Projection of climate change in Cyprus using a variety of selected regional climate models

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Abstract

This study examines the potential future climate changes in Cyprus using several projections derived by Regional Climate Models (RCM) simulations. Reference values of mean and extreme climatic parameters are presented for Cyprus for the period 1960-1990 (control period) while afterwards a comparison is being made to the projected climatic situation in the near future period 2021-2050. For the evaluation of near future climate conditions and extremes in Cyprus, PRECIS RCM has been employed as the main climate model. Except for PRECIS, six additional RCMs of the ENSEMBLES project have also been used namely KNMI, METNO, CNRM, METO, C4I and MPI. The results of six models were used as an ensemble mean for testing and comparing the respective results of PRECIS. All simulations concerning future predictions of climate change in Cyprus are driven by the A1B emission scenario. Also, time series plots of temperature and precipitation parameters are presented for selective representative locations of Cyprus derived from the regional climate models for the entire period 1951-2100. Observational data up to 2010 are also overplotted for comparison with the model results.

Keywords: Climate Change, Regional Climate Modeling, Extreme Indices, Time Series

Introduction

Climate in Cyprus is generally characterized by mild rainy winters, occasional droughts, and long, hot and dry summers. Recent studies on present and future climate have shown that the country is among the most vulnerable regions to climate change, as it is expected to be relatively strongly affected by the projected warming and related changes [2] due to man-made forcing by increased greenhouse gases (GHG) [8]. Therefore, Cyprus is likely to face increases in the frequency and intensity of droughts and hot weather conditions in the near future. Since the region is diverse and extreme climate conditions already common, the impacts may be disproportional.

Gradients and contrasts are characteristic for Cyprus, not only in climatic conditions, but also in social and economic aspects, access to natural resources, as well as cultural and religious traditions. This diversity is a regional attribute, but can also be associated with political tensions. Since the region is a primary climate change “hot spot”, there is concern about the future state of the environment and societal consequences [5, 9].

In this report, two time periods, namely the control period (1961-1990) and the future period (2021-2050), are examined, using output data from regional climate model (RCM) simulations driven by the IPCC SRES medium emissions A1B scenario [16].

Specifically, the main model used in this report is the PRECIS (Providing Regional Climates for Impact Studies) regional climate model provided by the United Kingdom (UK) Meteorological Office Hadley Centre. The original system is based on scientific formulations of the regional model HadRM3P [12, 13] as well as the HadAM3P, the global atmosphere model that provides the default lateral boundary conditions. Both are based on the atmospheric component of the Hadley Centre's coupled climate model, HadCM3 [6]. The model simulations were performed by the Cyprus Institute within the framework of the CIMME project, which studied ‘Climate Change and Impacts in the Eastern Mediterranean and Middle East’. Results of PRECIS simulations considered more accurate since Cyprus lies at the centre of the model domain. In this study, PRECIS used with horizontal resolution of 0.22° x 0.22° or 25 x 25 km with 19 levels in the atmosphere (from the surface to 30 km in the stratosphere) and four levels in the soil.

PRECIS is compared with an integrated set of model simulations, also developed to reproduce climate conditions and future climate changes for Europe. In these simulations, Cyprus is placed in the south-eastern part of the domain. The mean of these models, hereafter called “ENSEMBLE model mean”, is derived from 6 high resolution RCMs run to the year 2050, while 3 of them extend up to 2100:

- The ‘KNMI’ model, provided by the Royal Netherlands Meteorological Institute, widely known as KNMI, Koninklijk Nederlands Meteorologisch Instituut. The KNMI regional climate model RACMO2 [14, 17] is forced with output from a transient run conducted with the ECHAM5 GCM. This model uses 40 vertical levels on a horizontal 95*85 (lat x lon) grid.
- The ‘METNO’ model, developed in the Norwegian Meteorological Institute. It is based on version 5 of the HIRHAM regional climate model [1, 7]. This model uses 31 vertical levels and horizontal grid of 213*198 (lat x lon) grid points.
- The ‘CNRM’ model is the ALADIN-Climate which is developed at Météo-France CNRM, Centre National de Recherches Météorologiques [4, 15]. This model uses 31 vertical levels and 128*120 (lat x lon) grid points.
- The ‘METO’ model, produced in the UK Met Office and it based on the HadCM3Q global climate model. The RCM is projected on a rotated pole projection, with regular latitude/longitude. The number of horizontal grid points is 214 x 220 (lat x lon) and the number of vertical levels is 19 [3].
- The ‘C4I’ model, provided by the Community Climate Change Consortium for Ireland. This is based on the third version of the Rossby Centre regional Atmospheric Climate model (RCA3) driven by the HadCM3Q16 high-sensitivity simulation [12, 13]. The model uses 206*206 horizontal grid points and 31 vertical levels.
- The ‘MPI’ model, developed in the Max Planck Institute for Meteorology (MPIM), Hamburg, Germany [10, 11]. The parent GCM is the ECHAM5 and the RCM has been projected on a rotated spherical coordinate system. This model covers 109 x 121 grid points horizontally with 27 vertical levels in the atmosphere

The main purpose of the study is to present a comprehensive regional climate assessment in Cyprus, using PRECIS and ENSEMBLE model mean output data and to provide climate change projections and indices of climate extremes. The analysis of the data incorporates: (1) spatial distribution using maps of the distribution of the parameters of interest to illustrate the spatial variability of changes in mean and indices of climate extremes; and (2) data visualization tools, such as summary tables and time series plots, to explore the differences, trends and temporal variability in the compared datasets.

