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MARIE SKŁODOWSKA-CURIE ACTIONS

RESEARCH AND INNOVATION STAFF EXCHANGE

YADES

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Executive Summary

The current analysis focuses on developing advanced and reliable models to assess the impacts of natural and man-made hazards on critical archaeological sites in Greece. The study specifically targets two culturally significant sites; Delphi, and Meteora. These sites, vital to both Greece's cultural heritage and its economy, face increasing risks due to climate change.
A detailed climate analysis of past, present, and future conditions was performed, emphasizing in three key climatic factors: wind, temperature, and precipitation. Historical data showed that both sites experience strong seasonal variability, with Delphi exposed to higher wind speeds. Temperatures in both locations follow a typical Mediterranean pattern, with hot, dry summers and mild, wet winters.
Future climate projections under the RCP4.5 and RCP8.5 scenarios suggest significant increases in temperature anomalies by 2100, with summer temperatures rising by up to 5°C. Simultaneously, precipitation levels are expected to decrease during the summer months, with reductions of up to 80%, exacerbating the risks of erosion, structural damage, and material degradation. These findings highlight the need for climate-adaptive conservation strategies to protect Greece's invaluable archaeological sites from the impacts of climate change.
The data generated through this analysis provide essential tools for researchers, conservationists, and policymakers. By offering high-resolution insights, the YADES project supports the development of more effective measures to safeguard Greece's cultural heritage against future environmental threats.

1. Introduction

Archaeological sites in Greece possess historical, cultural and economic importance, playing a key role in numerous sectors. These locations attract millions of visitors each year, making them not only valuable for academic and educational purposes but also crucial for local economic development.
However, these are at constant risk and suffer from the effects of hazards (Mentzafou & Dimitriou, 2022). Preserving these sites has become increasingly challenging in the face of rapidly changing climate conditions. Climate analysis is essential for assessing and mitigating the effects of environmental factors on the structural integrity of these cultural sites. The last are frequently subjected to extreme conditions such as extreme temperatures, heavy rainfall and strong winds. These conditions can accelerate the deterioration of ancient structures and landscapes, potentially leading to irreversible damage. Through comprehensive climate analysis, researchers and authorities can gain deeper insights into local climate dynamics and identify emerging threats, enabling more effective protection and conservation of these invaluable sites (Nastos et al., 2021).

2. Locations of interest

The analysis is focused on two areas of archaeoflogical interest: Delphi and Meteora. Delphi was an ancient Greek sanctuary dedicated to the god Apollo (Figure 1a). Meteora (Figure 11b), located in central Greece, is famous for its rock formations topped with old monasteries and recognized as a UNESCO World Heritage site.

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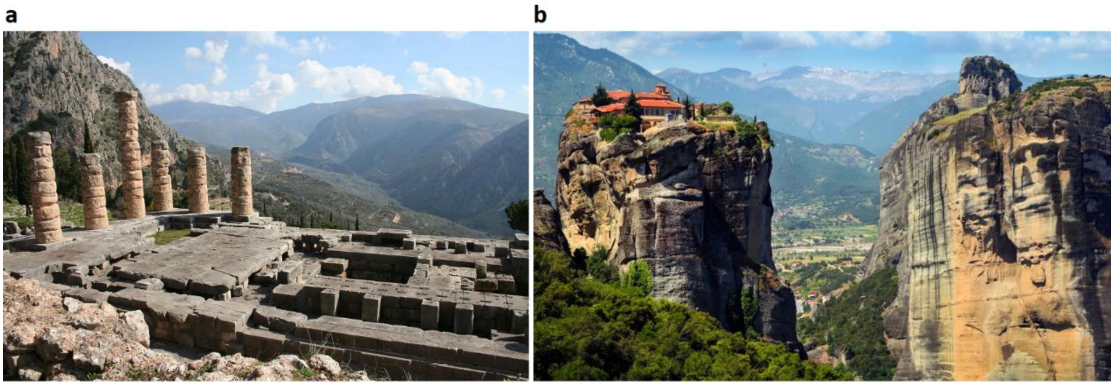

Figure 1: a) The archaeological site of Delphi (retrieved from https://www.britannica.com/place/Delphi-ancient-city-Greece) and b) Meteora (retrieved from https://throughtheblue.gr/meteora/).

3. Climate analysis (past & present)

The wind fields in Delphi have two dominant directions: west-southwest (WSW) and north-northeast (NNE) (Figure 2). The strongest winds, often exceeding 20 m/s, primarily come from the north-northeast due to general wind patterns and local topographic effects. However, most wind speeds fall within the range of 0 to 5 m/s. The histogram of wind speed measurements shows a right-skewed distribution, which aligns with the Weibull distribution fitted to the data (Figure 3).

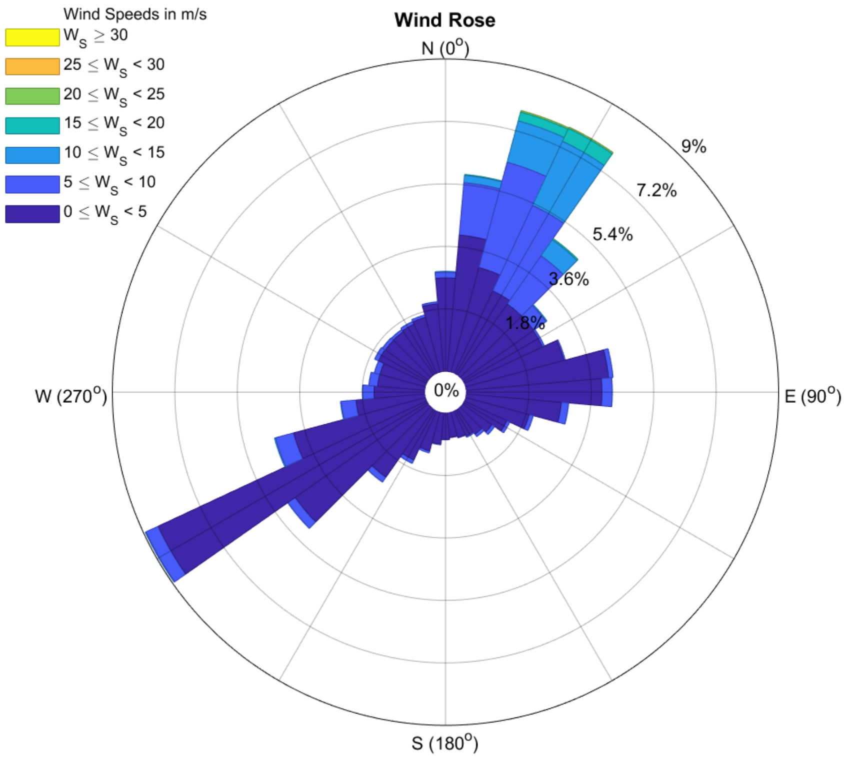

Figure 2: Wind rose for Delphi.

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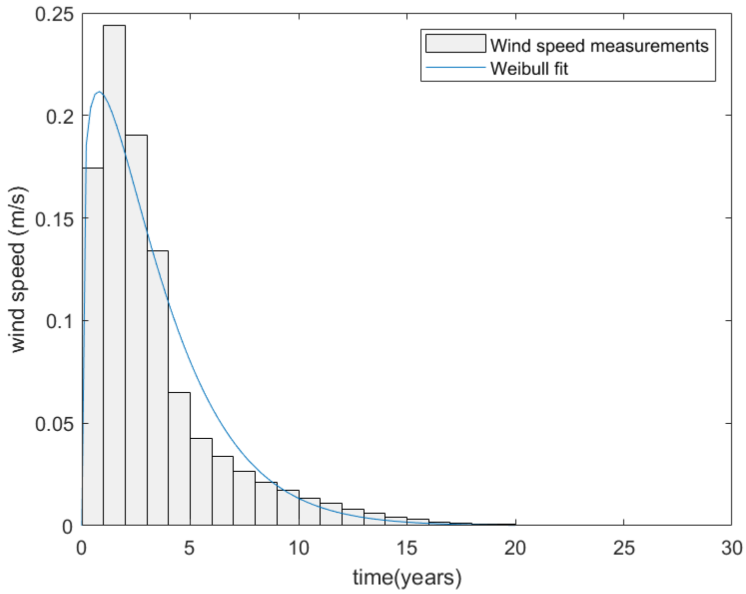

Figure 3: Histogram and Weibull fit for wind speed values (Delphi).

The wind fields in Meteora demonstrate two dominant directions: north-northeast (NNE) and south-southwest (SSW) (Figure 4). Strongest winds, with values exceeding 15 m/s, are predominantly from the north-northeast, influenced by regional wind patterns and the unique topography of the area. However, most wind speeds in Meteora are moderate, falling within the range of 0 to 5 m/s. The histogram of wind speed measurements exhibits a right-skewed distribution, closely matching a Weibull distribution (Figure 5).

