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Expected heat load of Dubrovnik, Osijek, Rijeka, Zadar and Zagreb based on the projections of regional climate models

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This paper examines the expected future heat load in five Croatian cities: Dubrovnik, Zadar, Rijeka, Zagreb, and Osijek. The heat load is estimated by temperature-related climate indices and mean, maximum and minimum daily temperatures obtained by climate simulations using two different regional climate models (DHMZ-RegCM4 and SMHI-RCA4) with a horizontal resolution of 12.5 km, forced with two global climate models (EC-EARTH and MPI-ESM-MR/LR) for two different greenhouse gas concentration scenarios (RCP4.5 and RCP8.5). By comparing these variables for the period 2041–2070 with respect to the current climate (defined as that of the period 1991–2020), a significant increase in mean, maximum and minimum temperatures was observed in all analysed combinations of regional and global climate models for all analysed cities. Although there is a difference in results depending on the combination of regional and global models, the largest increase is mainly found in the warm part of the year (April-October), with the strongest warming of Dubrovnik and Rijeka. Due to similar trends in minimum and maximum temperatures, the trend in the daily temperature range is weak. Under warmer climate conditions, the number of days with a maximum air temperature above 25 °C increases in all considered cities (especially in Dubrovnik), as does the number of days with a minimum air temperature exceeding 20 °C (especially in Rijeka and Zadar). Furthermore, a reduction in the number of days with maximum and minimum temperatures below 0 °C is projected for all cities. Nevertheless, some differences are found between coastal and inland cities caused by local factors.

Keywords: heat load of cities, climate indices, regional climate model projections

1. Introduction

There is an abundance of scientific evidence that shows that the Earth is becoming warmer as a result of anthropogenic influences (*e.g.*, IPCC, 2021). Particularly vulnerable are urban environments because they are under the influence of not only global warming but also urbanisation and related small-scale physical processes, which can lead to a synergistic effect among various physical processes and to exceptional heat loads in cities.

Urbanisation changes the characteristics of the Earth's surface, causing changes in the radiation balance and redistribution of heat and water. As a result, urban areas tend to have significantly higher air temperatures compared to the surrounding rural areas (Wong, Lai, and Hart, 2016), a phenomenon known as the urban heat island (UHI) effect. Most people live in cities, approximately 55% (in Croatia, more than 55% according to the report of the Central Bureau of Statistics of the Republic of Croatia from 2020), and it is expected that approximately 68% of the total population of the Earth will live in cities by 2050 (UN, 2018), making cities even more vulnerable, given that high air temperatures have a negative impact on human health. It has been shown that as global temperature rises, there is an increase in the problems associated with the occurrence of heat waves as well as their undesirable impact on humans (Founda and Santamouris, 2017).

Croatia is located in southeastern Europe and the Mediterranean, which, according to the latest report from the International Panel on Climate Change (IPCC, 2021), is one of the most vulnerable areas in Europe in terms of the effects of climate change. To date, trends of mean, mean minimum and mean maximum air temperatures have shown significant increases in Croatia. Annual air temperature trends are positive and statistically significant, with stronger warming of the continental part of the country than that of the coastal part. The strongest increase is detected for maximum air temperature (MINGOR, 2020).

Croatia is expected to experience a further temperature increase, with an average increase of 1.8-2.4 °C in the period P2 compared to the period 1961-1990, which is likely to be most pronounced in summer months (DHMZ, 2023). Most recent research (*e.g.*, IPCC, 2021) has been conducted for a large area (Europe or one part of it, such as the Mediterranean, the Alps, or a country), and there is a lack of research that is locally focused on cities in Croatia. Boras et al. (2022) have shown rising trends for mean, minimum and maximum temperatures in the city of Dubrovnik for the period 1961-2020, which are highest during summer months, but they did not investigate future trends of heat load. On the other hand, it has been shown that in different locations in Zagreb, the type of climate has already changed due to increasing air temperatures, and additional temperature increases are expected in the future (Nimac, 2022). It is obvious that there is a lack of systematic research focused on the expected heat load of cities in Croatia. Therefore, we have analysed several cities in Croatia that are located in areas with different geographical and climatic characteristics. The aim of this paper is to estimate the future heat load of the following Croatian cities: Dubrovnik, Zadar, Rijeka, Zagreb, and Osijek by comparing average, maximum and minimum daily air temperatures for two time periods, P0 and the P2. The P0 period represents the recent past— a reference period defined here as 1991-2020—and the P2 period is 2041–2070.

Different climate models (global and regional) are used to project future climate for specific greenhouse gas (GHG) concentration scenarios, such as the IPCC's Representative Concentration Pathways[1] (RCP). Global climate models (GCMs) are used to simulate the components of the climate system and their interactions. Because GCMs cover the entire Earth and their resolution is quite rough, dynamic downscaling is needed. Regional climate models (RCMs) have been developed to provide information at finer scales (finer than GCMs) and are more suitable for the study of regional phenomena. This is done by so-called nesting, where GCM results are used as boundary conditions for RCMs, which in turn simulate smaller scale processes such as mesoscale processes, the effects of complex topography, coastline, etc. (Giorgi et al., 2012). Currently, RegCM4 (Giorgi et al., 2012) is one of the latest versions of a regional climate model that can be used for any part of the Earth at a resolution of up to approximately 10 km (hydrostatic limit). The implementation of the RegCM4 model by the Croatian Meteorological and Hydrological Service (DHMZ) is evaluated in Güttler et al. (2020) and will be denoted DHMZ-RegCM4 in this paper. Similar to the RegCM4 model, the SMHI-RCA4 regional climate model was developed by the Swedish Meteorological and Hydrological Institute (SMHI; Wang et al., 2015).

2. Data and methods

2.1. Future climate projections

In this paper, we use the realisations of two RCMs, DHMZ-RegCM4 and SMHI-RCA4, with a 12.5 km horizontal resolution, forced by two different GCMs from Phase 5 of the Coupled Model Intercomparison Project (CMIP5): EC (EC-EARTH; Hazeleger et al., 2010) and MP (MPI-ESM-MR/LR; Giorgetta et al., 2013). The RCMs used differ in the number of vertical levels and various schemes and parameterisations (*e.g.*, Srnec et al., 2019). It should be noted that the grid cells at the Earth's surface in the DHMZ-RegCM4 model are either represented as land or sea, which affects the simulation of processes in coastal regions. In contrast, in the SMHI-RCA4 model, the cells of the Earth's surface model are represented as a fraction of grid cells occupied by land surfaces, which enables more accurate results for coastal areas. The results of the DHMZ-RegCM4 model were obtained from the repository of the Croatian Meteorological and Hydrological Service (MZOE, 2017), and the results of SMHI-RCA4 were provided by the Copernicus database (Copernicus, 2018). For the 1991-2005 period, the simulations are based on the observed greenhouse gas concentrations, while for the 2006-2070 period, there are two realisations based on the medium stabilisation RCP4.5 and high emission RCP8.5 greenhouse gas scenarios (Moss et al., 2010). Here, as a reference

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[1] IPCC glossary, URL: https://apps.ipcc.ch/glossary/

period (P0), we used the period 1991–2020, which is actually a combination of historical (1991–2005) and scenario-based (2006–2020) periods. Furthermore, the future climate is considered to be the one simulated for period P2 (2041–2070). The period between periods P0 and P2 is denoted as P1 and refers to 2021–2040. The RCM outputs were analysed for five Croatian cities located in different climate regions of the country: Dubrovnik, Zadar, Rijeka, Zagreb, and Osijek, for which the mean (*tas*), maximum (*tasmax*) and minimum (*tasmin*) daily air temperatures at a height of 2 m were analysed. Given that the climate model consists of a finite number of grid points indicating the centre of one cell of the model, these points do not necessarily coincide with the coordinates of the analysed cities. This is why the "nearest neighbour" approach was utilised (each city was represented with the centre of closest cell of the model). The combination of one RCM, one GCM and one RCP scenario represents one projection of the future climate.

