18th International Conference on Environmental Science and Technology

Athens, Greece, 30 August to 2 September 2023

Dynamical downscaling of medium- and short-term climate series for assessing climate impacts on a world heritage site

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Abstract The present work utilizes forecast models to dynamically downscale climatic series by performing high-resolution atmospheric simulations for the area of Dion, Pieria (Greece). The study area was selected due to the presence of an outdoors world heritage site that is exposed to hazards connected to extreme weather events and climate change. The site is situated in a coastal area and therefore is strongly influenced by wind flows originating from the sea. Convective precipitation exacerbates corrosion by enhancing the wet deposition of reactive species and meteorological factors can also cause fading and deterioration on stone monuments. Climate data used in the frame of the present analysis were downscaled from a low resolution down to a fine grid of 500 m, adequate to resolve local topography-induced flow and thermal phenomena. This approach aimed to validate and intercompare the performance of the two mesoscale models in simulating local flow and thermal effects at a very high resolution. While both models appear able to capture the local structures directly caused by the overlying synoptic circulation, notable differences are expected in the simulation of thermally induced flows, including sea- and land-breeze as well as cloud effects under strongly convective conditions.

Keywords: mesoscale meteorological models, dynamical downscaling, heritage site, extreme events

1. Introduction

This approach focuses on the methods, approaches and techniques utilized in order to prepare and deliver a set of appropriate indicators for climate impacts on the area of a cultural heritage structure. The general idea for the present approach is based on the analysis of climate impacts conducted for the cultural heritage area of Dion. The obtained information will be employed in determining site-specific harshness criteria as regards climate stressors. The meteorological parameters used in the framework of the present analysis are the ambient temperature and the precipitation. Additional variables, such as relative humidity, wind speed and wind direction will be employed for the overall analysis of the site at a later stage, using the same techniques presented herein.

2. Methods

2.1. Study area

The examined cultural heritage site is in Dion, which was an important religious center in ancient Greece and today it is a popular tourist attraction, possessing an inestimable value. The site is in the northern foothills of Mount Olympus, the highest mountain in Greece. The topography of Dion and its surroundings have a significant influence on the local climate conditions, particularly with regards to temperature, humidity, and wind patterns.

The surrounding area is characterized by a complex topography, with steep slopes and valleys that create a range of microclimates and environmental conditions. The site of Dion itself is situated on a relatively flat area at an elevation of approximately 15 meters above sea level and is bounded by the Vaphyras River to the west and the Pierian Mountains to the east. Vaphyras creates local breezes and increases humidity levels in the surrounding area. Also, there is a high occurrence of surface and groundwater, and after heavy rainfall Vaphyras overflows, covering parts of the monument site. The Pierian mountains provide a barrier to cold northerly winds. The steep slopes of the Mountains create shading and cooling effects on the site during the early morning and late afternoon, while the relatively flat area of the site may be subject to more direct sunlight and higher temperatures during the middle of the day. Moreover, the site is in a valley between the Pierian Mountains and the Olympus Range, which creates local breezes and wind patterns that influences the local climate of Dion. In addition, the prevailing winds in the region are generally from the north and west, with occasional southerly winds from the Mediterranean.

Dion is located near the coast of the Aegean Sea, which is part of the Mediterranean Sea. Coastal areas tend to have higher humidity levels, while inland areas can be drier. The site is a few kilometers inland from the Aegean Sea, and as a result, experiences lower humidity levels compared to coastal areas. Thus, the site is affected by coastal climate conditions, such as sea breezes, high humidity levels, and occasional storms. Sea breezes are winds that blow from the sea towards the land during the day and have a cooling effect on the local temperature. However, they can also bring moisture and sea salt, which may affect the site's buildings and structures. High humidity levels that exist due to the presence of the Aegean Sea, can also contribute to the deterioration of stone structures and increase the risk of biological growth. In addition, the proximity of the sea influences the overall climate of the region, particularly with regards to temperature and precipitation patterns. Dion has a Mediterranean climate, characterized by mild, wet winters and hot, dry summers. The area receives most of its precipitation during the winter months, with the summer months being mostly dry. The average daily temperature in Dion ranges from around 8°C in January to 28°C in July, with occasional heatwaves bringing temperatures well above 30°C. The site also experiences diurnal temperature variations, with cool temperatures in the early morning and late evening, and warmer temperatures during the middle of the day.