Results

Meteorological parameters

PRECIS model in Figure 1a shows that the average annual maximum temperature (TX) ranges from about 20-21°C in higher elevation areas to about 25°C in lowland and continental areas. All coastal parts of Cyprus have notable different temperature conditions with an average annual TX ranging from 20°C in northeastern and northwestern coastal areas, to about 24°C in southeastern coastal areas. According to the ENSEMBLE model mean (Figure 1b), the lowest average annual TX of about 20°C occurs in higher elevation areas. The average annual TX is higher in lowland and continental areas, reaching 25°C in Nicosia. The eastern and western coasts of the country have similar temperature conditions, while the average annual TX is about 24°C not only in Larnaca but also in Kyrenia at the northern coast. Compared with PRECIS, the ENSEMBLE model mean gives higher values of average annual TX in continental lowland and coastal areas and lower values in higher elevation regions. As regards future changes, PRECIS model in Figure 1c shows that changes in average annual TX range from 1.0°C at the eastern and northern coasts (Karpasia peninsula, Ayia Napa, Ayia Irini Forest) to 2.0°C in higher elevation areas and especially at the southwestern side of Troodos. The lowland and continental areas in the central part of the country also have a notable change in average annual TX (mainly more than 1.5°C), followed by the western and southern coasts with a temperature increase confined to 1.3-1.7°C. According to the ENSEMBLE model mean (Figure 1d), the lowest increase of 1.4°C in average annual TX occurs mainly at the eastern coasts similar to PRECIS. The average annual TX change is higher in all other coastal areas as well as in lowland continental areas, reaching almost 1.8°C in Nicosia. The higher elevation areas appear to have the highest temperature change, up to 2°C. Compared with PRECIS, the ENSEMBLE model mean depicts a warmer pattern for the future period 2021-2050, almost everywhere in the country, except from the southwestern side of Troodos.

Regarding the average annual minimum temperature (TN), PRECIS shows a range from about 10°C in higher elevation areas to about 20°C in coastal areas (Figure 2a). A temperature difference is also apparent between the warmer eastern coastal areas and the cooler western ones, the latter affected by the adjacent higher elevation regions. In Figure 2b, the ENSEMBLE model mean generally agrees with PRECIS, although lower temperatures are noted everywhere (e.g. in higher elevation areas, the average annual TN appears to be about 9-10°C). As far as future changes are concerned, PRECIS shows that changes in average annual TN range from 1.0°C at the eastern and northern coasts (Karpasia peninsula, Ayia Napa, Ayia Irini Forest) to 2.0°C in higher elevation areas, especially at the southwestern side of Troodos (Figure 2c). A difference in temperature change is also apparent among the northern and eastern coasts and the southern and western ones, the latter being affected by the adjacent higher elevation regions. In Figure 2d, the ENSEMBLE model mean generally agrees with PRECIS, but it presents a higher temperature increase in coastal areas and a lower temperature increase in higher-elevation and lowland continental areas. Thus, the range of temperature change is confined between 1.3°C and 1.8°C.

The warm summers in Cyprus are illustrated by the PRECIS average maximum temperature patterns for June-August (JJA) in Figure 3a, showing that summer TX approximates 25-26°C at the northern and western coasts (near Paphos), as well as in two southern regions, i.e. Limassol Salt Lake and the touristic area of Ayia Napa. Very hot summer conditions, with average summer TX reaching 35°C, appear in the lowland continental area around Nicosia and in the eastern part of Troodos mountains. Figure 3b confirms that the ENSEMBLE model mean generally agrees with PRECIS, but shows a smaller summer TX range, giving smaller gradients than those in Figure 3a. As regards future changes, PRECIS projections (Figure 3c) indicate that the summer average TX warming in Cyprus will be significant, ranging from 1°C to 3°C in the near future (2010–2050). More precisely, the summer TX increase reaches 1.0-1.5°C in the areas around Ayia Napa, Limassol Salt Lake and Akamas peninsula National Park. The summer TX increase does not exceed 2.3°C in all other coasts of the country, contrary to the continental lowlands where it is evident that summer TX will increase by at least 2.2°C (more than 2.5°C in Nicosia). The largest summer TX change, approaching 3.0°C, occurs in higher elevation areas and especially in the southern part and eastern side of Troodos Mountain. Figure 3d confirms that the ENSEMBLE model mean generally agrees with PRECIS, but presents a more moderate scenario, with a lower summer TX increase all over Cyprus, except from the areas around Ayia Napa, Limassol Salt Lake and Akamas peninsula National Park.

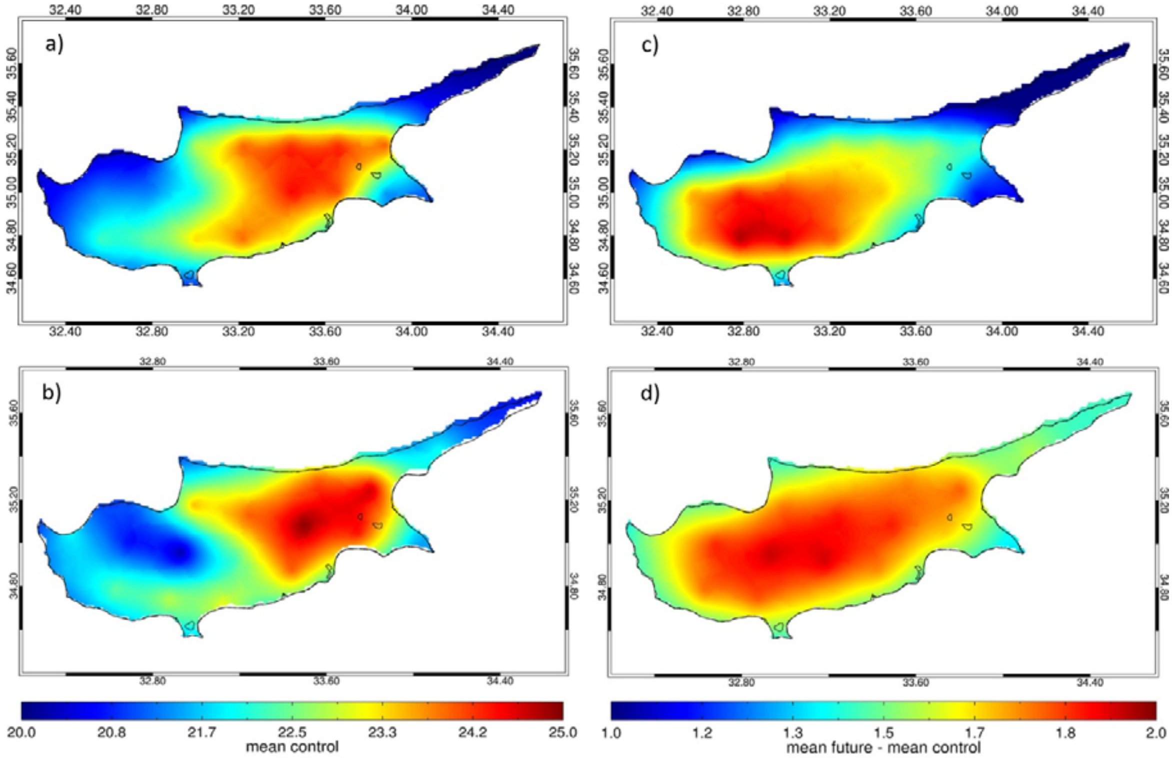

Figure 1: Average annual maximum temperature for the control period (1961 – 1990) using PRECIS (a) and ENSEMBLE model mean (b). Future changes in average annual maximum temperature (2021 – 2050) using PRECIS (c) and ENSEMBLE model mean (d).