2.2. Bias correction

The representation of the climate by climate models is not perfectly realistic, *i.e.*, there are systematic deviations between the modelled and observed values of a variable. One of the sources of unreliability is that the atmosphere in the model is represented by a finite number of variables, and additional unreliability arises from the parameterisation schemes and from the choice of model parameters (Ho et al., 2012). In addition, some small-scale processes and physical properties are not distinguished by the models and give rise to systematic errors; therefore, it is important to adjust the modelled data to the measurements. In this paper, bias correction was performed using the quantile mapping method (*e.g.*, Piani et al., 2010, Sokol Jurković et al., 2022). This adjustment was made on a monthly basis, which means that the observed and modelled daily data from a certain period were taken separately for each month, and the monthly means of modelled data corrected by this method match the monthly means of the measured values. The analysis of regional climate model systematic errors is provided in other studies (*e.g.*, Güttler et al., 2020 for the DHMZ-RegCM4 simulations). No additional adjustments were performed before the quantile mapping step.

After bias correction was performed for all considered projections of the future climate and for all variables (mean, maximum and minimum air temperatures at 2 m height), multiannual monthly means were calculated for them in periods P0 and P2 as well as the difference in multiannual monthly means between the data of these two periods for all future climate projections. Then, time series of variables throughout the analysed period (1991–2070) are analysed, for which linear trends expressed in °C/10 y are calculated and shown on the map of the Republic of Croatia.

2.3. Climate indices

To estimate the change in heat load of the analysed cities, different annual climate indices, as well as their averages and linear trends, were calculated (Tab. 1).

Table 1. Climate indices examined in this paper and their definitions (Climdex, 2021).

Climate index	Definition
Frost Days (FD)	Number of days in a year with minimum daily air temperature below 0 °C.
Icing Days (ID)	Number of days in a year with maximum daily air temperature below 0 °C.
Summer Days (SU)	Number of days in a year with maximum daily air temperature above 25 °C.
Tropical Nights (TR)	Number of days in a year with minimum daily air temperature above 20 °C.
Daily Temperature Range (DTR)	Annual mean of the daily extreme temperature range, defined as the ratio of the sum of the differences between the maximum and minimum temperatures for each day in a year and the number of days in the specific year.
Extreme Temperature Range (ETR)	Range of annual extreme temperatures, or the difference between the annual maximum temperature and the annual minimum temperature for the same year.

To assess the statistical significance of trends, the Mann–Kendall test (Mann, 1945; Kendall, 1975; Gilbert, 1987) was used to calculate *p* values, and the statistical significance of trends was estimated at a significance level of 95%.

3. Results

3.1. Mean, minimum and maximum daily temperatures

The multiannual monthly averages of variables *tas*, *tasmin* and *tasmax* were calculated. Previous research by Branković et al. (2017) indicated an increase in mean, minimum and maximum temperatures, and stronger, more frequent and longer temperature extremes are expected in Croatia; such changes can propagate to the city level as well. For the cities of Dubrovnik and Zagreb and the combination of the RCM DHMZ-RegCM4 and GCM EC models, *tas*, *tasmin* and *tasmax* are presented on the left side of Figs. 1 and 2, respectively. As expected, an increase in mean monthly *tas*, *tasmin* and *tasmax* is shown for period P2 compared to period P0 in both scenarios, which is also found for all combinations of the climate models used and is generally slightly higher for scenario RCP8.5 than for RCP4.5. The differences between projections under RCP4.5 and RCP8.5 are smallest in the warm season. This may be due to the overwhelming impact of solar radiation reaching the surface. In the warm season, solar shortwave radiation is more important in regulating the surface temperature, and this forcing is reduced in the colder months. At the same time, the differences between the RCP scenarios are related to the differences in higher GHG concentrations in RCP8.5, leading to stronger longwave forcing at the surface in RCP4.5, and these impacts are more obvious in the cold part of the year. This hypothesis should be explored in dedicated studies related to the impacts of shortwave and longwave radiation in relevant RegCM-EC simulations over Croatia (*e.g.*, such as the master's thesis by Lozuk (2022) but for different RCMs).

The period from April to October is generally considered the warm part of the year in Croatia; these are the months where there is at least one day with air temperatures above 25 °C, while the period from November to March is considered the cold part of the year. To determine in which months we can expect the largest temperature increase in the future, differences in multiannual monthly averages between periods P2 and P0 were calculated. The maximum differences between multiannual monthly averages for periods P2 and P0 and the month in which this maximum occurred are given in Tab. 2 for RCP4.5. We can observe that different combinations of RCMs and GCMs give different results, and there are certain deviations between the results due to different combinations of models. For example, for Dubrovnik, the largest increase in mean air temperature for the RCP4.5 scenario occurs in September for DHMZ-RegCM4-EC simulations, in March for DHMZ-RegCM4-MP, in May

Table 2. The months with the largest increase in temperature for the RCP4.5 scenario and the difference between the multiannual monthly averages for the period 2041–2070 (P2) compared to those for the period 1991–2020 (P0).

			Dubrovnik	Zadar	Rijeka	Zagreb	Osijek
RCP 4.5	*tas*	DHMZ-RegCM4-EC	IX., 1.76 °C	IX., 1.99 °C	VIII., 2.12 °C	VII., 2.27 °C	VII., 2.18 °C
		DHMZ-RegCM4-MP	III., 2.34 °C	III., 1.99 °C	III., 2.31 °C	VII., 1.97 °C	VII., 1.87 °C
		SMHI-RCA4-EC	V., 1.93 °C	V., 1.55 °C	VI., 1.89 °C	VIII., 2.04 °C	VIII., 1.83 °C
		SMHI-RCA4-MP	VI., 1.85 °C	VI., 1.51 °C	VI., 2.06 °C	VI., 2.34 °C	VI., 2.44 °C
	tasmax	DHMZ-RegCM4-EC	VII., 1.67 °C	VIII., 1.88 °C	VIII., 2.10 °C	VII., 2.36 °C	VII., 2.37 °C
		DHMZ-RegCM4-MP	III., 2.23 °C	III., 2.21 °C	III., 2.37 °C	III., 1.88 °C	VII., 1.85 °C
		SMHI-RCA4-EC	V., 1.98 °C	V., 1.64 °C	VIII., 1.98 °C	VIII., 2.15 °C	VIII., 1.84 °C
		SMHI-RCA4-MP	VI., 1.86 °C	VI., 1.64 °C	VI., 2.15 °C	VI., 2.53 °C	VI., 2.58 °C
	tasmin	DHMZ-RegCM4-EC	VIII., 1.84 °C	IX., 2.04 °C	VIII., 2.06 °C	VII., 2.21 °C	VII., 2.12 °C
		DHMZ-RegCM4-MP	III., 2.43 °C	III., 2.00 °C	III., 2.26 °C	VII., 2.09 °C	VII., 2.02 °C
		SMHI-RCA4-EC	V., 1.71 °C	VI., 1.39 °C	VI., 1.87 °C	VIII., 1.75 °C	VIII., 1.58 °C
		SMHI-RCA4-MP	VI., 1.80 °C	VII., 1.54 °C	VIII., 1.82 °C	XII., 1.83 °C	XII., 2.02 °C

