around 900 n/cm³ and are influenced by processes specific to the marine environment, such as the Lenard effect, mechanical fragmentation of water, and interaction with saline aerosols (Enache, 1977). In coastal areas, ionisation is strongly dependent on the dynamic value and circulation of the sea breeze, which can modify the ionic balance by transporting air masses with different charges (Feng et al., 2017; Jiang et al., 2018; Song et al., 2024). In the case of the Techirghiol resort, the higher values (1233 n/cm³) compared to resorts located directly on the coast suggest a more pronounced influence of continental input, a possibility associated with radon exhalation from the soil and a reduced direct influence of the sea breeze. Wind direction, relative to the underlying surface (dry versus water), can significantly modify ion concentrations, as confirmed by previous studies that highlight the role of air circulation in redistributing atmospheric ions (Wang, 2014; Wang et al., 2020).

In the mountainous environment, the higher concentrations at Râncă compared to the coast are consistent with previous observations on the increase in ionisation with altitude (Enache and Bunescu, 2019). At high altitudes, the contribution of cosmic radiation becomes more significant, and the geological substrate can influence the radon input, with a direct impact on ion production (Harrison and Usoskin, 2010; Golubenko et al., 2020). The difference between Râncă (1344 n/cm³) and the Bucegi Plateau (827 n/cm³) suggests that altitude is not the only determining factor, but that the geological structure and local atmospheric ventilation conditions can significantly modulate the aeroionization regime (Porstendörfer, 1994). Regarding the geological substrate, the Bucegi Mountains are predominantly composed of conglomerates and sandstones (Badea et al., 2001), sedimentary rocks with generally lower levels of naturally occurring radioactive elements, which may limit radon input and the intensity of ionisation from the substrate. In contrast, the Parâng Mountains, where the Râncă resort is located, are largely composed of crystalline schists and granitic intrusions, rocks recognised for a higher potential for radon emanation (Appleton, 2007). Recent studies in the field confirm that variations in atmospheric ionisation are closely correlated with the natural radioactive background and the radon flux from the soil (Chen et al., 2016; Golubenko et al., 2020).

World Health Organisation standards and various recent studies in the field (Lazzerini et al., 2018; Jiang et al., 2018) indicate that, for human health and well-being, fresh air must be associated with an n^- concentration of over 1000 n/cm³, and below 1000 n/cm³ in terms of n^+ . Studies in the field indicate that, in natural unpolluted air, typical concentrations of small ions vary between 500 and 1500 n/cm³ at ground level, and in mountain or marine environments, they can reach 2000–3000 n/cm³ under favourable conditions (Krueger and Reed, 1976; Charry and Kavet, 1987). In mountain resorts, values frequently exceed 1000 n/cm³, especially under stable weather conditions and with reduced ventilation (Kolarž et al., 2012). In seaside resorts, average concentrations of n^- varied between approximately 220 and 410 n/cm³, and n^+ between 440 and 890 n/cm³, depending on the location. In the mountainous area, average values of n^- were approximately 470 n/cm³ at Râncă and 210 n/cm³ on the Bucegi Plateau, while n^-

recorded approximately 874 n/cm³ at Râncea and 617 n/cm³ at Bucegi. Compared to the threshold of over 1000 n/cm³ considered optimal for negative ionisation, all values determined in the study are below the recommended level. In contrast, n⁺ concentrations remain below 1000 n/cm³, falling within limits considered acceptable from the perspective of aeroionic balance.

Numerous studies have analysed the biological effects of atmospheric ions on the human body. N⁻ are generally associated with beneficial physiological effects, such as reducing stress symptoms, improving mood effects and increasing sleep quality (Krueger and Reed, 1976; Charry and Kavet, 1987). On the other hand, the predominance of n⁺ has been associated with effects such as increased irritability, sleep disorders, headaches, and elevated blood pressure, especially at high concentrations and prolonged exposure (Pérez et al., 2013).

