THE CLIMATOLOGY OF AVIATION HAZARDS IMPACTING ROMANIAN AIRPORTS

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Abstract: *The increasing air traffic at Romanian airports in recent years has necessitated a heightened focus on aviation safety standards. Simultaneously, climate change has altered the frequency of meteorological phenomena that impact aviation activities. This study aims to establish a baseline climatology and identify evolving trends of hazardous weather phenomena for the main airports in Romania between 1941 and 2022. The study uses ERA5 data to derive the most important parameters to study the occurrence of thunderstorms, low-level wind shear, reduced visibility, and snowfall, the weather phenomena that are relevant for the air traffic safety. The results show an increase in the number of hours with thunderstorms in the eastern part of the country and a rising trend in events with low-level wind shear in the western and central regions. Conversely, events with significant snowfall are decreasing in the eastern Carpathians and Muntenia region, while those with limited visibility are decreasing in the coastal regions and northeastern Romania. These findings can inform aviation safety regulations and help mitigate the impact of hazardous weather conditions on aeronautical activities.*

Keywords: *climatology, weather hazards, climate changes, thunderstorms, wind shear, low visibility, snowfall, safety regulations.*

1. INTRODUCTION

In Europe and Romania, aviation transport has grown significantly over 20 years. According to the Romanian National Institute of Statistics [1], passenger numbers at airports increased from 9 million in 2008 to over 24 million in 2023 (**FIG. 1**). This aviation sector expansion has significantly increased carbon dioxide (hereafter CO_2) emissions, making it a major CO_2 contributor [2]. Jet fuel combustion releases CO_2 and greenhouse gases during flights, while airport infrastructure, aircraft manufacturing, and support activities add to environmental impact. International Air Transport Association (IATA) estimates aviation contributes 2.5% of global CO_2 emissions [3]. Though this percentage seems small compared to other sectors, aviation emissions have steadily increased with industry growth. The impact is amplified by greenhouse gas release at high altitudes, where warming effects are more significant. The industry is implementing measures to reduce environmental impact through fuel-efficient aircraft, sustainable aviation fuels, and optimized flight routes. However, due to fossil fuel dependence and projected growth, addressing emissions remains challenging. Studies predict air traffic will triple in 20 years [4] CO_2 emissions from aviation contribute approximately 4% to global warming [2], driving anthropogenic climate change that has modified severe weather phenomena affecting the aviation industry. Williams (2017) predicts increased clear air turbulence over the transatlantic region when doubling CO_2 levels [5], showing expansion in airspace affected by light, moderate, and severe turbulence.

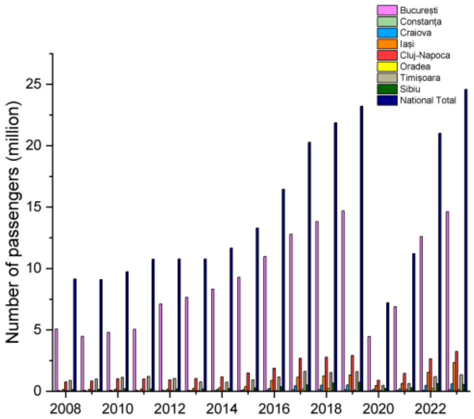


FIG. 1: Statistics on growth of passengers number on Romanian airports. Source: adapted from Wikipedia.

Flight operations face safety hazards including turbulence, storms, lightning, wind shear, reduced visibility, and snow [6]. Aviation safety regulations have become more restrictive due to meteorological hazards causing delays, cancellations, and casualties. Studies show 20-30% of global aviation accidents stem from unfavorable weather [7], while in Europe, weather causes 22% of air traffic delays [8].

Romania lacks climatology of severe weather conditions threatening aviation, including thunderstorms, wind shear, limited visibility, and snowfall. This study examines weather phenomena formation over Romania from 1941-2022, focusing on hazard trends at major airports.