for SMHI-RCA4-EC, and in June for SMHI-RCA4-MP. Despite the differences among the combinations of the regional and global climate models, in most cases, the largest increases in mean, minimum and maximum air temperatures consistently occur in the warmer parts of the year. The reason for the larger difference in the warmer part of the year may be caused by the intensification and increased frequency of heat waves under future climate conditions. Large-scale influences, *i.e.*, atmospheric conditions that enable the development and persistence of heat waves, certainly contribute to this. For example, certain patterns of atmospheric circulation are associated with the advection of warm air and thus contribute to higher temperatures. Additionally, local conditions such as reduced soil moisture support the development and persistence of heat waves. Therefore, drier summer conditions and related land-surface feedbacks can play a significant role (Fischer et al., 2007; Fischer and Schär, 2008, 2010). The results show an increase in multiannual monthly averages of *tas*, *tasmin* and *tasmax* between 1.5 °C and 2 °C in all cities. The increase is almost equal for *tas*, *tasmin* and *tasmax*; however, it is noticed that in Zadar, Rijeka, Osijek, and Zagreb, it is slightly higher for *tasmax* than for *tasmin*, while the opposite was shown for Dubrovnik.

Time series of mean annual *tas*, *tasmax* and *tasmin* with linear trends were analysed as well. The cities of Dubrovnik and Zagreb and the model combination DHMZ-RegCM4-EC are shown in the righthand parts of Figs. 1 and 2, respectively. There is an increase in mean, minimum and maximum air temperatures throughout the entire analysed period (1991–2070), which occurs for all cities and all combinations of climate models and both scenarios. As expected, the trends are higher for the RCP8.5 scenario (not shown) than for the RCP4.5 scenario.

To estimate the growth rate of the mean, minimum and maximum air temperatures in the selected cities and to show the differences between the continental (Osijek, Zagreb) and coastal (Dubrovnik, Rijeka, Zadar) cities, linear trends were calculated and shown on a map (Fig. 3) for comparison. This figure shows the results for the RCP4.5 scenario using GCM EC (not shown for GCM MP), while all the results are summarised in the upper part of Tab. 2. All the trends are statistically significant at the 95% significance level. Based on DHMZ-RegCM4 simulations, the projected growth rates of *tas* and *tasmax* are stronger in coastal cities than in continental areas, while according to the SMHI-RCA4 model, a slightly stronger warming signal is found for inland cities. For *tasmin,* DHMZ-RegCM4 generally simulates a stronger warming signal than SMHI-RCA4. The results for the RCP4.5 scenario indicate an increase in mean annual air temperature for the analysed cities between 0.18 and 0.27 °C/10 y, an increase in mean annual minimum air temperatures between 0.18 and 0.28 °C/10 y, and an increase in mean annual

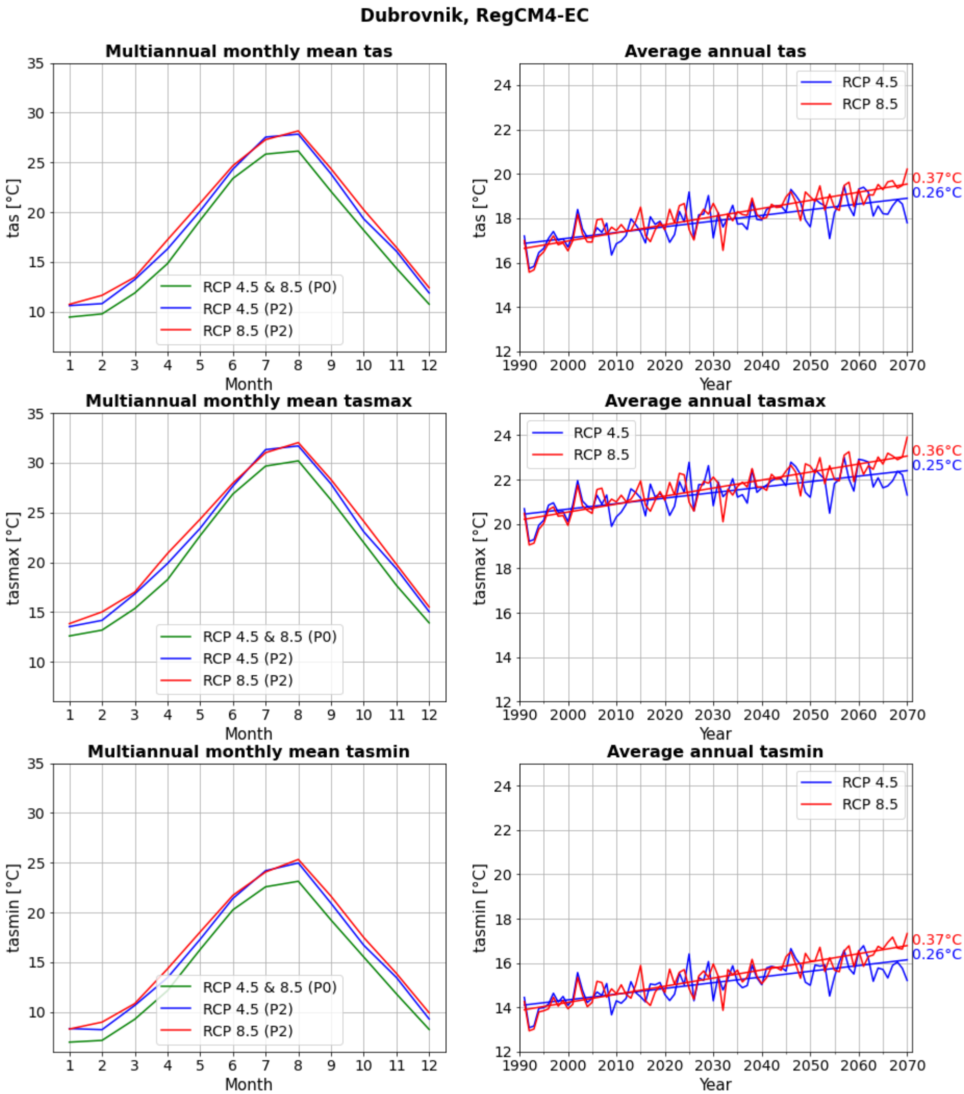

Figure 1. *Left*: Multiannual monthly average *tas* (*a*), *tasmax* (*b*), and *tasmin* (*c*) in 1991–2020. (P0; green), and in the period 2041–2070. (P2) for scenarios RCP4.5 (blue) and RCP8.5 (red). Right: time series and linear trends of mean annual *tas* (*a*), *tasmax* (*b*) and *tasmin* (*c*) for scenarios RCP4.5 (blue) and RCP8.5 (red). Statistically significant (nonsignificant) trends at the 95% significance level are marked with a solid (dashed) line. The presented results are for Dubrovnik obtained from the model combination DHMZ-RegCM4-EC.