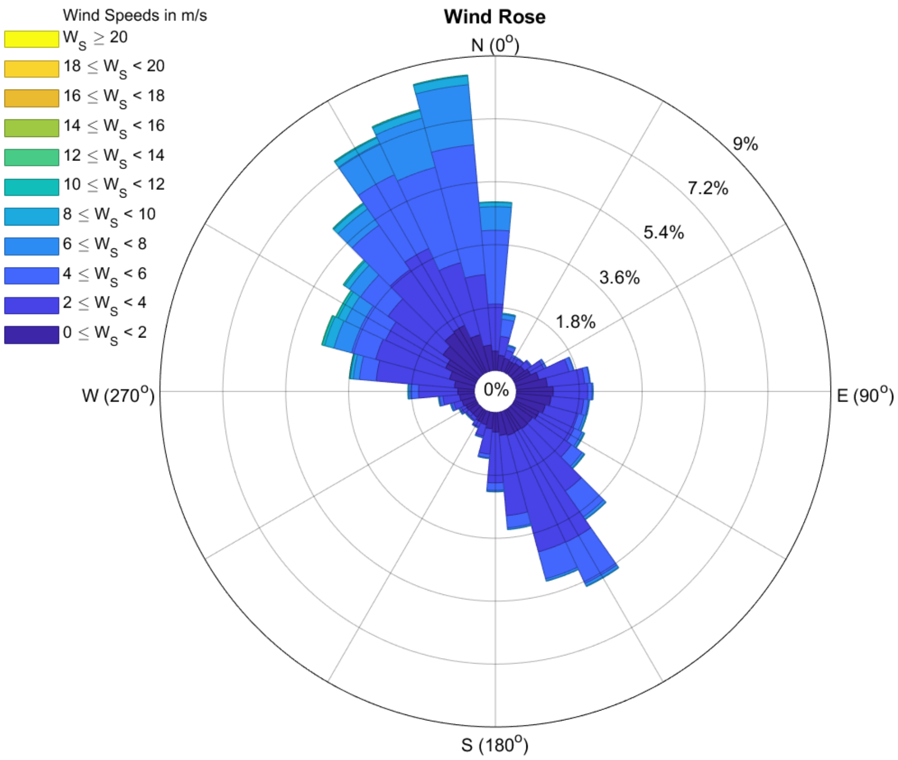

Figure 4: Wind rose for Delphi.

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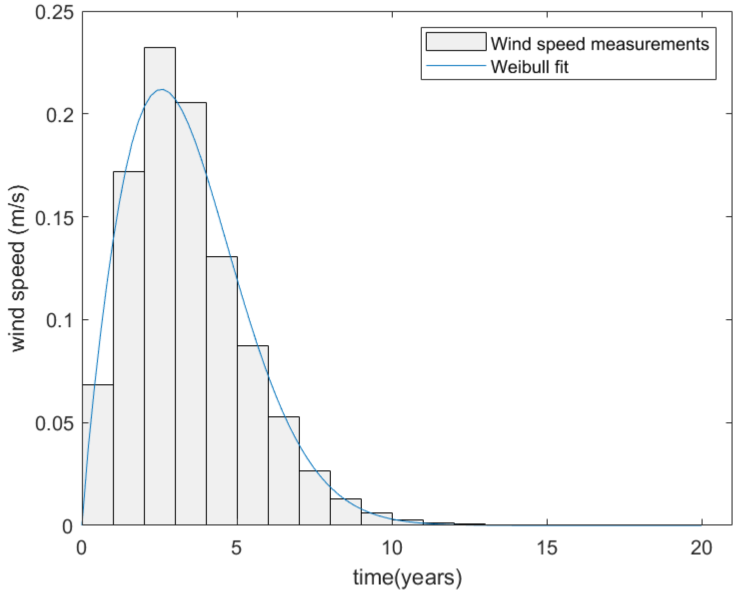

Figure 5: Histogram and Weibull fit for wind speed values (Delphi).

To quantify the extremity of wind speed values and estimate potential hazardous situations, an extreme value analysis was conducted using the Annual Maxima method. This approach, commonly used for analyzing extreme values in time series data (Coles, 2001), involves fitting a sample of annual maxima to a distribution from the Generalized Extreme Value (GEV) family. While wind speed is generally well-represented by the Weibull distribution (Hennessey, 1977), extreme wind speeds, such as annual maxima, are better modeled by the first type of GEV distribution (Cook, 1985). The Gumbel distribution, a specific case of the GEV family, was selected for this analysis due to its simplicity, requiring the estimation of only two parameters—location (β) and scale (α). These parameters were derived using the Maximum Likelihood (ML) method, as outlined by Patlakas et al. (2016).

Beginning with Delphi it was found that as the return period increases, the expected extreme wind speed also rises, with values ranging from around 26 m/s for a 5-year return period to approximately 34 m/s for a 50-year return period (Figure 6). The confidence intervals widen as the return period increases, reflecting greater uncertainty in the estimates for more extreme events.

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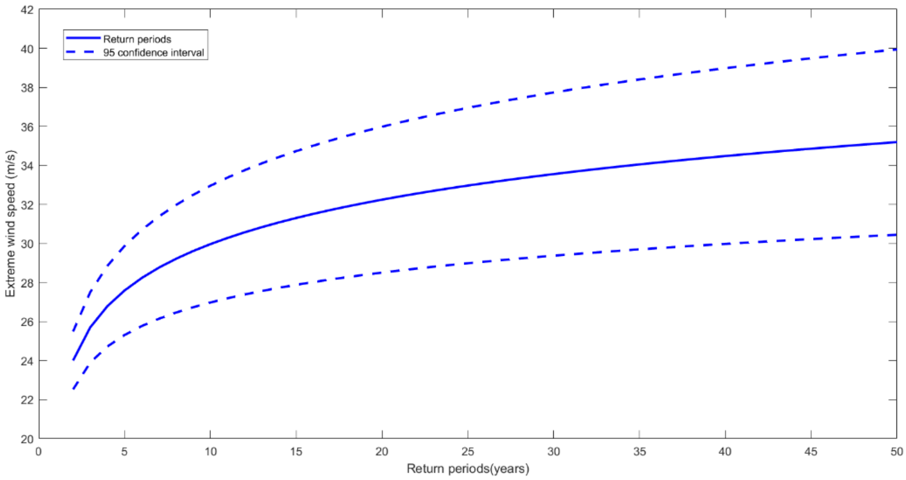

Figure 6: The extreme wind speeds and the corresponding return periods for up to 50 years for Delphi.

In Meteora, extreme wind speeds range from approximately 18 m/s for a 5-year return period to around 22 m/s for a 50-year return period (Figure 7). This indicates that the area is generally less affected by extreme winds, a trend also reflected in the wind roses and histograms presented above. The widening of the confidence intervals, which suggests increasing uncertainty in the estimates for longer return periods, is consistent with expectations.

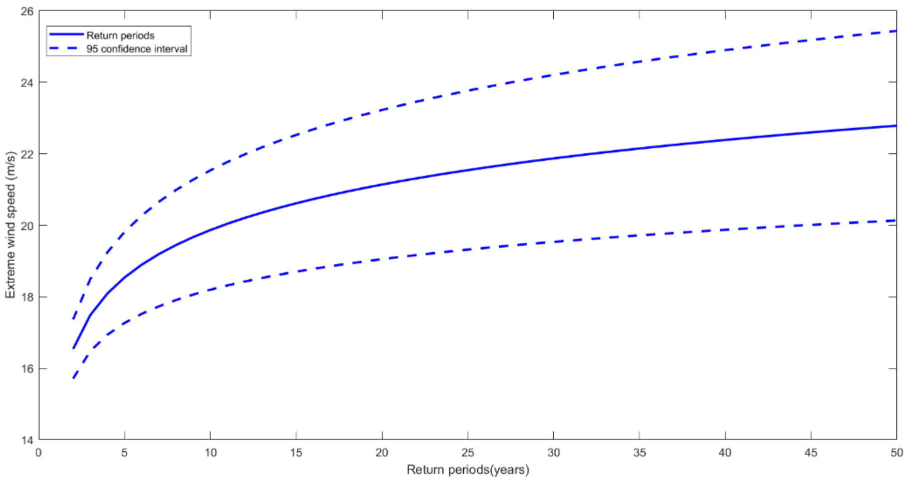

Figure 7: The extreme wind speeds and the corresponding return periods for up to 50 years for Meteora.

Regarding temperature, a monthly analysis was performed. In Delphi, temperatures in January are around 5°C, and gradually increase through the spring months, reaching approximately 20°C by May (Figure 8). The hottest months are June, July, and August, with temperatures peaking between 23°C and 25°C. After the summer season, temperatures begin to decline, dropping to around 10°C by November and decreasing further to 5°C in December. This indicates a typical seasonal pattern.

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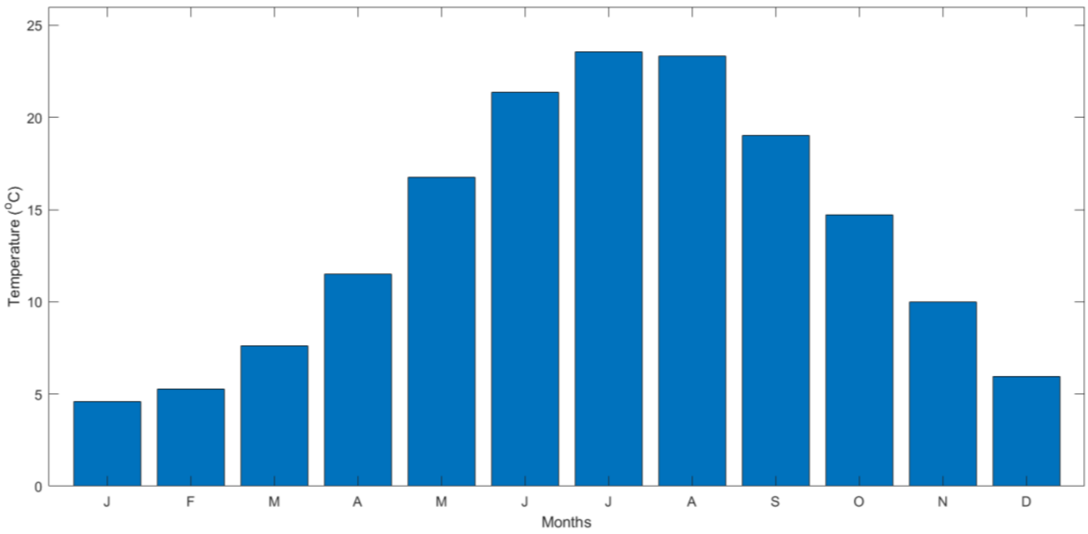

Figure 8: Mean monthly temperature for Delphi.