2. SEVERE WEATHER PHENOMENA IMPACTING FLIGHT ACTIVITY

Aeronautical activity signifies transportation and access to international facilities. For flight safety, operational airports maintain essential measures regarding communications, air traffic services, weather monitoring and forecasting. Meteorological analysis and documentation are necessary for flights [9]. Key meteorological elements reported include: air and dew point temperatures, atmospheric pressure at sea level, weather phenomena, cloud coverage and cloud base, wind parameters, and visibility. Certain meteorological phenomena pose dangers to aviation, potentially causing delays, cancellations, safety incidents and accidents. These hazards are emphasized in Table 1:

Table 1. Weather hazards impacting flight activity.

Airport terminal hazards	**En route hazards**
Storms: microbursts, hail, wind shear, thunderstorms	Storms (hail, turbulence)
Wake turbulence during takeoff/landing	Clear-air turbulence (CAT)
Frost on parked aircraft	Frost at lower altitudes
Low ceilings and reduced visibility	

This analysis focuses on thunderstorms, low-level wind shear, limited visibility, and snowfall [10]. These hazards' impact and formation are detailed in the following section.

2.1. Thunderstorms

Deep convection is the upward movement of warm, moist air into the atmosphere, often resulting in towering cumulonimbus clouds.

This process is a key driver of thunderstorms and severe weather events, as it releases latent heat, fueling the upward motion. This can lead to intense precipitation, strong winds, lightning, and hail. Storms are conditioned by three ingredients: conditionally unstable environment, sufficient moisture for air particles to reach free convection, and a triggering mechanism determining upward movement. Atmospheric convection can lead to simple storm structures from a single cumulonimbus cloud or developed storms from a group of clouds, extending hundreds of km. Storm formation is supported by wind shear, turbulent movements, and convergent surface winds [11].

Lightning is a visible electrical discharge produced by a storm, occurring in various forms such as within a cloud, from one cloud to another, cloud to ground lightning, and occasionally between a cloud and clear air. It is the result of the buildup and discharge of electrical energy between regions with differing electric potentials. The process begins in cumulonimbus clouds, where turbulent air currents cause ice and water particles to collide and interact, resulting in electron transfer and a separation of charges within the cloud. This separation can generate an extremely strong electric field, which causes the ground to become positively charged due to electrostatic induction. When the electric field strength exceeds the dielectric breakdown strength of air, a sequence of events leads to lightning. This discharge neutralizes the accumulated charges, equalizing the electric potential between the cloud and the ground or within the cloud itself [11].

2.2. Wind shear

Wind is a physical phenomenon characterized by the circulation of air in the Earth's atmosphere, typically in the troposphere. In conditions with different thermal and pressure characteristics, air moves vertically or horizontally, resulting in advection motions caused by differences in atmospheric pressure. Local winds can be caused by orographic winds, katabatic winds, anabatic winds, maritime and land breezes. Wind parameters, such as speed, direction, intensity, duration, and structure, can be observed and reported using special equipment at airport weather stations. Wind shear is a phenomenon caused by the interaction between different air masses with varying characteristics, such as warm and cooler air, and topographic features like mountains or coastlines. It can create a weather front, a sharp boundary layer, and can disrupt airflow, leading to local changes in wind speed and direction. Wind shear can be significant and potentially hazardous, especially in aviation, where it can cause abrupt changes in aircraft speed and altitude, making control challenging. It can also affect engine efficiency, leading to increased fuel consumption and reduced performance. Wind shear is an essential condition in weather forecasting, as it can contribute to the intensification of storms and create a rotating column of air, known as a mesocyclone, essential for tornado development. To mitigate risks, various technologies and strategies have been developed, such as Doppler radar systems, onboard systems in aircraft, and protocols in airports and air traffic control agencies. There are two main types of wind shear: vertical and horizontal wind shear [12].

Low-level wind shear is a sudden change in wind speed or direction within the first 2,000 feet above the ground, impacting aviation, weather patterns, and ground-based activities.