maximum temperatures between 0.18 and 0.27 °C every 10 years. For the RCP8.5 scenario, increases are higher (not shown) for *tas* between 0.26 and 0.39 °C/10 y, *tasmin* between 0.27 and 0.40 °C/10 y and *tasmax* between 0.26

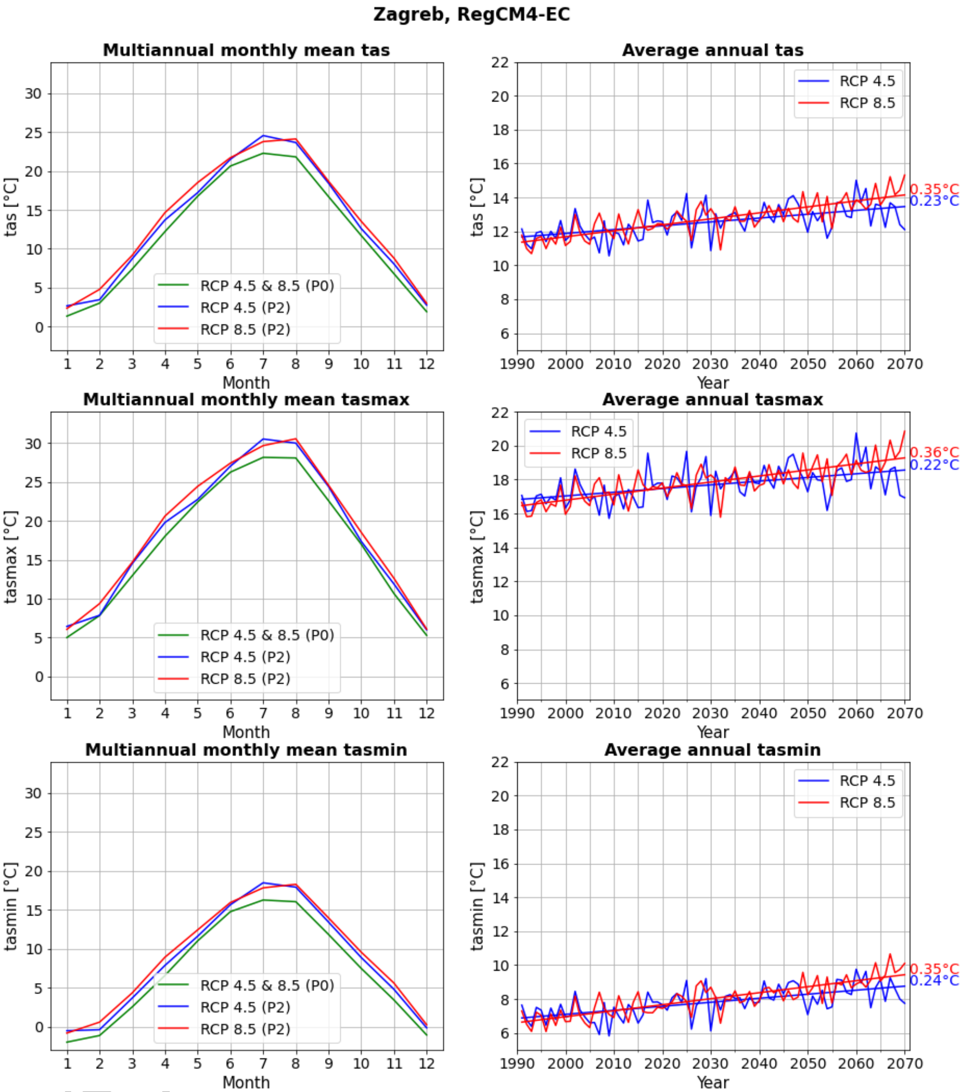

Figure 3.1.2: Left: Multiannual monthly average *tas* (*a*), *tasmax* (*b*), and *tasmin* (*c*) in 1991–2020. (P0; green), and in the period 2041–2070. (P2) for scenarios RCP4.5 (blue) and RCP8.5 (red). Right: time series and linear trends of mean annual *tas* (*a*), *tasmax* (*b*) and *tasmin* (*c*) for scenarios RCP4.5 (blue) and RCP8.5 (red). Statistically significant (nonsignificant) trends at the 95% significance level are marked with a solid (dashed) line. The presented results are for Zagreb obtained from the model combination DHMZ-RegCM4-EC.

and 0.41 °C/10 y. According to these simulations, we can expect increases in mean annual minimum, maximum, and mean temperature regardless of the station and scenario being considered and the combinations of RCM and GCM

