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Research Article

Climatic study of Weather Patterns and Sustainability of measured data in Kosova

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Abstract:

This scientific paper presents a climate study of cyclones, focusing on observed weather data in Kosova and examining the stability and implications of these data for climate modeling through a combined subjective and comparative approach. These methods were chosen due to the lack of similar research in the past. The study analyzes climatological data collected over a 20-year period (2003–2022), in conjunction with synoptic surface weather maps. The analysis identified a total of 328 cyclones during this period, with the highest intensity and maximum frequency occurring during the winter months. The conclusions of this paper are compared with findings from the wider region. As a result, a hypothesis was raised suggesting a reduction in the number of cyclones compared to earlier periods. The cyclones in this study are classified by intensity into three categories: weak, medium, and strong, based on atmospheric pressure values. Statistical analyses reveal a correlation between atmospheric pressure, wind dynamics, atmospheric precipitation, and cyclone activity analyzed using synoptic charts. Changes in the analyzed parameters highlight seasonal variations in cyclonic activity. Notably, atmospheric precipitation has increased by approximately 70.6 L/m² compared to three decades ago. This study also reveals low variability in wind speed, averaging 2.7 m/s over the 20-year period. By integrating the dynamics of weather systems with climatological data, this paper provides detailed insights into the number, frequency, and characteristics of cyclones affecting Kosova. The findings contribute valuable information on the stability and reliability of the latest climatological data, aligning with the standards set by the World Meteorological Organization.

1. Introduction

Cyclones are important atmospheric phenomena that have a fairly high frequency of formation in the mid-latitude belt. They affect atmospheric mixing on a large scale, both horizontally and vertically, and play a crucial role in the interaction between the atmosphere and the oceans. Cyclonic circulations, due to their frequency, duration and intensity, play an important role in the weather and climate of the Mediterranean region [1]. A wide range of atmospheric parameters and phenomena are associated with cyclones. Various variables such as: wind, pressure, temperature, clouds, precipitation, thunderstorms, floods, avalanche formation, ocean waves and fog depend on the formation and passage of cyclones. Some of these phenomena are beneficial from an agricultural, hydrological and economic point of view, however, some of them are harmful and sometimes even catastrophic. The Mediterranean region is known as a region quite favorable for the formation of cyclones, especially in the cold part of the year, where the formation and passage of cyclones are of higher frequency and intensity. This region contains geographical factors that can significantly modify the mechanism of cyclogenesis. The orography of this region can qualitatively and quantitatively change the process of baroclinic instability, usually favoring cyclogenesis or the formation of cyclones. [2]. Another effect on the intensification of cyclogenesis in the Mediterranean region is the effect of the release of latent heat, when cyclones come from the desert and begin to intensify as they reach the seas. The large baroclinic instability in saturated air affected by the release of latent heat in an environment with stable atmospheric conditions, are processes that contribute to cyclogenesis. Such complex dynamics and the potential for multiple mechanisms that favor cyclogenesis mean that we have a wide range of cyclone diversity, which are present in the Mediterranean region [3]. The orography of the Mediterranean and especially of the Western Balkans (WB), especially the high mountains, manage to hinder the advection of surface air masses within the Mediterranean basin, causing a decrease in the intensity of the fronts. However, in some cases, also the intensification of frontal activity. The preliminary list of mechanisms that cause cyclogenesis includes “Lee cyclones” and thermal lows. The seasonal variations in this work are very important because for different seasons different results have been obtained, where the factors that influence these changes are those that were mentioned before, as well as those that will be mentioned in the results section. Studies that analyze cyclonic systems affecting the Western Balkans region rely mainly on data from neighboring countries and major meteorological centers that possess archives of climatological data. However, there are few studies based on official meteorological data measured in the Republic of Kosova. The combination of reliable and qualitative statistical data, together with studies that have been conducted at the regional level, such as those presented in this paper, can contribute to the creation of a climate model in Kosova. One of the shortcomings that Kosova faces, in addition to the lack of such studies, is the lack of reliable climatological data that could be used for comparability. The identification and classification of cyclones in specific areas of the Mediterranean have been conducted by various authors. These studies address the formation, frequency, trajectories, and impacts of cyclones on weather and climate in specific regions of the Mediterranean. Three primary regions of cyclogenetic activity affecting the Balkan Peninsula (BP) have been identified: Cyprus, the Gulf of Genoa (commonly referred to as the "Genoa Low"), and Southern Italy [4]. Results from multiple authors [4-8] indicate a decrease in the frequency of cyclones, suggesting a trend toward stability in the data compared to the period from 1950 to 1999. Examining the stability of this more recent data provides valuable insights into the weather systems of the BP. Since no prior studies are available for Kosova, this work compares its results with those of the aforementioned authors. Different studies have employed specific methodologies. For instance, [4] only counted cyclones of recent origin that had at least one closed isobaric curve on synoptic maps (standard analysis with a 5 hPa pressure difference) and a duration exceeding 30 hours. This research utilized synoptic surface atmospheric pressure maps from the Synoptic Archive of the National Institute of Meteorology and Hydrology of Bulgaria. Additionally, [4] compared their findings with those of other researchers [1, 5, 7], who identified October as the onset of the winter cyclonic period and May as the transition month from the cyclonic to the non-cyclonic period. However, the results of [4] suggest a strong onset of cyclonic activity in November, with April identified as the transition month when cyclonic activity begins to decline. It is important to note that replicating the methodologies of the aforementioned authors and others for cyclone research is challenging [8]. Each method is based on a specific approach to studying cyclones within a given region. Unfortunately, Kosova currently lacks comprehensive studies on atmospheric circulation, particularly concerning cyclones and anticyclones. This deficiency hinders the ability to obtain reliable and qualitative information about weather patterns in Kosova. Addressing this issue is essential for improving our understanding of the interactions between global climate change and local atmospheric parameters, making it a central focus of this research paper.

