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Climate change and extremes in the Mediterranean island of Cyprus: from historical trends to future projections

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Abstract

Cyprus is a European island state in the eastern Mediterranean climate change hotspot. Despite being a relatively small island, it has diverse climatic zones, ranging from semi-arid to subhumid in the mountains and humid on Mount Olympos. Given the accelerated rate of environmental change in the region, the present study aims to identify, and update observed trends of critical climate parameters, highlighting vulnerable climatic areas within the island. Moreover, since nationwide multi-model assessments of future climate conditions are limited or outdated, we aim to investigate the range of future climate projections using a 21-member EURO-CORDEX ensemble under pathways RCP2.6 and RCP8.5. Besides mean conditions, we analyze various extreme climate indicators relevant to socio-economic activities such as agriculture, biodiversity, tourism, energy and water resources. Our historical analysis revealed a statistically significant increasing temperature trend (0.4 °C–0.6 °C per decade), which is more pronounced during the summer and spring. Concerning precipitation, the observed trends are not as robust, nevertheless, the southeastern coast and the central regions near the capital city of Nicosia are substantially drier and more prone to further changes in precipitation regimes. The projections for the end of the 21st century, according to the high radiative forcing scenario (RCP8.5), indicate that Cyprus is likely to experience an annual temperature increase of over 4 °C and an approximate 20%–30% reduction in annual rainfall, relative to 1981–2000. These projections highlight an alarming trend that requires urgent attention and proactive measures to mitigate the potential impacts of climate change on the island.

1. Introduction

According to climate reconstructions and observational records, the eastern Mediterranean currently experiences the warmest and driest conditions of at least the last 500 years (Lelieveld *et al* 2012, Cook *et al* 2016). Particularly over the last four decades, regional warming has accelerated, surpassing global warming rates (0.45°/decade versus 0.27°/decade) (Zittis *et al* 2022, Urdiales-Flores *et al* 2023). Besides the radiative forcing from anthropogenic activities which is a dominant driver, the warming acceleration in this region is also driven by recent declining aerosol trends and soil moisture decreases that can impact land-atmosphere interactions (Urdiales-Flores *et al* 2023). These combined drying and warming trends in the eastern Mediterranean will likely continue in the 21st century, but the extent of these changes is quite uncertain and depends on socioeconomic drivers and future greenhouse gas emissions (Zittis *et al* 2019, 2022). The impact of climate change may also result in more frequent or intense extreme weather events, including heatwaves, droughts, and, more rarely, torrential rainfalls and flooding (Spinoni *et al* 2021, Zittis *et al* 2021a, 2021b, Hochman *et al* 2022).

Compared to the mainland, islands are more vulnerable to the impacts of climate change and their adaptive capacity is limited. For instance, inadequate access to resources such as water or energy, dependence on imports

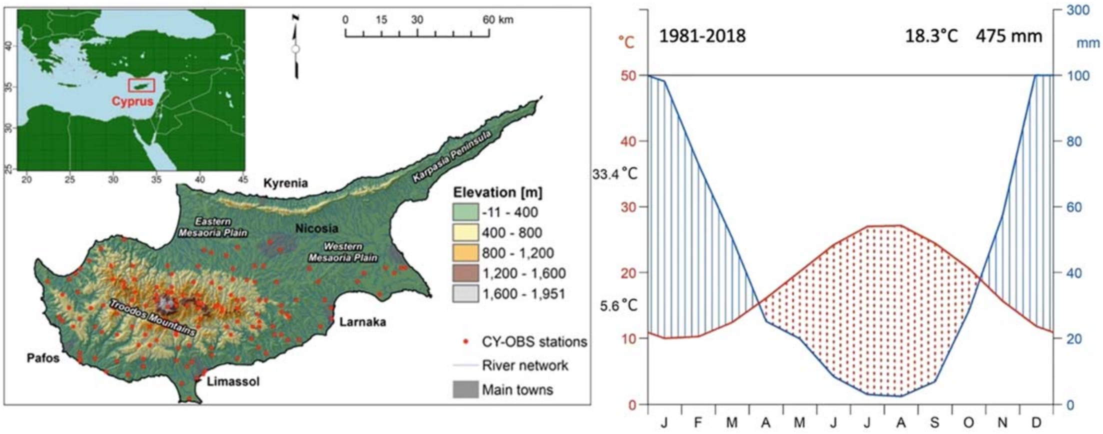

Figure 1. Topographic map of Cyprus and location of the meteorological stations used to create the CY-OBS dataset of gridded meteorological observations—left panel. Ombrothermic diagram (temperature: red curve and precipitation: blue curve) averaged for Cyprus for 1981–2018—right panel.

for food, materials and other essential goods, and limited transportation options are only some of the factors that limit the capacity of islanders to adapt. To develop effective and meaningful adaptation strategies, it is essential to first identify the potential impacts and risks (Linares *et al* 2020, Zagaria *et al* 2023). For Cyprus and other eastern Mediterranean countries, such impact assessments have only recently started to receive attention from the scientific community. The socio-economic sectors that are expected to be impacted most include human health (Heaviside *et al* 2016, Neira *et al* 2023), tourism (León *et al* 2021, Vrontisi *et al* 2022, Monioudi *et al* 2023), agriculture (Adamides *et al* 2020, Markou *et al* 2020, Papadaskalopoulou *et al* 2020, Stylianou *et al* 2020, Moriondo *et al* 2021), water end energy resources (Sofroniou and Bishop 2014, Zachariadis and Hadjinicolaou 2014, Giannakopoulos *et al* 2016, Papadopoulou *et al* 2020, Kiriakidis *et al* 2024), transportation (Zittis *et al* 2023), and ecosystem services (Vogiatzakis *et al* 2023).

Based on the Köppen–Geiger classification system (Kottek *et al* 2006), Cyprus is characterized by a temperate climate with hot and dry summers, while part of the island is classified as hot and arid (Zittis *et al* 2020). Several studies discussed observed trends of climate parameters, mainly temperature and precipitation (Price *et al* 1999, Zhang *et al* 2005, Seyhun and Akıntuğ 2013, Katsanos *et al* 2018, Mathbout *et al* 2018, Hadjinicolaou *et al* 2023, Bey *et al* 2024), however, these are either outdated or are based on a limited number of stations, unevenly spread over the island. According to these studies, the increasing temperature trends are more robust and follow the global or regional average rates. On the contrary, precipitation trends strongly depend on the period of assessment as far as it concerns direction, magnitude and level of significance. Similarly, country-focused future climate assessments are outdated in terms of scenarios or based on single-model studies or small ensembles (Giannakopoulos *et al* 2010, Hadjinicolaou *et al* 2011, Camera *et al* 2017, Zittis *et al* 2020).

Considering the need for a better understanding of past and future climate changes, and any adverse impacts on ecosystems and societies, the objective of the present assessment is to provide an up-to-date analysis of observed variations in the island's climate. We focus on key variables, as well as extreme climate indicators more relevant for impact assessments. Taking all the above into account this study's primary objective is to pinpoint the island's most vulnerable areas to facilitate targeted impact studies. Additionally, recognizing the urgency posed by future changes impacting various socioeconomic sectors, the secondary aim is to conduct a comprehensive analysis of projected climate conditions in Cyprus, thereby identifying associated risks. The results are presented in the form of an informative atlas of future climate projections that provide insights to climate and environmental scientists, impact modellers, stakeholders, and policymakers.

2. Data and methods

2.1. Observations and climate projections

To assess the observed climate trends, we have analyzed the CY-OBS gridded observational dataset (Camera *et al* 2014, Sofokleous *et al* 2021). This dataset is available at a very high spatial resolution of 1 × 1 km. It is derived from a dense network of meteorological stations (figure 1), also considering a variety of topographical parameters, such as elevation, distance from the coast and mountain ridges, slope and orientation. Only meteorological records from the territories controlled by the Republic of Cyprus were considered during the dataset compilation. Thus, our analysis of the historical period is also confined to these areas. The CY-OBS data are available at a daily temporal resolution, and they cover the period from 1981 to 2018. The available parameters are daily maximum (TX), minimum temperature (TN) and precipitation (PRCP).

