CROATIAN METEOROLOGICAL AND HYDROLOGICAL SERVICE

REPUBLIC OF CROATIA

SELECTED CHAPTERS OF THE EIGHT NATIONAL COMMUNICATION OF THE REPUBLIC OF CROATIA UNDER THE UNITED NATION FRAMEWORK CONVENTION ON THE CLIMATE CHANGE (UNFCCC)

DHMZ

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- Weather Observation and Climate Data Sector
- Air Quality Sector
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6. Vulnerability assessment, climate change impacts and adaptation measures

6.1 Observed and projected climate changes

6.1.1 Trend analysis methods and climate models

Observed climate change in Croatia was performed in terms of trends of annual and seasonal time series of air temperature and precipitation amount and the associated indices of extremes (WMO, 2009). The period of analysis compared to the previous Report was expanded with additional ten years series covering the overall period of 1961–2020. Daily data of mean and extreme air temperatures and precipitation amounts were used from 35 and 143 meteorological stations, respectively. The stations belong to the regular DHMZ network of stations. Trend values were estimated using Sen's slope (Sen, 1968) and expressed per 10 years. The statistical significance at the 95% significance level is assessed using the Mann-Kendall rank test (Gilbert, 1987).

About selected models, scenarios, periods compared to the previous report

The main basis for making projections of the future climate in the previous, Seventh National Communication and the Third Biennial Report of the Republic of Croatia under the United Nations Framework Convention on Climate Change (UNFCCC) was the "Draft Climate Change Adaptation Strategy in the Republic of Croatia for the period to 2040 with a view to 2070"[1]. Future climate projection simulations were obtained by the regional climate model RegCM (Giorgi et al., 2012, Güttler et al. 2020). For the "historical" climate, the period 1971 - 2000 was used, while the changes of the future climate (projections) were considered for two 30-year periods: 2011 - 2040 and 2041 - 2070. For the purposes of the Report, a "moderate" scenario (RCP4.5) of the greenhouse gases concentrations pathway was considered. As boundary and initial conditions for the RegCM numerical integrations the results from four different global climate models (GCMs) were used: the model of the French meteorological service CNRM-CM5, the model of the Dutch EC-Earth consortium, the MPI-ESM model of the German Max-Planck Institute for Meteorology and the HadGEM2 model of the British Met Office. Horizontal spatial resolution of the RegCM model was 50 km.

The ensemble of models used in the assessment of climate change in this (eighth) National Report of the Republic of Croatia under the United Nations Framework Convention on Climate Change was composed of 12 individual members - a combination of three regional climate models (RCM): RegCM[2], RCA4[3] and CCLM4[4], and boundary and initial conditions from same four global climate models (GCMs) used in previous National Report. The used ensemble of twelve simulations, compared to the ensemble of four members, includes more sources of uncertainties in climate modelling. In comparison to the previous report, we use the simulations integrated at a horizontal spatial resolution of 12.5 km and this gives us opportunity to better examine the spatial variability of variables, especially precipitation and precipitation extremes. We define historical climate from 1981 - 2010 (P0 period), which includes several "warm years" that are more frequent at the end of the 20th and the beginning of 21st century. We analyse future climate projections for one future period 2041 - 2070 (period P1), assuming a moderate (RCP4.5) greenhouse gas concentrations scenario. Since the climate projection protocol defined that the simulations of the future climate start with December 2005 (Giorgi and Gutowski, 2015), the last five years of the historical climate were obtained from the projection simulations for the RCP4.5 scenario. The assumption is that the concentrations of

[1] https://prilagodba-klimi.hr/wp-content/uploads/docs/Draft%20CC%20Adaptation%20Strategy.pdf
[2] https://www.ictp.it/research/esp/models/regcm4.aspx
[3] https://www.smhi.se/en/research/research-departments/climate-research-at-the-rossby-centre/rossby-centre-regional-atmospheric-model-rca4-1.16562
[4] https://clmcom.scrollhelp.site/clm-community/

greenhouse gases in the first few years did not change more significantly than the actual ones during the same years.

The change of the analysed variables in the future climate (P1) compared to the historical one (P0) was obtained as the difference (absolute for temperature and number of days with a fixed threshold, and relative for precipitation and some indices) of mean values in these two periods. The difference of the ensemble means represents the change of the variable in relation to the historical climate. Changes are observed for the whole year (ANN) and each climatological season: winter (December, January, February; DJF), spring (March, April, May; MAM), summer (June, July, August; JJA), autumn (September, October, November; SON). The most relevant results are presented in the report.