2. Material and methodology

2.1 Data sources

There are two official sources of meteorological measurements in Kosova: The Kosova Hydro Meteorological Institute (HMIK) and the Air Navigation Services Agency (ANSA). HMIK has been collecting data since 1922. However, there have been periods when the data were incomplete and inconsistently formatted, causing difficulties in interpolating them to create a continuous 30-year dataset. Since the war, ANSA has resumed operations with commercial flights, and consequently, its meteorological department has also resumed work. The meteorological department at ANSA, operating under the International Civil Aviation Organization (ICAO) code BKPR, is responsible for weather monitoring and forecasting. The Meteorological Department at ANSA has archived meteorological data since 2003. These data are reported through METAR (Meteorological Aerodrome Report) reports. These reports are issued every 30 minutes and supplemented by SPECI Reports in cases of significant or extreme weather changes. The data comply fully with the standards set by the World Meteorological Organization (WMO) and ICAO. Due to their quality, quantity, and accuracy, this paper uses data from the BKPR meteorological station for the years 2003–2022 for analysis. This dataset is supplemented with synoptic maps from the archives of the UK Met Office (UKMO) and the National Centers for Environmental Prediction (NCEP), as well as findings from other authors who analyzed meteorological parameters for periods prior to 2003.

2.2 Methodology

The data used in this paper include systematic information on the duration, intensity, positions of cyclone centers, and their impacts on various meteorological parameters at the Earth's surface. The methodology employed for researching cyclones affecting the territory of Kosova combines subjective and comparative approaches. The subjective methodology for detecting cyclones has been utilized by various authors [1, 9-12] in previous studies and has produced highly efficient results. Additionally, the combined methodology, integrating subjective and objective approaches, has also been applied by other authors [13]. Since no similar research has been conducted in Kosova, it was necessary to compare the results of this study with those from other authors' findings. A cyclone climatology involves defining what constitutes a cyclone and establishing a method for selecting and describing that cyclone. Both of these steps allow for significant subjective approaches, which can lead to notable variations in results. Historically, when subjective methods of analysis were used, cyclones were typically identified as systems characterized by a minimum pressure on synoptic weather charts surrounded by closed isobars. Naturally, the results depend on the spacing between the isobars and the scale of the chart, so the more detailed the synoptic maps, the higher the number of cyclones identified. The definition used in this paper is the minimum atmospheric pressure at ground level. However, not all atmospheric pressure minima can be accepted as cyclones, because many cyclones are either very weak or very close to each other. Therefore, restrictions must be set (in this paper, atmospheric pressure for a 48-hour period), which