Turbulence, caused by the movement of disturbed air, can occur thermally or mechanically and can occur within or outside clouds. The severity of turbulence depends on the airflow's speed or direction intensity. Turbulence is associated with disorderly air movements and can occur in the friction layer, clouds, mountainous areas, and clear air. Factors contributing to these movements include uneven heating of the Earth's surface, atmospheric pressure variations, air currents, and aircraft interaction with air currents.

2.3. Limited visibility

Limited visibility is a critical factor affecting flight activity, affecting safety and efficiency in aviation operations. It is caused by atmospheric conditions such as fog, mist, low clouds, rain, snow, haze, or smoke, which increase the complexity of flight operations and require pilots to rely more on instruments rather than visual cues. The primary concern with limited visibility is the increased risk of collisions, both with other aircraft and ground obstacles. Pilots struggle to maintain proper situational awareness, increasing the likelihood of mid-air collisions and runway incursions during takeoff and landing [13].

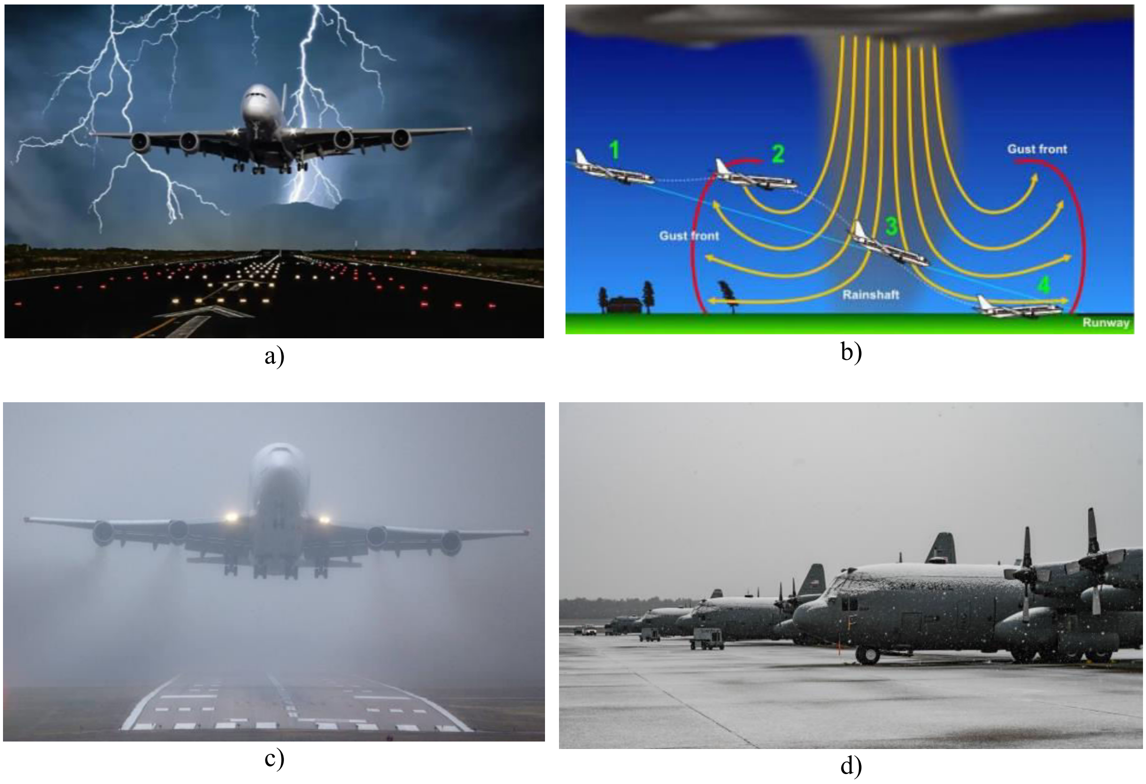


FIG. 2. Weather hazards impacting aeronautical activity.

