Principal Component Analysis of Climatic Parameters in the Mat River Basin, Northern Albania

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Abstract

Principal Component Analysis (PCA) is widely applied across diverse scientific fields, including meteorology, agriculture, tourism, and environmental studies. In this work, we provide a systematic examination of the capacity of PCA to explain variability and reduce dimensionality in multivariate datasets. Our findings confirm the methodological effectiveness of PCA while demonstrating that data standardization can substantially influence the resulting component structure. These insights are particularly relevant for researchers aiming to use and interpret PCA within climatology and related disciplines.

The present study offers a critical evaluation of how one of the oldest and most broadly utilized statistical techniques—PCA—is applied to a set of meteorological variables collected from stations distributed across the Mat River Basin in northern Albania. The primary objective is to identify the dominant climatic gradients in the basin and to assess spatial and temporal variability in temperature, precipitation, and derived bioclimatic indicators. The results indicate that the first two principal components explain 94.53% of the total variance, reflecting a high degree of structural coherence within the regional climate system.

***Keywords**: Principal component analysis; meteorological variable; climatic classification; Mati river basin.*

Introduction

Atmospheric Science PCA methodology comes from the atmospheric sciences, where standard PCA is applied to spatiotemporal data; that is, a time series of measurements (Demšar et al., 2013) collected at specific spatial locations. The essence of PCA applications, therefore, consists in simplifying the original data with minimum loss of overall dispersion, paving the way to a reduction of dimensionality in which the data is represented (Gewers et al., 2022). This approach can imply in substantial computation cost because of the non-linear optimization required by many of the aforementioned projections. In addition, the use of high-dimensional data as input to projection methods can imply in problems of statistical significance (Bishop & Bishop, 2024). By applying PCA to meteorological data from multiple stations, this study elucidates the key climatic drivers and their recent evolution in response to regional climatic change.

It is considered an understanding spatial and temporal climatic variability within mountainous basins is essential for hydrological modelling, agricultural planning, and ecosystem management. The Mat River Basin, characterized by strong altitudinal contrasts and diverse microclimates, offers an ideal setting for such an analysis (Group of authors, 1985; Hasimi, Papajani, et al., 2025). In this paper, we present a comprehensive approach to some practical aspects of PCA on climate variables in the Mat River basin. This study is the final part of a comprehensive environmental study for the Mat River Basin, in terms of the use of meteorological measurement data in Albania, available from the Department of Meteorology, Institute of Geosciences.

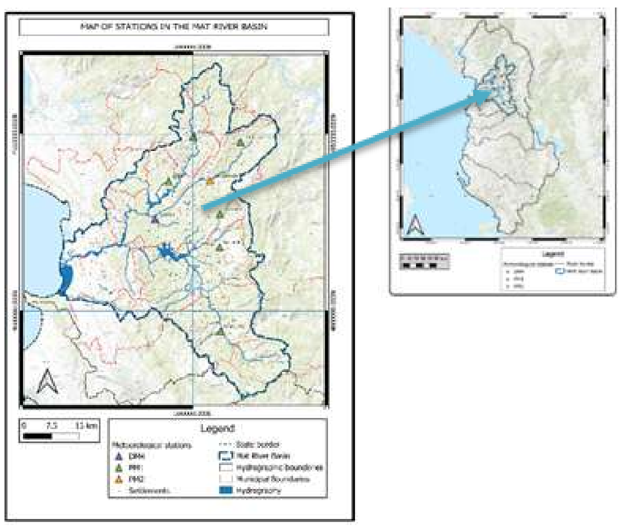
Materials and Methods

There are some important issues that need to be borne in mind when applying PCA. These include underdetermination of the direction of the PCA axes, the stability of the transformation matrix, and the interpretation of the relative importance of the original variables (Gewers et al., 2022).