The mean monthly temperatures in Meteora follow a similar seasonal pattern to Delphi. Here the temperatures begin at around 5°C in January and increase steadily through the spring, peaking at approximately 24°C in July. Like Delphi, the warmest months are June, July, and August, with temperatures ranging between 22°C and 24°C. The temperatures then decrease, falling to around 5°C by December (Figure 9).
In comparison, Delphi has slightly higher peak temperatures in the summer, reaching around 25°C, while Meteora peaks at around 24°C. Both sites experience similar seasonal transitions, although Delphi generally shows a broader range in monthly temperatures.

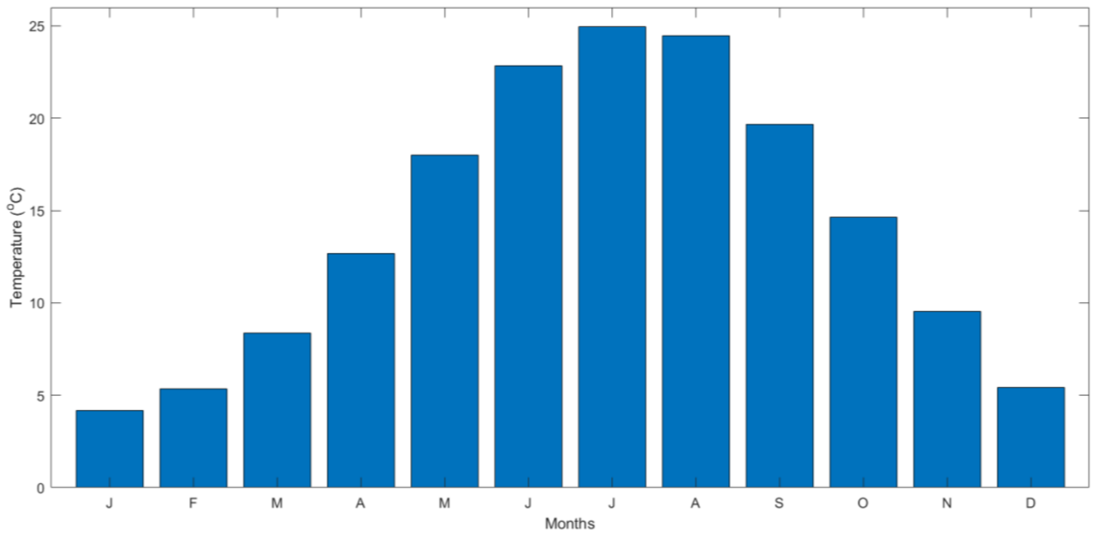

Figure 9: Mean monthly temperature for Delphi.

Focusing on precipitation patterns, Delphi experiences a clear seasonal variation (Figure 10). The wettest months are in winter, with December receiving the highest precipitation at around 80 mm, followed by January and February, both around 70 mm. As spring approaches, precipitation begins to decline, reaching its lowest levels in May, with less than 40 mm. During

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the summer, precipitation remains low, consistent with the high temperatures, with June, July, and August averaging between 20 and 30 mm. This dry period is characteristic of Mediterranean climates, where hot summers coincide with limited rainfall. In contrast, the fall months see a gradual increase in precipitation, peaking again in December.

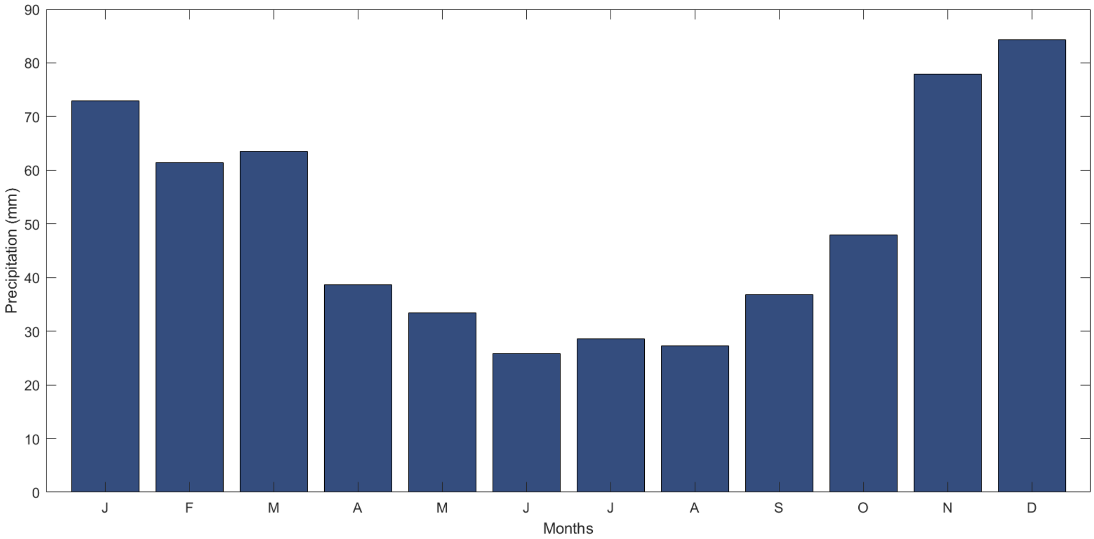

Figure 10: Mean monthly accumulated precipitation for Delphi.

In the same framework, Meteora experiences its highest precipitation in December, reaching close to 90 mm, followed by October and November, which also receive significant rainfall (Figure 11). The winter months of January and February show slightly lower precipitation, around 70 mm. Like Delphi, precipitation drops during the spring and summer months, with May and June receiving the least rainfall, averaging around 30 mm. Precipitation begins to rise again in the fall, with a sharp increase from September onwards.

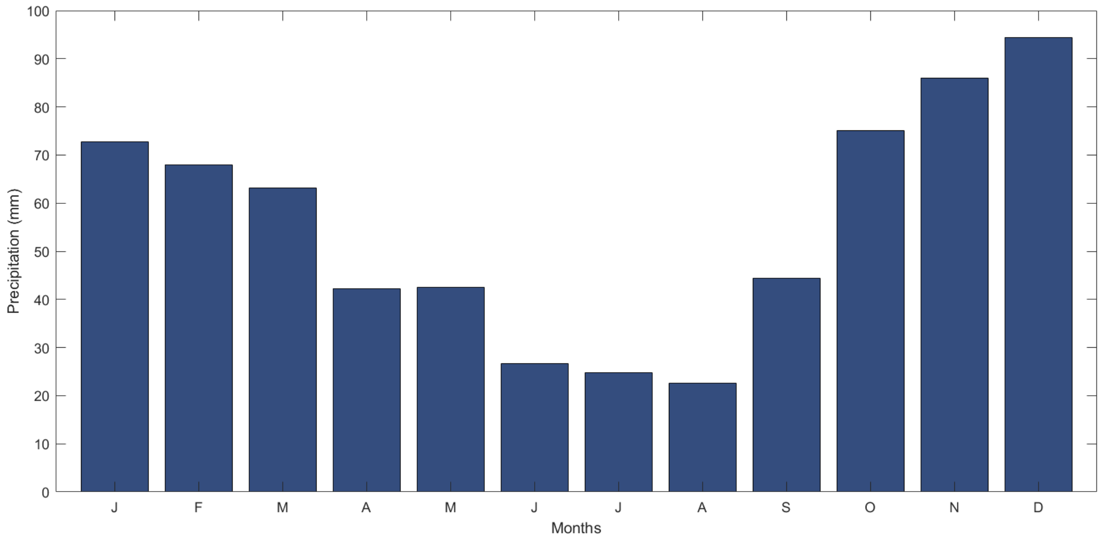

Figure 11: Mean monthly accumulated precipitation for Delphi.

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4. Climate analysis (future)

To assess the potential climate impacts in the near future (2031-2050) and far future (2081-2100), both the KNMI and RCA models were used. KNMI, developed by the Royal Netherlands Meteorological Institute, provides global climate projections, while the RCA (Rossby Centre Regional Atmospheric Model) focuses on regional-scale. The combination of these models will give an insight in potential uncertainties. The study focuses specifically on changes in temperature and precipitation under these two emissions scenarios. RCP4.5 represents a moderate emissions pathway, while RCP8.5 simulates a high-emissions scenario.
Starting with temperature, the KNMI model driven by the RCP4.5 scenario for Delphi shows increasing monthly temperature anomalies from the near future (2031-2050) to the far future (2081-2100), with the largest anomalies occurring from March to May (Figure 12). These range from about 1-2°C in the near future to 2.5-3.2°C in the far future. The overall warming trend is evident across all months, with the most significant increases during spring and early summer.