To mitigate risks associated with limited visibility, aviation authorities and operators implement various strategies and technologies. Advanced weather forecasting systems provide real-time information about current and forecasted weather conditions, enabling pilots to plan alternate routes or adjust departure and arrival times to avoid adverse weather conditions. Aircraft are equipped with sophisticated navigation and communication systems, such as radar, GPS, and instrument landing systems (ILS), which allow pilots to navigate safely in low-visibility conditions and conduct precision approaches and landings even when visibility is severely restricted. Training and proficiency in instrument flying techniques are essential for pilots to effectively manage limited visibility situations and safely operate aircraft under adverse weather conditions. Airports employ ground-based visibility aids, such as runway lighting systems, runway markings, and precision instrument approaches, to assist pilots during takeoff, landing, and taxiing in reduced visibility conditions.

2.4. Snowfall

Snowfall significantly impacts flight activity, affecting all aspects of aviation operations from takeoff to landing. It reduces visibility, alters runway conditions, and increases the risk of aircraft icing.

Pilots face challenges in maintaining situational awareness and navigating safely. Snow accumulation on runways reduces surface friction and increases braking distances, posing hazards during landing and takeoff procedures. Snow and ice buildup on aircraft surfaces disrupt airflow and compromise aerodynamic performance, leading to reduced lift and increased drag. Runway contamination is a primary concern during snowfall, reducing aircraft traction and increasing the likelihood of skidding or hydroplaning during landing and takeoff. Airport operators use snow removal equipment to clear runways and taxiways. Air traffic control personnel face challenges in managing air traffic flow and ensuring safe separation between aircraft. Special procedures, such as increased spacing between aircraft, altered approach and departure routes, and enhanced communication protocols, are implemented to mitigate these risks. Pilots play a crucial role in mitigating snowfall risks by closely monitoring weather conditions, adhering to standard operating procedures, and exercising sound judgment during flight [13].

3. DATABASE, METHODOLOGY AND LIMITATIONS

The study uses ERA5 reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) to investigate hazardous weather phenomena affecting flight activity at major Romanian airports. The dataset, which includes observations from satellites, ground stations, aircraft, and radiosondes, is reliable for long-term climatological analysis due to its temporal continuity, spatial coverage, and ability to provide consistent reconstructions of meteorological conditions over extended periods. Variables such as temperature, pressure, humidity, wind components, and cloud parameters were selected to compute key atmospheric indices and thresholds for identifying and assessing severe weather events. The methodology involved extracting, interpolating, and analyzing specific parameters to characterize the occurrence, frequency, and spatial distribution of thunderstorms, wind shear, limited visibility, and snowfall. The data were processed through vertical interpolation of pressure, height, temperature, dew point, and wind vector components. Thermodynamic indices (LCL, LFC, and EL) were computed using Skew-T diagrams to assess atmospheric instability. The study aims to evaluate the climatology of hazardous weather phenomena affecting aviation in Romania.

Specific threshold values were defined to determine the presence of each hazard, as emphasized in Table 2:

Table 2. Threshold values for proxies defining particular types of hazardous weather.

Hazard type	Threshold values
TSTM (Thunderstorm)	ML CAPE > 150 J kg^{-1} and CP>0.075 mm h^{-1}
LLWS (Low-Level Wind Shear)	0 to 100m AGL vertical wind shear gradient > 5m s^{-1} per 100
SNOW (Snowfall)	Snowfall > 0.5mm h^{-1} LWCE (Liquid Water Content Equivalent)
LIMV (Limited Visibility)	Ceiling height < 60m AGL and low-level cloud cover = 100%

Initially, stricter thresholds were tested, but they underestimated the occurrence of events due to the spatial averaging inherent in ERA5 data; therefore, more relaxed yet physically justified thresholds were adopted. Since the thresholds represent proxies rather than direct observations, the results are subject to uncertainties and must be interpreted probabilistically, acknowledging the limitations of reanalysis datasets in capturing localized, high-intensity events. Reanalysis provides continuous data in time and space but is only an approximation of real atmospheric conditions and may inaccurately estimate thermodynamic instability or vertical wind shear.