Study Area

The Mat River basin, one of the seven major river basins of Albania, is noteworthy for its significance (see fig.1). Covering approximately 8.49% of the country's territory (Pano, 2009), the basin plays a vital role in the functioning of all municipalities within its boundaries, making both the quantity and quality of its water resources critically important

FIGURE 1. Map of Albania and Study Area. The watershed of the Mati River (left) and the meteorological stations with geographic coordinates (right)



	Altitude	Width	Length
Shënkoll	10	41.68688	19.65046
Rrëshen	89	41.76764	19.87675
Fshat Klos	366	41.48401	20.08921
Gojan	428	41.97816	20.0003
Domgjon	652	41.96489	20.15431
Kurbnesh	761	41.78206	20.08814
Macukull	1007	41.69741	20.08666

Over the past decade, several small and medium hydroelectric power plants have been built along the river. Despite their size, they play a decisive role in meeting Albania's energy demand. At the same time, the riverbed provides raw materials for the construction and civil industry, further increasing the basin's economic importance.

Analyses and Calculations Performed

The dataset sourced from the IGEO archive comprises long-term climatic records, including 1990 climatic norms and mean values from the most recent decade, collected from seven meteorological stations of the Mati basin river: Shën Koll, Rrëshen, Klos, Gojan, Domgjon, Kurbnesh, and Macukull. To characterize present climatic conditions, four largely independent variables were derived from monthly mean temperature and monthly total precipitation datasets. The analytical parameters incorporated mean annual temperature (°C), mean annual precipitation (mm), altitude (m a.s.l.), and climatic classifications according to the Köppen–Geiger and De Martonne systems.

Principal Component Analysis (PCA) was undertaken to reduce the dimensionality of the dataset and to delineate the dominant climatic gradients explaining the greatest proportion of variance. The resulting biplot simultaneously depicts station scores and variable loadings along the first two principal components (PC1 and PC2), thereby illustrating the principal axes of climatic differentiation across the study area.

Data visualization and statistical interpretation were conducted using OriginLab Pro, which facilitated the production of high-resolution graphical outputs, supported multivariate comparative assessments, and enabled a rigorous quantitative evaluation of climatic trends and intervariable relationships.

Results and Interpretation

Climatic zones and subzones of the Mat River Basin were classified based on two climate models commonly applied in climate science (Beck et al., 2006; Belda et al., 2014). Based on our analyses and published findings, the documented climatic changes within the Mat River Basin are expected to exert significant impacts on the basin's hydrological regime and ecosystem dynamics.(Hasimi et al., 2026; Hasimi, Çomo, et al., 2025; Çomo et al., 2025;).

TABLE 1. The changes in temperatures and precipitation for meteorological station of Mati basin river, Albania and Climate type according to the Köppen-Geiger and the Köppen-Trewartha classification (Hasimi et al., 2026).

Meteo Station	Altitude m a.s.l	$\Delta T_{mes\ annual}$	$\Delta P_{mes\ annual}$	KCC		KTC	
		%	%	norms 1990	Last decade results	norms 1990	Last decade results
Shënkoll	10	no last decade data		Cfa		Cf	
Rrëshen	89	+ 8.15	+12.96	Cfa	Csa	Da	Da
F Klos	366	+ 19.60	-5.90	Cfa	Cfa	Da	Cf
Gojan	428	+ 11.77	-3.78	Cfb	Cfa	Da	Cf
Domgjon	652	+ 24.66	-21.63	Cfb	Bkf	Da	Da
Kurbnesh	761	+ 21.64	- 2.57	Cfb	Cfa	Da	Da
Macukull	1007	no historical data			Cfb		Da

In general, the observed temperature increases of 2.0–2.5°C across all meteorological stations, combined with a mean precipitation decline of 5–20%, demonstrates a systematic regional warming and drying trend throughout the Mat River Basin. The spatial distribution of these changes suggests an elevation-dependent response, whereby lower and mid-elevation areas experience more pronounced thermal increases and shifts in climate classification (Hasimi et al., 2026). Studying in more detail the nuances in the climate analysis for this basin, we perform a statistical analysis from the data presented in Table 1.

These shifts in climatic subzones are closely related to rainfall anomalies, but also to extreme phenomena that are becoming more evident and frequent day by day throughout the territory of Albania, including the Mat River basin (Gimeno et al., 2022; Intergovernmental Panel On Climate Change (Ipcc), 2023; Papajani et al., 2025). In the continuation of this analysis, the following session will present a principal component analysis of the factors that drive the shifting of climatic zones.