introduce arbitrariness in determining the number of cyclones and, consequently, in the overall results [3]. In this paper, low-pressure systems, or cyclones, are analyzed using synoptic weather maps obtained from the synoptic archives of the UKMO (United Kingdom Meteorological Office) and NCEP (National Center for Environmental Prediction), which are presented with closed isobars and pressure gradients of 4 hPa and 5 hPa, respectively (maps analyzed at 0000 UTC). The time period for this investigation spans from 2003 to 2022. Initially, the values of low-pressure systems observed at surface weather stations, along with the amount and types of atmospheric precipitation and wind direction tendencies, were analyzed. The values of these parameters are modified depending on the intensity and position of the center of the cyclone, or the cyclone as a whole. For this reason, analyzing only the parameters recorded at the surface meteorological station does not provide a complete set of results. Therefore, the analysis was supplemented with synoptic weather charts from UKMO and NCEP.The analysis of meteorological parameters was conducted using climatological data. Following comparisons with synoptic maps from meteorological archives, a subjective method was used to identify and classify low-pressure systems that could be accepted as cyclones. The low-pressure systems recorded as cyclones in this paper are those that were in the initial stages of formation up to a period of 48 hours, with at least two closed isobars on the analyzed synoptic charts. Due to the intensity and varying effects of cyclones, their classification has been divided into three categories: weak cyclones, which have pressure gradients between 5 and 15 hPa over a 48-hour period; moderate cyclones, which have pressure gradients between 15 and 25 hPa over 48 hours; and strong cyclones, which have pressure gradients between 25 and 35 hPa or more over 48 hours. These classifications are summarized in Table 1.

Table 1. *Classification of cyclone*

Pressure change	Cyclone intensity
5-15 hPa	Week
15-25 hPa	Moderate
25-35 hPa	Strong

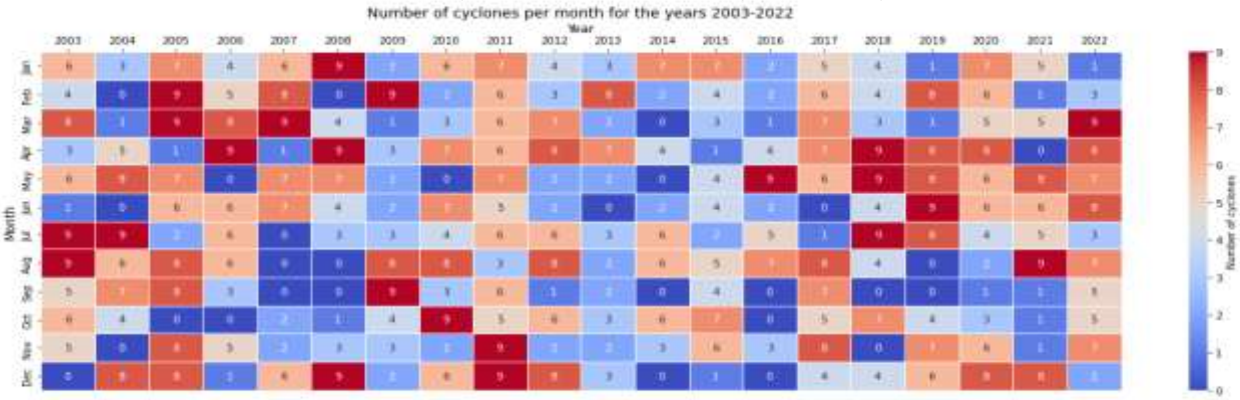
In this study of cyclones, during the analysis of precipitation amounts, situations were encountered where there was significant precipitation but with very small changes in pressure (< 5 hPa) observed at the Earth's surface. These situations were quite frequent and were associated with shallow cyclones that appear in the lower layers of the atmosphere, due to the complex topography of the land surface in the region and thermal contrasts. Therefore, hundreds of cyclonic circulations can be detected subjectively and objectively in the Mediterranean every year , but many of these low-pressure systems are shallow depressions, which cannot be considered deep cyclones. However, they often play an important role in the formation of deep cyclones [13]. Some of these low-pressure systems are formed a long time ago, and during their movement, they underwent modifications in the composition of the air mass. By the time they reached the Kosova region, they were very weak. Although such cyclones appeared quite often in the WB, they did not meet the criteria of the aforementioned methodology, and therefore, were excluded from the count.