Surface meteorological observations, such as SYNOP or METAR reports, have limitations in climatological aspects, including human contributions, spatial coverage limitations, ground variables, short temporal records, and station displacement.

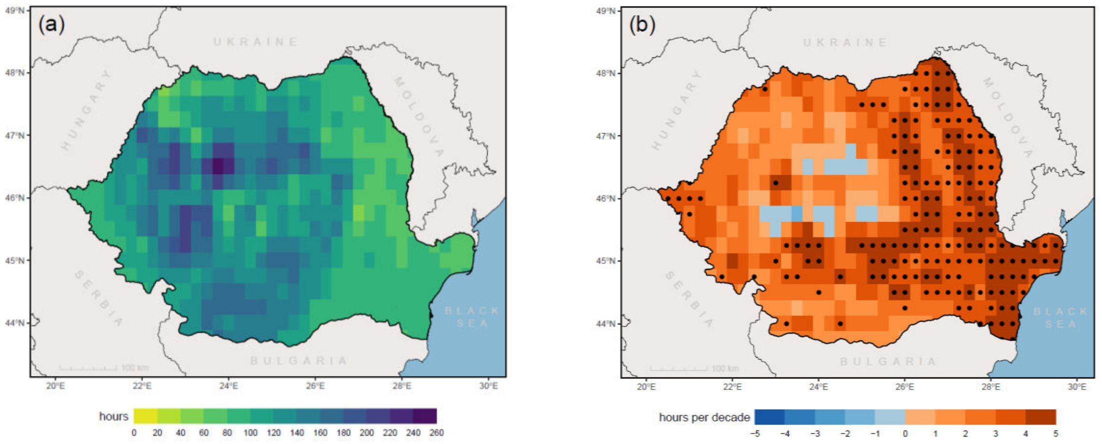
4. RESULTS AND DISCUSS

This study examines the climatological aspects of hazardous weather conditions that can disrupt air traffic, particularly during takeoff and landing. It discusses the spatial distribution of each type of hazard and the year-to-year variability and long-term changes at Romanian airports.

The analysis reveals that precipitating and unstable environments are most frequent during summertime, characterized by strong diurnal heating and evapotranspiration. The peak activity is observed over the western region of Romania, with a significant number of hours with thunderstorms (over 200 hours per year) observed over the Occidental Carpathians Mountains and western part of Muntenia (**FIG. 3a**). Over the eastern part of Romania, Dobrogea, Moldavia, Banat, and the northernmost part, the number of TSTM hours is lower (40 to 100 hours per year). However, the frequency of hours with thunderstorms over 10 years confirms an increasing trend over the eastern area of Romania (**FIG. 3a**).

Low-level wind shear (LLWS) events pose a significant threat to Romania's aviation sector, with the southern and western regions experiencing the highest number of LLWS events, with over 300 hours per year (**FIG. 4a**). The eastern part of the country experiences up to 500 hours of LLWS per year, posing significant challenges for flight safety and operations. In the Muntenia region, western part of the country, and Transylvanian Depression, the number of LLWS hours reaches 450 hours per year. Mountainous areas show a less significant number of LLWS hours, but the complex terrain can exacerbate the effects of wind shear. Long-term trends show an increase in LLWS frequency in western Romania, the southern part of Muntenia, Dobrogea, and southern Moldavia, requiring ongoing monitoring and adaptation (**FIG. 4b**). The aviation sector must invest in research to understand the underlying factors driving these trends and develop robust response strategies.

The Eastern Carpathians experience a high frequency of limited visibility hours (LIMV), with ceiling heights below 60m AGL and low-level cloud cover of 100% (**FIG. 5a**). The trend of limited visibility hours in the western part of the country and along Oriental Carpathians is increasing over a 10-year period (**FIG. 5b**).. Accurate predictions and historical data on low-visibility conditions help in planning and mitigating the impacts of reduced visibility on safety and operations.



a) b)

FIG. 3. (a) Spatial distribution of the mean annual number of hours with TSTM. (b) Spatial distribution of long-term trends (denoted as a slope of linear regression with values normalised to changes per decade) in hours with TSTM. Points denote statistically significant trend (p-value < 0.05). Based on ERA5 hourly data for the years 1941–2022.