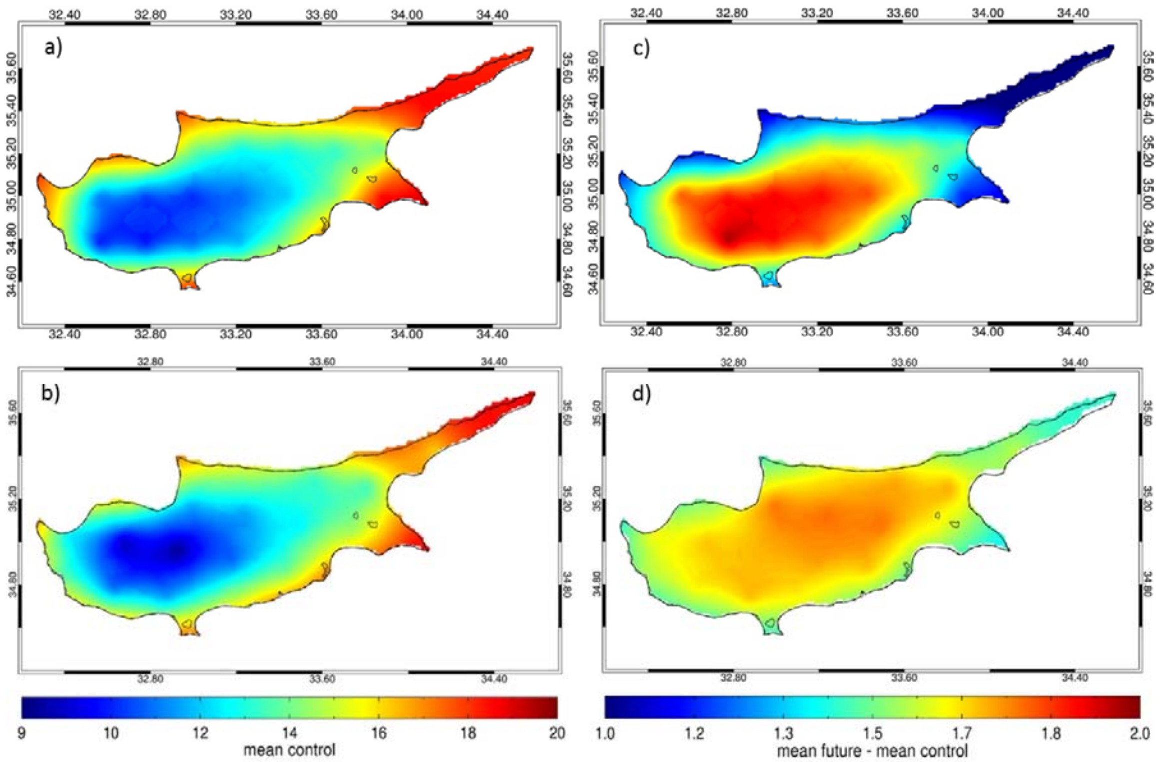

Figure 2: Average annual minimum temperature for the control period (1961 – 1990) using PRECIS (a) and ENSEMBLE model mean (b). Future changes in average annual minimum temperature (2021 – 2050) using PRECIS (c) and ENSEMBLE model mean (d).

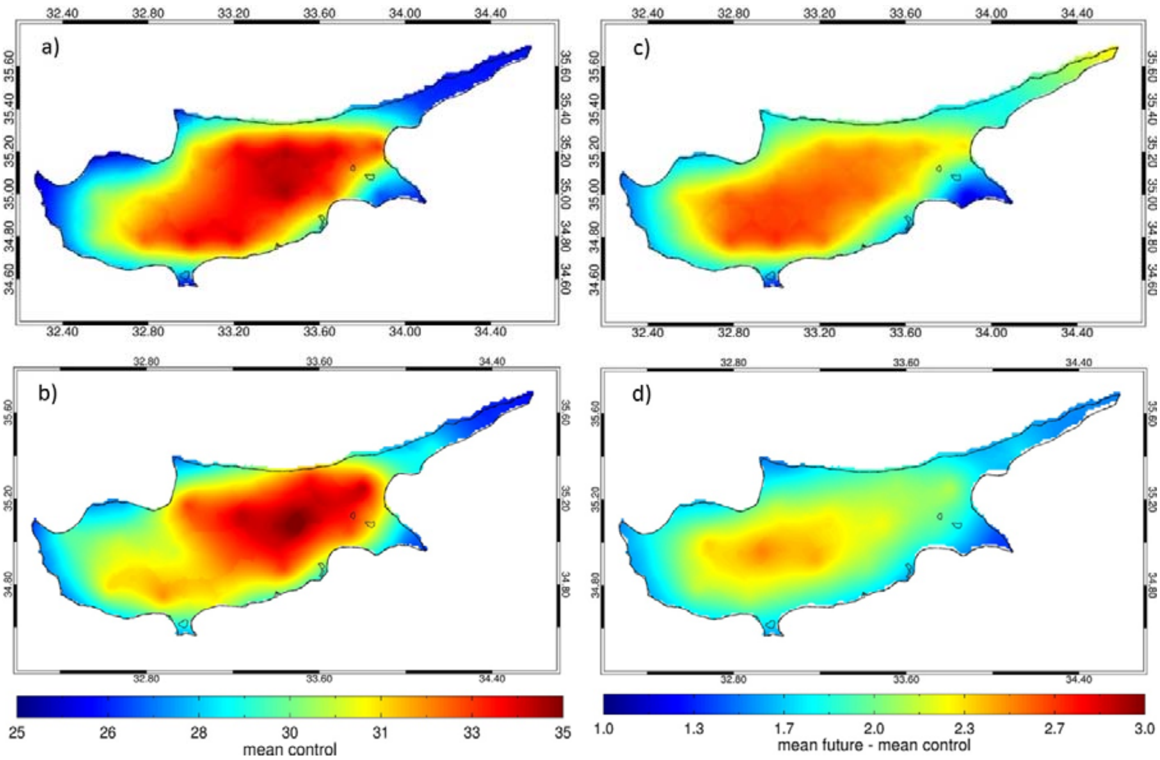

Figure 3: Average summer (JJA) maximum temperature for the control period (1961 – 1990) using PRECIS (a) and ENSEMBLE model mean (b). Future changes in average summer maximum temperature (2021 – 2050) using PRECIS (c) and ENSEMBLE model mean (d).