6.1.2 Global climate change

A detailed overview of current climate change on a global scale is given in the report of Working Group 1 of the Intergovernmental Panel on Climate Change (IPCC, 2021).

Global climate change is the result of an increase in the concentration of greenhouse gases, such as carbon dioxide, methane and nitrous oxide. In 2019, the atmospheric concentration of these gases was 410 ppm for carbon dioxide (the highest concentration in the last 2 million years), 1866 ppb for methane and 332 ppb for nitrous oxide (the highest concentration in the last 800 thousand years).

The increase in global air temperature in the period 2011-2020 was estimated at 1.09 °C with respect to the period 1850-1900, comparable to temperature anomalies 125 thousand years ago. The global amount of precipitation has increased since 1950, with a more intense increase since 1980. For the mid-latitude areas where Croatia is located, a poleward shift in the path of cyclonic systems and changes in the amount of precipitation of different sign depending on the season have been detected.

In addition to the rise in the temperature of the world's oceans, the continuation of the sea level rise was also recorded. The average level of the world's oceans has risen by 20 cm in the period from 1901 to 2018. Reduction of the sea ice-covered Arctic area by 40% in September and 10% in March when comparing the period 2010-2019 with respect to the period 1979-1988 is also recorded.

Changes in (1) the occurrence of extreme weather events in the wider Mediterranean area indicate an increase in hot extremes and high confidence in the attribution of these changes to human influence, (2) low agreement in the Mediterranean area in estimates for changes in extreme precipitation amounts, but (3) an increase in the occurrence of agricultural and ecological drought. Regarding the drought in the Mediterranean area, the attribution of human influence is moderately confident but significant.

According to the projections of global climate models, an increase in air temperature in the wider area of the Mediterranean and Croatia is to be expected in all analysed scenarios. A decrease in the annual precipitation amount of up to 10% and 20% over parts of the Adriatic region is expected in scenarios that correspond to an increase in global temperature of 2 °C and 4 °C by the end of the 21st century.

6.1.3 Observed trends and future climate projections

Observed air temperature trends

Since the second half of the 20th century, a consistent warming has been observed in Croatia. Mean annual air temperature trend values range from 0.2 to 0.3 °C / 10 years along the Adriatic and up to 0.5 °C / 10 years in central Croatia (Figure 6.1.3.1). The observed warming on an annual scale resulted from a significant increase in air temperature in all seasons, particularly in summer (0.3–0.6 °C / 10 years). Significant positive trends were also observed in the mean minimum and mean maximum air temperature values in all seasons and on an annual basis.

The monthly and annual temperature trends calculated from a high-resolution (1 km) monthly gridded dataset for 1981–2018 period show a significant strong warming of 0.3–1.0 °C/decade in