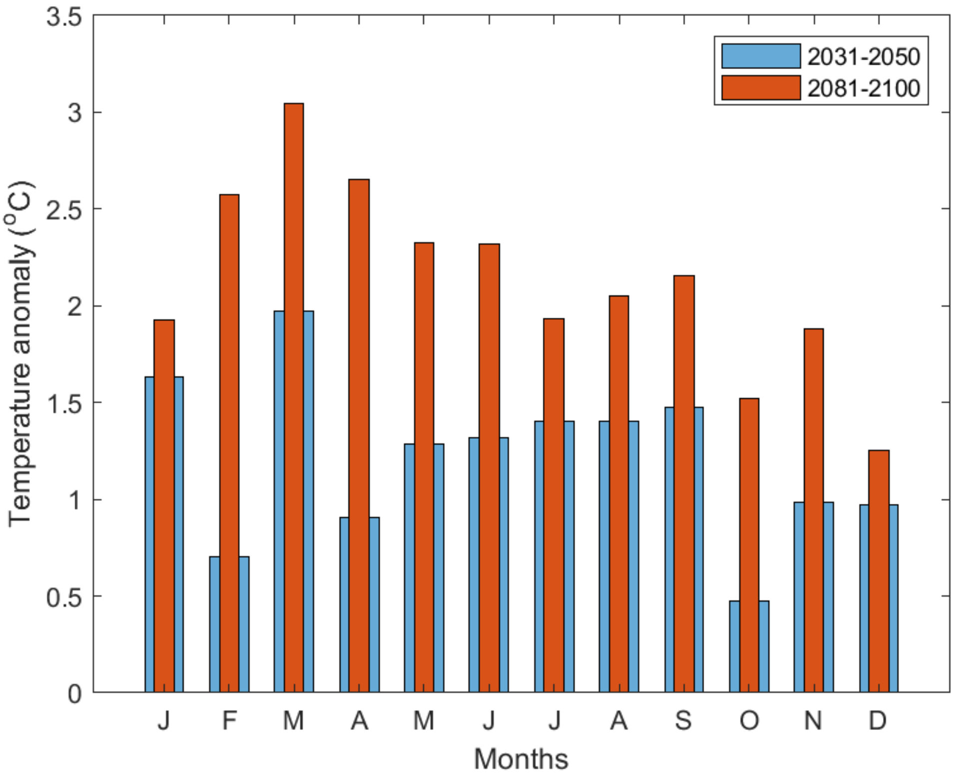

Figure 12: Mean monthly temperature anomalies of the KNMI model for the RCP4.5 scenario (Delphi)

Under the RCP8.5 scenario for the same site, shows temperature anomalies increase significantly and range from 1.5-2.5°C in the near future to 4-5°C in the far future, with the highest increases occurring from July to September (Figure 13).

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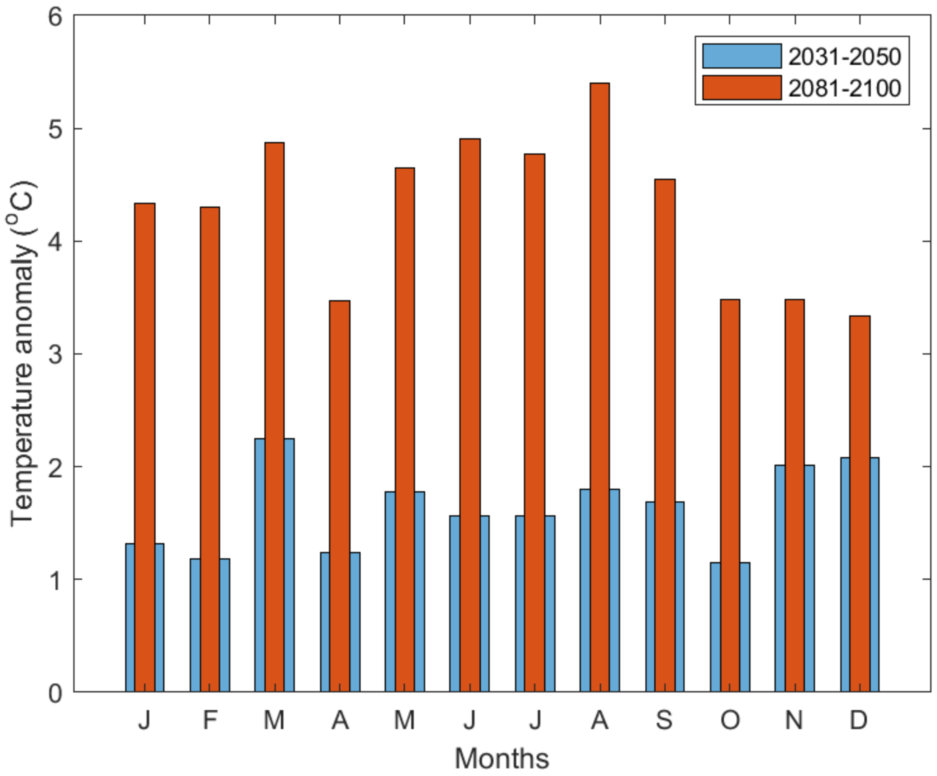

Figure 13: Mean monthly temperature anomalies of the KNMI model for the RCP8.5 scenario (Delphi)

For Meteora under the RCP4.5 scenario (KNMI model), mean monthly temperature anomalies range from about 1-1.5°C in the near future to 2-2.7°C in the far future, with the largest increases occurring from March to May (Figure 14). The overall warming trend is consistent across all months, with the most significant increases seen in spring and summer.

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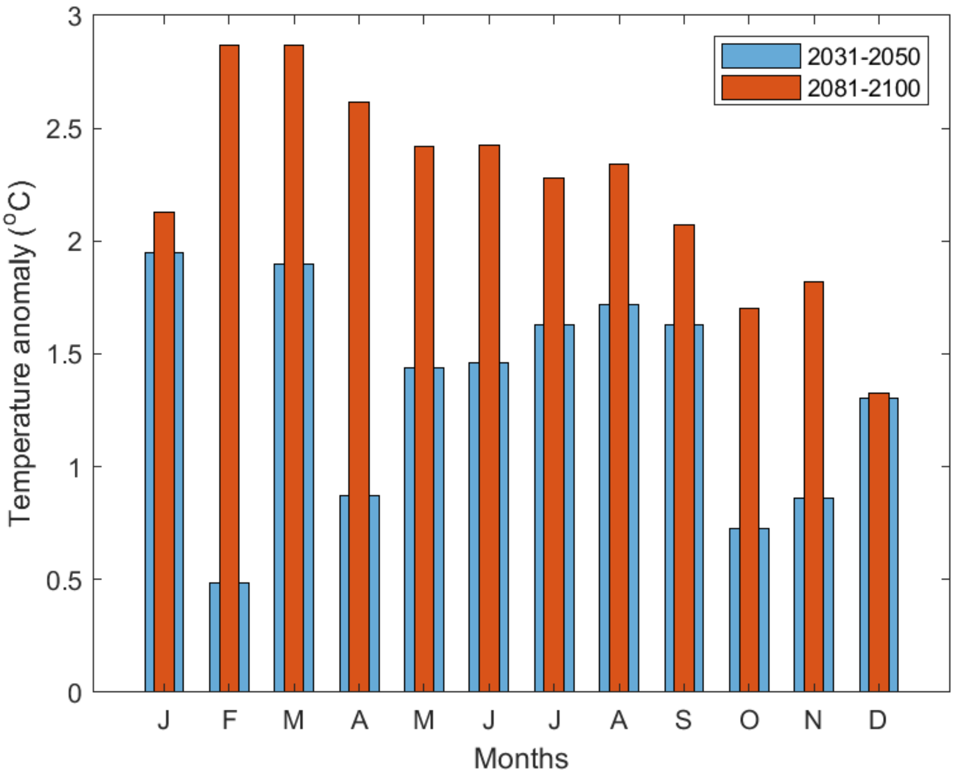

Figure 14: Mean monthly temperature anomalies of the KNMI model for the RCP4.5 scenario (Meteora)

Under the RCP8.5 scenario, temperature anomalies are increased, ranging from 2-3°C in the near future (2031-2050) to 4-6°C in the far future (2081-2100), with the highest anomalies occurring from July to September (Figure 15).

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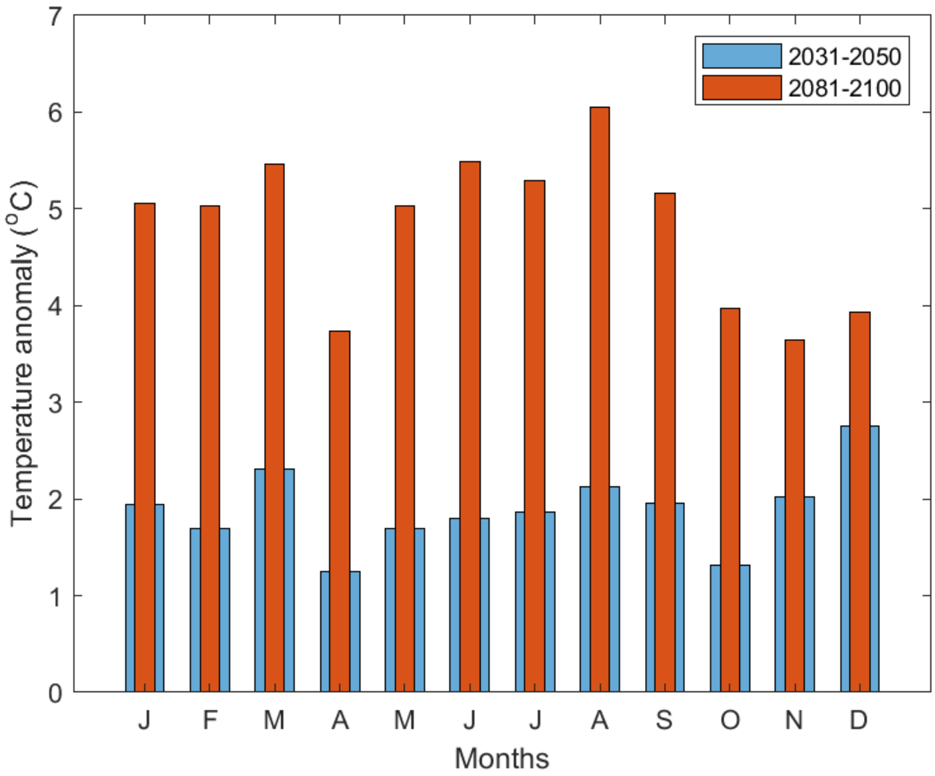

Figure 15: Mean monthly temperature anomalies of the KNMI model for the RCP8.5 scenario (Meteora)

The RCA model has a rather similar behavior. Under the RCP4.5 scenario for Delphi, temperature anomalies increase from 1-1.5°C in the near future (2031-2050) to 2-2.7°C in the far future (2081-2100), with the highest anomalies occurring in May and June (Figure 16). Under the RCP8.5 scenario, anomalies rise and range from 2-3°C in the near future to 4-5.5°C in the far future, peaking in June and July (Figure 17).