As regards precipitation, three discrete regions are identified depending on the amount of the annual total precipitation according to PRECIS model (Figure 4a): a) the central lowlands of Cyprus (190-300mm); b) the eastern coasts and the eastern side of Troodos (300-450mm); and c) the western area and western side of Troodos (450-630mm). Hence, the maximum annual total precipitation occurs at the western coasts, unlike Figure 4b, where the ENSEMBLE model mean locates the maximum in Troodos Mountain. Concerning future changes, PRECIS shows that northern coastal areas, especially Karpasia peninsula, are expected to receive less annual total precipitation in the future, than that estimated for the recent past 1961-1990 (Figure 4c). In all other parts of Cyprus, the annual total precipitation appears to have minor decreases or no changes at all. The only region with an increase in total annual precipitation, minor though (up to 5mm), is the area around Orites Forest, east of Paphos. On the other hand, in Figure 4d, the ENSEMBLE model mean presents a decrease in annual total precipitation all over Cyprus, with the highest one (about 100-120mm) located in Troodos Mountain.

Regarding winter total precipitation, it ranges from about 75mm in the lowlands of central Cyprus to 270mm in the western higher elevation areas, woodlands and wetlands (Figure 5a). During winter, the ENSEMBLE model mean is wetter than PRECIS (Figure 5b). In both cases though, the dominance of local topography is evident from high winter precipitation amounts over the windward slopes (exposed to moist air masses) in the southwestern region. As far as future changes are concerned, PRECIS testify almost no changes all over Cyprus (Figure 5c). However, a decrease of about 120mm is projected to the peninsula of Karpasia while lower reductions of about 40mm are anticipated in Ayia Napa as well as in northern and western coastal areas such as Ayia Irini Forest and Akamas peninsula. Regarding the ENSEMBLE model mean, it shows an almost reverse image from compared to PRECIS (Figure 5d). In this case, the highest decreases, up to 70mm, are located in western and mountain areas, while the eastern and northern regions of the country are affected by a minor drought.

It is important to mention that METNO model is excluded from all the ENSEMBLE model mean precipitation projections, including extremes, since it projects very high values and its differences with the other 6 models is very large.

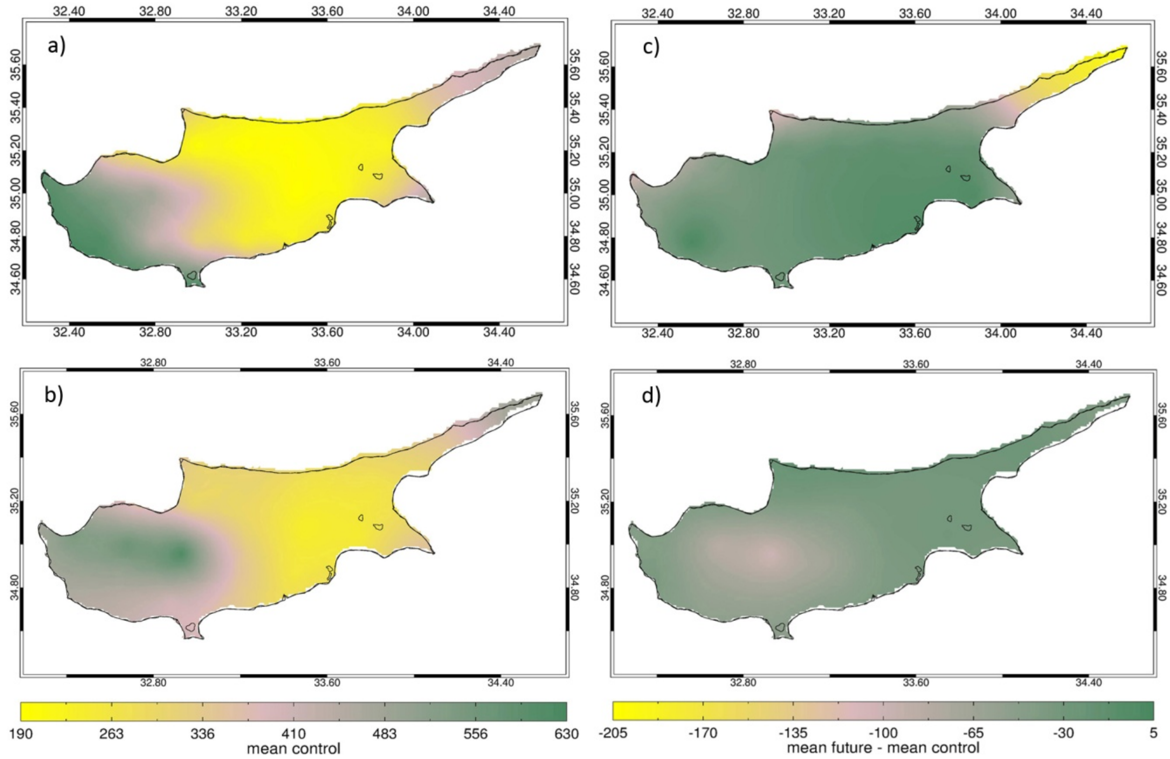

Figure 4: Annual total rainfall for the control period (1961 – 1990) using PRECIS (a) and ENSEMBLE model mean (b). Future changes in annual total rainfall (2021 – 2050) using PRECIS (c) and ENSEMBLE model mean (d).