3. Results and Discussions

3.1 Cyclones in WB – Kosova

Table 2 presents the number of cyclones that have passed over the Western Balkans and affected the territory of Kosova over a 20-year period, from 2003 to 2022. Using this data and applying the methodology outlined above, a total of 328 cyclones were recorded over the 20-year period, yielding an average of 16 cyclones per year The results (Figure 1) indicate that the period with the highest number of cyclones occurs during the cold season, from November to March. Similar findings have been reported by other authors[3] In November, the frequency of cyclones increases by 73% compared to October, while the frequency begins to decrease by 40% in April compared to March. During the warmer months, the number of cyclones decreases due to the dominance of

Table 2. *Cyclone distribution table by month and year*



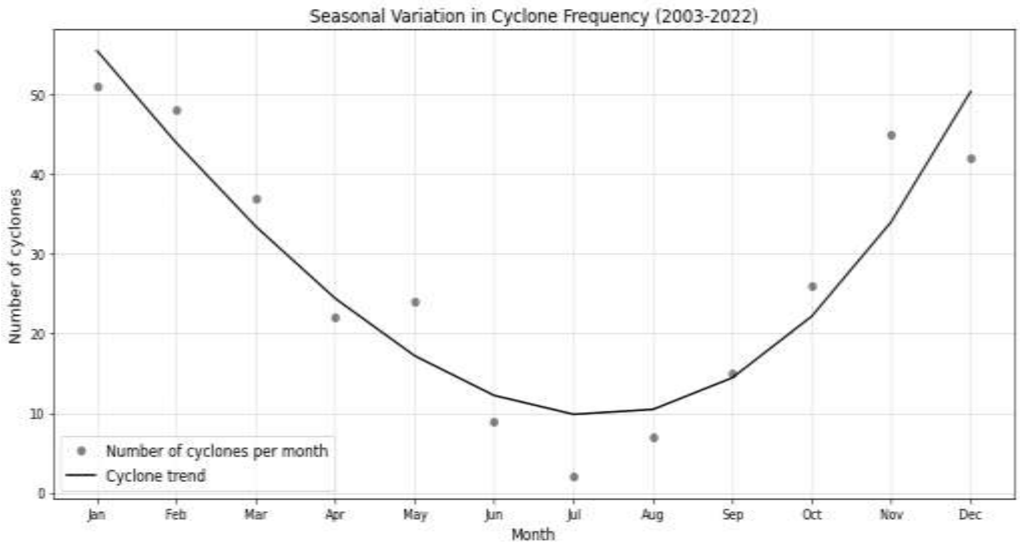


Figure 1. *Graphical representation of cyclones that have affected the data measured on the earth's surface*.