In the case of the resorts analysed, moderate total ionisation values and the predominance of n⁺ in summer anticyclonic conditions suggest a balanced bioclimatic potential, but not optimal in terms of negative ionisation. For tourists, this means that the perceived benefits of the natural environment (clean air, lack of pollution, climatic comfort) are not necessarily automatically associated with a high level of n⁻. In the mountainous environment, especially in Râncea, higher total concentrations may contribute to a more stimulating bioclimatic experience, but the predominance of positive ionisation indicates that the ionic balance remains dependent on the meteorological conditions specific to the analysed period. In coastal resorts, the influence of breeze and wave dynamics can temporarily modify the ionic balance, which could explain the observed diurnal variations (O'Dowd and Leeuw, 2007; Harrison et al., 2014).

5. Conclusions

The air ionisation regime in the analysed resorts is predominantly controlled by summer anticyclonic meteorological conditions, characterised by high atmospheric pressure and stability, which favour n⁺ and superunitary values of the unipolarity coefficient across all investigated locations. In the coastal area, ionic concentrations are mainly regulated by sea breeze dynamics and air-surface interaction, and hydroions generated by mechanical water fragmentation do not significantly modify the general character of the ionic regime; the higher values recorded at Techirghiol suggest a more pronounced influence of the continental input, associated with the wind direction from land to sea.

In the mountainous area, the total ion concentration was higher at Râncea (1344 n/cm³) than at the Bucegi Plateau (827 n/cm³), a difference attributed to lithological particularities and local ventilation conditions, as well as to the characteristics of the underlying surface and the structure of the alpine vegetation. The diurnal variation of ionisation revealed, in most coastal locations and on the Bucegi Plateau, a Δ -type profile with a maximum at noon, whereas at Râncea the distribution was U-shaped, with higher values in the morning and evening.

The results obtained demonstrate that the aeroionic regime in the analysed resorts has a moderate character in the summer anticyclonic conditions and is mainly controlled by meteorological factors and local physical-geographical particularities, highlighting a constant predominance of n⁺ and clear differences between the environment and the mountainous one, with the total values of the coastline being higher in the area. At the same time, the agreement with previous studies conducted on the Romanian coastline confirms the regional specificity of this ionic regime, but the absence of optimal levels of n⁻ indicates that the evaluation of the sanogenetic potential must be carried out integratively, by analysing the balance between the types of ions and their interactions with all local bioclimatic factors.

6. Limitations and future works

The measurements were carried out only during the summer season and under anticyclonic conditions, which does not allow extrapolation of the conclusions to cyclonic regimes or other seasons. The determinations were punctual, without continuous long-term monitoring, and the influence of the geological substrate was evaluated indirectly, without direct measurement of radon flux. Also, parameters such as aerosol concentration or atmospheric electric field were not analysed. Future studies will consider extending measurements under cyclonic conditions, determining radon emissions, and integrating continuous monitoring to provide a more comprehensive assessment of the aeroionic regime.

Author contributions: All authors had equal contributions.

Funding Declaration: The authors do not receive any funding for this research.