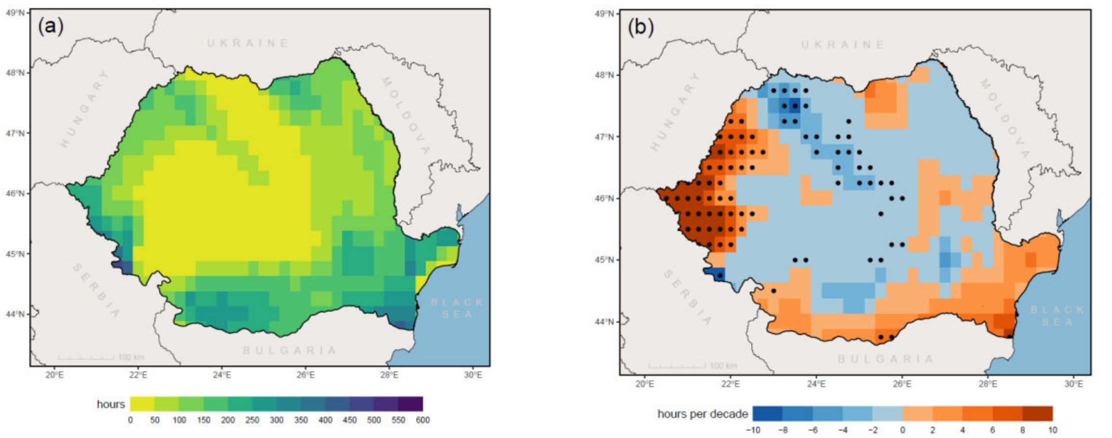


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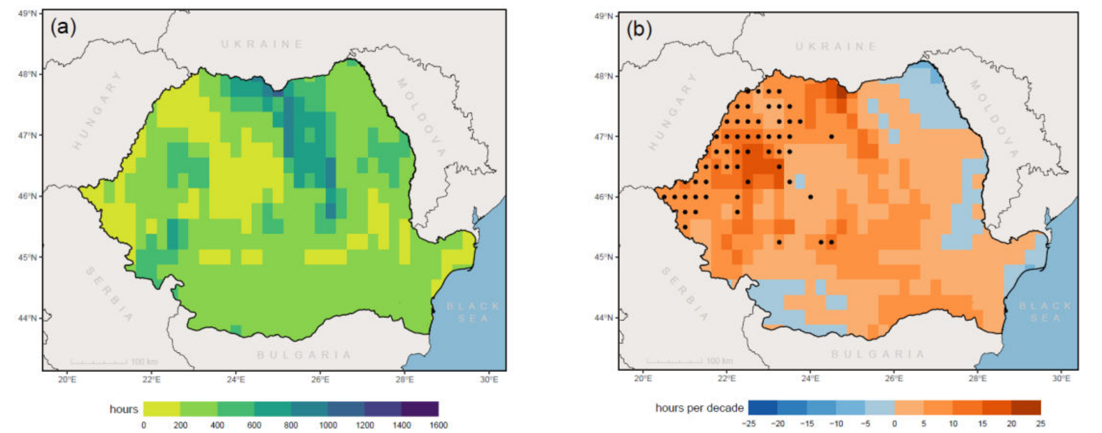
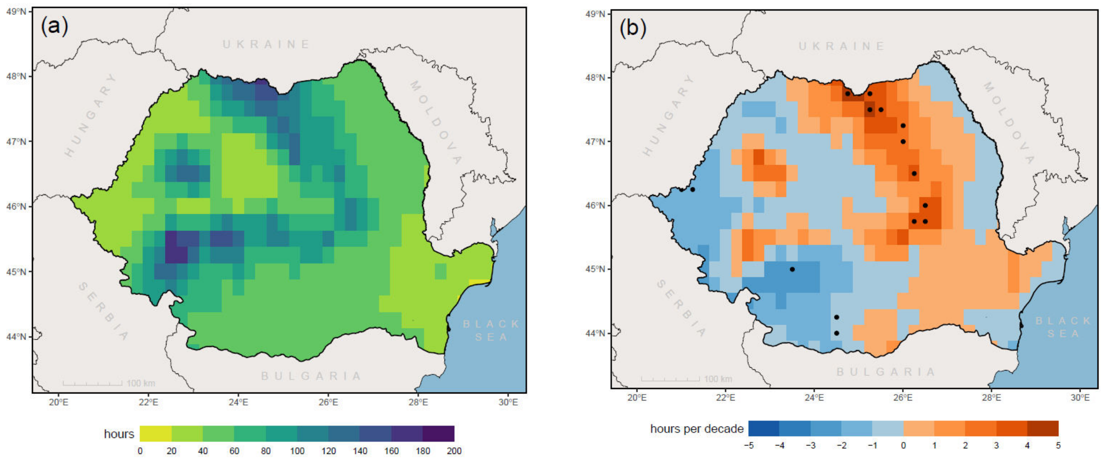
FIG. 4. (a) Spatial distribution of the mean annual number of hours with LLWS. (b) Spatial distribution of long-term trends (denoted as a slope of linear regression with values normalised to changes per decade) in hours with LLWS. Points denote statistically significant trend (p-value < 0.05). Based on ERA5 hourly data for the years 1941–2022.