2.2. Extreme climate indices

The core set of the 27 descriptive indices of extremes defined by the Joint CCl/CLIVAR/JCOMM Expert Team on Climate Change Detection and Indices (ETCCDI; URL1) are separated into two distinctive categories, more specifically those related to ambient temperature and those referring to precipitation. Out of the full set of 27 indicators, only the following ten indicators provide information relevant to the application in cultural heritage site:

Temperature indices

- FD: count of days where TN (daily minimum temperature) < 0 ℃. Calculation steps: Let TN_{ij} be the daily minimum temperature on day i in period j. Count the number of days where $TNij < 0\ °C$.

- ID: count of days where TX (daily maximum temperature) < 0 ℃. Calculation steps: Let TX_{ij} be the daily maximum temperature on day i in period j. Count the number of days where $TXij < 0\ °C$.

- TXx: monthly maximum value of daily maximum temperature (TX). Calculation steps: Let TX_{ij} be the daily maximum temperature on day i in period j. The j represents the total number of days in a month and then the monthly maximum value in period j is $TXx = max(TXij)$.

- TNn: monthly minimum value of daily minimum temperature (TN). Calculation steps: Let TN_{ij} be the daily miniimum temperature on day i in period j. The j represents the total number of days in a month and then the monthly minimum value in period j is $TNn = min\ (TNij)$.

- DTR: mean difference between TX and TN (℃) Calculation steps: Let TX_{ij} and TN_{ij} be the daily maximum and minimum temperature on day i in period j. If I represents the total number of days in j then the mean diurnal temperature range in period j is $DTRj = sum\ (TXij - TNij)/I$.

Precipitation indices

- RX1day: highest precipitation amount in one-day period. Calculation steps: Let RR_{kj} be the precipitation amount for the one-day interval k in period j, where k is defined by the last day. The maximum one-day values for period j are $RX1dayj = max\ (RRkj)$.

- SDII: annual total precipitation amount divided by the number of wet days in the year. Calculation steps: Let P be the total precipitation amount over the year and WD be the number of wet days (defined as $PR \geq 1mm$) in the year, so: $SDII = P/WD$.

- CDD: maximum number of consecutive days with $PR < 1mm$. Calculation steps: Let $C_1, C_2, C_3, ..., C_N$ represents the length of consecutive dry periods each of which is defined as a period of continuous days with precipitation less than 1 mm, so: $CDD = max\{C1, C2, C3, ..., CN\}$

- CWD: maximum number of consecutive days with $PR \geq 1mm$. Calculation steps: Let $C_1, C_2, C_3, ..., C_N$ represents the length of consecutive wet periods each of which is defined as a period of continuous days with precipitation greater than or equal to 1 mm, so: $CWD = max\{C1, C2, C3, ..., CN\}$

- PRCPTOT: annual total precipitation in wet days ($PR \geq 1mm$). Calculation steps: Let P represents the precipitation amount on each wet day, which is defined as a day with precipitation greater than or equal to 1 mm so: $\sum P$.

3. Results

3.1. Trend analysis

Table 1 summarizes the temperature-related indicators for the site of Dion. The most prominent trend visible in the future under the RCP4.5 scenario is the reduction of frost days (FD) by almost a half and the elimination of icing days (ID) to one-fourth, compared to the 1970-2005 period. TXx and TNn (°C) show an increasing trend (almost 2.5 °C) in both maximum and minimum temperatures. All above indices indicate a general increase in temperature, which is of great importance as low temperatures have a negative impact on the materials of the monument. The diurnal temperature range mean values (DTR) has a relative high value, as the area of Dion is characterized by large temperature fluctuations. This indicator shows little variation in terms of period averages.