Eigenvalues and Explained Variance

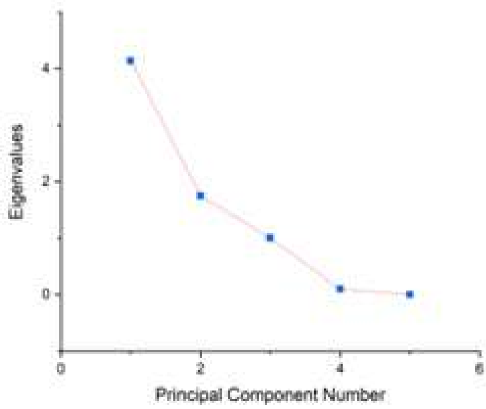
Principal Component Analysis (PCA) was applied to standardized climatic variables (temperature and precipitation indicators, including their decadal changes) in order to identify dominant modes of variability across the meteorological stations. The eigenvalue spectrum (Table 2; Figure 2) indicates that the first three principal components (PCs) have eigenvalues greater than 1, jointly explaining **98.55% of the total variance**, indicating that the multidimensional dataset can be reliably summarized in a reduced three-dimensional space.

TABLE 2. The eigenvalue spectrum

	Eigenvalue	Percentage of Variance e	Cumulative
1	4.14342	59.19%	59.19%
2	1.75293	25.04%	84.23%
3	1.00203	14.31%	98.55%
4	0.10162	1.45%	100.00%

The **first principal component (PC1)** accounts for **59.19%** of the total variance (eigenvalue = 4.14), indicating a dominant climatic gradient affecting all stations. The **second principal component (PC2)** explains an additional **25.04%** of the variance (eigenvalue = 1.75), while the **third principal component (PC3)** contributes **14.31%** (eigenvalue = 1.00). The remaining components explain negligible variance (<2%) and were therefore excluded from further interpretation, in accordance with the Kaiser criterion and scree plot inspection.

FIGURE 2. Screen plot (explained variance of each principal component) calculated for the reference (1961–1990) climate



Structure and Interpretation of Principal Components

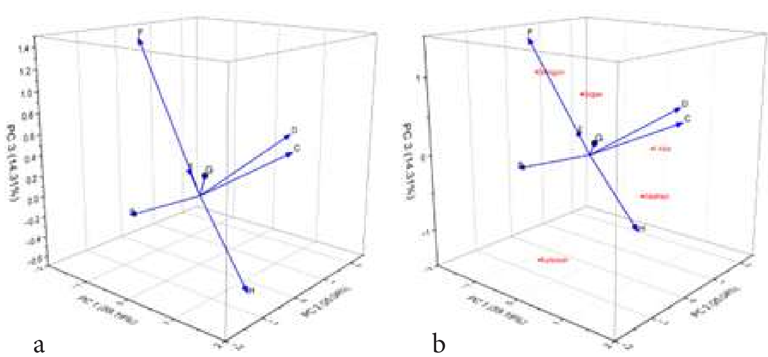
Figure 3 presents the projection of three-dimensional PCA biplots clustering of stations with similar climatic trajectories. At figure 3a is shown the projection of PC1 - representing the primary climatic variability axis; PC2 - reflecting altitude-related climatic differentiation; PC3 - suggesting the influence of local microclimatic factors. At figure 3b is shown the distribution of stations relative to these vectors

Principal Component 1 (PC1 – 59.19%) represents the dominant axis of climatic variability across the study area and encapsulates the most pronounced expression of recent climate change. This component is strongly associated with increases in annual mean temperature (ΔT) and exhibits an inverse relationship with changes in annual precipitation (ΔP), indicating that warming trends are frequently accompanied by declining or only weakly positive precipitation responses.

Stations exhibiting high positive scores along PC1—particularly **F. Klos, Gojan, Domgjon, and Kurbnesh**, located at low to mid altitudes—display substantial increases in mean annual temperature over the last decade, reaching values of up to **+2.7 °C**, alongside notable reductions in annual precipitation, in some cases exceeding **−20%**. The coherent clustering of these stations along PC1 suggests the presence of a **regional-scale warming signal**, rather than isolated or site-specific anomalies.

The opposing orientation of temperature and precipitation variables along this axis further highlights the emergence of **hydro-climatic stress**, whereby thermal amplification is coupled with reduced moisture availability. Such a pattern is consistent with broader regional climate projections for Mediterranean and mountainous transitional zones, where warming-induced changes in atmospheric circulation and evapotranspiration increasingly affect precipitation regimes (Nistor et al., 2022; Sparey et al., 2023).