For assessing future climate conditions, we explored daily temperature and precipitation data from 21 EURO-CORDEX regional climate simulations (Jacob *et al* 2014, 2020), available at a spatial resolution of $0.11 \times 0.11^{\circ}$ (approximately 12.5×12.5 km at these latitudes). The analysis was conducted individually for each model, followed by aggregation to form an equal-weighted ensemble of results. The models included in our ensemble are listed in Supplementary table 1. The assessment spans from 1981 to 2100 and is segmented into four 20-year sub-periods: a historical one for reference climate conditions (1981–2000) and three future periods (2021–2040, 2041–2060, 2081–2100). This selection was made to encompass the near-term, mid-century, and end-of-century projections. These are based on two future scenarios from the Representative Concentration Pathways (RCP) family: RCP2.6, a scenario that aligns closely with the main targets of the Paris Accord, and RCP8.5, a high-emission pathway that more closely resembles what is often described as business-as-usual (Meinshausen *et al* 2011). The large number of these pairs of global and regional climate model runs allows us to account for various types of uncertainty in regional projections (Giorgi and Gutowski 2015), e.g. those related to model construction and representation of physical processes. We have followed the 'one model, one vote' approach, meaning that each ensemble member is equally weighted.

A comparison of the observed climate conditions and the historical data from the EURO-CORDEX ensemble (1981–2005) can be found in Supplementary table 2. The ensemble mean accurately represents the average climate conditions of the island for both temperature and precipitation. The observed trends are also generally well represented, although there is an underestimation of the strong summer warming observed (0.6–0.7°/decade) by the EURO-CORDEX simulations (0.3°/decade).

2.2. Developing climate zones

Cyprus is an area with steep topography and complex coastlines (figure 1). For example, Mount Olympus, the highest peak of the Troodos Mountains has an elevation of 1952 meters above mean sea level. Consequently, distinct climate regimes exist, despite the island's relatively small size. For summarizing and visualizing parts of the results (historical assessment based on high-resolution observations), we applied a multivariate cluster analysis, specifically using Principal Component Analysis (PCA) combined with K-means clustering (Hartigan and Wong 1979). This clustering considers CY-OBS temperature (maximum and minimum) and precipitation to better represent the island's environmental characteristics. As input data, we used monthly, deseasonalized time series of the above-mentioned parameters.

PCA was performed to reduce the dimensionality of our dataset, which included CY-OBS temperature (maximum and minimum) and precipitation data, retaining most of the variability while simplifying the analysis. The Scree Plot criterion was used to determine the number of Principal Components (PCs), identifying the optimal number at the point before the curve flattens. We then applied K-means clustering to the PCA scores, partitioning the observations into clusters with the nearest mean, which allowed us to better represent the island's environmental characteristics and analyze relationships between climatic variables.

2.3. Climate indicators

In addition to the analysis of mean climate conditions, the observed trends and future changes for a wide list of extreme climate indicators have also been explored (Karl *et al* 1999). The trend analysis is based on a generalized linear model (Firth *et al* 1991), while we consider statistically significant the trends with p-values $\leqslant 0.05$.

Our selection includes indicators that characterize various types of extreme events, such as heatwaves, extreme rainfall, and droughts, along with impact-related indicators for sectors relevant to the Cyprus societies, such as agriculture, water, and energy resources management, etc The climate extreme and impact indicators are defined as:

1. **Annual maximum value of daily maximum temperature (TXx):** The maximum value of daily maximum temperature or the hottest day for each year (units: °C).
2. **Annual maximum value of daily minimum temperature (TNx):** The maximum value of daily minimum temperature or the hottest night for each year (units: °C).
3. **Number of summer days (SU):** The annual count of days when TX (daily maximum temperature) is greater than 25 °C (units: number of days per year).
4. **Number of tropical nights (TR):** The annual count of days when TN (daily minimum temperature) is greater than 20 °C (units: number of nights per year).

5. **Warm spell duration index (WSDI):** The annual count of days with at least six consecutive days when TX is greater than the 90th percentile. It is considered an indicative number of heatwave days (units: number of days per year).
6. **Growing Degree Days (GDD):** The annual sum of TM—n, where TM is the mean daily temperature, and n is a user-defined location-specific base temperature. For Cyprus, we used an n value equal to 4 °C, which is within the range used in other eastern Mediterranean locations (Paparrizos and Matzarakis 2017, Gürkan *et al* 2024). It is a measure of heat accumulation to predict plant and animal developmental rates (units: degree days).
7. **Growing season length (GSL):** The annual count between the first span of at least six days with daily mean temperature (TM) greater than 5 °C and the first span after July 1st of six days with TM lower than 5 °C (units: number of days per year). The growing season can be approximated as the period between the average date of the last killing frost in the spring and the average date of the first killing frost in the fall.
8. **Heating Degree Days (HDD18):** The annual sum of (n-TM), where TM is the mean daily temperature, *n* is a user-defined location-specific base temperature, and TM is lower than n. For Cyprus, we used an n value equal to 18 °C. It is considered a measure of the energy demand needed to heat a building (units: degree days).
9. **Cooling Degree Days (CDD22):** The annual sum of (TM-n), where TM is the mean daily temperature, *n* is a user-defined location-specific base temperature, and TM is lower than n. For Cyprus, we used an n value equal to 22 °C. It is considered a measure of the energy demand needed to cool a building (units: degree days). The HDD and CDD temperature thresholds are not universal, nevertheless, the selected values are representative of Cyprus (Zachariadis and Hadjinicolaou 2014, Papakostas *et al* 2020).
10. **Consecutive Dry Days (CDD):** The maximum dry spell length per year or the maximum number of consecutive days with precipitation lower than 1 mm (units: number of days).
11. **Consecutive Wet Days (CWD):** The maximum wet spell length or the maximum number of consecutive days with precipitation greater than 1 mm (units: number of days).
12. **Simple precipitation intensity index (SDII):** The average daily precipitation intensity, defined as the annual total precipitation divided by the number of rainy days, i.e., days with precipitation greater than 1 mm (units: mm/day).
13. **Maximum 1-day precipitation (Rx1day):** The annual maximum value of daily precipitation (units: mm/day).
14. **Number of heavy precipitation days (R20mm):** The annual count of days when precipitation is greater than 20 mm (units: number of days per year).
15. **Number of rainy days (RR1mm):** The annual count of days when precipitation is greater than 1 mm (units: number of days per year).

3. Results

3.1. Developing climate zones

The Scree Plot (figure 2—left panel) shows the results of the K-means clustering and the eigenvalues for each Cluster (Principal Component). This is based on the ombrothermic (temperature/precipitation) characteristics of Cyprus. According to this criterion, we consider that five classes, hereafter referred to as climate zones, are sufficient for spatially representing the climatic features of the island. The resulting climate zones map has several similarities with the topographical map of Cyprus (cf figures 1 and 2) since the distribution of temperature and precipitation strongly rely on the elevation and other topographic characteristics such as the orientation of slopes.

The grid points with the highest altitude are clustered in one class (Climate Zone 1), while the lower-elevation mountainous grids are generally represented by two classes (Climate Zones 2 and 3). The coastal areas (west and south) are grouped in Climate Zone 4, while Climate Zone 5 includes most of the inland plains and southeast coast of the island, which overall receive less precipitation amounts through the course of the year.