a) b)

FIG. 5. (a) Spatial distribution of the mean annual number of hours with LIMV. (b) Spatial distribution of long-term trends (denoted as a slope of linear regression with values normalised to changes per decade) in hours with LIMV. Points denote statistically significant trend (p-value < 0.05). Based on ERA5 hourly data for the years 1941–2022.



a) b)

FIG. 6. (a) Spatial distribution of the mean annual number of hours with SNOW. (b) Spatial distribution of long-term trends (denoted as a slope of linear regression with values normalised to changes per decade) in hours with SNOW. Points denote statistically significant trend (p-value < 0.05). Based on ERA5 hourly data for the years 1941–2022.

The number of hours with snow events exceeding 0.5 mm h^{-1} LWCE is larger in mountainous and hilly areas, with over 100 hours per year (**FIG. 6a**). The intracarpathian area, western part of the Occidental Carpathians, and southern and western parts of Muntenia have medium snow hours, with more pronounced orographic lift and cooler temperatures. These regions may be experiencing changes in atmospheric circulation patterns that bring more moisture and cold air, increasing the frequency and intensity of snow events. The trend of SNOW hours per decade is decreasing across the country, with the Eastern Carpathians experiencing a significant increase in snow events per decade, while surrounding areas, including Dobrogea and Muntenia, experience a decline (**FIG. 6b**). This trend may be due to rising temperatures and altered precipitation patterns due to climate change, with precipitation now occurring as rain, reducing the overall number of snow hours. The overall decreasing trend of SNOW hours per decade suggests a broader climatic shift, with urbanization and land-use changes contributing to the heat island effect.

The study reveals that the number of hours with TSTM increases at each airport, with statistically significant increases in Constanţa and Cluj-Napoca airports. LLWS events also increase at Constanţa, Oradea, and Timişoara. These airports are located in areas with increasing convective phenomena and strong winds, indicating atmospheric instability in the Muntenia region, Transylvanian Depression, and Carpathian Mountains. However, at Bucharest, Cluj-Napoca, Oradea, Timişoara, and Sibiu airports, the trend of hours with limited visibility increases. The trend of hours with significant snowfall decreases over the 82-year period of study.