FIGURE 3. The three-dimensional PCA biplots clustering of stations with similar climatic trajectories. ***a*** The projection of PC1 - represents the primary climatic variability axis; PC2 - reflects altitude-related climatic differentiation; PC3 - suggests the influence of local microclimatic factors, ***b*** The distribution of stations relative to these vectors.



a b

Stations with weaker projections along PC1 tend to exhibit either relatively stable climatic conditions or incomplete long-term records, which may limit their contribution to the dominant variability captured by this component. Nonetheless, the overall structure of PC1 clearly indicates that temperature-driven change constitutes the primary source of variance within the dataset.

Taken together, PC1 can be robustly interpreted as a **climate change signal integrating both thermal and hydrological dimensions**, capturing the prevailing trend of regional warming and associated precipitation decline that defines the current climatic trajectory of the study area.

Principal Component 2 (PC2 – 25.04%) captures a secondary axis of climatic variability that is closely associated with **altitude-dependent thermal and pluviometric regimes**. Unlike PC1, which reflects the overarching warming–drying trend, PC2 differentiates stations according to their **baseline climatological conditions and elevation**, revealing the moderating influence of topography on local climate dynamics.

Stations at higher elevations—such as **Domgjon, Kurbnesh, and Macukull**—project positively along PC2, consistent with **lower baseline temperatures** and a heightened sensitivity to recent warming trends. In contrast, lowland stations, including **Shën Koll and Rrëshen**, exhibit lower or negative PC2 scores, reflecting **warmer baseline conditions** and distinct precipitation responses. Intermediate-elevation stations such as **Gojan** demonstrate moderate projections, suggesting relatively stable or slightly declining precipitation coupled with moderate warming.

The orthogonality of PC2 relative to PC1 indicates that the altitude-driven variability captured by this component is largely **independent of the dominant regional warming–drying signal**, highlighting the role of **orographic effects and elevation gradients** in shaping local climate patterns. Collectively, PC2 can be interpreted as a **topographic–climatic gradient**, emphasizing how elevation modulates both temperature and precipitation dynamics, and providing insight into the spatial heterogeneity of climate change impacts across the study area.

Principal Component 3 accounting for **14.31% of the total variance**, captures **localized and station-specific climatic variability** that is not fully explained by the dominant large-scale patterns represented by PC1 and PC2. This component primarily differentiates stations according to **asymmetric temperature–precipitation responses**, highlighting heterogeneity in how individual locations respond to recent climatic changes.

In the three-dimensional biplot, PC3 separates stations such as **Domgjon, Kurbnesh, and Rrëshen**, which exhibit pronounced temperature increases accompanied by substantial precipitation anomalies—both negative and, in some cases, positive—from stations characterized by more moderate or balanced climatic responses. The distinct projection of these stations along the PC3 axis indicates departures from the regional mean behavior captured by the first two components.

The variability associated with PC3 likely reflects the influence of **local microclimatic controls**, including geographic and topographic exposure, basin effects, elevation-related atmospheric processes, and proximity to mountainous terrain. These factors may act to either amplify or attenuate regional warming and precipitation trends, underscoring the importance of site-specific conditions in shaping local climate responses.

Spatial Distribution of Stations

The spatial arrangement of the stations in the PCA biplot (figs. 3) delineates three climatic clusters:

1. **Mountainous cluster** (Domgjon, Kurbnesh, Macukull) — characterized by high precipitation (>1500 mm) and lower mean annual temperature (10–12 °C), corresponding to the Cfb–Bkf climatic types.
2. **Intermediate cluster** (Gojan, Klos) — transitional climate with moderate thermal and pluviometric conditions, influenced by both maritime and continental factors.
3. **Lowland cluster** (Rrëshen, Shën Koll) — warmer and drier conditions (T > 14 °C), increasingly associated with Mediterranean classifications (Cfa–Csa).

The PCA thus reveals a coherent **vertical climatic stratification**, confirming the strong influence of topography and altitude on the regional climate system.

Stations positioned close together in the PCA space exhibit comparable temperature and precipitation trends, whereas those farther apart reflect divergent climatic responses. The orientation of the loading vectors indicates that temperature-related variables dominate the variance structure, while precipitation contributes primarily to secondary and tertiary variability. This asymmetry highlights the stronger and more spatially coherent signal of temperature change compared to precipitation variability.