3.2. Overview of mean historical climate

The right panel of figure 1 displays the ombrothermic diagram for Cyprus, which summarizes the average climate conditions for the period of CY-OBS availability (1981–2018). The blue curve shows the monthly precipitation, while the red curve shows the monthly mean temperature values. In this type of plot, the blue- and

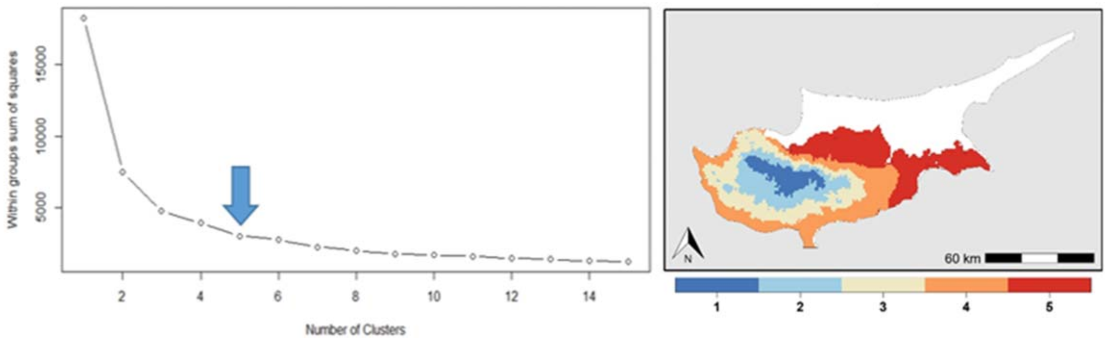

Figure 2. The Scree Plot for deciding the number of representative clusters for Cyprus (left panel) and the results of the K-means cluster analysis, showing the five climate zones (right panel).

red-shaded represent the wet and dry seasons of the year, respectively. Thus, the average annual temperature in Cyprus is 18.3 °C, and the average annual precipitation total is 475 mm. The annual temperature range, derived from the monthly maximum (33.4 °C) and minimum temperature (5.6 °C), is 27.8 °C. The wet season in Cyprus is from mid-October to the end of March, while the rest of the year is considered the dry season. October also coincides with the beginning of the hydrological year (i.e., October to September), according to the water management authorities of the island. From June to September, there is virtually no precipitation, while the mean monthly temperature is the highest. This pattern of minimum summer precipitation and maximum temperature is typical for Mediterranean climate types.

Additionally, the climatological means of TX, TN and PREC for the same period (1981 to 2018) are presented in figure 3 and summarized in table 1. This table also provides statistical properties such as the standard deviation (for temperature) and coefficient of variation (for precipitation) to demonstrate the interannual variability, along with linear trends for each of the five climate regimes defined in section 2.2. According to table 1, the warmest annual temperatures of 25.3 °C are found in Climate Zone 5, mainly over inland plains. These regions experience the highest monthly maximum temperatures in July and August, which are the warmest months of the year, with temperatures reaching near 34 °C. On the other hand, the lowest average annual temperatures of 10 °C are observed in Climate Zone 1 regions in the high-elevation parts of the Troodos Mountains. This is also the case for the minimum and maximum temperatures (figure 3). This climate zone receives the highest average precipitation of 768 mm per year, with most of it (about 56%) occurring during the winter season (434 mm). Conversely, the inland and eastern coasts (Climate Zone 5) are the driest areas of the island with an average precipitation of 323 mm per year. More than half of this is a result of winter precipitation. The transitional spring and autumn seasons contribute about 42% of the annual precipitation budget.

A spatial analysis is presented in the Supplementary Material showing the seasonal climatology maps of TX, TN and PREC. According to these, the highest values of daily maximum temperature are recorded on the central inland part of the island, while the minimum is observed in the highlands of Troodos Mountains at areas with an elevation greater than 1000–1500 m above sea level. During summer, the hottest season, the daily maximum temperature ranges from 22 to 38 °C, while in winter, it ranges from 2 to 20 °C. The highest summertime temperatures are observed in the inland parts of the island and the area of Nicosia, while the lowest are in the mountains. A similar pattern is observed for the daily minimum temperatures, where the lowest values are recorded in the areas with high altitudes, while the maximum ones are in the coastal regions because of the moderating effect of the Mediterranean Sea. Annual values in mountainous regions are 5 °C, reaching 16 °C on the coastal parts of the island. In terms of precipitation, the greatest amounts are recorded in the highlands during all seasons, while the lowest is in the central part of the island. Summer is the driest season, as precipitation does not exceed 60 mm even in the mountainous areas. However, during winter, the wettest season of the year, precipitation can reach 600 mm. Annually, the observed rainfall amounts range from 250 mm in the coastal and inland plains to 1100 mm in the peaks of the Troodos Mountains.

The interannual variability (standard deviation in table 1) is overall higher for the maximum than for the minimum temperature and tends to be greater for the higher-elevation Climate Zones (i.e., Classes 1 and 2). This indicates that the surrounding Mediterranean Sea has a climate-moderating effect. The same pattern is observed for the annual precipitation total, where the coefficient of variation is approximately 10% for Climate Zone 1, 8% for Climate Zone 5, and considerably lower for the remaining regions. In all Climate Zones, interannual variability is much higher for summer precipitation, which is caused by small rainfall amounts (9 to 36 mm) during this season.

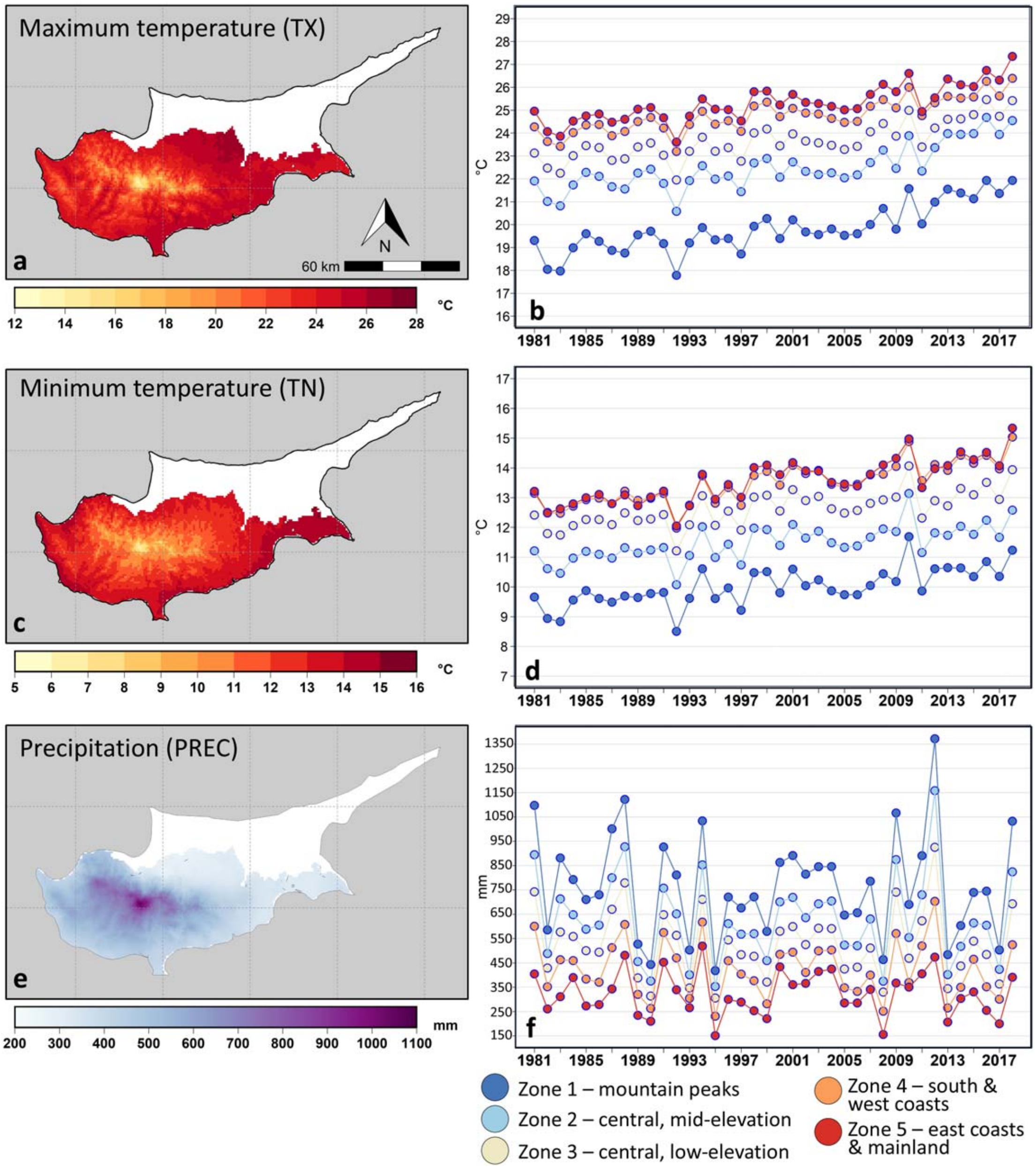

Figure 3. Maps of climatological mean values (left panels) and annual time series (right panels) for daily maximum temperature (a), (b), daily minimum temperature (c), (d) and precipitation totals (e), (f) for 1981–2018 and five climate zones, based on the CY-OBS gridded observations for Cyprus.