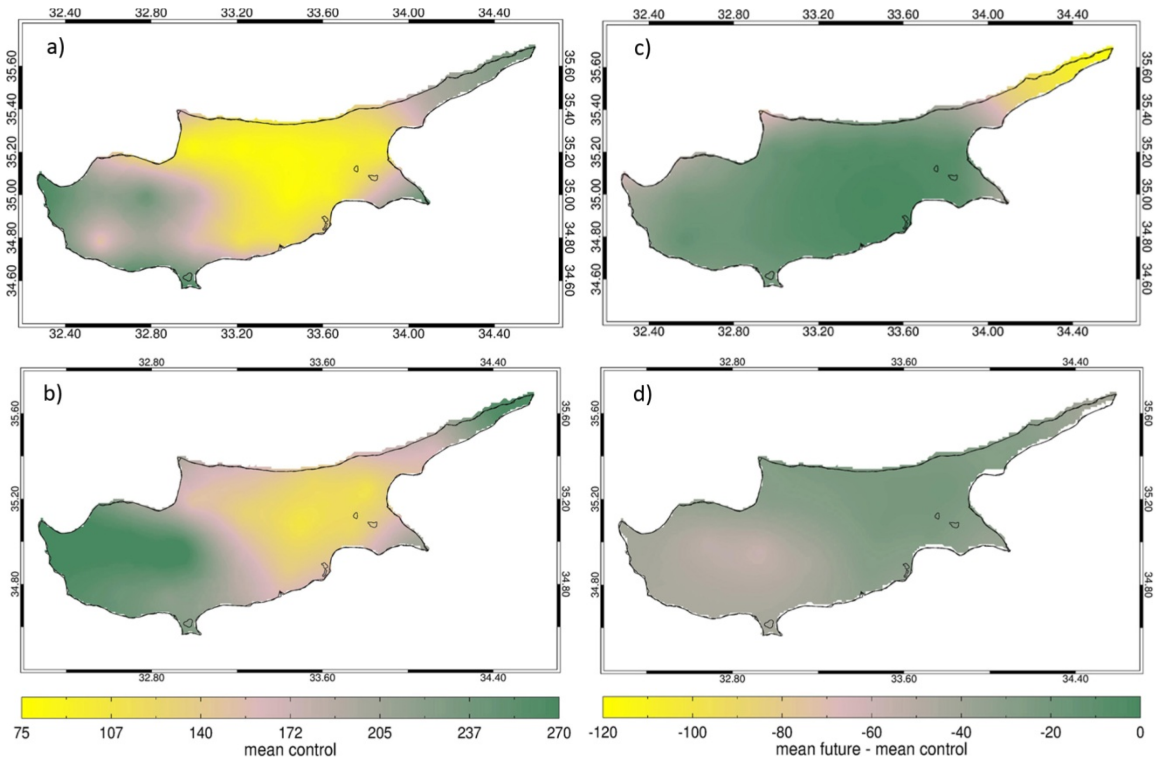

Figure 5: Winter total rainfall for the control period (1961 – 1990) using PRECIS (a) and ENSEMBLE model mean (b). Future changes in winter total rainfall (2021 – 2050) using PRECIS (c) and ENSEMBLE model mean (d).

Climate Extremes Indices

To assess changes in extreme temperature and precipitation in Cyprus between the control (1961–1990) and the future period (2021-2050), climate indices were taken into account using PRECIS output, as well as mean output of the ENSEMBLE models. More specifically, two indices were analyzed for the case of extreme temperature namely the number of heatwave days and the number of tropical nights. Also, for the case of extreme precipitation the index of the number of dry days (days with rain rate RR<0.5mm) was examined in order to investigate the periods of drought in Cyprus

Regards the control period, PRECIS shows that the number of days per year with daily maximum temperature higher than 35°C (heatwave days) is about 10 in western and southeastern areas while in mountain and southern regions it ranges from 15 to 30. The continental lowlands, especially near Nicosia present the higher number of heatwave days i.e. 40 days. The ENSEMBLE model mean, in general, presents a similar pattern of heat wave days, as shown in Figure 6b. In this case though, the number of heat wave days is less than a month/year in the greater region of Limassol, including the southeastern part of Troodos. Again, in the central continental part of the domain, around Nicosia, extended heat periods, i.e. 40–45 days/year, with TX>35°C are common. Regarding future changes, PRECIS shows (Figure 6c) that the increase in heatwave days is about 20 days in coastal areas, with the exception of Ayia Napa, Paralimni and the western coastal area of Paphos, where the increase is smaller i.e. 10 days. The highest increase of about 30-35 days is anticipated in southeastern part of Troodos Mountain as well as in continental lowlands, especially in Nicosia. The ENSEMBLE model mean presents in general a similar pattern of heat wave day changes, as shown in Figure 6d. In this case though, the highest increase in the number of heat wave days reaches 32 days appearing in the central continental part of the domain and in the greater area of Nicosia.

With regard to the number of tropical nights (i.e. the nights with minimum temperature higher than 20°C), PRECIS shows that it varies from about 30 nights in the higher elevation regions and 65 nights in inland areas to 120 nights in southern and southeastern coastal area (Figure 7a). ENSEMBLE model mean presents similar pattern with PRECIS, however, it shows fewer tropical nights in mountain regions i.e. 15 nights (Figure 7b). As far as future changes are concerned, PRECIS shows that the tropical night index is expected to increase by 20-25 days in almost all north coasts of the country, Ayia Napa, Limassol Salt Lake and the area of Larnaca (Figure 7c). A moderate increase of about 30 days is evident in continental lowlands, whereas higher elevation areas, especially northwestern Troodos, are characterized by a maximum increase of 40-45 days per year. On the contrary, the ENSEMBLE model mean shows an increase of about 25-35 nights for the entire domain (Figure 7d).

To continue with the extreme precipitation indices, PRECIS shows that all the western part of the country present the lowest values, as far as the number of dry days is concerned (Figure 6a). However, even in this region, dry days occur during more than half of the year (200-250 days). The rest of the country is characterized by a number of dry days varying between 250 and 300 days. Contrary to PRECIS, the east-west difference is considerably smoothed, as shown in the pattern derived from the ENSEMBLE model mean (Figure 8b). Thus, the number of dry days is more than 260 in the whole country, implying that even higher elevation areas are relatively dry. As for future changes, Figure 8c depicts (PRECIS) that the annual number of dry days is not expected to change much over the southern coastal part of the domain. A significant increase of up to 20 days/year is noted though in Ayia Irini Forest, Karpasia peninsula and in the northwestern part of Paphos Forest, as well as in some other highlands. Additionally, the ENSEMBLE pattern demonstrates that most parts of Cyprus will face a 1-2 weeks/year increase in the number of dry days, with the minimum and maximum values located in the northeastern part and in the western high-elevation continental areas respectively (Figure 8d).