thermal low-pressure systems, commonly referred to as 'thermal lows.' These low-pressure systems are more frequent in spring and summer, where their formation and dissipation are influenced by the daily temperature cycle. Consequently, their development depends on the amplitude of this cycle as well as the land-sea temperature contrast. Many of these systems remain shallow depressions confined to the lower troposphere, and the atmosphere is primarily driven by convection or by the energy accumulated within the atmosphere. Some studies suggest that these systems also form over the sea during autumn and winter when the sea-land temperature gradient reverses [3]. Local effects, arising from changes in surface temperatures and the varied orographic structure, can alter the characteristics of air masses. The absence of measured meteorological parameters or inconsistent, poor-quality data presents challenges for analyzing and monitoring meteorological phenomena and climate change. To obtain a clearer picture of the climate, a larger dataset of meteorological measurements over a 30-year period is essential.The results of this study emphasize the activation period of cyclones, which occurs in November, and the decline in cyclone frequency during the transitional period in April. Due to the lack of such studies and the insufficient quality of meteorological data meeting climatological standards in our country before 2003, it was necessary to rely on studies conducted by other authors in various Balkan countries. Some of these authors used similar methodologies, while others employed different approaches, including computer algorithms. Research by [1, 5, 7, 14-15, 17] for the years 1951-1966 identified October as the month of cyclone intensification and May as the transitional period when the number of cyclones decreased. In contrast, cyclonic research [4] for the years 1980-1999 found November to be the month of cyclone intensification and March the month of cyclone decline. During the study period, a two-month decrease in the activity of Mediterranean winter cyclones was observed. In this study, a comparative approach was adopted by comparing the results with those of the aforementioned authors. The research period spans the years 2003–2022, during which November was identified as the month marking the intensification of cyclones, while March represented the period of cyclonic intensity reduction. These transitional periods align closely with other findings [4], supporting the conclusion that there has been a two-month reduction in cyclone activity. A negative trend in the number of cyclones over the years was also observed, consistent with some other findings [16], but specifically in relation to the most intense systems. Similarly, another author [17] noted a negative trend in the eastern Mediterranean, particularly with winter cyclones. Another significant orographic phenomenon frequently occurring in Kosova is the formation of Lee Lows. These cyclones are generated by the passage of large synoptic low-pressure systems in the northern part of the region, with their development highly sensitive to the movement of the main cyclone center. Lee cyclones typically form on the southern slopes of mountain ridges, with the 'Genoa Low' in northern Italy serving as a classic example. This region experiences the highest frequency of cyclogenesis in the Mediterranean [3]. However, such cyclones can also form on a more localized scale. According to some data (Figure 2a, b, c), though not fully analyzed or studied, Lee Lows may also develop in the Gjakova region of Kosova. Figure 3 presents a simulation of surface atmospheric pressure, visualizing a small-scale cyclone using HORACE software, which employs Numerical Weather Prediction (NWP) data from the United Kingdom Meteorological Office (UKMO). The simulation clearly shows the development of Lee Lows in two regions of Kosova. During such periods, heavy rainfall often occurs in these areas, occasionally resulting in flooding.

3.2 Pressure

Atmospheric pressure plays a significant indirect role. Key factors driving wind formation include variations in mean sea level pressure across mountainous regions, changes in potential temperature along mountain slopes, the downward movement of isotropic air from ridges or depressions, and wind at higher atmospheric levels [18- 21]. Statistical measurements of atmospheric pressure are shown in Figure 3, with pressure values recorded in hPa according to QFE standards. A notable correlation can be observed between the number of cyclones, as presented in the cyclone table, and the pressure fluctuations depicted in Figure 3. Table 1 highlights that the peak cyclone activity occurs during the cold season, spanning November to March. Correspondingly, Figure 4 demonstrates that during this period, when cyclones are more intense, the minimum observed pressure values are significantly lower compared to those recorded during the summer. This observation aligns with expectations and is supported by evidence. In contrast, during the summer, the minimum observed pressure values

Figure 2. *(a) "Lee Low" over the Gjakova region on February 25, 2005, at 18:00 UTC. (b) The same cyclone, 6 hours later, on February 26, 2005. (c) "Lee Low" over the Podujeva region on February 26, 2005, at 15:00 UTC. Simulation generated by the UKMO NWP model using HORACE.*