Following the global and regional warming trends, both maximum and minimum temperatures have accelerated in the assessed period (figure 3—right panels). On an annual basis, the warming rates for maximum temperature are stronger (0.55 °C–0.79 °C/decade) than the ones for minimum temperature (0.36 °C–0.52 °C/decade), with trends being statistically significant (table 1). For maximum and minimum temperatures, trends are stronger for Climate Zones 3 and 2, respectively (semi-mountainous regions). The seasonal TX and TN trends highlight profound warming during the warm part of the year (spring and summer).

The annual precipitation trend is negative in all climate regimes (figure 3); however, it is not statistically significant. This ranges from −6 to −9 mm per year and is mostly driven by a negative spring and autumn season rainfall decline. Particularly for autumn, this is up to −10 mm per decade and statistically significant, with Climate Zones 3 and 5 being mostly affected. Wintertime precipitation, which contributes more to the annual budget shows an increasing trend, however, this is not statistically significant.

3.3. Trends of extreme climate and impact indicators

Besides mean climate conditions, we explored the observed trends of several extreme climate indicators that are also useful for climate change impact-related studies. Figure 4 illustrates the temperature-driven indicators. The

Table 1. Means, standard deviation (or coefficient of variation) and trend values for the annual (ANN) and seasonal (winter: DJF, spring: MAM, summer: JJA, and autumn: SON) maximum (TX), minimum (TN) temperatures and precipitation (PREC) of the five climate zones (see figure 2) for 1981–2018. Statistically significant trends (p-values ⩽ 0.05) are highlighted in bold.

	Climatological mean value (°C)					Standard Deviation (°C)					Trend (°C per decade)				
Climate zone	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
TX (ANN)	19.8	22.5	23.7	24.8	25.3	2	1.3	1	0.7	0.6	**0.59**	**0.58**	**0.79**	**0.55**	**0.71**
TX (DJF)	10	13.1	15	16.7	16.5	2	1.4	1.2	1.3	0.8	**0.47**	**0.53**	**0.77**	**0.50**	**0.64**
TX (MAM)	18	20.5	21.6	22.8	23.5	1.9	1.3	1	0.7	0.6	**0.67**	**0.67**	**0.85**	**0.62**	**0.79**
TX (JJA)	29.5	31.7	32.2	32.6	33.7	2	1.3	1.1	1.1	1.5	**0.66**	**0.56**	**0.80**	**0.55**	**0.75**
TX (SON)	21.7	24.4	25.7	26.9	27.4	2	1.3	1.1	0.8	0.5	**0.54**	**0.57**	**0.73**	**0.52**	**0.66**
TN (ANN)	10	11.5	12.6	13.5	13.6	1	0.7	0.8	0.8	0.9	0.38	**0.52**	**0.40**	**0.50**	0.36
TN (DJF)	2.7	4.7	6.2	7.2	6.9	1.3	1	1	1.2	1	**0.30**	**0.39**	**0.40**	**0.41**	**0.32**
TN (MAM)	7.9	9.3	10.4	11.1	11.1	1	0.7	0.7	0.8	0.8	**0.39**	**0.58**	**0.43**	**0.50**	**0.38**
TN (JJA)	17.7	18.8	19.6	20.2	20.8	0.8	0.5	0.5	0.5	0.7	**0.43**	**0.62**	**0.41**	**0.57**	**0.40**
TN (SON)	11.5	13.1	14.3	15.3	15.4	1	0.8	0.8	1	1.1	0.38	0.51	0.35	0.53	0.33
	Climatological mean value (mm)					Coefficient of variation (%)					Trend (mm per decade)				
PREC (ANN)	768	629	528	425	323	9.7	5.5	5.5	6.5	8.0	−6	−4	−7	−9	−6
PREC (DJF)	434	359	309	250	178	10.4	5.3	6.4	9.7	13.3	8	4	6	5	8
PREC (MAM)	162	130	104	80	69	9.5	7.7	9.1	13.1	13.4	−6	−4	−8	−7	−7
PREC (JJA)	36	22	12	9	11	25.7	47.5	73.5	91.8	60.4	1	1	5	0	3
PREC (SON)	136	118	104	86	66	7.7	4.9	6.8	8.0	10.8	**−9**	**−5**	**−10**	**−6**	**−10**

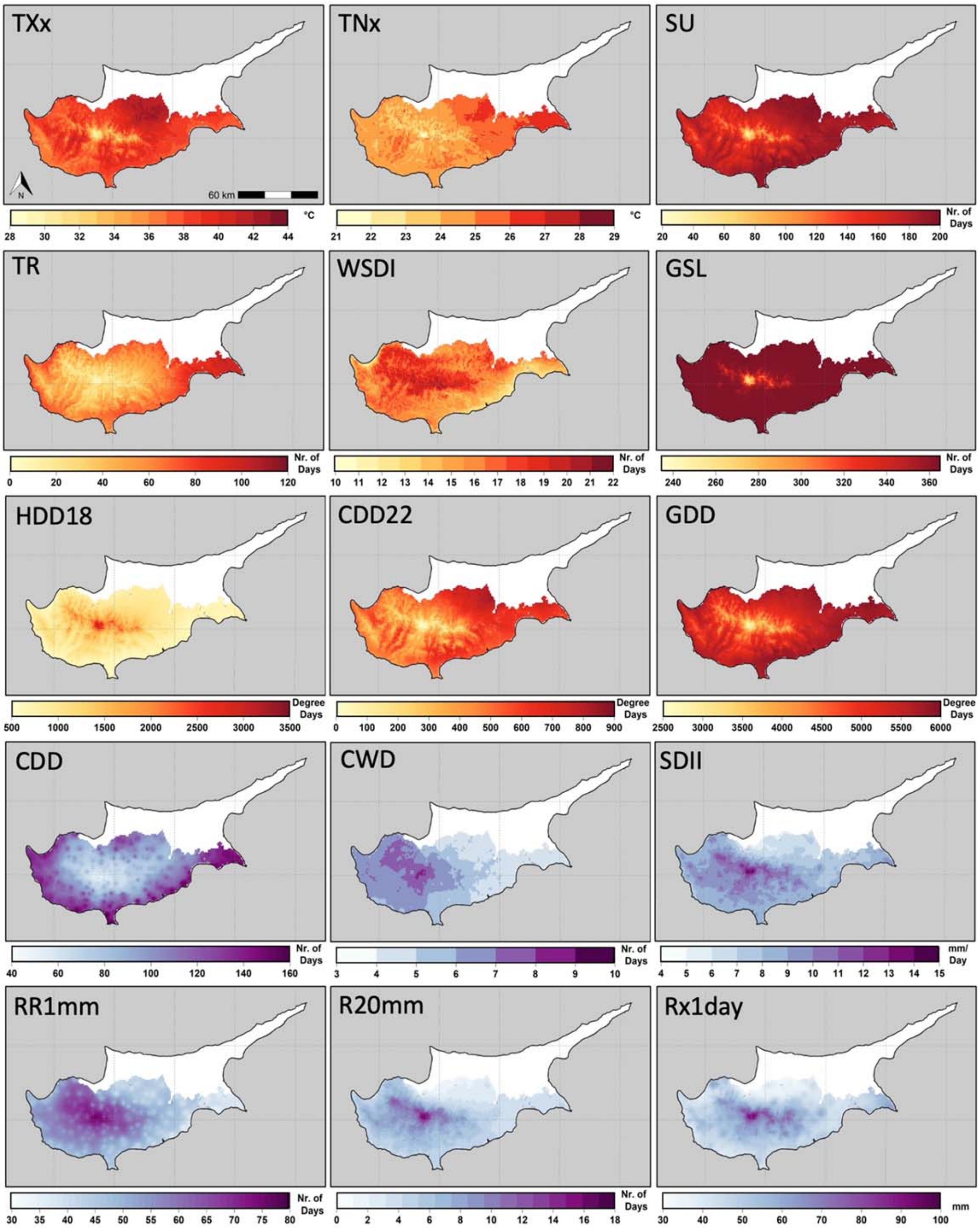

Figure 4. Maps of extreme climate and impact indicators for Cyprus, presented as averages for the period 1981–2018 based on the CY-OBS gridded observations. For a detailed definition of indices see section 2.3.

maps of the absolute maximum values of daily maximum (TXx) and daily minimum temperatures (TNx) show that the lowest extreme daily temperatures are recorded in the highlands (28 °C and 21 °C, respectively). The highest value of TXx equals 43 °C and is observed in the central inland part of Cyprus near the capital city of Nicosia. On the other hand, the highest TNx is nearly 28 °C and is found on the island's eastern coasts.