An overview of the findings of all the analysis regarding both meteorological parameters and extremes indices for the control period (1961-1990) as well as future changes (Future – Control Period) is available in Tables 1& 2 where PRECIS model can be easily compared to ENSEMBLE model mean. The five areas of interest are:

- Western areas: the greater area of Paphos
- Southern areas: the greater area of Limassol
- Eastern areas: the greater area of Famagusta, Ayia Napa and Larnaca
- Continental lowland areas: the greater area of Nicosia
- Mountain areas: The Troodos Mountain

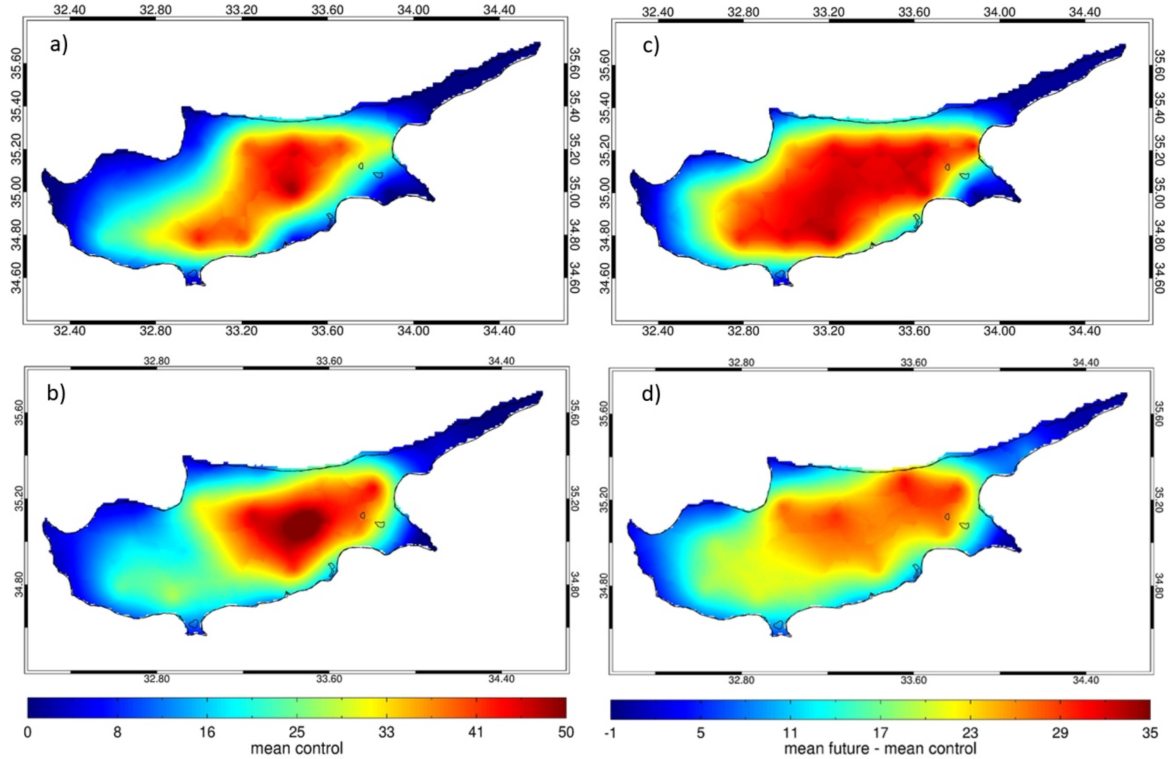

Figure 6: Number of heatwave days for the control period (1961 – 1990) using PRECIS (a) and ENSEMBLE model mean (b). Future changes in the number of heatwave days (2021 – 2050) using PRECIS (c) and ENSEMBLE model mean (d).

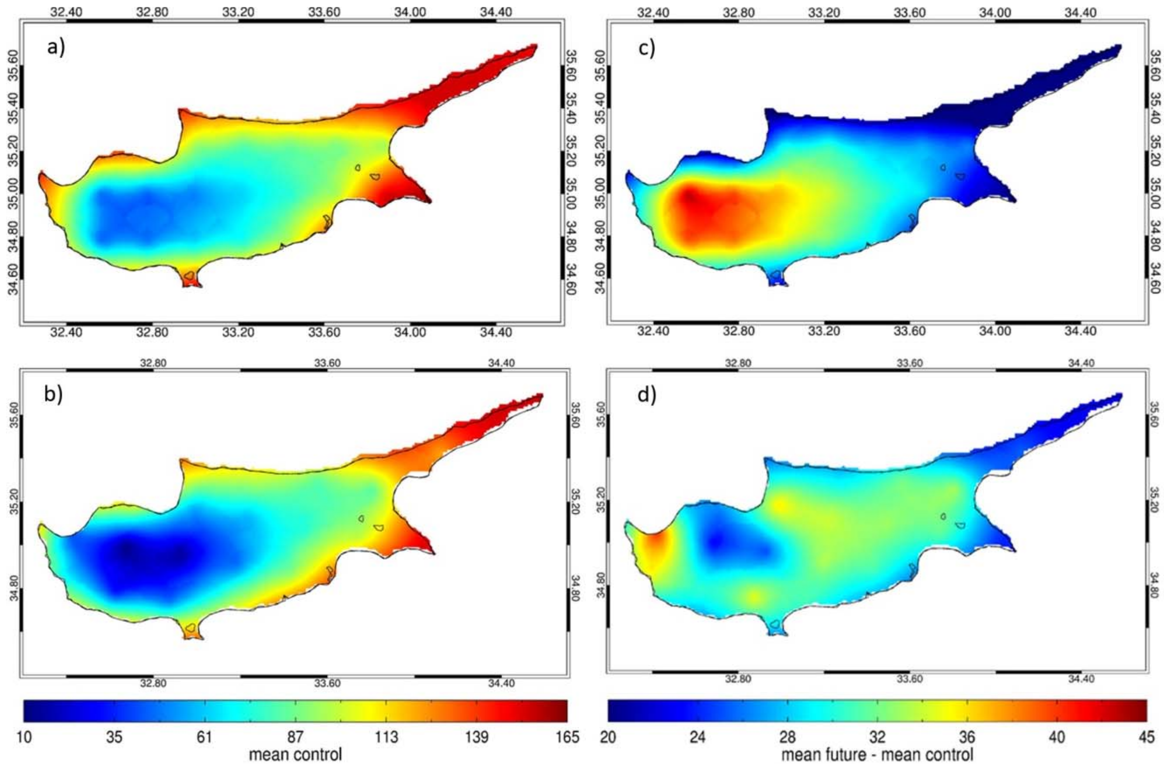

Figure 7: Number of tropical nights for the control period (1961 – 1990) using PRECIS (a) and ENSEMBLE model mean (b). Future changes in the number of tropical nights (2021 – 2050) using PRECIS (c) and ENSEMBLE model mean (d).