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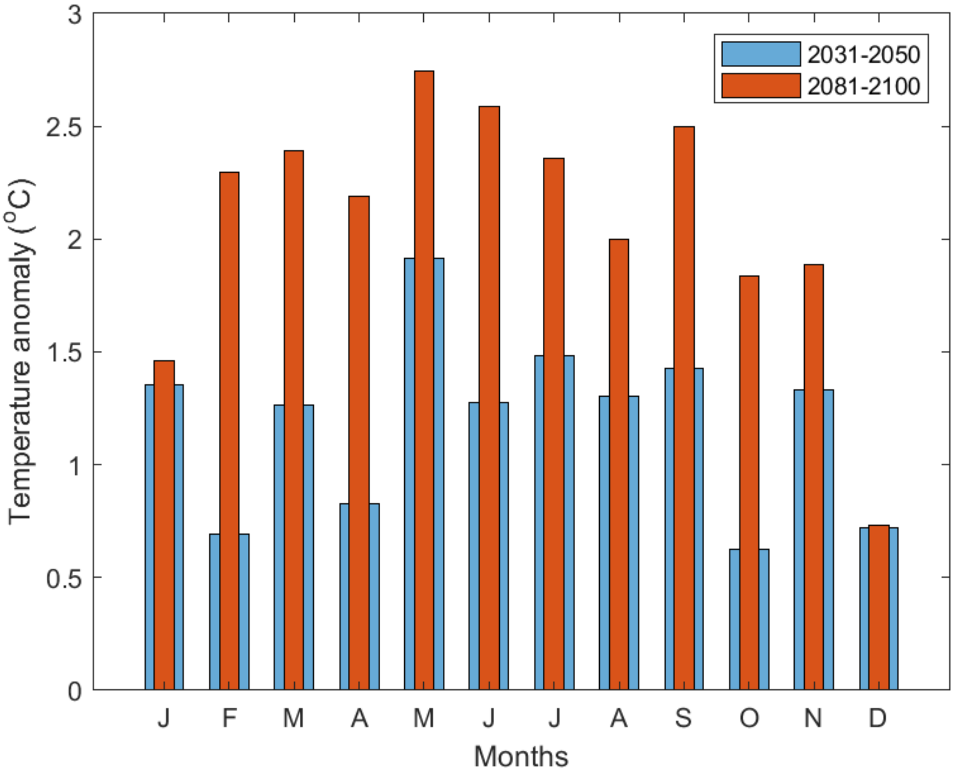

Figure 16: Mean monthly temperature anomalies of the RCA model for the RCP4.5 scenario (Delphi)

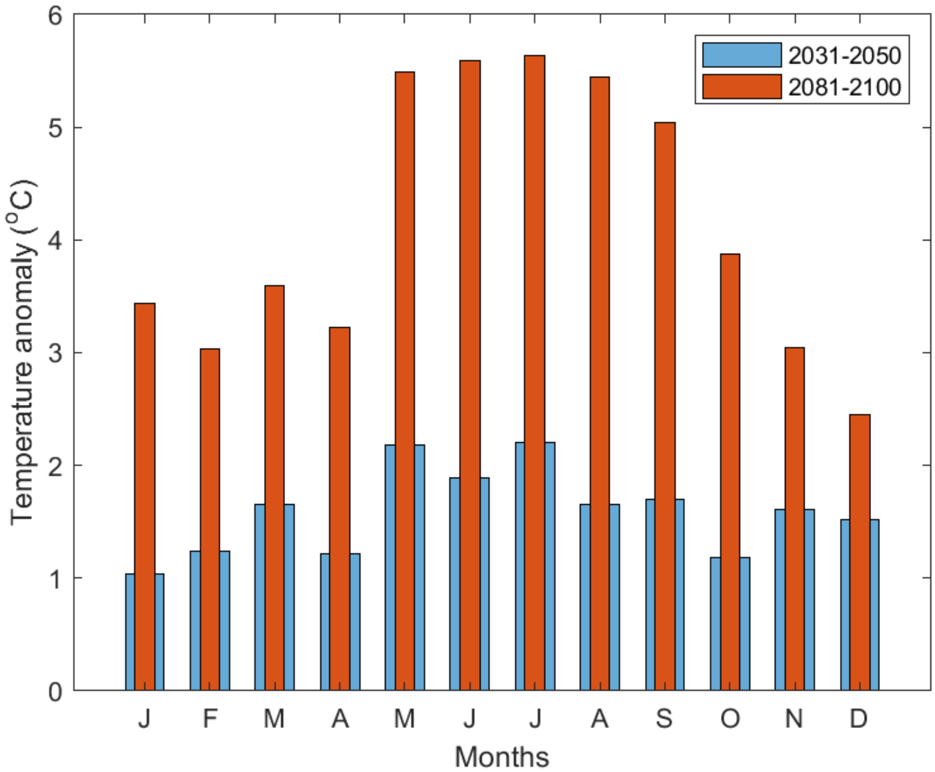

Figure 17: Mean monthly temperature anomalies of the RCA model for the RCP8.5 scenario (Delphi)

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For Meteora, under the RCP4.5 scenario, temperature anomalies increase from 1-1.5°C in the near future (2031-2050) to 2-2.8°C in the far future (2081-2100), with the largest anomalies occurring from May to July (Figure 18). Under the RCP8.5 scenario, the anomalies rise more sharply, from 2-3°C in the near future to 4.5-6°C in the far future, with the highest peaks in May and June (Figure 19).

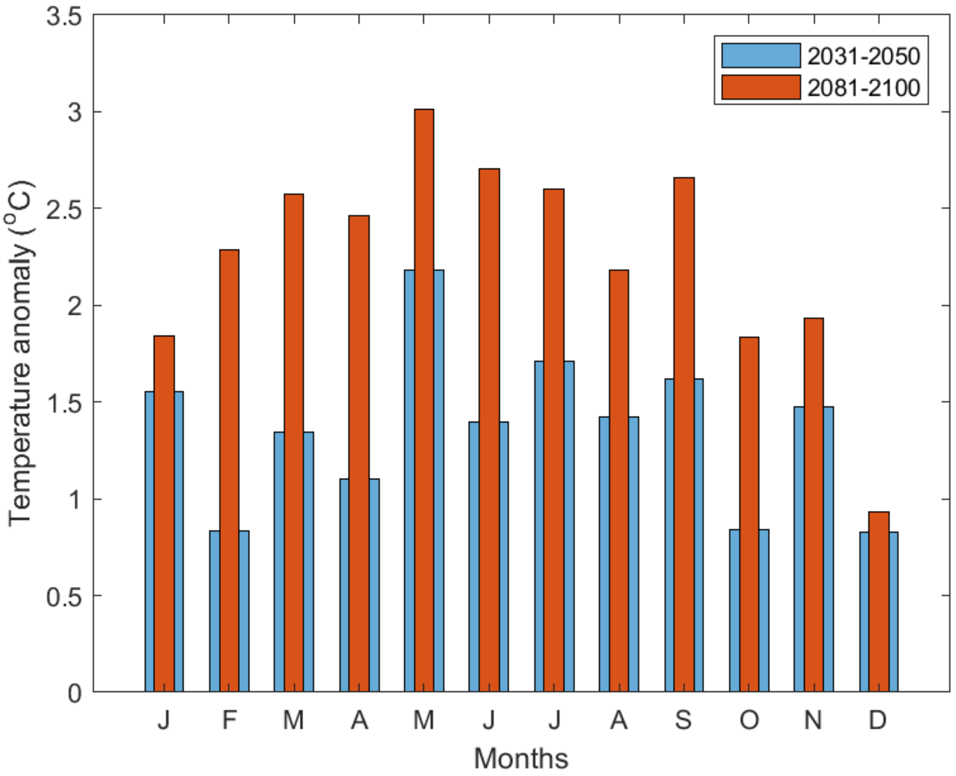

Figure 18: Mean monthly temperature anomalies of the RCA model for the RCP4.5 scenario (Meteora)