References

1. Adrović, F. (2017) Introductory chapter: The radon phenomenon. In *Radon*. InTech. <https://doi.org/10.5772/intechopen.70170>
2. Appleton, J.D. (2007) Radon: sources, health risks, and hazard mapping. *AMBIO: A Journal of the Human Environment*, 36(1), 85-89. [https://doi.org/10.1579/0044-7447\(2007\)36\[85:RSHRAH\]2.0.CO;2](https://doi.org/10.1579/0044-7447(2007)36[85:RSHRAH]2.0.CO;2)
3. Badea, L.; Niculescu, G.; Roată, S.; Buza, M.; Sandu, M. (2001) Relief units of Romania, I, Southern Carpathians and Banat Mountains. *Edita. Ars Docendi*, Bucharest.
4. Baldoncini, M.; Albéri, M.; Bottardi, C.; Minty, B.; Raptis, K.G.C.; Strati, V.; Mantovani, F. (2017) Exploring atmospheric radon using airborne gamma-ray spectroscopy. *Atmospheric Environment*, 170, 259–268. <https://doi.org/10.1016/j.atmosenv.2017.09.048>
5. Caciara, T.; Ilieș, A.; Berdenov, Z.; Al-Hyari, H.S.; Ilieș, D.C.; Safarov, B.; Pereș, A.C. (2024) Comprehensive analysis of classroom microclimate in the context of national and international health-related indoor air quality standards. *Front Public Health*, 12, 1440376. <https://doi.org/10.3389/fpubh.2024.1440376>
6. Caciara, T.; Ilieș, D.C.; Costea, M.; Blaga, L.; Berdenov, Z.; Ilieș, A.; et al. (2024a) Microclimate assessment in a 19th century heritage building in Romania. *Indoor Air*, 1, 2989136. <https://doi.org/10.1155/2024/2989136>
7. Charry, J.M.; Kavet, R.I. (1987) *Air ions: physical and biological aspects*. CRC Press.
8. Chen, Q., Wang, R., Zhang, X., Liu, J., & Wang, D. (2021). Effects of different site conditions on the concentration of negative air ions in mountain forest based on an orthogonal experimental study. *Sustainability*, 13(21), 12012. <https://doi.org/10.3390/su132112012>
9. Chen, X.; Kerminen, V.M.; Paatero, J.; Paasonen, P.; Manninen, H.E.; Nieminen, T.; Petäjä, T.; Kulmala, M. (2016) From ionizing radiation to the formation of air ions in the lower atmosphere. *Discussions of Atmospheric Chemistry and Physics*, 1–45. <https://doi.org/10.5194/acp-2016-440>
10. Deleanu, M.; Aionesei, M.; Alexa, M.E. (1988). Negative air ionization. *Technical Publishing House*, Bucharest, Romania.
11. Della Vecchia, A.; Mucci, F.; Pozza, A.; Marazziti, D. (2021) Negative Air Ions in Neuropsychiatric Disorders. *Curr Med Chem.* 28 (13), 2521-2539. <https://doi.org/10.2174/0929867327666200630104550>
12. Enache, L.M. (1977) *Studies of air ionization in balneoclimatic resorts in RS Romania*. Abstract. [Abstract]. University of Bucharest.
13. Enache, L.M. (2011) General aspects regarding the natural ionization of the air on the Romanian Black Sea coast and the Danube Delta. *National Balneology Conference*, Neptun.
14. Enache, L.M. (2017) Biomedical aspects of air ionization. *Sitech Publishing House*.
15. Enache, L.M.; Bunescu, I. (2019) Air ionization - an environmental factor with therapeutic potential. *GEOREVIEW: Scientific Annals of the Stefan Cel Mare University of Suceava. Geography Series*, 29(1), 31–39.