Table 1. ETCCDI temperature-related indicators for the site of Dion

Period	FD	ID	TXx	TNn	DTR
1970-2005	2864	408	20.9	-0.3	9.16

2006-2040	2144	286	22.5	1.1	9.35
2041-2070	1527	150	23.2	2	9.32
2071-2100	1563	118	23.3	2.2	9.42

In Table 2, the precipitation-related indicators are presented. The RX1day (mm) values are high because it experiences high precipitation amounts and extreme weather events, such as heavy rainfall, which are characteristic of the region. This indicator shows a significant decrease by almost half, compared to the 1970-2005 period. The CDD extreme indicator shows an increase in consecutive dry days that are under 1 mm while the CWD indicator demonstrates a reduction in consecutive wet days that are greater or equal to 1 mm. The daily SDII (mm/day) precipitation index shows a nuanced pattern of changes in precipitation intensity. The annual total precipitation in each period with precipitation greater or equal to 1 mm is presented by PRCPTOT (mm) indicator which suggests a decreasing trend in the total amount of precipitation by almost half.

Table 2. ETCCDI precipitation-related indicators for the site of Dion

Period	RX1 day	SDII	CDD	CWD	PRC PTOT
1970-2005	366.83	11.95	87	18	36.10
2006-2040	208.47	9.721	86	13	21.70
2041-2070	206.49	11.24	96	12	20.43
2071-2100	183.01	10.51	93	15	18.14

The monthly variation of diurnal temperature range (DTR) presents a clear trend of increasing variability throughout the simulation period of 2005-2100 (Figure 1). The estimated slope of the trend line is: $1.65 \times 10^{-6} \pm 4.51 \times 10^{-6}$. The diurnal temperature range (Table 1) shows little variation indicating unstable and potentially unpredictable behaviour of diurnal temperature cycles even though the averages remain constant.

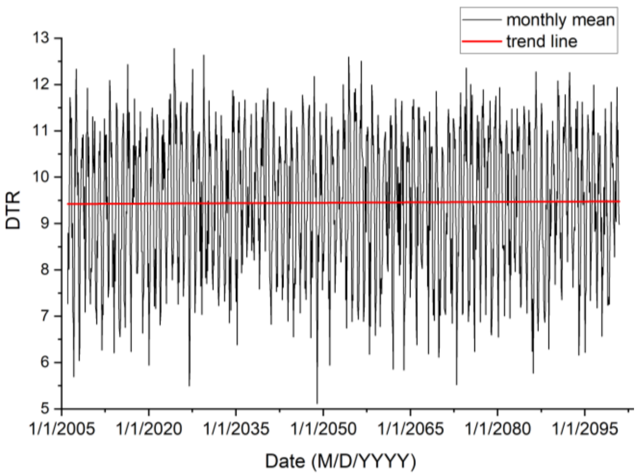

Figure 1. Time series of monthly DTR for the site of Dion.

The following time series (Figure 2) of monthly maximum values of TXx index shows a significant trend of increasing throughout the simulation period of 2005-2100. The estimated slope of the trend line is: $4.5 \times 10^{-5} \pm 2.41 \times 10^{-5}$. Since the slope is positive and has a high value, it means that there is a clear increasing trend. This suggests that the local weather patterns will be impacted, leading to an increase in the overall temperature of the study area.

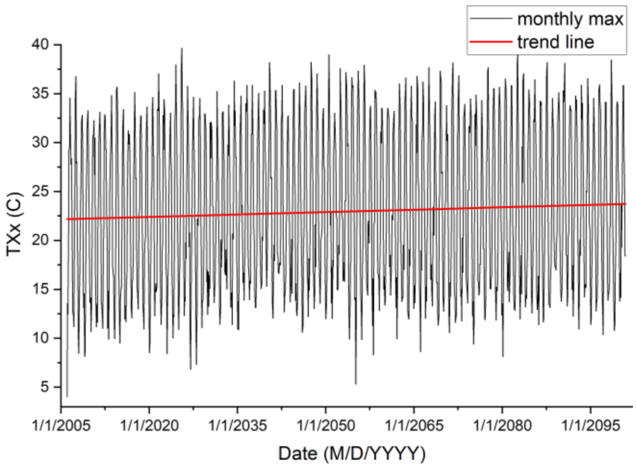

Figure 2. Time series of monthly TXx for the site of Dion.

The time series of annual mean values (Figure 3) of SDII index shows that there is a decreasing trend throughout the simulation period of 1970-2100. The estimated slope is: $-3.36 \times 10^{-5} \pm 1.77 \times 10^{-5}$.