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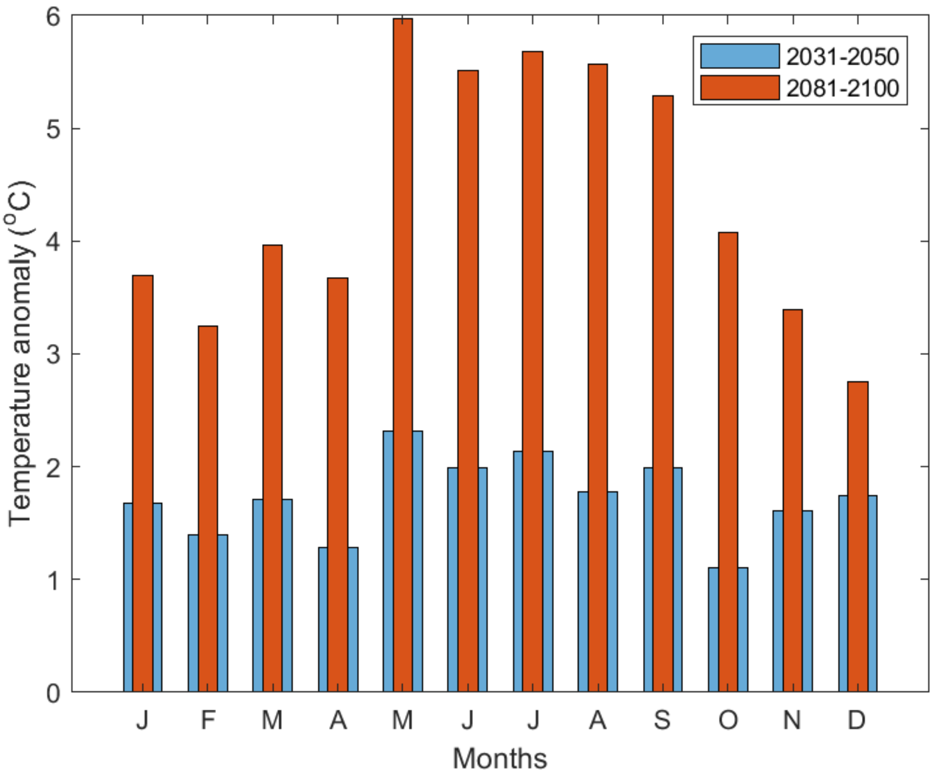

Figure 19: Mean monthly temperature anomalies of the RCA model for the RCP8.5 scenario (Delphi)

A similar approach was followed for precipitation. Beginning with KNMI, for Delphi, under RCP4.5, positive precipitation anomalies are found in January-February (up to 60%) and negative anomalies in July (down to -60%) towards the far future (Figure 20). Under RCP8.5, early months remain wetter, but summer shows clear reductions (up to -80% in July-August) (Figure 21).

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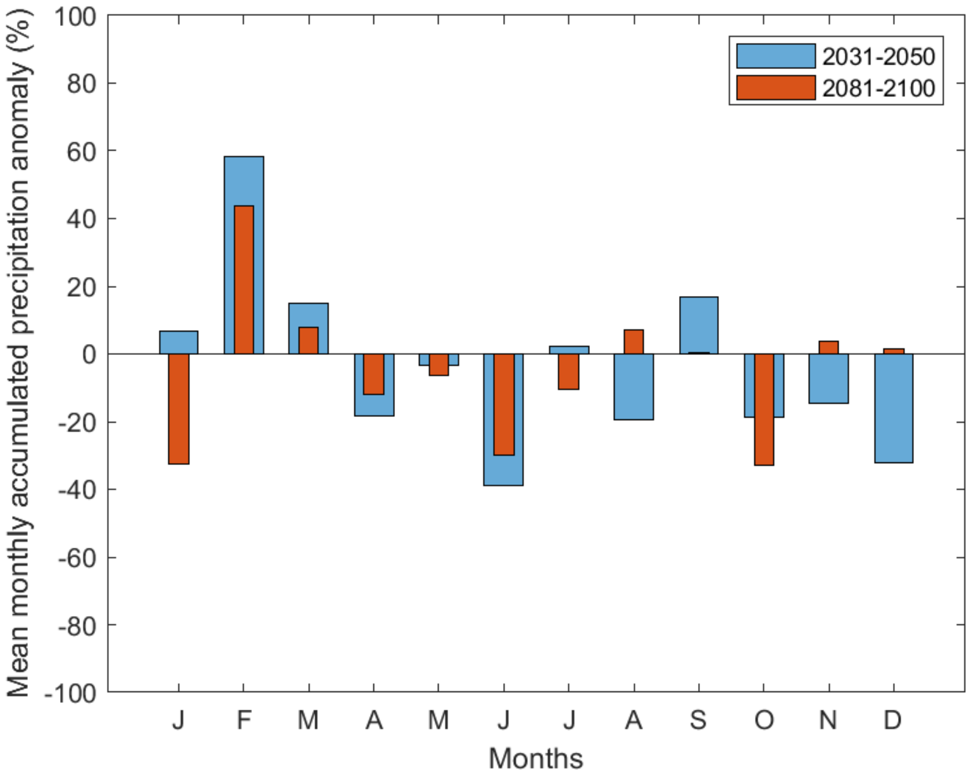

Figure 20: Mean monthly accumulated precipitation anomalies of the KNMI model for the RCP4.5 scenario (Delphi)

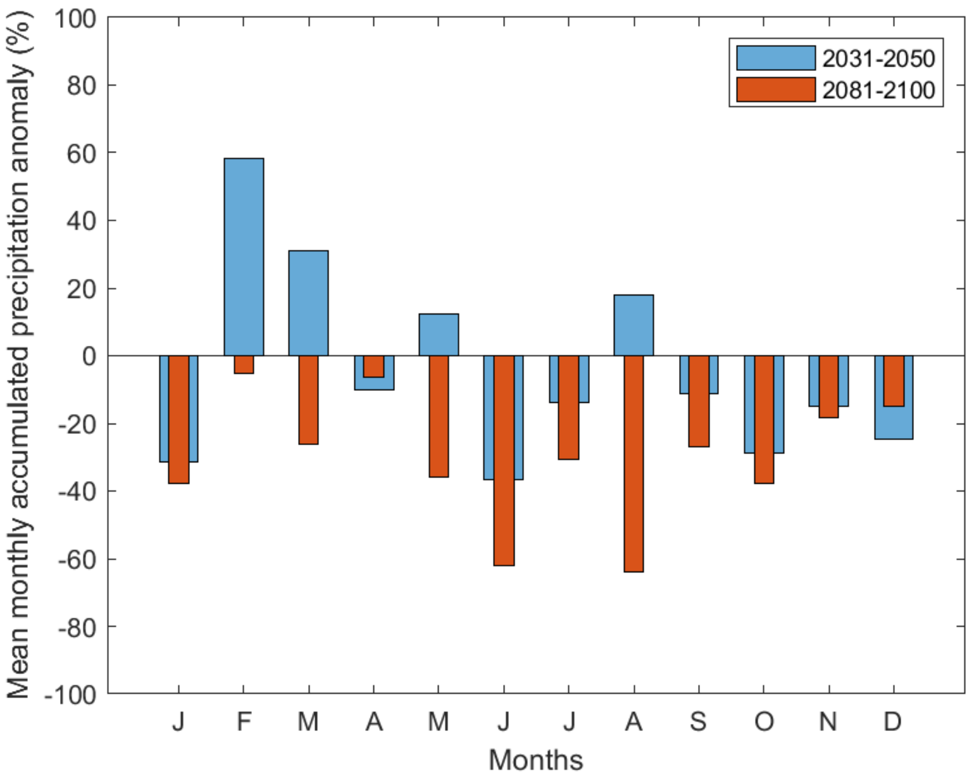

Figure 21: Mean monthly accumulated precipitation anomalies of the KNMI model for the RCP8.5 scenario (Delphi)

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For Meteora, under RCP4.5, the KNMI model resulted in positive precipitation anomalies in February and March (up to 50%), but strong negative anomalies in July and December (down to -60%) (Figure 22). Under RCP8.5, February and March show smaller increases, while July experiences reductions up to -80% by the far future (Figure 23).

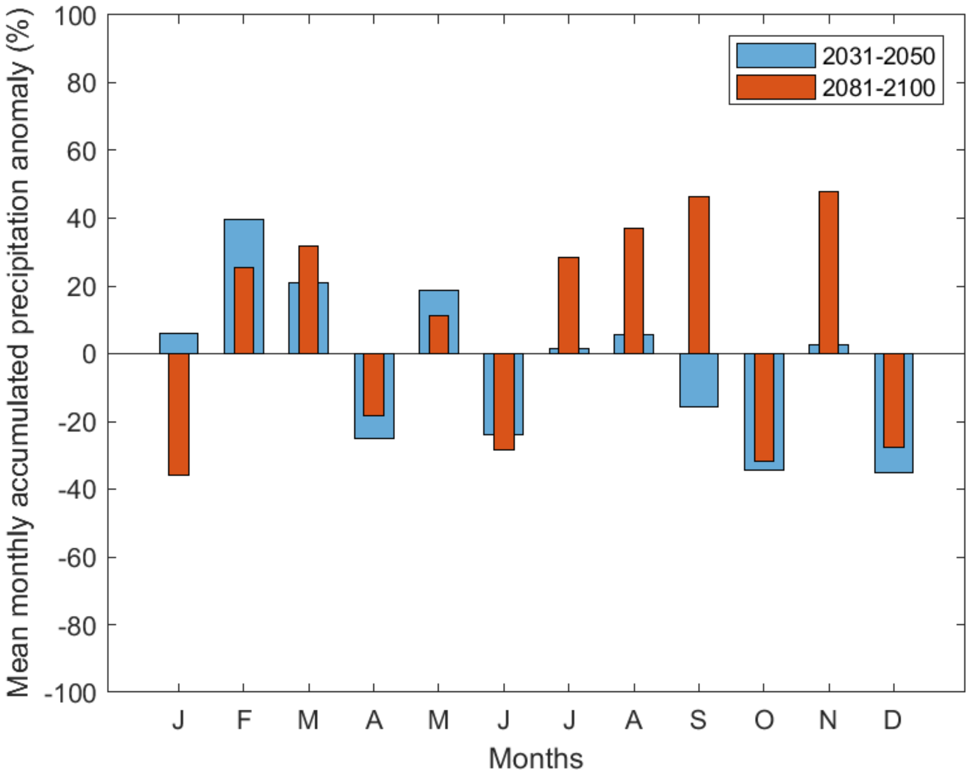

Figure 22: Mean monthly accumulated precipitation anomalies of the KNMI model for the RCP4.5 scenario (Meteora)