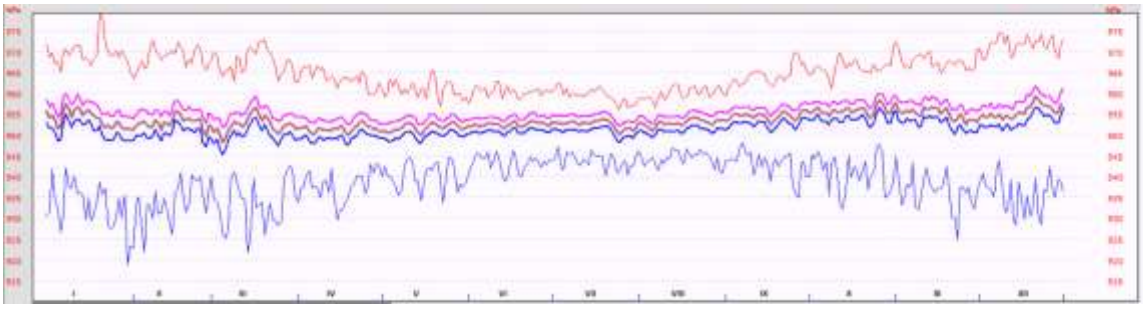


Figure 3. *Statistical measures of atmospheric pressure (hPa) from 2003 to 2022: Maximum (red), Minimum (thin blue), Mean of maximum values (purple), Mean of minimum values (thick blue), Overall mean (brown), and Standard deviation (thick light blue).*

are higher, reflecting the prevailing convective conditions, as previously mentioned. The lowest atmospheric pressure ever recorded at BKPR was 918.7 hPa on 30 January 2015. This extreme event was accompanied by 10 L/m² of accumulated precipitation and a maximum wind speed of 15.4 m/s, with two cyclones documented in the same month. Furthermore, as shown in Figure 2, atmospheric pressure exhibited periodic behavior during the same annual period, underscoring the stability of this climatic parameter.

3.3 Wind

The Mediterranean region undeniably exhibits a greater diversity of local winds than any other geographical area of comparable size [21]. However, it is important to note that some well-known local winds in the Balkans, such as the Koshava, Bora, Jugo, and Vardar, are not strongly pronounced in Kosova. Instead, local winds in Kosova primarily interact with regional wind patterns, with their direction and speed being heavily influenced by the topography of the terrain. An analysis of statistical wind data from major centres in Kosova reveals that wind direction is significantly shaped by local terrain characteristics [22-24].

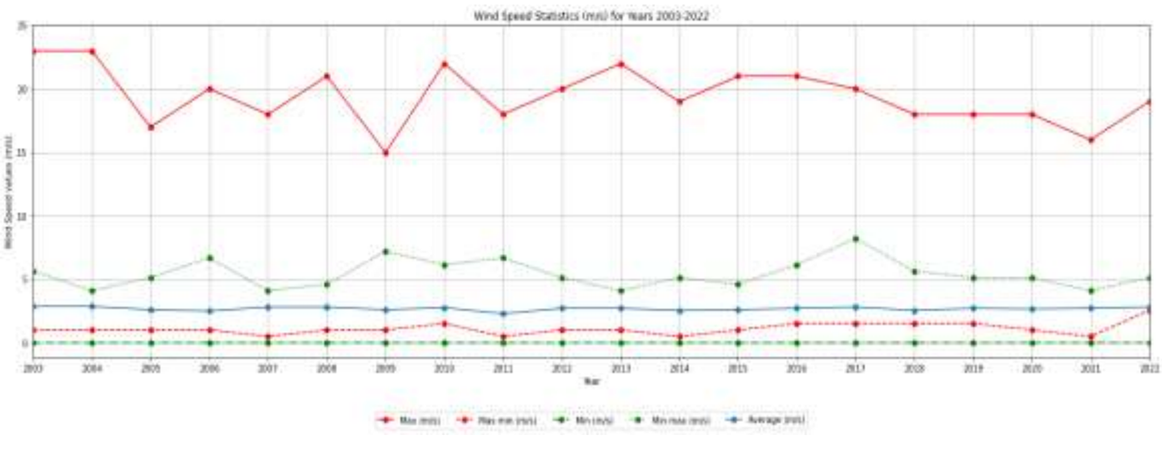


Figure 4. *Analysis of Maximum, Maximum Minimum (Max(min)), Minimum, Minimum Maximum (Min(max)), and Average Wind Speeds (m/s) for the Period 2003–2022.*