The number of summer days (SU) and tropical nights (TR) per year are based on the maximum and minimum daily temperatures. These are crucial indicators of human discomfort, especially during the warm parts of the year. The highest number of both SU (>180 days per year) and TR (>100 nights per year) is recorded in the same regions where the maximum values of TXx and TNx occur, respectively. Conversely, the lowest SU and TR values (an average of 40 days and 0 nights per year, respectively) are observed in the Troodos Mountains (figure 4).

Apart from the annual count of summer days and the maximum recorded temperatures, the duration of extreme heat events is relevant for impacts. In the present assessment, this is represented by the warm spell duration index (WSDI). The WSDI values are lower in the coastal areas (between 10 and 15), whereas, in the inland plains, this number can reach or exceed 20 days per year (figure 4). In the latter regions, temperatures during heat wave events typically exceed 40 °C (e.g., average TXx values of 43 °C). On the contrary, TXx in the coasts does not reach these levels, while the lower WSDI values also highlight the moderating effect of the Mediterranean Sea during extreme heat events.

The Growing Season Length index (GSL) equals 365 days in almost the entire island (figure 4), with some exceptions in the highest altitudes of Troodos (GSL values between 240 and 300 days per year). Therefore, the air and, therefore, soil temperatures allow crops and plants to grow throughout the year. The heat accumulation related to the plants' developmental rates, described by the Growing Degree Days (GDD), is higher in the coastal and inland areas of Cyprus, where GDD exceeds 5000 degree-days. In the colder parts of the Troodos Mountains, the average GDD values can be less than 3000 degree-days.

The Heating and Cooling Degree days have been estimated for assessing the energy demand for heating and cooling buildings, with reference thresholds equal to 18 °C and 22 °C, respectively (HDD18, CDD22). On average, the highest energy demand for heating buildings is estimated in the highlands (~3500 degree-days), while in the rest of the island, such needs are much lower (between 500 and 1000 degree-days). A reverse spatial pattern is estimated for cooling buildings during the warm part of the year. Nevertheless, the required energy for summer cooling is lower than for wintertime heating. Specifically, the CDD22 value is close to zero in the higher-elevation parts of Troodos, while it is significantly higher (up to 900 degree-days) in the central lowland region near Nicosia.

Apart from the spatial analysis of the indicators, a statistical summary is presented in table 2. Particularly, the trends of all indicators related to temperature extremes have increased, indicative of the transition to warmer conditions. The absolute highest maximum temperature per year (TXx) is increasing faster than mean conditions, while this is also the case for TNx. Statistically significant trends in the number of summer days (up to eight additional days per decade) and tropical nights (up to 13 additional nights per decade) are also evident, with stronger trends in Climate Zones 2 and 4 regions. Finally, the warm spell duration index has also increased significantly, at a rate of 8 to 12 additional days per decade. The indicators related to heating and cooling needs (HDD18 and CDD22, respectively) have also changed accordingly (figure 4 and table 2). The trend of HDD18 is negative and statistically significant throughout the island. The strongest decreases are observed for Climate Zones 3 and 5 (up to −143 degree days per decade). The demand for space cooling, higher in the low-elevation regions (Climate Zones 4 and 5), has increased significantly (up to 80 degree days). The indicators related to plant development, growing season lengths (GSL) and growing degree days (GDD), indicate optimum conditions for all regions, with the GDD showing an increase, which is not statistically significant.

The climatological averages of the extreme precipitation indicators are also presented in figure 4. The number of rainy days in a year affects many sectors, including agriculture, water resources, and ecosystem functioning. On average, the number of rainy days varies from 30 days in the driest coastal and inland areas (mostly in the east). This increases to 80 days per year in the wettest parts of the Troodos Mountains, which are influenced by the predominantly westerly synoptic systems from the Mediterranean Sea). Also, the Troodos Mountain range creates a rain shadow effect in the eastern and inland regions. The longest dry spells per year (CDD) can be up to 160 days and are mainly observed in the coastal areas, specifically in the southeastern parts of the island. On the other hand, the lowest number of consecutive dry days (~40) is found in the Troodos Mountains, where precipitation (mostly convective) can also occur during the summer season. The number of consecutive wet days can range from six to ten days in the western and mountainous parts, which receive most of the precipitation. In the driest eastern parts of Cyprus, the longest wet spells typically last for four to five days (figure 4).

Except for the number of rainy days and duration of wet/dry spells, other extreme rainfall characteristics are equally important. For instance, the SDII index represents the average intensity of daily rainfall, defined as the annual precipitation total divided by the annual count of rainy days. On the west coast and the highlands, the average precipitation range during a rainy day is between 10 to 15 mm (figure 4). However, this value is significantly lower in the inland regions and eastern coasts (5–9 mm per rainy day). On average, the maximum daily rainfall (Rx1day) is almost 100 mm day^{-1}, observed in the Troodos Mountains peaks, while the minimum amount (~30 mm day^{-1}) is recorded in the central inland part of the island and some coastal regions. These values reflect the multi-year mean conditions for the 1981–2018 period, and the most extreme cases have substantially higher rainfall heights. The R20mm index provides information on the number of very wet days (rainfall higher than 20 mm day^{-1}), showing very similar spatial patterns as the Rx1day index. On average, the highest value of the R20 mm index is 18 days per year, recorded in the mountainous regions, while it is near zero in the central lowlands.

The observed trends for the extreme precipitation indicators are less profound and not statistically significant (table 2). For example, the number of rainy days per year (Rx1day) has been reduced by one day per

Table 2. Climatological mean values, standard deviation and linear trends for the extreme climate and impact indicators for the five climate zones (see figure 2) for 1981–2018. Statistically significant trends (p values ⩽ 0.05) are highlighted in bold.

	Climatological mean value					Standard deviation					Decadal trend				
Climate Zone	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
TXx (°C)	35.6	37.8	38.2	38.4	39.7	2.2	1.5	1.1	1.1	1.7	**0.73**	**0.56**	**0.89**	**0.58**	**0.78**
TNx (°C)	23.7	24.3	24.5	24.9	25.8	0.7	0.6	0.5	0.5	0.6	0.5	**0.57**	0.51	**0.56**	0.44
SU (nr. of days)	124	156	168	182	187	27	15	13	9	6	**7**	**8**	**7**	**8**	**7**
TR (nr. of nights)	24	36	49	62	73	8	8	10	11	16	**8**	**12**	**5**	**13**	**6**
GSL (nr. of days)	341	361	364	365	365	24	5	1	1	0	0	0	6	0	1
WSDI (nr. of days)	19	18	17	16	16	1	1	1	1	2	**9**	**8**	**12**	**8**	**11**
HDD18 (degree-days)	1837	1336	1041	810	833	356	221	181	182	127	**−91**	**−95**	**−143**	**−93**	**−115**
CDD22 (degree-days)	255	400	470	542	657	102	91	82	71	78	**62**	**78**	**50**	**71**	**59**
GDD (degree days)	4048	4753	5168	5525	5636	474	341	276	231	166	175	201	203	191	193
CDD (nr. of days)	69	82	102	117	112	10	15	18	21	20	−6	−8	−5	−7	−5
CWD (nr. of days)	7	7	6	6	5	0	0	1	1	0	0	0	0	0	0
SDII (mm/day)	11	10	9	8	7	1	0	1	1	1	0.1	0.0	0.0	0.0	0.1
Rx1day (mm/day)	69	58	52	47	43	8	6	6	5	6	0.9	−1.0	−0.7	0.5	−0.3
R20mm (nr. of days)	11	8	6	5	3	2	1	1	1	1	0	0	0	0	0
RR1mm (nr. of days)	71	65	58	50	43	3	3	3	4	4	−1	−1	−1	−1	0