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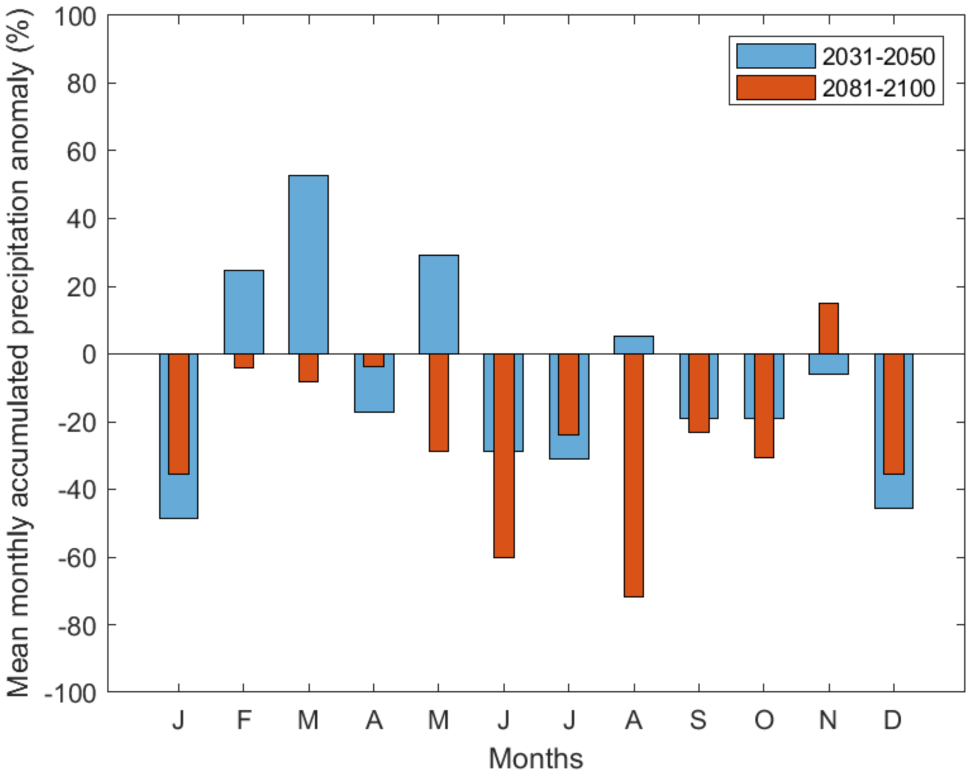

Figure 23: Mean monthly accumulated precipitation anomalies of the KNMI model for the RCP8.5 scenario (Meteora)

Focusing on the RCA model output for Delphi, under the RCP4.5 scenario, the near future (2031-2050) shows positive precipitation anomalies in June to August, with July peaking at around 60% (Figure 24). However, by the far future (2081-2100), the model projects significant negative anomalies, especially in July, which sees a decrease of almost -80%. Under the RCP8.5 scenario, similar trends appear, with positive anomalies in the near future and substantial reductions in the far future, particularly during summer months (Figure 25).
Comparing the two models, the KNMI model also shows positive anomalies in early summer for the near future, but the increases are less significant than in RCA. In the far future, both models indicate a drying tendency, though RCA projects more extreme reductions, especially in July.

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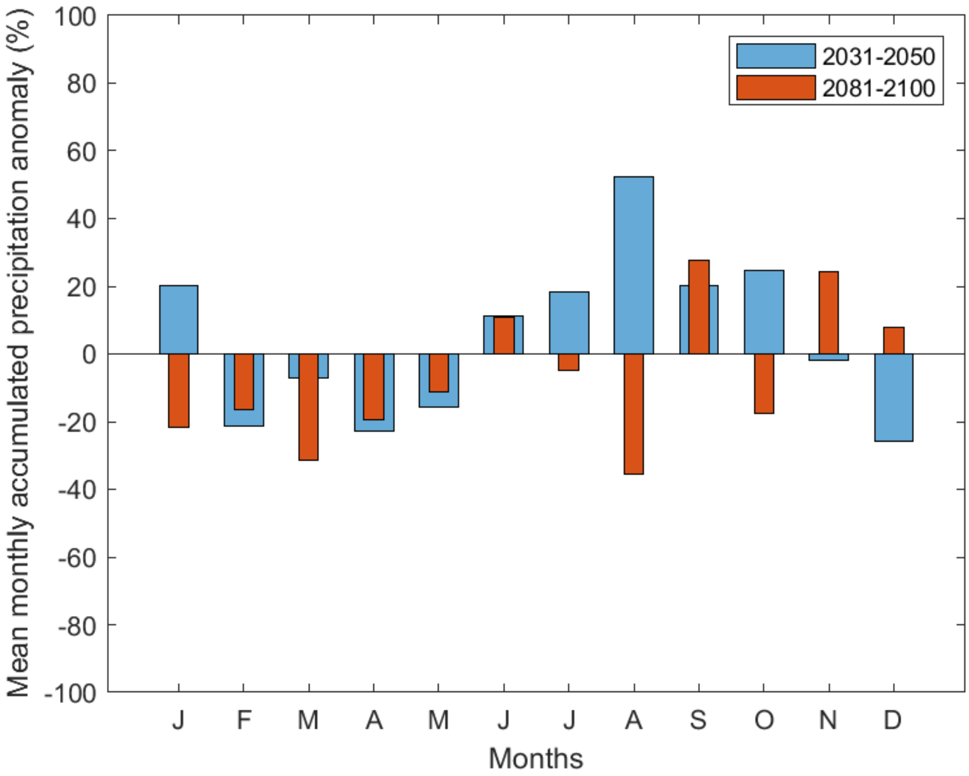

Figure 24: Mean monthly accumulated precipitation anomalies of the RCA model for the RCP4.5 scenario (Delphi)

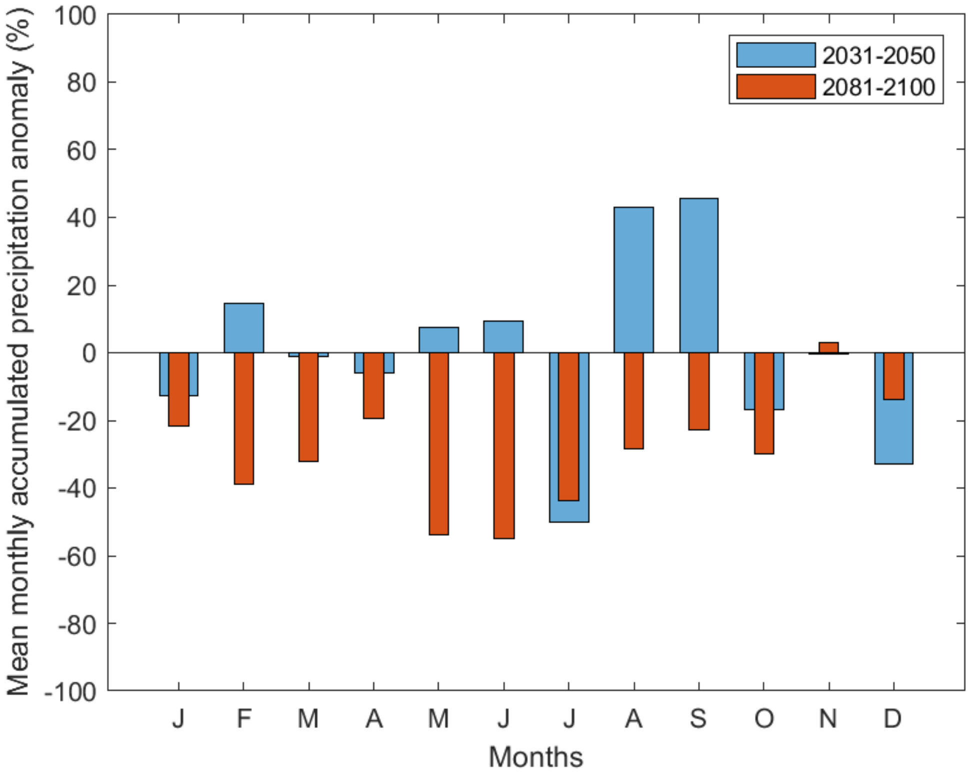

Figure 25: Mean monthly accumulated precipitation anomalies of the RCA model for the RCP8.5 scenario (Delphi)

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Focusing on Meteora, under the RCP4.5 scenario, the near future (2031-2050) shows mild positive precipitation anomalies in August and September, but in the far future (2081-2100), significant negative anomalies are projected (especially in July) (Figure 26). For the RCP8.5 scenario, the near future also shows similar increases during August, but the far future exhibits more severe reductions, particularly during summer months (Figure 27). In comparison to the KNMI model, the RCA model tends to show more significant drying tendencies during the summer months in the far future.