The wind fluctuations, including mean, extreme, and absolute values, are presented in Figure 4, with wind speeds measured in meters per second (m/s). According to the findings summarized in Table 1, the cyclone period in this study is two months shorter than the durations reported in previous research. Figure 5 illustrates the variability in average wind speeds over a 20-year period, ranging from 2.3 to 2.9 m/s. For comparison purposes, two distinct six-month periods were analyzed: the first period (November to April) shows an average wind speed of 2.9 m/s, while the second period (May to October) records an average wind speed of 2.5 m/s. These findings suggest that during the months with higher cyclone frequency, the average wind speed tends to be slightly elevated compared to the months with lower cyclone frequency. When comparing the winter cyclonic period with the data in Figure 4, no significant discrepancies in average wind speed are observed. However, it is important to note that during summer, convective conditions have a greater influence, occasionally resulting in short bursts of strong winds that can momentarily increase average wind speeds. Overall, as shown in Figure 3, no significant annual fluctuations in wind speed were detected.

3.4 Precipitations

Orography plays a significant role in the distribution of precipitation, as precipitation generally increases with altitude, although exceptions to this pattern are not uncommon. Kosova has maintained precipitation records since 1925 for various cities, with data from 1961–1990, meeting WMO standards, selected from a comprehensive network of stations [22]. According to the author's data, the average annual precipitation in Prishtina during the standard period 1961–1990 was 599 L/m². For comparison, data from another standard period, 1931–1960, show an average annual precipitation of 576 L/m², indicating a difference of 23 L/m² between the two periods. These datasets contributed to the development of the Climatic Atlas of the former SFRY.This analysis also incorporates data from the BKPR station, which adheres to WMO standards, for the 20-year period 2003–2022. As depicted in Figure 5, the average annual precipitation during this period is 669.6 L/m². When comparing the three periods, an increase in average annual precipitation is evident: 70.6 L/m² more than the 1961–1990 standard period and 93.6 L/m² more than the 1931–1960 period. Figure 6 further demonstrates that the accumulated annual precipitation at the BKPR station over the 20-year period has remained relatively stable. However, when compared to the earlier standard periods, a clear upward trend in the average annual precipitation is observed.