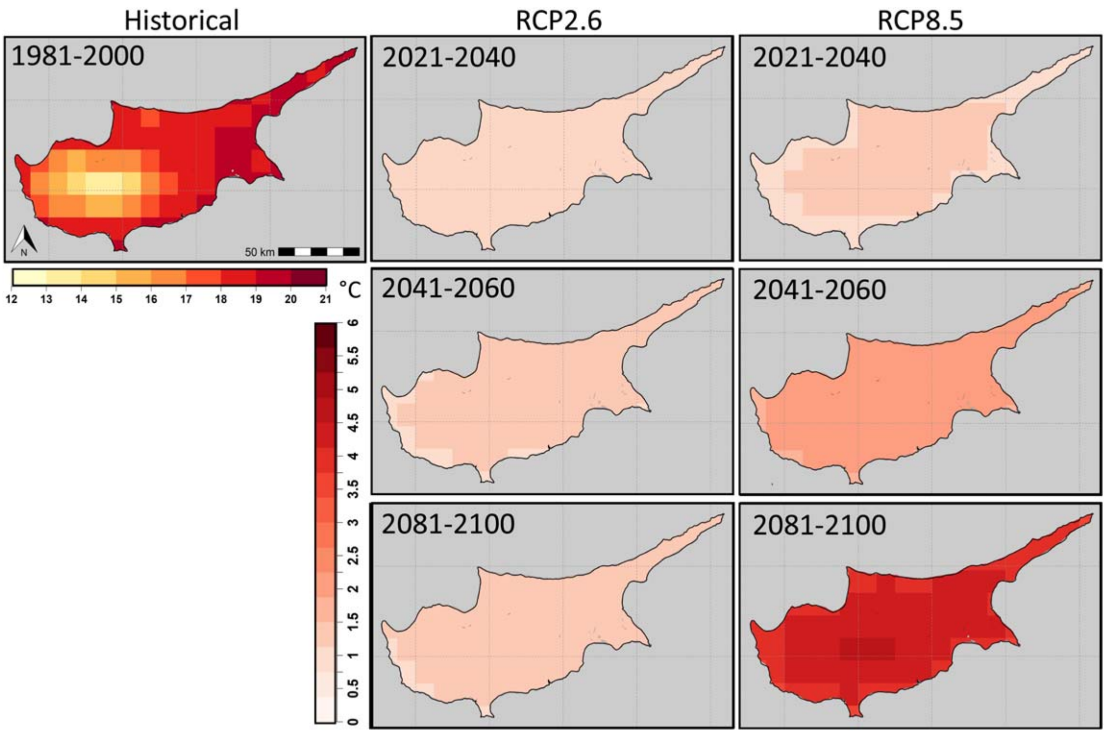

Figure 5. Projected changes of mean annual temperature between the historical (1981–2000) and three future periods according to the 21-member EURO-CORDEX ensemble average for pathways RCP2.6 (center panels) and RCP8.5 (right panels).

decade in most climate zones, while the maximum dry spell length per year (CDD) is also slightly decreasing, indicating changes in the rainfall distribution within the year.

3.4. Future projections

3.4.1. Mean temperature

According to the 21-member EURO-CORDEX ensemble average, the mean temperature in Cyprus during the historical period (1981–2000) ranges from 12 °C to 21 °C (figure 5). The projections indicate a temperature increase across all future periods for both scenarios. Under RCP2.6, the projections indicate an increase of approximately 0.5 °C for the near-term future period, while the subsequent periods show more substantial increases, reaching approximately 1.5 °C with respect to the end of the previous century. The RCP8.5 scenario, characterized by business-as-usual emissions, forecasts more robust warming, particularly towards the century's end. Specifically, projections suggest an increase of around 1.5 °C for 2021–2040, 2.5 °C for 2041–2060, and exceeding 5 °C across the entire island by 2100, relative to 1981–2000.

Maps for seasonal temperature projections are provided in the Supplementary Material. During the winter season, which spans from December to February, the lowest average temperatures in Cyprus are found on the Troodos mountains and are around 4 °C, while in coastal areas, the average is around 15 °C, for 1981–2000. Winter temperatures are projected to rise across the island in all future periods and scenarios. Under RCP2.6, the temperature increase is estimated to be no more than 0.5 °C with respect to the end of the 20th century. On the other hand, under RCP8.5, temperatures are expected to rise by about 3 °C and 4 °C for the mid-century and end-of-century periods, respectively. During the spring season (March to May), temperatures in Cyprus range from 10 °C to 19 °C. Future warming under RCP2.6 is projected to be between 0.5 °C (near-term) and 1 °C (end of the century). Under RCP8.5, temperatures are expected to increase by 1 °C initially and then escalate to 2 °C by mid-century across the island. By the end of the century, this warming will likely exceed 4.5 °C. Notably mountainous regions may experience a higher increase of up to 6 °C, possibly due to earlier snowmelt. Summer (June to August) temperatures in Cyprus usually vary between 21 °C at higher altitudes to 29 °C in the eastern part of the island. Future temperature increases are more pronounced compared to the rest of the seasons. For instance, under pathway RCP2.6, warming can reach up to 2 °C with respect to the reference period (1981–2000). Under pathway RCP8.5, warming could reach this level in the coming two decades (2021–2040), while temperature is projected to rise even more during the mid-century period (2.5 to 3.5 °C). The inland and mountainous regions are expected to see the strongest warming. By the end of the century, the summer warming could exceed 6 °C with respect to the reference period. In autumn, during the reference period, mean

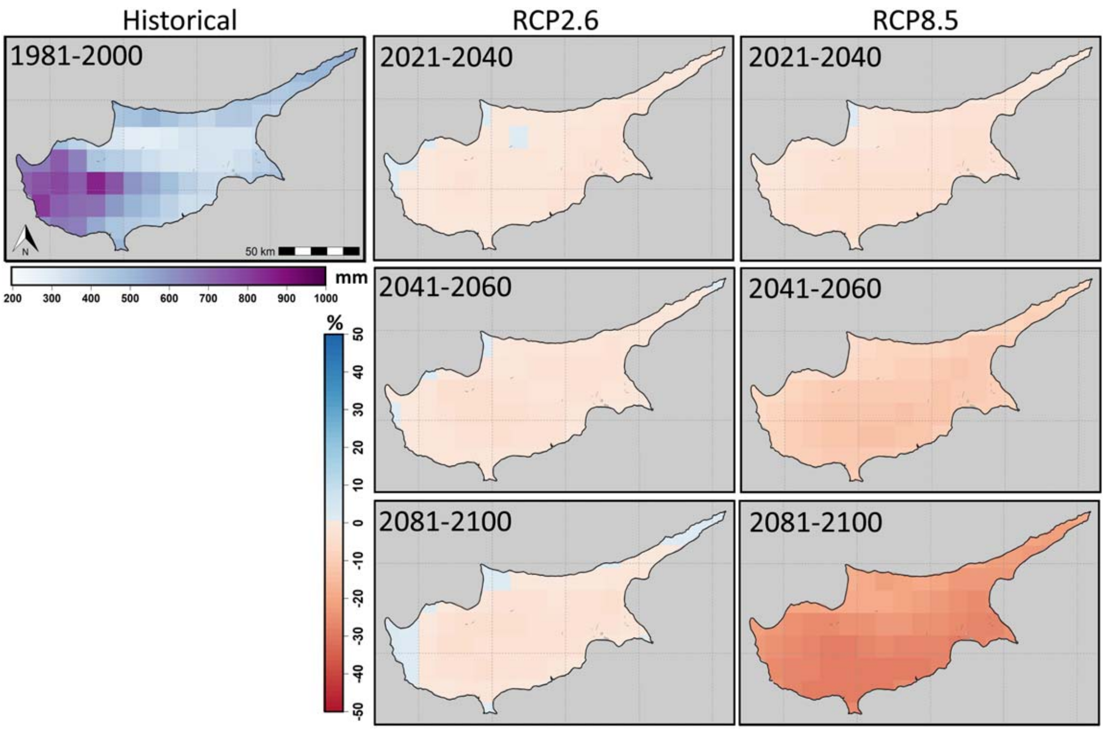

Figure 6. Projected changes of annual precipitation between the historical (1981–2000) and three future periods according to the 21-member EURO-CORDEX ensemble average for pathways RCP2.6 (center panels) and RCP8.5 (right panels).

temperatures range from 14 °C to 20 °C. Projected increases for this transitional season resemble those of spring. Under RCP2.6, the projected warming remains below 1.5 °C throughout all future periods. However, RCP8.5 presents a more significant increase of up to 4 °C by 2100.