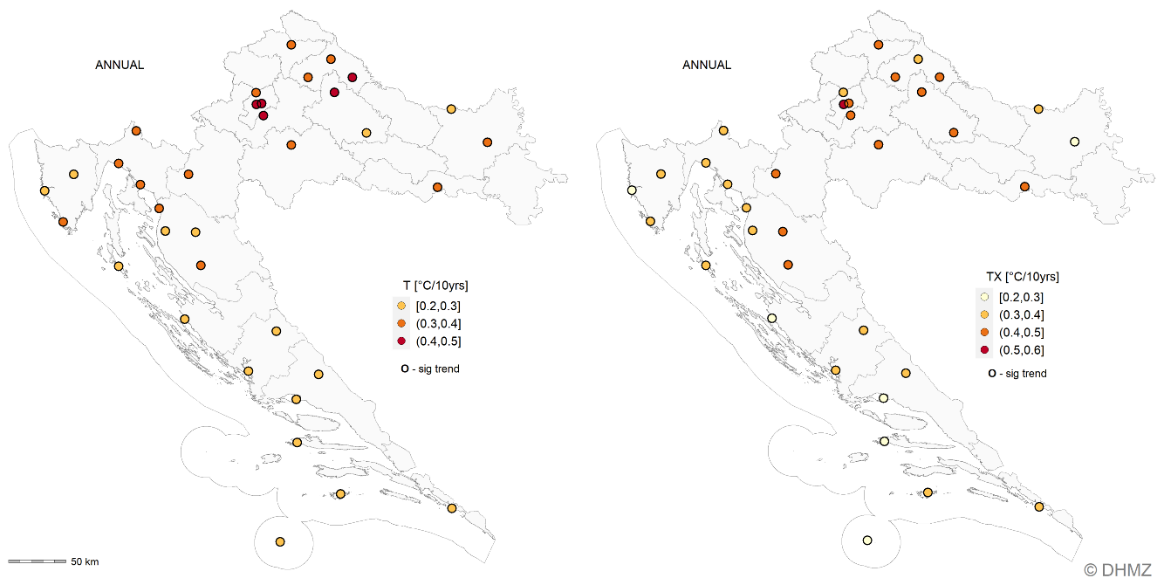

Figure 6.1.3.1. *Decadal trends in annual mean (T; left) and mean maximum (Tx; right) air temperature values (°C / 10years) in Croatia during the period 1961–2020. Statistically significant trends at meteorological stations are denoted by bolded circles.*

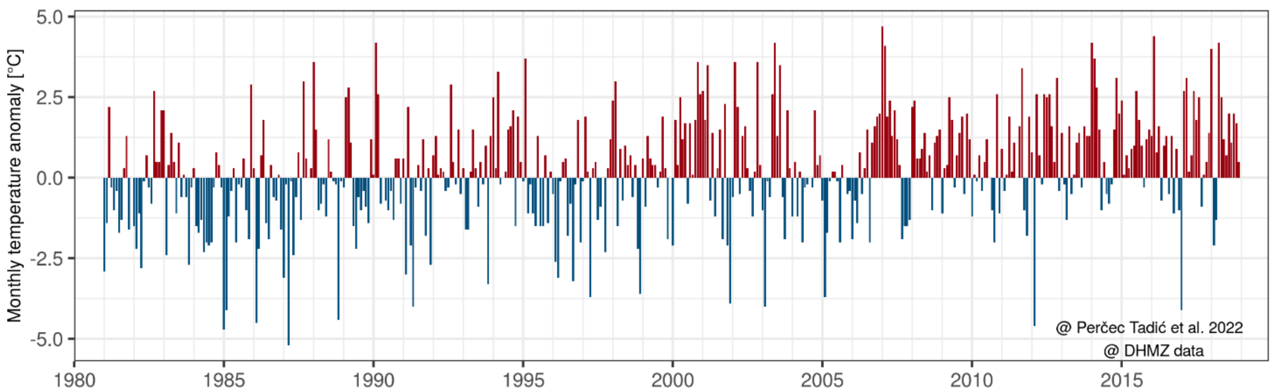

Figure 6.1.3.2. *Time evolution of the monthly temperature anomalies [°C] over the 1981–2018 period averaged for the country. The anomalies were calculated from monthly grids by subtracting the gridded monthly normals for 1981–2010. (Fig. 14 in Perčec Tadić et al., 2022, data DHMZ)*

April, June, July, August and November (Perčec Tadić et al. 2022). Annual trends of 0.3–0.7 °C/decade were significant all over the country and stronger inland than on the coast (Perčec Tadić et al. 2022). From the beginning of the twenty-first century, monthly anomalies averaged over a country were often positive and up to 4.7 °C warmer (January 2007) than the average for 1981–2010 and only occasionally negative (Figure 6.1.3.2). Positive anomalies in the twenty-first century prevail on an annual level also (Perčec Tadić et al. 2022).

Future changes in seasonal and annual air temperature

Changes in mean air temperature at 2 m (differences between periods P1 and P0) indicate a clear signal of an increase in both mean annual and seasonal values over the entire Republic of Croatia. The largest part of the country will experience an increase in the mean annual temperature in the amount of 1.5 - 1.6 °C. The mountainous area expects a slightly higher increase, between 1.6 and 1.7 °C (Figure 6.1.3.3).

Minimum and maximum annual air temperature is expected to increase over the entire Republic of Croatia. Except for the easternmost regions of the country, where the projected increase is between 1.4 and 1.5 °C, the increase in minimum air temperatures in other parts of the country is between 1.5 and 1.6 °C. The expected increase in maximum air temperatures of 1.5 - 1.6 °C will affect the areas of the Adriatic but also central and eastern Croatia, while the projected increase in maximum temperatures over the mountains and interior of Istria is between 1.6 and 1.7 °C, only over limited area 1.8 °C.