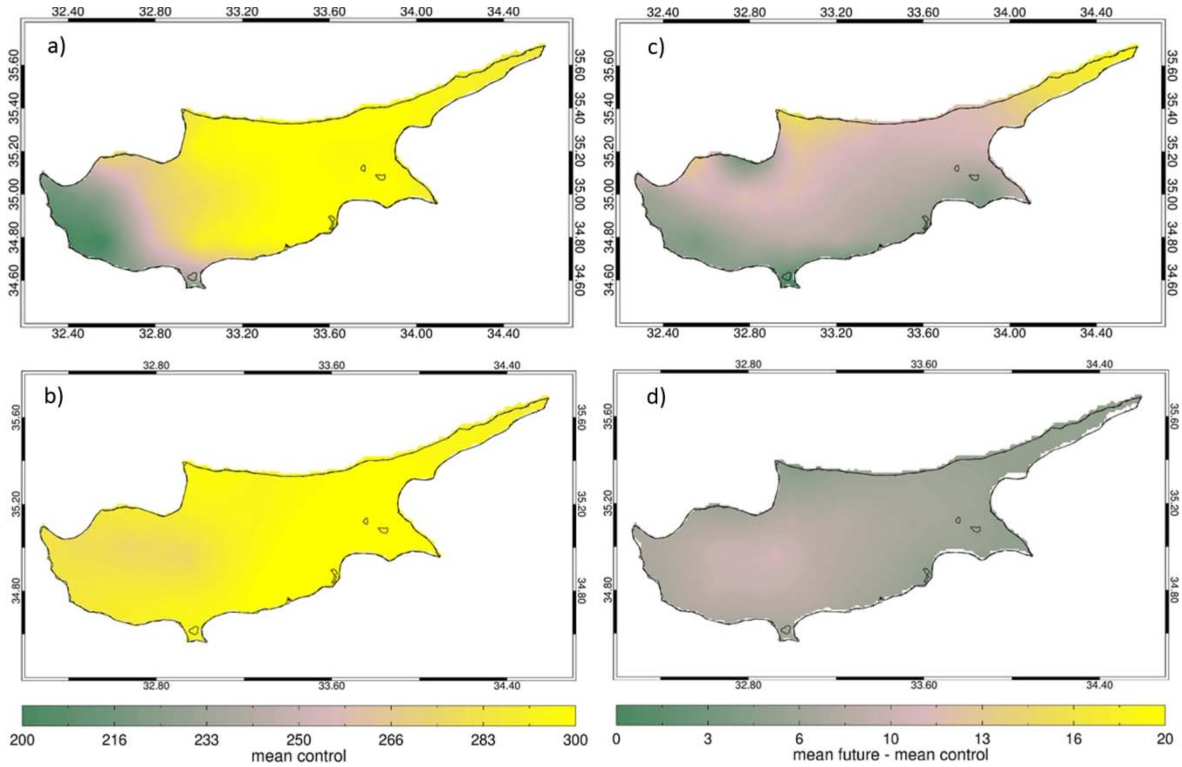

Figure 8: Number of dry days (RR<0.5mm) for the control period (1961 – 1990) using PRECIS (a) and ENSEMBLE model mean (b). Future changes in the Number of dry days (RR<0.5mm) (2021 – 2050) using PRECIS (c) and ENSEMBLE model mean (d).

Time series

To test the performance of the various models used for the future climate projections, time series of observational data derived from various meteorological stations in Cyprus along with the corresponding time series from the climate model simulations were analyzed. Below, the time series of observational data(period 1951-2010) and model simulations (period 1951 – 2100) for mean annual maximum temperature (Figure 9a-c) and the mean annual precipitation (Figure 9d-f) for representative meteorological stations i.e. Larnaca (coast), Nicosia (inland) and Prodromos (mountain) are presented.

The analysis of the mean annual maximum temperature time series shows that almost all models have a narrow spread, which is consistent with the corresponding spread of observations, a positive conclusion for the assessment of the ability of the models to simulate the current climate of the study area. In addition, the relatively strong upward trend of all model outputs indicates a future increasing intensity and duration of heat waves observed in Cyprus in the current and future climate As for the mean annual precipitation time series, Figures 9d-f depict that most of the models demonstrate a good agreement with the observed values. The downward trend of all model output for the future indicates a continuation of the decreasing precipitation amounts observed in Cyprus in the recent past.

Conclusions

This study investigates the potential future climate changes in Cyprus using several projections derived by Regional Climate Models (RCM) simulations. The results show that the 1961-1990 temperature patterns generally illustrate the different climatic zones within Cyprus, from the cool higher elevation conditions to the hot and dry lowlands and the warm and humid coasts. The annual maximum TX in coastal regions is about 33°C, while further inland often exceeds 40°C, In addition the average maximum temperature in summer is about 25-35°C.As for extremes, western side of the islands presents generally lower values in extremes indices of temperature and precipitation compared with the eastern side. As regards precipitation pattern, it does not depend solely on the synoptic weather conditions but also on the pronounced topography, for example Troodos mountains through which rivers supply the much needed water downstream. According to PRECIS model, the annual total precipitation ranges from 190-300mm in the central part of Cyprus (from the north and the south) to 450-630mm in the western part of the country.