3.4.2. Precipitation

As described in section 3.1, Cyprus experiences the highest annual precipitation amounts in the western and central regions, including the mountainous areas. This spatial pattern is also displayed by the 21-member ensemble average (figure 6). In these wetter parts of the island, annual precipitation ranges from 700 to 1000 mm. Conversely, due to rain shadow effects, the eastern and central parts receive less than half of that amount, averaging between 200 and 500 mm annually. Projections suggest a general decrease in annual precipitation for future periods. Under the pathway RCP2.6, the anticipated decrease is insignificant and remains under 5% for the remainder of the 21st century. This is comparable to the natural interannual variability (table 1) and therefore is considered insignificant. On the other hand, RCP8.5 implies a more substantial decline. By mid-century, a 10% reduction in total rainfall is expected, while by 2081–2100, the decrease could exceed 30%, relative to 1981–2000, with the western (and the wettest) part of the island being most affected.

During winter, the wettest season, total precipitation ranges from 120 mm in the northeastern part to approximately 500 mm in the western mountainous regions. Under RCP2.6, the projected decrease ranges from 5 to 10% with stronger changes expected for the end of the century. Notably, exceptions occur in the northeastern part during the second future period and in certain coastal areas during the last period (2081–2100), where a slight increase of 5% in precipitation is projected. In spring, historical rainfall ranges from 40 to 220 mm across the island.

Both scenarios indicate a tendency toward decreased rainfall, except for the 2021–2040 period under RCP2.6, where the signal of changes is mixed and in some regions of the central part of Cyprus a lower than 5% increase is expected. For RCP8.5 the decrease is more profound (15%–30%), with stronger drying projected for the end of the 21st century. Cyprus has a typical Mediterranean climate and experiences the driest season during summer, with total precipitation ranging from 5 to 35 mm across most of the island. However, there are mountainous areas with rainfall reaching up to 50 mm. Future changes in summer precipitation are expected to be mostly negative, ranging from a mixed signal in the near term (RCP2.6) to strong declines at the end of the century (RCP8.5). It should be noted that the reference amounts are already very low, so changes may not have much impact on water resources. For autumn there is a higher uncertainty concerning future projections. Pathway RCP2.6 implies an overall precipitation increase (5%–10%). This is also the case for the near-term

Table 3. Average values of 12 extreme climate and impact indices for Cyprus for four historical and future periods according to the EURO-CORDEX ensemble. The future results have been calculated according to the scenarios RCP2.6 and RCP8.5.

	1981–2000	2021–2040		2041–2060		2081–2099	
	Historical	RCP26	RCP85	RCP26	RCP85	RCP26	RCP85
TXx (°C)	38.2	39.7	39.6	39.9	40.8	39.6	43.6
TNx (°C)	25.7	27	27.1	27.2	28.1	26.9	30.9
SU (nr. of days)	142	155	156	157	169	157	197
TR (nr. of nights)	61	81	83	84	100	81	137
HDD18 (degree-days)	1121	948	930	929	792	921	531
CDD22 (degree days)	442	601	623	615	775	589	1116
CDD (nr. of days)	84	89	90	90	96	89	106
CWD (nr. of days)	7	7	7	7	7	7	6
SDII (mm/day)	6.5	6.8	6.7	6.8	6.8	6.8	6.5
Rx1day (mm)	38.7	41.8	40.9	40.4	40.2	41.7	38.7
RR1mm (nr. of days)	70.8	68.4	67.4	67.3	61.9	67.6	52.9
R20mm (nr of days)	4.3	4.5	4.4	4.5	4.1	4.5	3.2

changes under RCP8.5; however, this is not consistent with the observed precipitation trends (table 1). On the contrary, for the rest of the century, the EURO-CORDEX ensemble projects an overall drying (up to 25%–30%), relative to 1981–2000.

3.4.3. Extreme climate and impacts

Table 3 provides a summary of the future evolution of various extreme climate indicators. In general, indices related to high temperatures are expected to increase over time, while those related to precipitation indicate a future transition to drier conditions. For instance, the TXx index, which represents the maximum temperature during the hottest day of the year, is projected to increase from 38.2 °C for 1981–2000 to 43.6 °C by the end of this century under RCP8.5. It is important to note that these are 20-year country averages, and in the most extreme cases and for certain locations (e.g., in the inland parts), these values are expected to be even higher. The expected temperature increase during the warmest night of the year (TNx) is of a similar magnitude. Pathway RCP2.6 implies milder changes (up to 2 °C–2.5 °C), more pronounced in the middle of this century. Conversely, TNx values under RCP8.5 are expected to increase by more than 5 °C.

The number of summer days (SU) and tropical nights (TR) will increase as temperatures rise. In the historical period, the average values for these indices were 142 days and 61 nights per year, respectively (table 3). Under the RCP8.5 pathway, the number of SU days is likely to increase by up to 40% or 55 days per year by the end of the century, while under the RCP2.6 pathway, it is expected to increase by about 15 days per year. Similarly, the TR index, which had a historical value of 61 tropical nights per year, is projected to increase by approximately 20 days (~30%) by the end of the century under the RCP2.6 scenario. Pathway RCP8.5 implies a gradual increase in the number of tropical nights in Cyprus, which are expected to more than double by the end of the century.

The Heating Degree Days (HDD18) index is a measure of energy demand for space heating. It is expected to decrease in future years due to higher temperatures overall. The historical period had around 1100 heating degree days, but this is projected to decrease by 18% under the optimistic scenario (table 3). The decrease in heating demand for buildings will be more significant under RCP8.5. Particularly towards the end of the century, it is expected to decrease by more than 50% compared to the historical reference values. Cooling Degree Days (CDD22) refer to energy demand for space cooling mainly during the warm part of the year. It is expected to increase under both pathways and for all time horizons. Pathway RCP2.6 implies a moderate increase of about 30% compared to the 442 degree days of the historical period (table 3). On the contrary, the high-forcing pathway RCP8.5 implies a three-fold increase in cooling demand by the end of the century (1116 degree days per year).

The indices of precipitation characteristics are less likely to undergo significant changes as compared to temperature-related indices (figure 7). According to the EURO-CORDEX projections, the number of rainy days per year (RR1mm) will decrease from 71 days (1981–2000) to 53 days (2081–2100), under RCP8.5. Pathway RCP2.6 implies a decrease of the order of 3–4 days per year. Similarly, the Simple Daily Intensity Index (SDII), which measures the average rainfall intensity, will likely remain unchanged at values between 6.5 and 7 mm per rainy day. This is also the case for the maximum daily rainfall (Rx1day) and the annual count of days with precipitation exceeding 20 mm (R20mm). For the mean values of both indicators, insignificant changes (mostly positive) are projected only for RCP2.6, nevertheless, the year-to-year variability is expected to increase in both