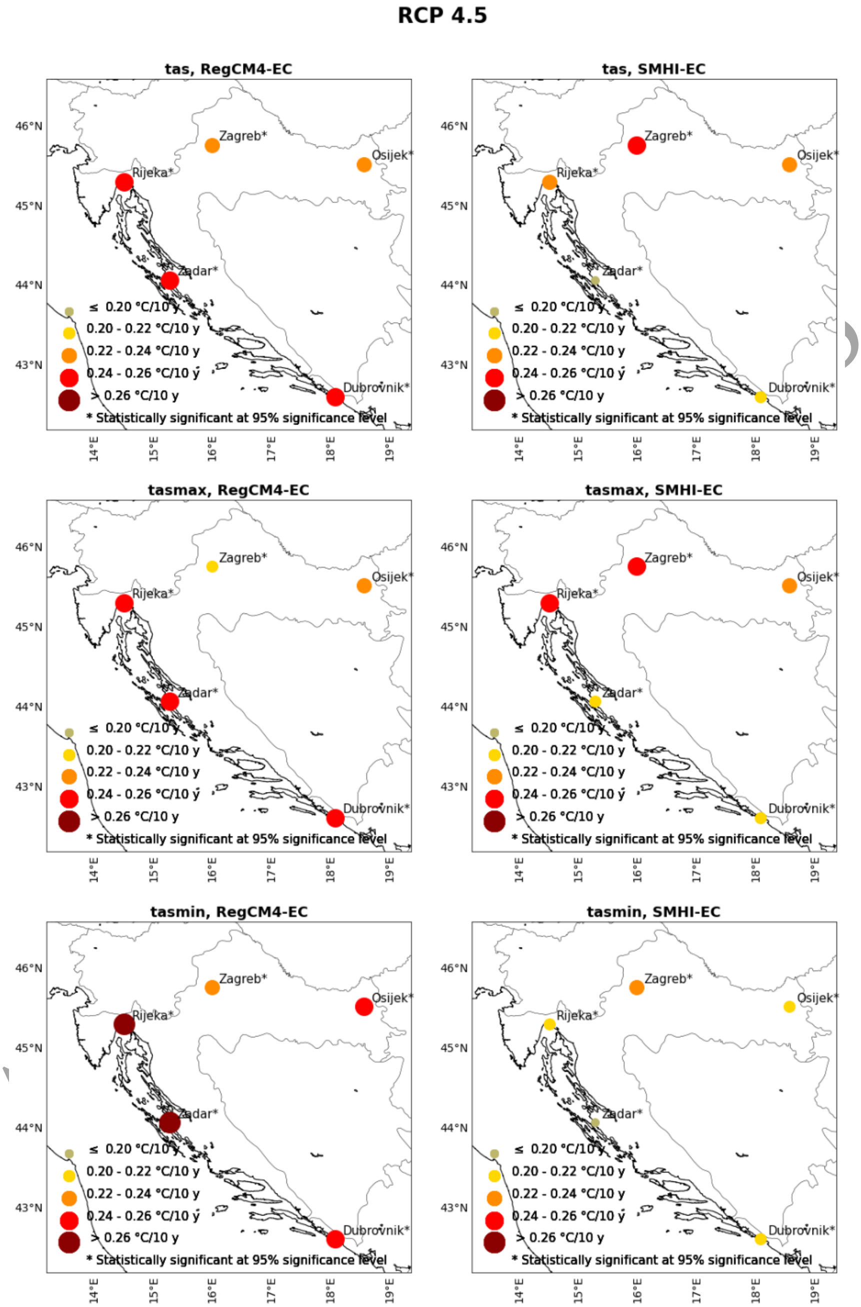

Figure 3. Map of the Republic of Croatia with trends of average annual *tas* (*a*), *tasmax* (*b*) and *tasmin* (*c*) given in °C/10 y. The results for the RCP4.5 scenario obtained with the model combination DHMZ-RegCM4-EC (*left*) and SMHI-RCA4-EC (*right*) are presented. Cities where the trend is statistically significant at the 95% significance level are marked with an asterisk.

used. However, the results for *tasmin* and *tasmax* are almost identical, although a stronger increase is expected for *tasmin*. Namely, it would be expected for minimum temperatures to increase faster in cities due to the urban heat island phenomenon (UHI) – urban structures absorb more heat and release it (*e.g.*, Nimac et al., 2022). Considering that the UHI influence is strongest at night when urban structures release the heat accumulated during the day, it manifests most strongly in *tasmin*. However, cities are not represented in the RCMs we used here. Therefore, neither of the processes related to their influence are resolved in the models, which at least partially explains the somewhat weaker *tasmin* trend.

It was also shown that the use of GCM EC gives smaller differences in the trends of *tas*, *tasmax* and *tasmin* between the two scenarios in contrast to GCM MP (not shown).

Under the conditions of the RCP4.5 or higher scenario, Dubrovnik is expected to have an increase in the average annual air temperature between 0.21 and 0.39 °C every 10 years, an increase in the average annual minimum between 0.20 and 0.40 °C/10 y and an increase in the mean annual maximum between 0.20 and 0.38 °C every 10 years. In Osijek, in these conditions, the average annual temperature could increase between 0.18 and 0.37 °C/10 y, the average annual minimum between 0.18 and 0.38 °C/10 y and the average annual maximum between 0.19 and 0.39 °C/10 y. In Rijeka one could expect an increase in *tas* 0.23–0.39 °C/10 y, *tasmin* 0.20–0.40 °C/10 y and *tasmax* 0.23–0.41 °C/10 y, and in Zadar an increase in *tas* between 0.18–0.37 °C/10 y, *tasmin* 0.18-0.38 °C/10 y and *tasmax* 0.18–0.38 °C/10 y. If the conditions of the RCP4.5 or higher scenario are met in Zagreb, *tas* could increase between 0.20 and 0.38 °C every 10 years, *tasmin* 0.21 and 0.37 °C/10 y and *tasmax* 0.20 and 0.39 °C, with higher values corresponding to the RCP8.5 scenario everywhere. Slightly larger values of *tas* and *tasmax* in the RCP4.5 scenario compared to the RCP8.5 scenario were observed for the period of approximately 2025–2030, and these larger values are internal variability effects. The two scenarios start to strongly diverge in terms of concentrations and forcing later in the 21st century, which is also seen in the *tasmin* and *tasmax* time series.

3.1. Climate indices

Time series of climate indices *FD*, *ID*, *SU*, *TR*, *DTR* and *ETR* and associated linear trends are calculated for the entire analysed period, 1991–2070, for all cities and all combinations of climate models and scenarios. An example is presented for Dubrovnik (Fig. 4) and Zagreb (Fig. 5) for a combination of RCM DHMZ-RegCM4 and GCM EC. Dashed lines indicate trends that are not statistically significant. There is a negative trend in the climate indices *ID* and *FD*, meaning a decrease in the number of days with a

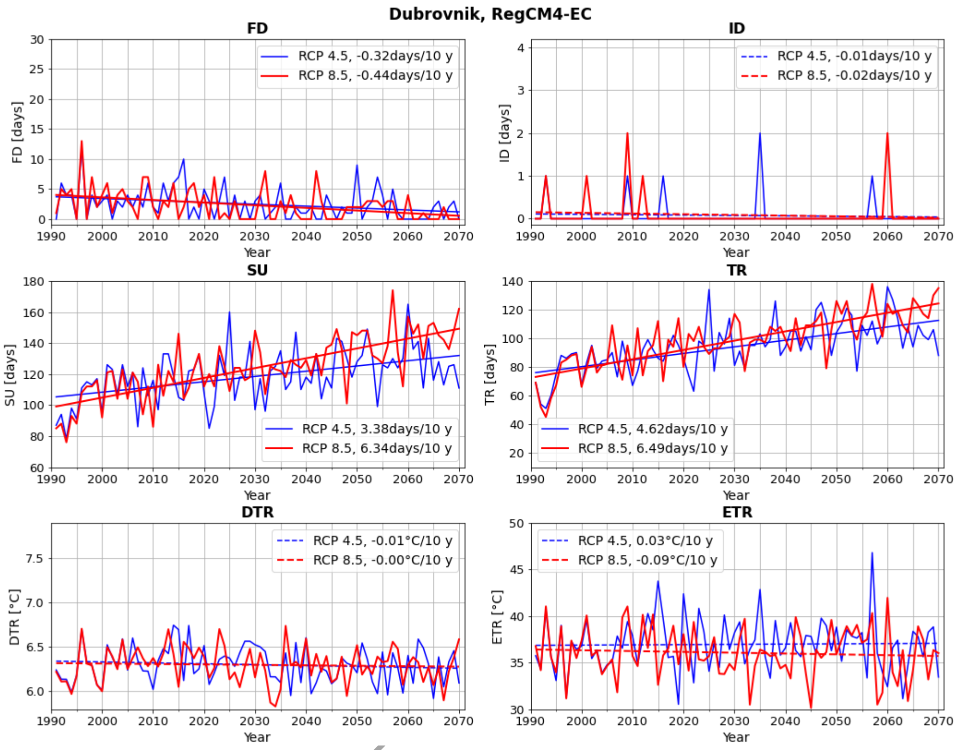

Figure 4. Time series of climate indices *FD*, *ID*, *SU*, *TR*, *DTR* and *ETR* for scenarios RCP4.5 (blue) and RCP8.5 (red). The results for the city of Dubrovnik obtained from a combination of RCM DHMZ-RegCM4 and GCM EC are presented. Trends that are statistically significant (nonsignificant) at the 95% level are marked with a solid (dashed) line.