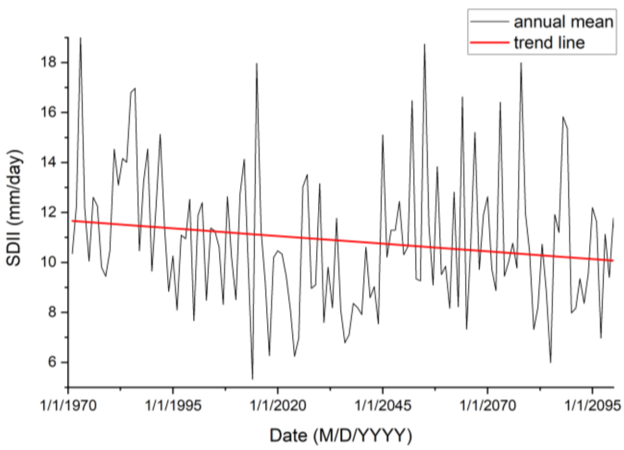

Figure 3. Time series of annual SDII for the site of Dion.

The time series of daily mean values (Figure 4) of PRCPTOT index shows that there is a decreasing trend throughout the simulation period of 1970-2100. The estimated slope is: $-3.27 \times 10^{-5} \pm 4.01 \times 10^{-6}$. A decrease in the SDII and PRCPTOT indices indicates a reduction in both the overall amount of precipitation and the intensity of extreme rainfall events. These changes in local climate conditions may also impact the vegetation surrounding the monument, which in turn could affect soil moisture levels and erosion patterns. It is therefore evident that the long-term primary and secondary hydrological effect of these reductions on the total flood hazard needs to be further investigated.

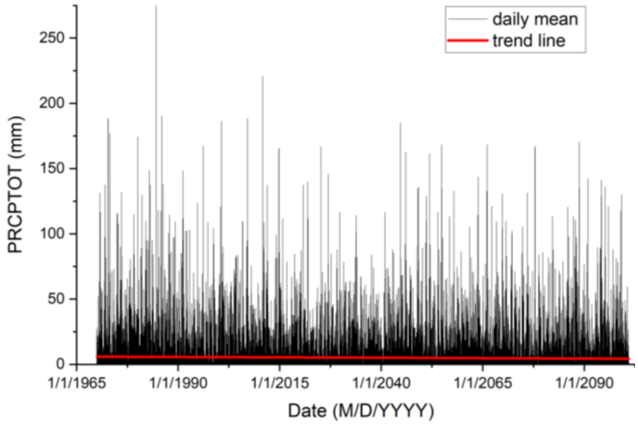

Figure 4. Time series of daily PRCPTOT for the site of Dion.

4. Conclusions

This paper aimed to provide qualitative and quantitative assessment on the relevance of primary and secondary impact indicators derived from climate calculations based on historical data and future climatic scenarios. A set of 10 ETCCDI indices, selected to represent the most relevant atmospheric stressors for cultural heritage were calculated based on a GCM to RCM downscaling approach, as implemented within the EURO-CORDEX project, covering a period from 1970 to 2100. The RCP4.5 emissions scenario was used for future predictions, representing a medium-situation estimate with regards to climate change mitigation. The meteorological indicators considered in this analysis are related to averages and extremes of ambient temperature and precipitation. Results were presented in the form of tabulated index values for four intervals, starting from 1970 and ending to the end of the century, as well as with graphical representations of some of the corresponding time series. Regarding thermal effects, one of the most consistend predicted trend throughout the simulation period is a decrease in the number of frost days (by almost half) and icing days (to one-fourth). This projected change would of course severely affect the freezing-thawing cycles of the monument as well as the seasonal patterns of surface growths an local microflora. Another prominent trend is the increase in maximum and minimum temperatures, as well as the decrease in precipitation amount and the number of wet days. These changes have an impact on the vegetation surrounding the monument, which in turn, could affect soil moisture levels and erosion patterns. Together with return intervals and estimation of absolute extremes these results provide strong indicators on the frequency and magnitude of effects that long-term planning should take account of.

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