The 3D biplots simultaneously display station scores and variable loadings. Vectors for ΔT_{mes} annual and ΔPmes annual point in contrasting directions, suggesting an inverse relationship between temperature increases and precipitation changes across stations. This pattern aligns with the observed negative precipitation anomalies at stations experiencing the strongest warming. The proximity of stations such as F. Klos and Domgjon to the ΔT_{mes} vectors confirms their status as hotspots of recent climatic change, whereas stations near the origin (e.g., Shen Koll) correspond to either missing recent data or relatively stable climatic conditions.

Interpretation of Variable Loadings

The PCA variable loadings quantify the contribution of each climatic parameter to the principal components, providing insight into the underlying drivers of basin-wide variability.

The orientation and relative magnitude of the ΔTmes and ΔPmes vectors (figure 3b) in the biplots visually represent these loading patterns: vectors pointing in opposite directions denote a negative correlation between warming and precipitation changes, whereas the length of each vector corresponds to its contribution to total variance. Stations positioned along these vectors reflect the dominant influence of temperature and precipitation on their climatic trajectories, with F. Klos and Domgjon illustrating strong alignment with warming trends, and Shen Koll exemplifying minimal deviation from the basin mean.

Overall, variable loadings confirm that temperature is the primary driver of spatial and temporal variability (PC1), while precipitation exerts secondary and localized influence (PC2 and PC3), providing a robust mechanistic interpretation of the basin's multivariate climatic structure.

Discussion and Conclusions

The PCA results demonstrate that recent climatic changes in the study area are primarily driven by temperature increases, while precipitation changes exhibit more heterogeneous and localized behavior. The first three principal components collectively capture nearly all the observed variance, confirming the robustness of the multivariate structure and supporting the use of PCA as an effective tool for summarizing complex climatic datasets.

Climatic and Environmental Implications

PC1 reflects the dominant warming signal, with stations experiencing strong temperature increases also showing reductions in precipitation, particularly at mid- to high-altitude locations. PC2 captures secondary variability associated with altitude and topographic gradients, highlighting systematic differences between lowland and mountainous stations. PC3 represents localized climatic fluctuations, capturing station-specific anomalies and finer-scale heterogeneity. This is evident in the observed transition from humid temperate climates (Cfb, Cf) at higher elevations toward drier Mediterranean types (Cfa, Csa) in lower-lying areas

Together, these three components reveal spatially structured patterns of climatic change that extend beyond simple geographic proximity, with important implications for: **Hydrological resources**, given the observed link between warming and precipitation decline; **Ecosystem resilience**, particularly in mountainous regions sensitive to thermal and moisture stress; **Regional climate adaptation strategies**, as stations cluster according to shared climatic trajectories rather than purely spatial location (Sparey et al., 2023).

The PCA of the Mat River Basin indicates that its climatic structure is primarily governed by an altitudinal thermo-pluviometric gradient (PC1) and, secondarily, by recent temporal climatic variability and typological shifts (PC2). High-altitude stations are characterized by cool, humid climates with relatively low temporal variability, whereas lowland and mid-altitude stations exhibit pronounced warming and drying trends over recent decades.

The observed shifts in Köppen–Geiger classifications over the last decade are consistent with broader Mediterraneanization trends documented across the western Balkans (European Commission. Joint Research Centre., 2024; Haidu et al., 2024). These results suggest a gradual encroachment of semi-arid and warm-temperate conditions into formerly humid mountainous zones, with significant implications for hydrological resources, agricultural productivity, and vegetation dynamics. Collectively, the PCA provides a robust multivariate framework to quantify both spatial and temporal dimensions of climatic change in the Mat Basin. Overall, the results support the hypothesis of a **progressive climatic transition toward warmer and more Mediterranean conditions** in the lower and central parts of the basin, consistent with observed regional climate trends in Balkans and southeastern Europe.

Acknowledgment

This study is conducted as part of the project titled "Impacts of Heavy Metals from the Mining Industry and Assessment of Pollution Distribution in the Mati River Basin." The project is funded by the National Agency for Scientific Research and Innovation (NASRI) of Albania under the National Research and Development Projects (NRDP) program for the period 2024–2026

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