maximum temperature below 0 °C and a minimum temperature below 0 °C. Negative trends in *ID* and *FD* are also found for all cities, for both scenarios and for all combinations of RCM and GCM models (not shown). Additionally, there is a positive trend in the climate indices *SU* and *TR*, meaning an increase in the number of days with a maximum temperature above 25 °C and a minimum temperature above 20 °C, which are statistically significant for all climate projections. According to the simulations, the range of change of the *ID* index for the RCP4.5 scenario is between +0.04 and –0.93 days/10 y, while the *FD* index in the analysed cities decreases at a rate between –0.02 and –3.22 days/10 y. For the RCP8.5 scenario, the decrease in *ID* and *FD* is more pronounced and takes on values, for *ID* between –0.00 and –1.59 days/10 y, and for *FD* between –0.07 and –5.02 days/10 y. The RCP4.5 scenario gives an increase in *SU* between 1.75 and 4.30 days/10 y and increase in the *TR* index between 1.50 and 5.01 days/10 y. These values are higher for RCP8.5 where the increase in *SU* is 3.70–6.34 days/10 y, and *TR* from 2.03 to 6.79 days/10 y.

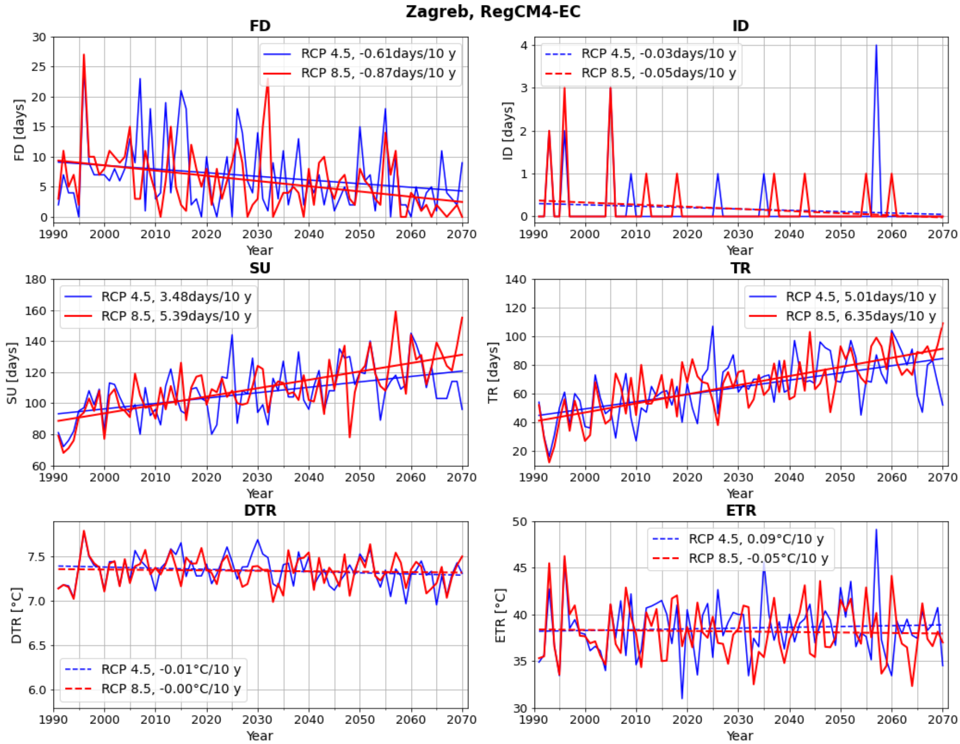

Figure 5. Time series of climate indices FD, ID, SU, TR, DTR and ETR for scenarios RCP4.5 (blue) and RCP8.5 (red). The results for the city of Zagreb obtained from a combination of RCM DHMZ-RegCM4 and GCM EC are presented. Trends that are statistically significant (nonsignificant) at the 95% level are marked with a solid (dashed) line.

Additionally, climate indices related to temperature range were also calculated: *DTR* - annual mean of the range of daily extreme temperatures (annual mean of the difference between maximum and minimum temperature in one day) and *ETR* - range of annual extreme temperatures (the difference between maximum and minimum temperature in a year). Different combinations of RCMs, GCMs, cities and scenarios give different results, and no specific pattern of behaviour is found for the *DTR* index. However, for the RCP4.5 scenario, the *ETR* index increases for all combinations of RCM and GCM. On the other hand, for the RCP8.5 scenario, DHMZ-RegCM4 indicates a decrease in *ETR,* while SMHI-RCA4 shows an increase.

The linear trends of the *FD*, *ID*, *SU*, and *TR* indices for the RCP4.5 scenario for the combination of RCM DHMZ-RegCM4 and GCM EC are shown on the map in Fig. 6. Climate projections show that the *ID* and *FD* indices have a stronger negative trend in inland cities (Zagreb and Osijek) than in coastal cities. The difference in trends between continental and coastal cities is even more pronounced for the RCP8.5 scenario (not shown), and it is expected to

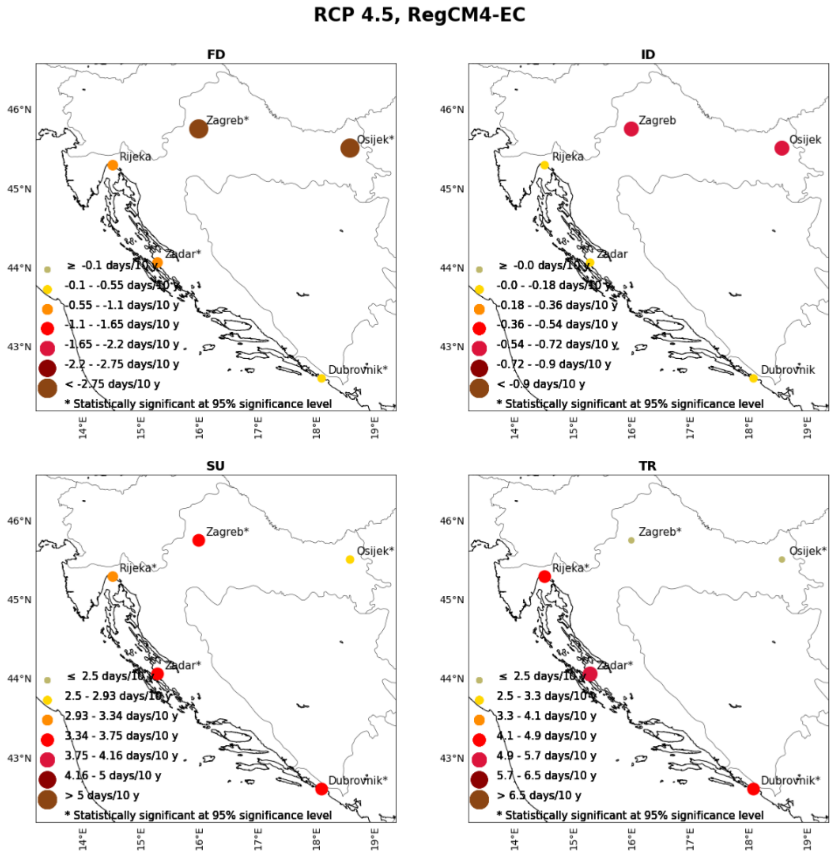

Figure 6. Map of the Republic of Croatia with linear trends of climate indices *FD*, *ID*, *SU* and *TR*. The results for the RCP4.5 scenario obtained with the model combination DHMZ-RegCM4-EC are presented, and cities where the trend is statistically significant at the 95% significance level are marked with an asterisk.