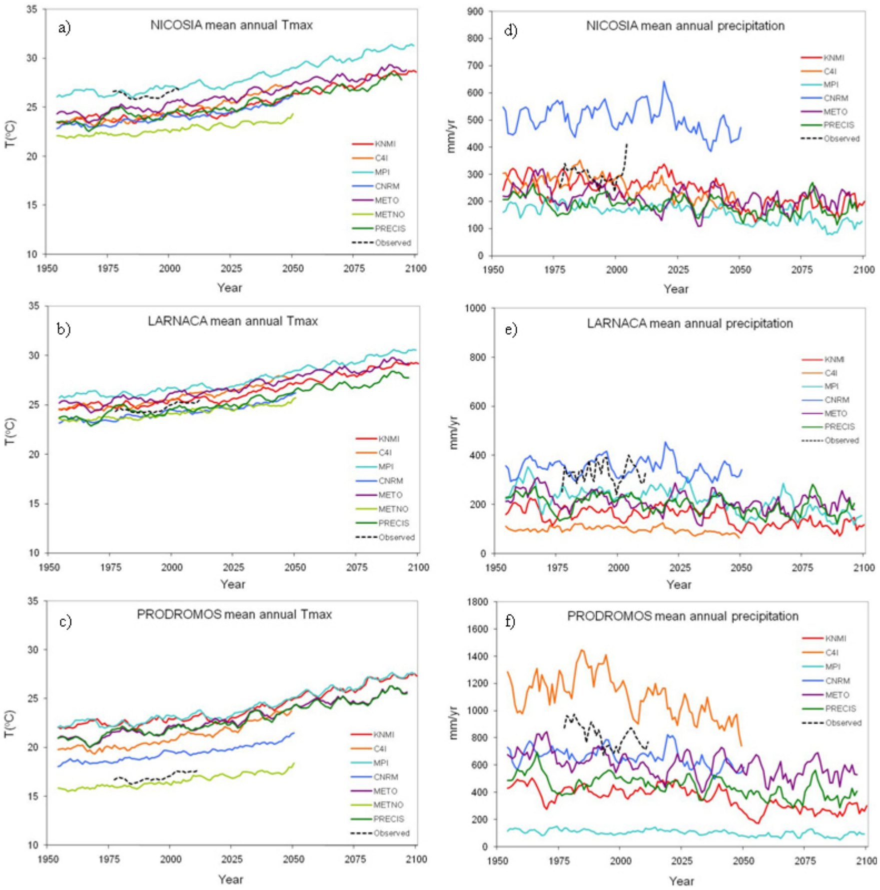

Figure 9: Observational data and climate model simulations time series for the mean annual maximum temperature (a-c) and the mean annual precipitation (d-f) for the Nicosia, Larnaca and Prodromos meteorological stations.

As far as future changes are concerned, the projected changes in temperature are remarkable. In particular, a continual, gradual and relatively strong warming of about 1.0 to 2.0°C may occur between the 1961-1990 reference period and the future period 2021–2050, as shown by the annual maximum temperature patterns. Interestingly, in summer the increase of maximum TX will exceed 2.5°C. Hot summer conditions that rarely occurred in the reference period may become the norm by the middle of the 21st century.

Cyprus projected precipitation changes are quite variable among models. Winter drying will be modest in PRECIS with precipitation decreasing by 5-15mm but larger in the ENSMEBLEs model mean with precipitation decreases reaching 50mm in higher elevation areas. Throughout the year, Cyprus will not be affected by large changes according to PRECIS but according to the ENSEMBLES model mean reductions in precipitation may reach 60mm in southern coastal areas and 80 mm at higher elevation sires. Therefore, Cyprus precipitation patterns must be interpreted with caution, owing to the large temporal variability of rainfall, the inherent limitations of climate models to simulate accurately the hydrological cycle and the large variations of future projected changes among models.

Future temperature extremes projections show that almost one additional month with temperature higher that 35°C is anticipated in the domain of study expect for the coastline where the increase is lower i.e. 5-15 days. Similarly, the increase in the number of days with TN>25°C (tropical nights) is expected to be approximately 1 month, which is of great since it is highly contribute to the intensification of people discomfort. Precipitation extremes indices projections do not present any significant change in the future period. Pronounced warming and precipitation reductions are also detected from time series of temperature and precipitation parameters, regarding representative locations of Cyprus during the period 1951-2100. It is also appeared that all models data demonstrate a quite narrow spread and a good agreement with the observed values, as derived by the time series of mean annual maximum and minimum temperatures.

Table 1: Meteorological parameters and Extreme indicies in Cyprus averaged over the control period (1961–1990)

	Western Areas		Southern areas		Eastern areas		Continental lowland areas		Mountain areas	
	PRECIS	ENSEMBLE	PRECIS	ENSEMBLE	PRECIS	ENSEMBLE	PRECIS	ENSEMBLE	PRECIS	ENSEMBLE
Meteorological Parameters										
TXa	21.2	21.6	22.5	22.8	23	23.5	24.2	24.5	21.5	21.0
TNa	14	13.5	14	14	16	17	14	13	11	10
TXJJA	27	28	30	30.5	30.0	30.5	34	34	33	32
PRa	630	470	490	410	280	300	230	300	430	580
PRDJF	230	260	230	220	140	160	100	130	220	260
Extreme Indices										
TX>35°C	4	8	18	16	15	17	41	43	25	20
TN>20°C	100	85	100	110	130	125	90	85	45	30
RR<0.5mm	200	280	250	280	280	300	280	300	265	270

Table 2: Future Changes in Meteorological Parameters and in indices of extremes in Cyprus (Future – Control)

	Western Areas		Southern areas		Eastern areas		Continental lowland areas		Mountain areas	
	PRECIS	ENSEMBLE	PRECIS	ENSEMBLE	PRECIS	ENSEMBLE	PRECIS	ENSEMBLE	PRECIS	ENSEMBLE
Meteorological Parameters										
TXa	1.4	1.5	1.5	1.6	1.3	1.6	1.6	1.8	1.9	1.9
TNa	1.4	1.5	1.5	1.6	1.3	1.6	1.8	1.7	1.8	1.7
TXJJA	1.6	1.7	2.0	1.9	1.8	1.8	2.5	2.1	2.6	2.4
PRa	0	-40	-5	-60	0	-30	0	-30	-5	-85
PRDJF	-15	-40	-10	-40	-10	-30	-5	-30	-10	-55
Extreme Indices										
TX>35°C	2	5	19	13	17	15	34	30	30	21
TN>20°C	32	30	30	30	25	29	29	32	38	26
RR<0.5mm	4	8	4	8	8	6	8	7	11	11

TXa: Average annual Tmax
TNa: Average annual Tmin
TXJJA: Average summer Tmax
PRa: Annual total precipitation
PRDJF: Winter total precipitation

TX>35°C: Heat wave days: Number of days per year with daily maximum temperatures TX>35°C
TN>20°C: Tropical nights: Number of days per year with minimum nighttime temperatures TN>20°C
RR<0.5mm: Dry days: Number of days per year with precipitation RR<0.5mm

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