Bucharest Airport serves as a pivotal site for the examination of trends in significant meteorological events, including thunderstorms, low-level wind shear, restricted visibility, and snowfall. Its location inside Romania's varied climatic landscape for a targeted evaluation of the influence of these weather conditions on aviation operations in the area. The distinct local weather patterns in Bucharest, shaped by geography and elevation, offer critical insights into regional variances that impact flight safety and airport administration.

The annual trend of hours with TSTM at Bucharest airport is generally increasing, reaching a maximum of 200 hours per year in 1956.

The trend declines to 50 hours per year after this period (**FIG. 7a**). The trend of hours with LLWS at Bucharest airport is decreasing after 1990, reaching a maximum of over 300 hours per year in 1992 (**FIG. 7b**). The trend of hours with LIMV increases in the first 30 years of study, reaching up to 600 hours per year. In 2013, the maximum value of hours with LIMV reached 800 hours per year (**FIG. 7c**). The number of hours with significant snowfall at Bucharest airport is constant, with a maximum peak in 1969, confirmed by recorded weather data (**FIG. 7d**).

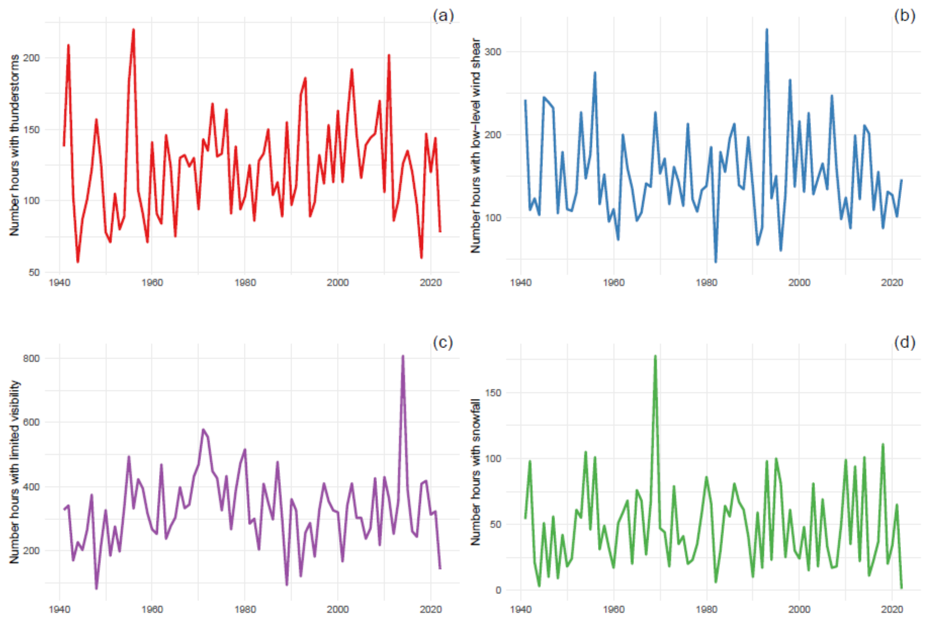


FIG. 7. Annual number of hours with (a) thunderstorms, (b) low-level wind shear, (c) limited visibility, and (d) snowfall between 1941–2022 for Bucharest airport.

CONCLUSIONS

The study reveals significant variability and trends in the climatology of aviation hazards at Romanian airports. Meteorological phenomena such as thunderstorms, low-level wind shear, limited visibility, and snow exhibit distinct patterns across different regions and airports. Thunderstorm occurrence increases in the first half of the study period, followed by a decline post-1990. Low-level wind shear hours increase across the entire study period, while limited visibility trends remain stable across several airports. Snowfall hours exhibit a decreasing trend over the 82-year period, with initial highs dropping to values below 20 hours per year at various airports. Regional differences in hazard frequencies are highlighted, with mountainous regions experiencing higher frequencies of thunderstorms and LLWS. The study recommends enhancing aviation hazard management and operational strategies at Romanian airports, including improved forecasting, advanced warning systems, and strategic infrastructure investments. Further research could focus on detailed characterization of each severe weather event and associated risks, as well as integrating climate change projections for future trends.

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