have even fewer days with air temperatures below 0 °C in the analysed inland cities. The *SU* and *TR* indices have a statistically significant positive trend for both future climate projections and for all considered cities and model combinations. Trends are stronger for the RCP8.5 scenario. The *TR* index trend is stronger for coastal cities. The values of the *DTR* and *ETR* index trends are generally very small, indicating small changes in the range of daily and annual temperatures, respectively. This result also indicates similar expected average annual increases in minimum and maximum air temperatures, which has already been shown in the previous chapter. This result must be interpreted cautiously because the regional models used here do not resolve the effects of urban structures on temperature, which certainly significantly affects the modelled *tasmin*. Therefore, unresolved processes related to urban structures can be one of the causes of the uniform increase in the minimum and maximum temperatures.

For the future climate associated with the conditions of the RCP4.5, Dubrovnik can experience the trend of the *FD* index between –0.02 and –0.48 days/10 y, in Osijek between –1.31 and –5.02 days/10 y, in Rijeka –0.23 to –2.18 days/10 y, in Zadar between –0.09 and –1.34 days/10 y, and in Zagreb between –1.83 and –4.90 days/10 y. Therefore, a reduction of days with *tasmin* below 0 °C are expected, especially in the inland cities (Zagreb, Osijek) where statistically significant trend of the *FD* index is obtained. As expected, trends are stronger for the RCP8.5 scenario. For Dubrovnik, the expected trend of the index *ID* is between –0.00 and –0.02 days every 10 years, in Osijek between –0.17 and –1.58 days/10 y, in Rijeka +0.04 to –0.16 days/10 y, in Zadar between –0.01 and –0.05 days/10 y, and in Zagreb between –0.24 and –1.59 days every 10 years. Similar to the trends of FD, the trends of ID are stronger in the inland cities (Zagreb, Osijek), and statistically significant trends of the *ID* index for the RCP8.5 scenario are obtained. The expected trend of the *SU* index in Dubrovnik is between 3.16 and 6.34 days/10 y, in Osijek between 1.75 and 3.70 days/10 y, in Rijeka between 2.38 and 4.98 days/10 y, in Zadar between 1.82 and 5.39 days/10 y, and in Zagreb between 2.52 and 5.36 days every 10 years. Therefore, of these five analysed cities, the fastest and largest increase in the number of days with a maximum temperature above 25 °C is expected in the city of Dubrovnik. The expectation of the *TR* index trend is between 3.01 and 6.49 days/10 y in Dubrovnik, between 1.50 and 3.21 days/10 y in Osijek, between 4.17 and 6.51 days/10 y in Rijeka, between 3.69 and 6.79 days/10 y in Zadar, and in Zagreb, between 1.99 and 3.58 days every 10 years. Therefore, of these five analysed locations of the Croatian cities, the fastest and largest increase in the number of days with a minimum temperature above 20 °C is expected in Zadar and Rijeka. These data are summarised in Tab. 3.

Table 3. The range of linear trends of mean, maximum and minimum temperature and climate indices FD, ID, SU, TR, DTR and ETR for Dubrovnik, Zadar, Rijeka, Zagreb and Osijek according to simulations of RCMs DHMZ-RegCM4 and SMHI-RCA4 forced with GCMs EC and MP for the RCP4.5 scenario.

	Dubrovnik	Zadar	Rijeka	Zagreb	Osijek	Units
tas	0.21, 0.27	0.18, 0.25	0.23, 0.27	0.20, 0.25	0.18, 0.24	
tasmax	0.20, 0.25	0.18, 0.25	0.23, 0.27	0.20, 0.25	0.19, 0.24	[°C/10 y]
tasmin	0.20, 0.28	0.18, 0.27	0.20, 0.27	0.21, 0.24	0.18, 0.25	
FD	–0.32, –0.02	–0.61, –0.09	–1.06, –0.23	–2.92, –1.83	–3.22, –1.31	
ID	–0.02, –0.01	–0.04, –0.01	–0.15, +0.04	–0.83, –0.24	–0.93, –0.17	[days/10 y]
SU	2.47, 3.77	1.82, 3.93	2.38, 4.30	2.52, 3.54	1.75, 2.92	
TR	3.01, 4.62	3.69, 5.01	4.17, 4.28	1.99, 2.53	1.50, 2.18	
DTR	–0.02, +0.01	–0.01, +0.02	–0.01, +0.05	–0.02, +0.03	–0.02, +0.01	[°C/10 y]
ETR	0.03, 0.22	0.09, 0.27	0.03, 0.37	0.10, 0.76	0.10, 0.39	

4. Discussions and conclusions

This study presents the expected future heat load for five Croatian cities: three coastal cities (Dubrovnik, Zadar and Rijeka) and two inland cities (Zagreb and Osijek). Historical simulations and future projections of mean, minimum and maximum air temperatures were analysed, alongside climate indices *DTR*, *ETR*, *FD*, *ID*, *TR,* and *SU*. The expected future heat load was estimated for the period P2 (2041–2070) and compared with that for the past period P0 (1991–2020). The results are based on simulations of two regional climate models for the RCP4.5 and RCP8.5 GHG scenarios.

For all cities, the findings indicate a significant increase in mean (0.18–0.27 °C/10 y for RCP4.5, 0.26–0.41 °C/10 y for RCP8.5), maximum (0.18–0.27 °C/10 y for RCP4.5, 0.26–0.39 °C/10 y for RCP8.5) and minimum (0.18–0.28 °C/10 y for RCP4.5, 0.2–0.40 °C/10 y for RCP8.5) air temperatures during the entire period (1991–2070) for all combinations of the climate models. The fastest increase in heat load was found for the coastal cities of Dubrovnik and Rijeka. The positive temperature trend is statistically significant for all cities, and as expected, it is more pronounced for the RCP8.5 scenario than for the RCP4.5 scenario. However, the difference between temperature trends for the RCP8.5 and RCP4.5 scenarios is the smallest in the warm part of the year. This may be explained, at least partially, by the preponderance of surface shortwave and longwave radiation impact on the temperature. One of the most important factors determining near-surface air temperature is the amount of incoming solar radiation at the surface. Shortwave solar radiation reaching the surface is strong during the warm season, while it is much weaker during the winter. At the same time, longwave radiation depends on GHG concentration, and radiative forcing is stronger in the RCP8.5 scenario than in RCP4.5, with prominent manifestation of its impact on temperature during the cold part of the year. Therefore, since the main difference between simulations (GHG concentration) is associated with the effect that is apparent during the cold part of the year, the greatest difference in temperature is also expected. In the future, this hypothesis should be explored in detail by a dedicated study considering the relative impacts of shortwave and longwave radiation in relevant RegCM-EC simulations over Croatia (*e.g.*, similar to Lozuk (2022) but for different RCMs).