Analysing the seasons, the highest increase in mean air temperature at 2 m is expected in summer. The expected summer increase during P1 period will be at least 1.8 °C. Over the largest area of Croatia, the increase will be in the range between 2.0 and 2.2 °C, while over the Dalmatia inland, temperatures may be up to 2.4 °C higher than in the P0 period. The expected increase in mean winter temperatures is the largest in mountainous Croatia and the north-western parts of the country, ranging from 1.6 to 1.8 °C. In the eastern parts of the country, an increase of 1.5 to 1.6 °C prevails, and a bit smaller increase occurs over the entire coastal area (between 1.4 and 1.5 °C). The autumn increase in mean temperatures, in the range of 1.5 to 1.6 °C, covers almost entire country. The exception are the mountainous area and the far east, where the projected mean temperature increase is between 1.4 and 1.5 °C, and the part of the Kvarner bay, where the mean temperature increase is between 1.6 and 1.8 °C. The mildest increase in air temperature at 2 m is predicted for the spring season, in which most of the country could experience an increase between 1.1 and 1.2 °C. More intense increase, between 1.2 and 1.3 °C, is expected in the coastal area, while in eastern Croatia the increase is less intense - between 1.0 and 1.1 °C.

Most intense increase in both, minimum and maximum, temperatures is predicted for the summer season. Spatially, the summer maximum temperature change is similar to the mean temperature change, while the changes differ in absolute terms. The area of the Adriatic, central and eastern Croatia may expect an increase in summer maximum temperatures between 2.0 and 2.2 °C, while the projected increase in mountainous Croatia and the Istria inland is between 2.2 and 2.4 °C. The summer minimum temperature change in coastal area, including the inland areas of Istria and Dalmatia, is characterized by an increase of 2.0 to 2.2 °C. In the rest of the country, the increase in minimum summer temperatures will be between 1.8 and 2.0 °C.

An increase in winter maximum temperature over the mountainous regions and mainland ranges from 1.5 to 1.8 °C, while over the Istria and the coast the increase is between 1.4 and 1.5 °C, and between 1.3 and 1.4 °C over the Adriatic area. Winter minimum temperatures show a slightly greater spatial variability, but the temperature change is positive over the entire country and ranges from 1.3 °C to 1.8 °C.

Maximum autumn temperatures during the P1 period in the coastal areas of the Adriatic, Gorski kotar and Lika, in the westernmost parts of continental Croatia and part of central Croatia will rise between 1.5 and 1.6 °C compared to the maximum autumn temperatures during the P0 period. In Istria region, the maximum autumn temperature will be higher by 1.6 to 1.8 °C, and majority of continental Croatia will experience the rise of 1.4 to 1.5 °C. The increase in projected minimum autumn air temperatures is most pronounced over the Kvarner bay (up to 1.8 °C), above Adriatic and central Croatia, where it is between 1.5 and 1.6 °C. The expected minimum temperature changes in the largest part of the mountain area and in the central part of eastern Croatia are between 1.4 and 1.5 °C.