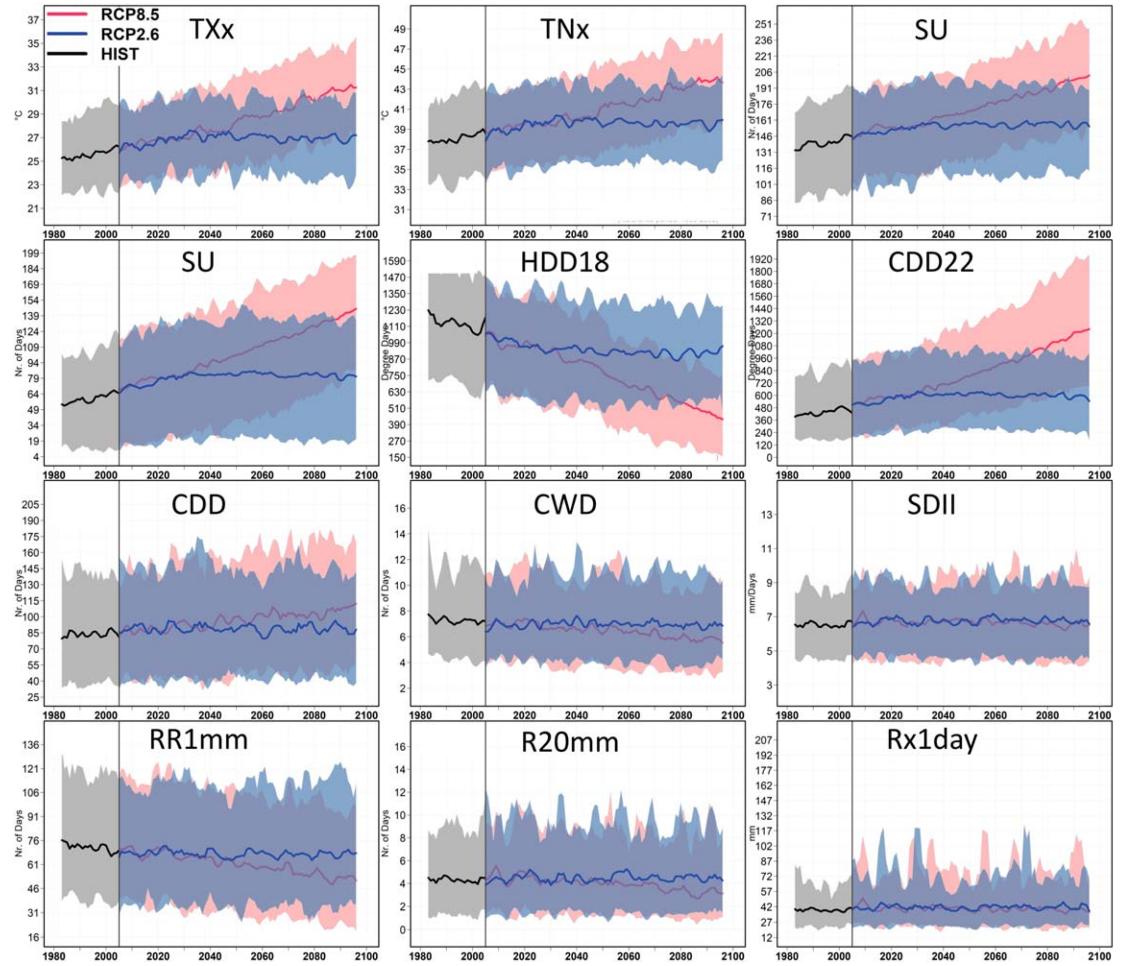

Figure 7. Projected changes of extreme temperature and precipitation indicators according to the 21-member EURO-CORDEX ensemble for pathways RCP2.6 (red curve) and RCP8.5 (blue curve). Moving averages of three years were applied.

scenarios. For example, during the most extreme years of the future, the number of rainy days could be higher than in the historical period (RR1mm in figure 7). Although Rx1day values are smoothed from country averaging, the most extreme daily rainfall values are also expected to be higher than in the historical period (e.g., > 120 mm day). This is the case even under RCP2.6 (Rx1day in figure 7).

The maximum number of consecutive dry days per year (CDD), an indicator of drought, is expected to marginally increase under RCP2.6, from 84 to 90 days. However, under the business-as-usual scenario (RCP8.5), the dry season is estimated to expand up to three weeks by 2100. On the other hand, the maximum number of consecutive wet days per year (CWD) is expected to remain unchanged on average, irrespective of the periods and pathways being examined.

4. Conclusions and discussion

The present research aims to assess the historical climate trends of Cyprus for the 1981–2018 period, with a focus on identifying and updating any observed changes, while highlighting regions that are particularly vulnerable to climate change. We analyzed near-surface air temperature, precipitation, and various extreme climate indicators relevant to the impact community. Furthermore, the lack of updated multi-model assessments for Cyprus motivated us to examine future projections for a range of future periods and two scenarios: an optimistic (RCP2.6) and a business-as-usual pathway (RCP8.5).

The mean climatological values of various extreme climate indicators in Cyprus reveal a nuanced pattern of temperature and precipitation extremes. Temperature-driven indicators, including absolute annual maxima of daily maximum and minimum temperatures, exhibit notable variations across the island. The lowest extreme daily temperatures are recorded in the highlands, while the highest values are observed near Nicosia and the eastern coasts. Summer days and tropical nights correlate with these temperature extremes, with the highest occurrences in regions experiencing maximum temperatures. The Warm Spell Duration Index highlights the moderating effect of the Mediterranean Sea during extreme heat events, showing lower values in coastal areas and higher values in inland plains and mountainous regions. Precipitation indicators, including rainy days, dry spell duration, and rainfall intensity, show distinct patterns across the island, influenced by the Troodos Mountain range and tracks of synoptic systems, typically approaching the island from the west. Our analysis reveals statistically significant increasing trends in temperature-related indicators, while precipitation trends are less robust. One exception is significant decreasing precipitation trends during the autumn season (−5 to −10 mm/decade). These findings indicate shifts towards warmer conditions, impacting energy demand, plant development, and various sectors reliant on precipitation patterns and seasonality.

The analysis of future climate scenarios for Cyprus reveals significant shifts in temperature and precipitation patterns, focusing on three 20-year periods (2021–2040, 2041–2060, 2081–2100) under RCP2.6 and RCP8.5 pathways, relative to 1981–2000. Temperature projections indicate a consistent rise, with RCP8.5 foreseeing substantial increases exceeding 5 °C across the island by the century's end. Seasonal analyses reveal diverse trends in winter, spring, and autumn temperatures, with notable increases anticipated. These are expected to be more pronounced in the warm part of the year and mainly during the summer months. Precipitation faces a general decrease, particularly under RCP8.5, signifying a 30% reduction in total rainfall by the century's end. In certain locations, e.g., the western part of the island this drying could be even more pronounced. Seasonal analyses indicate variations in rainfall patterns, emphasizing reductions in spring and autumn precipitation. For the driest months of the year, the projected changes are insignificant in terms of absolute rainfall amounts.

The examination of climate indicators, including TXx, TNx, SU, TR, HDD18, CDD22, and various precipitation indices, further emphasizes the impact of climate change on intensifying extreme hot weather and energy demand. Temporal analysis from 1981 to 2100 underscores a consistent upward trend in all extreme temperature-related indices. While the precipitation-related indices are, on average, not expected to change significantly, challenges in managing water resources may arise due to increased year-to-year variability.

Although different models, scenarios or future periods might have been used, our results for future projections are within the range of projections from other studies for Cyprus (Hadjinicolaou *et al* 2011, Cherif *et al* 2020, Zittis *et al* 2020, 2022). Our study corroborates the transition to a hotter and drier climate regime, with more pronounced warming during the summer season. These results are also comparable to projections for other eastern Mediterranean countries, such as Israel, Greece, Egypt, and Turkey (Önol and Unal 2014, Hochman *et al* 2018, Georgoulias *et al* 2022, Hamed *et al* 2022, Mavromatis *et al* 2022, Gumus *et al* 2023, Zanis *et al* 2024).

These findings and the comparison between the two pathways underscore the urgency of addressing climate change and its potential implications for Cyprus, where temperature increases may adversely influence local society and ecosystems, and precipitation patterns undergo significant alterations, particularly under the business-as-usual scenario.

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Data availability statement

The EURO-CORDEX data are openly available through the Earth System Grid Federation (https://esg-dn1.nsc.liu.se/) and the Copernicus Climate Change Services Data Store (https://cds.climate.copernicus.eu). The CY-OBS are available upon reasonable request from the authors.

Conflicts of interest

The authors declare that there is no conflict of interest.

Ethics statement

The authors declare that this research does not require any ethics approval.

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