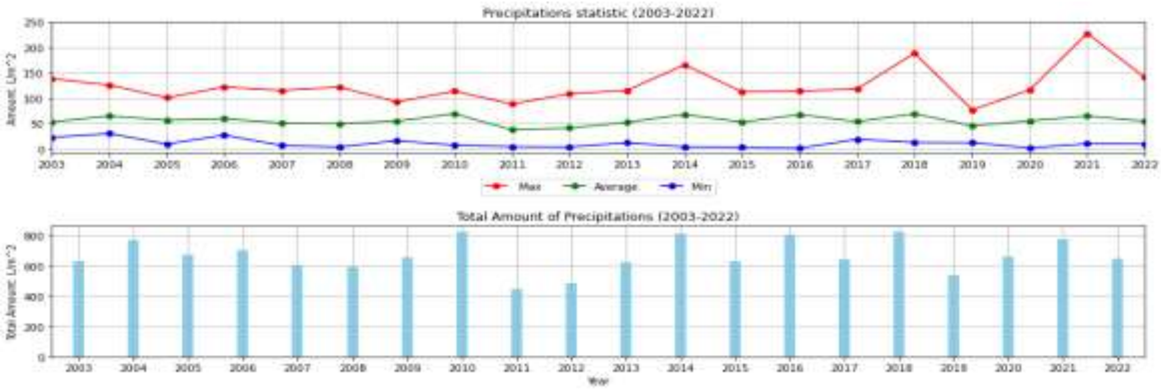


***Figure 5**. Precipitation statistics and total precipitation amount in L/m^2 for the years 2003-2022.*

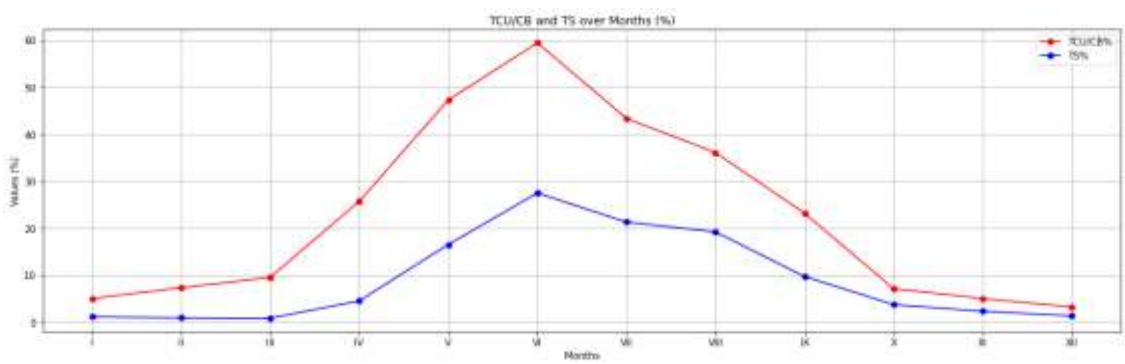


***Figure 6.** Monthly count of convective cloudy days and storms for the years 2003-2022*

Referring to Table 1 and Figure 5, there appears to be a discrepancy in the data. The highest average monthly accumulated precipitation, reaching 72.9 mm/m², occurs in May and June. Interestingly, this peak is observed after the transition month of March, rather than during the colder periods typically dominated by cyclone activity. A comparison of the data in Figure 6, which illustrates the average monthly accumulated precipitation alongside the frequency of different precipitation types, reveals that rainfall predominates in May and June. Specifically, in May, 56% of the precipitation is categorized as downpour, while 44% is attributed to dynamic precipitation. In June, 71% of the precipitation is downpour, with the remaining 29% categorized as dynamic rain. These months mark the onset of the convection period, which is characterized by convective cumulus (TCU) and cumulonimbus (CB) clouds, thunderstorms (TS), showers, and other convective phenomena(TS), showers, and other convective phenomena.

Conclusion

This study provides a comprehensive analysis of cyclonic activity and its impact on Kosova's climate over a 20-year period (2003–2022), employing both subjective and comparative methodologies to offer novel insights into regional climatic patterns. The results confirm that cyclones are most frequent during the colder months, particularly from November to March, with a notable reduction in frequency during the warmer months. Additionally, the cyclonic period has been shortened by approximately two months compared to previous studies conducted on data prior to 2000. The study also emphasizes the significant role of orographic features, such as Lee Lows, in the formation of localized cyclones, which contribute to significant precipitation events and flooding in Kosova. The correlation between atmospheric pressure variations and cyclone occurrence further reinforces the impact of these systems on local weather patterns. Lower minimum pressure values during the cold season correspond to periods of increased cyclone intensity, while higher pressures in the summer are associated with prevailing convective conditions. These seasonal pressure fluctuations highlight the indirect but crucial role of atmospheric pressure in shaping local wind and weather dynamics.

Wind data reveals that local wind patterns are primarily influenced by Kosova’s varied topography, with wind speeds tending to be higher during the cyclone season (November to April) compared to the warmer months. However, occasional bursts of strong winds, driven by convective activity, also affect wind patterns in the summer. Despite these seasonal variations, no significant annual fluctuations in wind speed were observed, indicating the general stability of wind conditions in the region.

Precipitation trends show a significant increase in annual rainfall over the past two decades compared to earlier periods, particularly from the 1961–1990 standard period. The data 2003-2022 indicate a shift toward wetter conditions, with the peak rainfall months of May and June coinciding with the onset of convection, marked by thunderstorms and convective cloud formations. This seasonal shift contrasts with the winter months, typically characterized by cyclonic activity, and highlights the growing influence of local convective patterns on precipitation distribution.

In conclusion, the study underscores the complex interplay between atmospheric pressure, wind dynamics, and precipitation in Kosova, shaped by both regional and local climatic factors. The findings not only enhance our understanding of Kosova’s evolving climate patterns but also stress the importance of long-term, high-quality data for accurate climate analysis and forecasting. These insights are crucial for improving future weather predictions and climate models for the region, and they highlight the need for continued monitoring and data collection to better understand the impacts of cyclonic activity, wind behavior, and changing precipitation trends in Kosova.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:**The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper
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- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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