16. Ewing, R.G.; Hart, G.L.; Nims, M.K.; Murphy, S.E.; Johnson, S.I.; Chun, J.; Denis, E.H. (2023) Reducing ion diffusion at atmospheric pressure by mixing positive and negative ions. *International Journal of Mass Spectrometry*, 492, 117115. <https://doi.org/10.1016/j.ijms.2023.117115>
17. Feng, L.; Shen, H.; Zhu, Y.; Gao, H.; Yao, X. (2017) Insight into generation and evolution of sea-salt aerosols from field measurements in diversified marine and coastal atmospheres. *Scientific reports*, 7(1), 41260. <https://doi.org/10.1016/10.1038/srep41260>
18. Frimescu, M.; Crețeanu, V. (1964) Study of natural air ionization in Mangalia and Sinaia.
19. Golubenko, K.; Rozanov, E.; Mironova, I.; Karagodin, A.; Usoskin, I. (2020) Natural sources of ionization and their impact on atmospheric electricity. *Geophysical Research Letters*, 47(12). <https://doi.org/10.1029/2020gl088619>
20. Harrison, R.G.; Carslaw, K.S. (2003) Ion-aerosol-cloud processes in the lower atmosphere. *Rev. Geophys*, 41 (3). <https://doi.org/10.1029/2002rg000114>
21. Harrison, R.G.; Nicoll, K.A.; Aplin, K.L. (2014) Measurements of the vertical profile of lower troposphere ionization. *J. Atmos. Sol. Terr. Phys.* 119, 203–210, <https://doi.org/10.1016/j.jastp.2014.08.006>
22. Harrison, R.G.; Usoskin, I.G. (2010) The Energetic Effect of Cosmic Rays on Atmospheric Aerosols and Clouds. *Environmental R.*
23. Herrington, L.P. (1935) The influence of ionized air on normal subjects. *The Journal of Clinical Investigation*, 14(1), 70–80. <https://doi.org/10.1172/JCI100660>
24. Ilies, A.; Caciara, T.; Ilies, G.; Hassan, T.H.; Berdenov, Z.; et al. (2025a) An integrated risk assessment model for the impact of indoor air quality on museum exhibits and human health, using microclimatic indices and AgNP treatment. *PLOS ONE* 20(12), e0336594. <https://doi.org/10.1371/journal.pone.0336594>
25. Ilies, A.B.; Vlad, S.; Caciara, T.; Ciobanu, D.; Ianc, D.; Peres, A.C.; Hassan, T.H.; Liviu, L. (2025b) Rehabilitation of patients at home through physical exercises in the context of indoor air quality. *Healthcare*, 13, 1493. <https://doi.org/10.3390/healthcare13131493>
26. Jayaratne, E.R.; Ling, X.; Morawska, L. (2011) The role of vegetation in increasing radon concentration and ion production in the atmosphere. *Environmental Science & Technology*, 45(15), 6350–6355. <https://doi.org/10.1021/es201152g>
27. Jiang, S.Y.; Ma, A.; Ramachandran, S. (2018) Negative air ions and their effects on human health and air quality improvement. *International Journal of Molecular Sciences*, 19(10), 2966.
28. Koch, W. (1962) Atmospheric ions and comfort. *The Journal of Hygiene*, 60(2), 183–192. <https://doi.org/10.1017/s0022172400039450>
29. Kolarž, P.; Nicoll, K.A.; Harrison, R.G. (2012) Atmospheric ionization and human health. *Atmospheric Environment*, 50, 175–181.
30. Krueger, A.P.; Reed, E.J. (1976). Biological impact of small air ions: Despite a history of controversy, there is evidence that small air ions can affect vital processes. *Science*, 193 (4259), 1209–1213.
31. Lazzerini, F.; Orlando, M.; De Prá, W. (2018) Progress in the use of negative air ions in medical tourism environment applications. *Bol. Soc. Esp. Hidrol. Méd*, 33, 27–46. <https://doi.org/10.23853/bsehm.2018.0450>
32. Luts, A.; Parts, T. (2002) Evolution of small negative air ions at two different temperatures. *Journal of Atmospheric and Solar-Terrestrial Physics*, 64(7), 763–774.
33. Mihăilă, D.; Roșu, C.; Bistricean, P.I.; Prisăcariu, A.; Mihăilă, E.V.; Boiciuc, C. (2023) Research on air ionization in the tourist resorts of Solca, Cacica, Gura Humorului and in the Cacica salt pan - north-eastern Romania. *Present Environment and Sustainable Development*, 17(2). <https://doi.org/10.47743/pesd2023172008>
34. O'Dowd, C.D.; de Leeuw, G. (2007) Marine aerosol production: a review of current knowledge. *Philos. Trans. A Math. Phys. Eng. Sci.*, 365, 1753–1774, <https://doi.org/10.1098/rsta.2007.2043>
35. Perez, V.; Alexander, D.D.; Bailey, W.H. (2013) Air ions and effects on mood: a review and meta-analysis. *BMC Psychiatry*, 13(1), 29. <https://doi.org/10.1186/1471-244X-13-29>
36. Porstendörfer, J. (1994) Properties and behavior of radon and thoron and their decomposition products in air. *J. Aerosol Sci.*, 25, 219–263. [https://doi.org/10.1016/0021-8502\(94\)90077-9](https://doi.org/10.1016/0021-8502(94)90077-9)
37. Roșu, C.; Mihăilă, D.; Bistricean, P.-I.; Mihăilă, E.-V.; Mihalache, A., & Boiciuc, C. (2024). The favorability for aeroionotherapy on two touristic resorts from The Eastern flank of Romanian Carpathian mountains. *Geographia Technica*, 104–123. https://doi.org/10.21163/gt_2024.192.09
38. Song, Y.; Li, J.; Tsona Tchinda, N.; Li, K.; Du, L. (2024) The role of marine aerosol at the air-sea interface in the transport of aromatic acids in the atmosphere. *Atmos. Chem. Phys.*, 24, 5847–5862, doi:10.5194/acp-24-5847-2024.