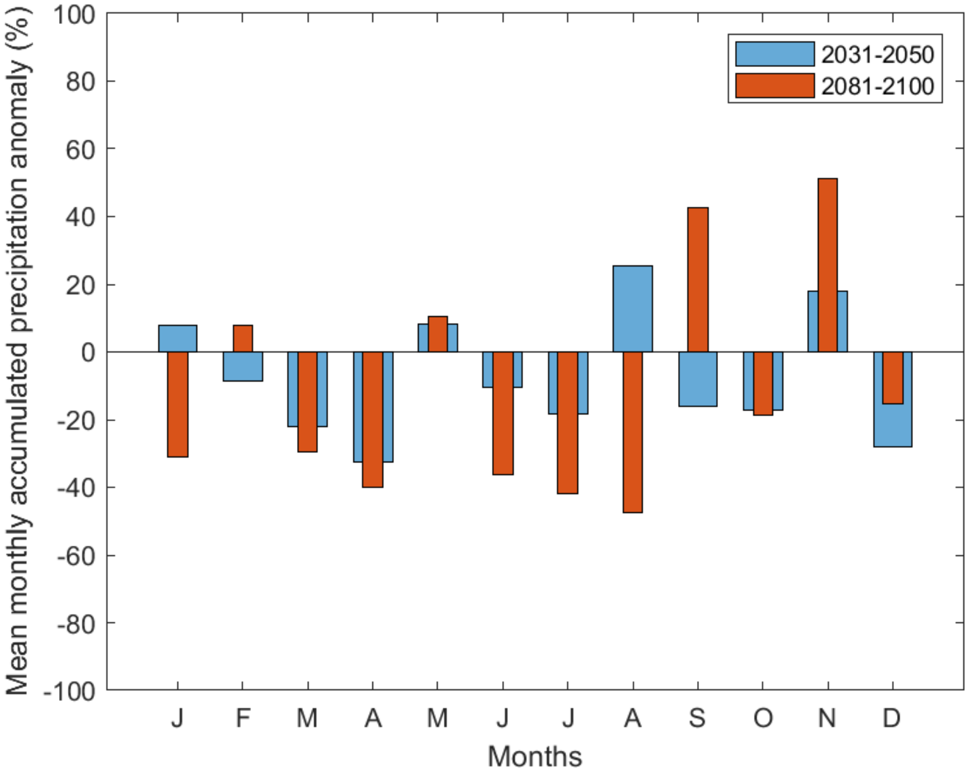

Figure 26: Mean monthly accumulated precipitation anomalies of the RCA model for the RCP4.5 scenario (Meteora)

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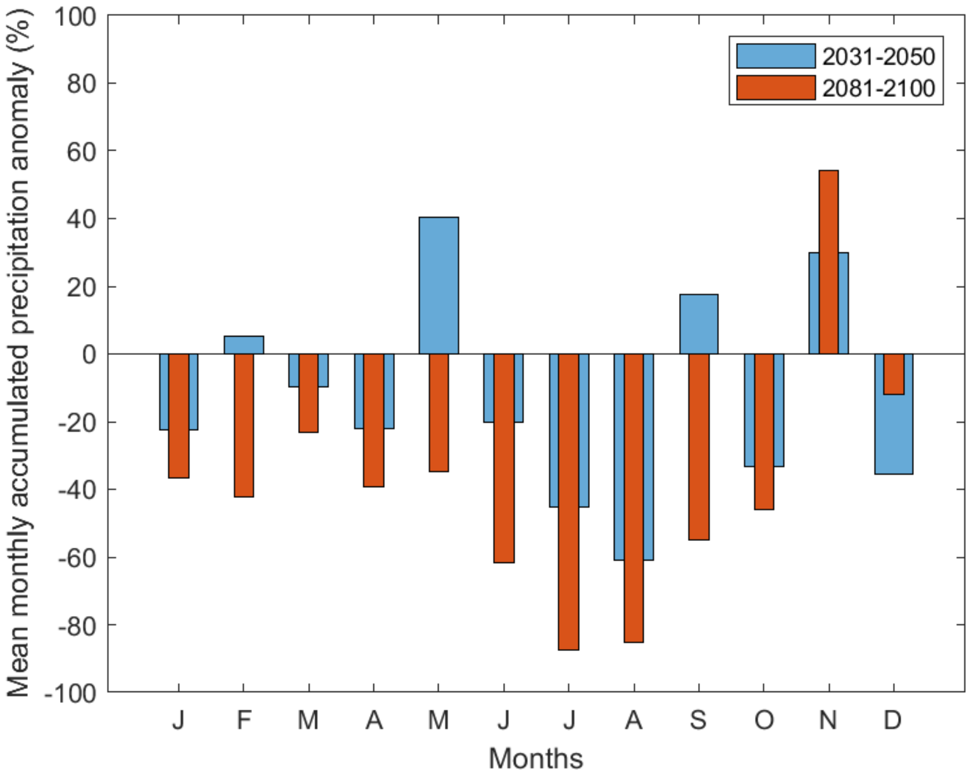

Figure 27: Mean monthly accumulated precipitation anomalies of the RCA model for the RCP8.5 scenario (Meteora)

In addition to the anomalies analysis, an additional analysis was conducted based on several extreme indices:

- **Mean Consecutive Dry Days**: This index measures the average number of consecutive days with no significant precipitation (threshold=1 mm), which is useful for understanding drought risk and dry spell frequency.
- **Mean Consecutive Wet Days**: This index calculates the average number of consecutive days with significant precipitation (threshold=1 mm), indicating how often prolonged wet periods occur.
- **SDII (Simple Daily Intensity Index)**: SDII represents the average precipitation intensity on wet days, giving insight into the typical strength of rainfall on days where it occurs.

The extreme precipitation indices reveal significant variations in climate patterns across different scenarios and regions. In Delphi, the KNMI model projects a decrease in consecutive dry days (CDD) under the RCP4.5 scenario, from 53.2 (per year) in the historical period to 43.5 (per year) by the end of the century. However, under RCP8.5, CDD reaches 56.8, indicating persistent dry conditions. The consecutive wet days (CWD) increase slightly under RCP4.5 but decrease under RCP8.5, while the simple daily intensity index (SDII) shows minor increases across both scenarios. Similarly, in Meteora, CDD trends diverge between scenarios, with RCP4.5 predicting a gradual rise and RCP8.5 projecting an increase to 71.05 by 2100. In contrast, the RCA model for Delphi suggests milder variations, with relatively stable CDD values under RCP4.5 but an increase under RCP8.5. Meanwhile, Meteora sees a high rise in

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CDD under RCP8.5, reaching 92.75 days. Across both locations, the SDII metric shows moderate increases, implying that when precipitation does occur, it may be more intense, even as overall wet periods decline, especially under RCP8.5 (Tables 2-5).

Table 1: Extreme precipitation indices (KNMI – Delphi)

	CDD	CWD	SDII
Historical (1981-2005)	53.2	8.1	7.87
RCPP4.5 (2031-2050)	43.95	8.55	8.32
RCPP4.5 (2081-2100)	43.5	9.35	8.47
RCPP8.5 (2031-2050)	45.25	8.05	8.18
RCPP8.5 (2081-2100)	56.8	7.95	8.07

Table 2: Extreme precipitation indices (KNMI – Meteora)

	CDD	CWD	SDII
Historical (1981-2005)	47.5	8.6	6.65
RCPP4.5 (2031-2050)	48.8	6.55	6.82
RCPP4.5 (2081-2100)	51.2	7.5	7.23
RCPP8.5 (2031-2050)	46.1	7.45	6.77
RCPP8.5 (2081-2100)	71.05	6.05	7.05

Table 3: Extreme precipitation indices (RCA – Delphi)

	CDD	CWD	SDII

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Historical (1981-2005)	39.24	9.4	10.44
RCPP4.5 (2031-2050)	39.5	8.5	10.39
RCPP4.5 (2081-2100)	43.25	8.1	10.65
RCPP8.5 (2031-2050)	36.35	7.4	11.14
RCPP8.5 (2081-2100)	44.75	6.25	10.51

Table 4: Extreme precipitation indices (RCA – Meteora)

	CDD	CWD	SDII
Historical (1981-2005)	69.4	6.4	7.12
RCPP4.5 (2031-2050)	67	5.8	6.59
RCPP4.5 (2081-2100)	82.95	4.9	7.42
RCPP8.5 (2031-2050)	67.8	6.4	7.26
RCPP8.5 (2081-2100)	92.75	5.05	7.17

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5. Conclusions

The current analysis is focused on the development of advanced models to assess the impact of natural and man-made hazards on archaeological sites in Greece, particularly Delphi and Meteora. Through a comprehensive analysis of past, present and future climate patterns, it has provided critical insights into the environmental threats posed by wind, temperature and precipitation changes on these cultural heritage sites.

The analysis of wind patterns revealed dominant directions from the north-northeast and west-southwest in Delphi, with extreme wind speeds exceeding 20 m/s, while in Meteora, the dominant directions were north-northeast and south-southwest, with lower extreme wind speeds reaching 15 m/s. These wind patterns are influenced by regional climatic factors and the topography of each site, with higher wind speeds posing risks to the structural integrity of ancient monuments.

Temperature analysis for both sites shows a typical Mediterranean seasonal pattern, with peak temperatures reaching 25°C in Delphi and 24°C in Meteora during the summer months. Such high temperatures can affect the materials. Precipitation patterns also demonstrate strong seasonality, with wetter winters and drier summers. Both Delphi and Meteora experiences the highest precipitation in December. Heavy rainfall can contribute to the degradation of archaeological structures through processes like erosion.

Future projections using the KNMI and RCA models under the RCP4.5 and RCP8.5 scenarios indicate a significant rise in temperature, with anomalies reaching up to 5°C by 2100 under the high-emissions scenario (RCP8.5). This increase will accelerate the effects of thermal stress on the sites, especially during the summer months. Precipitation patterns are also expected to shift, with reductions in summer rainfall of up to 80% under RCP8.5.

Overall, the findings underscore the increasing vulnerability of Greece's archaeological heritage to climate change. The analysis performed provides the essential data to policy makers and stakeholders into organizing tailor-made mitigation strategies that can help preserve these culturally and historically significant sites in the face of a changing climate.

6. References

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