Generally, the trends of *tas*, *tasmin* and *tasmax* are almost identical, although it is expected that *tasmin* exhibits a stronger trend. Regarding diurnal temperature variation, minimum temperature usually occurs before sunrise and thus provides information about the coldest part of the day, while the maximum temperature is a measure of the warmest part of the day (Zaninović et al., 2008). Urbanisation significantly contributes to an increase in minimum temperature because heat accumulates during the day in urban structures and is released during the night. However, regional climate models do not simulate the effects of urbanisation, *i.e.*, there is no influence of urban structures on air temperature. Unresolved urban structures and related physical processes significantly affect the modelled minimum temperature, causing it to be lower than the real values and may be, at least partially, the cause of similar trends of *tasmin* and *tasmax*. In general, small-scale atmospheric processes are not presented realistically in regional models, which contributes to the unreliability of the results. Especially in the case of complex orography and coastline, as is the case with the Croatian coast, small-scale atmospheric processes are very important. Additionally, neither small-scale convection nor related clouds and precipitation are realistically reproduced in these models, which certainly affects the representation of temperature and temperature change.

The results show an increase in multiannual monthly averages of *tas*, *tasmin* and *tasmax* in a range between 1.5 °C and 2 °C in all cities. The largest increase occurs mainly in the warm parts of the year (April-October). This may be caused by the intensification and increased frequency of heat waves under future climate conditions. Additionally, certain boundary conditions, such as decreased soil moisture, support the development and persistence of heat waves. Therefore, drier summer conditions and related land-surface feedbacks can play a significant role (Fischer et al., 2007, Fischer and Schär, 2008, 2010).

Climate indices also show warming trends in the considered Croatian cities. For all analysed locations, an increase in the number of summer days was obtained (1.75–4.30 days/10 y for RCP4.5 and 3.70–6.34 days/10 y for RCP8.5), and the largest increase was obtained for Dubrovnik. There was also an increase in the number of tropical nights (1.50–5.01 days/10 y for RCP4.5 and 2.03 to 6.79 days/10 y for RCP8.5), which is most pronounced in coastal cities (especially Rijeka and Zadar) and slightly milder in continental cities. This result indicates the strengthening of undesirable climate conditions with many negative consequences. For example, such climate conditions contribute to the occurrence of droughts and are associated with a greater need for irrigation. In addition, high temperatures have a negative impact on human health, especially in chronic patients (McMichael and Lindgren, 2011). Warmer and longer dry periods also increase the risk of wildfires (IPCC, 2021).

The results for so-called ‘cold indices’ also indicate further warming with decreased occurrence of frost days (–0.02 to –3.22 days/10 y for RCP4.5 and –0.07 and –5.02 days/10 y for RCP8.5) and ice days (+0.04 to –0.93 days/10 y for RCP 4.5 and –0.00 to –1.59 days/10 y for RCP8.5). The most pronounced decrease was obtained for the continental cities of Zagreb and Osijek. A decrease in frost and ice days is associated with changes in winter conditions and could have many negative implications. At temperatures above 0 °C, the retention of snow and ice on the ground is reduced, which causes poorer insulation of plants in winter (Soong et al., 2020) and a higher risk of negative effects of cold. On the other hand, warmer soil in the winter season supports the development of various disease-carrying parasites, such as ticks and mosquitoes (Patz et al., 2003; McMichael and Lindgren, 2011), and plant parasites (Pritchard, 2011; Huang, 2016). The harmful effects of frost-free periods are multiple—ecological, agricultural, human health, economic, etc. As expected, coastal cities do not show such a significant decrease in frost days and ice days because there are already very few such days. The values of trends in annual averages of daily extreme temperature ranges (*DTR* index) and trends in annual extreme temperatures (*ETR* index) are generally very weak. This result is associated with similar trends of *tasmin* and *tasmax*.

For many European and Mediterranean cities and for the cities included in this analysis, warming is expected to continue in the future. However, there are certain differences among numerical simulations and also between continental and coastal cities that are primarily determined by climatic, geographical and local conditions. Certainly, important factors that affect the reliability of the estimated heat load are climate projections, *i.e.*, the effectiveness of the global and regional climate models used. To achieve robust results, it is necessary to use as many numerical simulations as possible and different GCM-RCM combinations. In addition, urban structure, soil type, proximity to the sea and other local factors have a strong impact on urban heat load. Therefore, to assess the expected future climate conditions in urban environments, especially for the purpose of planning measures to adapt to the consequences of climate change, it is necessary to consider the results of urban microscale models as well as high-resolution convection-permitting models.

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SAŽETAK

Očekivano toplinsko opterećenje Dubrovnika, Osijeka, Rijeke, Zadra i Zagreba prema projekcijama regionalnih klimatskih modela

Mia Agapito, Ivana Herceg-Bulić i Ivan Güttler

U ovom radu ispitano je očekivano buduće toplinsko opterećenje u pet hrvatskih gradova: Dubrovniku, Zadru, Rijeci, Zagrebu i Osijeku. Toplinsko opterećenje je procijenjeno pomoću temperaturnih klimatskih indeksa te srednjih, maksimalnih i minimalnih dnevnih temperatura na temelju simulacija dvaju regionalnih klimatskih modela horizontalne rezolucije 12,5 km (DHMZ-RegCM4 i SMHI-RCA4), uz rubne uvjete dobivene dvama globalnim klimatskim modelima (EC-EARTH i MPI-ESM-MR/LR), za dva različita scenarija koncentracija stakleničkih plinova (RCP4.5 i RCP8.5). Uspoređivanjem ovih varijabli za razdoblje 2041.–2070. u odnosu na klimu iz razdoblja 1991. – 2020., uočen je značajan porast srednjih, maksimalnih i minimalnih temperatura u svim analiziranim kombinacijama regionalnih i globalnih klimatskih modela za sve promatrane gradove. Iako postoje određene razlike u rezultatima ovisno o kombinaciji regionalnog i globalnog modela, najviše se ističe porast u toplom dijelu godine (travanj-listopad) s najvećim iznosima za Dubrovnik i Rijeku. Zbog približno jednakih trendova maksimalne i minimalne temperature, trend dnevnih raspona temperature je malog iznosa. U uvjetima toplije klime se u svim promatranim gradovima povećava broj dana s maksimalnom temperaturom zraka iznad 25 °C (posebice u Dubrovniku) i broj dana s minimalnom temperaturom iznad 20 °C (osobito u Rijeci i Zadru). Nadalje, u svim je gradovima dobiveno smanjenje broja dana s maksimalnom i minimalnom temperaturom ispod 0 °C. Ipak, uočavaju se određene razlike između kontinentalnih i obalnih gradova koje su uvjetovane lokalnim faktorima.

Ključne riječi: toplinsko opterećenje gradova, klimatski indeksi, regionalne klimatske projekcije

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