39. Tammet, H.; Hörrak, U.; Laakso, L.; Kulmala, M. Air ionic balance factors in a coniferous forest as measured in Hyytiälä, Finland. *Atmos. Chim. Fiz.* 2006, 6, 3377–3390, <https://doi.org/10.5194/acp-6-3377-2006>
40. Teodoreanu, E.; Dacoș-Swoboda, M.; Ardeleanu, C.; Enache, L.M. (1984) Bioclimate of balneoclimatic resorts in Romania. *Sport-Tourism*.
41. Terman, M.; Terman, J. S. (2006) Controlled trial of naturalistic dawn simulation and negative air ionization for seasonal affective disorder. *Am. J. Psychiatry*, 163, 2126–2133. <https://doi.org/10.1176/ajp.2006.163.12.2126>
42. Wallner, P.; Kundi, M.; Panny, M.; Tappler, P.; Hutter, H.P. (2015) Exposure to air ions in indoor environments: An experimental study with healthy adults. *International Journal of Environmental Research and Public Health*, 12(11), 14301–14311. <https://doi.org/10.3390/ijerph121114301>
43. Wang, H.; Wang, B.; Niu, X.; Song, Q.; Li, M.; Luo, Y.; Liang, L.; Du, P.; Peng, W. (2020) Study on the change of negative ion concentration in the air and its influencing factors at different spatio-temporal scales. *Global Ecology and Conservation*, 23, e01008. <https://doi.org/10.1016/j.gecco.2020.e01008>
44. Wang, W. (2014) Characteristics of negative ion concentration in air and its relationships with environmental factors. *Ecology and Environmental Sciences*, 23(6), 979–984.
45. Wright, M. D., Holden, N. K., Shallcross, D. E., & Henshaw, D. L. (2014). Indoor and outdoor atmospheric ion mobility spectra, diurnal variation, and relationship with meteorological parameters. *Journal of Geophysical Research. Atmospheres: JGR*, 119(6), 3251–3267. <https://doi.org/10.1002/2013jd020956>
46. Xiao, S.; Wei, T.; Petersen, J.D.; Zhou, J.; Lu, X. (2023) Biological effects of negative air ions on human health and integrated multiomics for biomarker identification: a literature review. *Environ Sci Pollut Res Int.*, 30(27), 69824–69836. <https://doi.org/10.1007/s11356-023-27133-8>
47. Yue, C., Yuxin, Z., Nan, Z., Dongyou, Z., & Jiangning, Y. (2020). An inversion model for estimating the negative air ion concentration using MODIS images of the Daxing'anling region. *PloS One*, 15(11), e0242554. <https://doi.org/10.1371/journal.pone.0242554>
48. Zhou, P.; Yang, Y.; Huang, G.; Lai, A.C.K. (2018) Numerical and experimental study on air disinfection by negative ions in air duct flow. *Building and Environment*, 127, 204–210. <https://doi.org/10.1016/j.buildenv.2017.11.006>