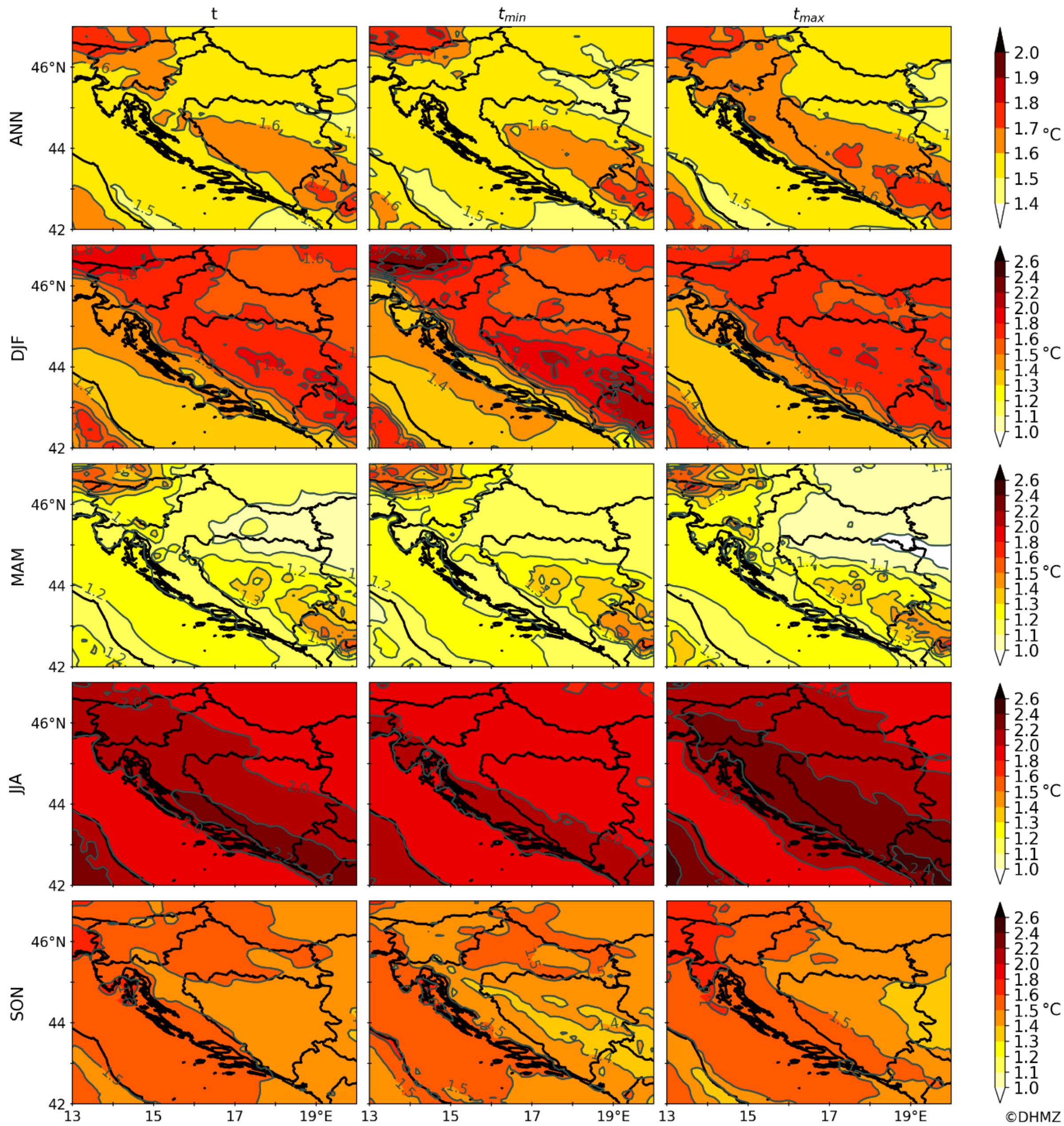

Figure 6.1.3.3. *Change in the mean air temperature at 2 m (t; first column), minimum air temperature at 2 m (t_{min}; second column) and maximum air temperature at 2 m (t_{max}; third column) of the ensemble mean for selected models for the period 2041 – 2070 compared to the reference period 1981 – 2010 for RCP4.5. Annual change (ANN; first row), change in winter (DJF; second row), spring (MAM; third row), summer (JJA; fourth row) and autumn (SON; fifth row).*

Spring maximum air temperatures increase will be smallest over the east and central part of Croatia (from 1.0 to 1.1 °C). Slightly larger increase (from 1.1 to 1.2 °C) is shown over the western parts of the mainland and parts of Dalmatia. For most of the coastal area, including Istria and its inland, the increase in maximum spring temperatures will be in the range from 1.2 to 1.3 °C. A greater increase in maximum spring air temperatures can be expected in isolated mountain areas. Changes in spring minimum temperatures in the majority of continental Croatia are between 1.1 and 1.2 °C, only in the mountainous part and the greater part of the Adriatic from 1.2 to 1.3 °C.

Observed precipitation trends

The results of the precipitation trend show distinct seasonal changes in Croatia (Figure 6.1.3.4). The main trend feature is a significant summer drying along the Adriatic coast and its hinterland (5% - 15% / 10 years compared to the reference mean of 1981–2010). On the other side, a consistent increase in autumn precipitation amount was observed across the country which is significant in the central mainland (up to 15% / 10 years). During the winter, a negative precipitation trend prevails in the central and southern Adriatic and the easternmost parts of Croatia, whereas a positive trend was found in the rest of Croatia. The opposite trend signs were observed in the spring season. Such a seasonal distribution of the trend resulted in weak precipitation trends on the annual level, both in terms of signs and slopes.

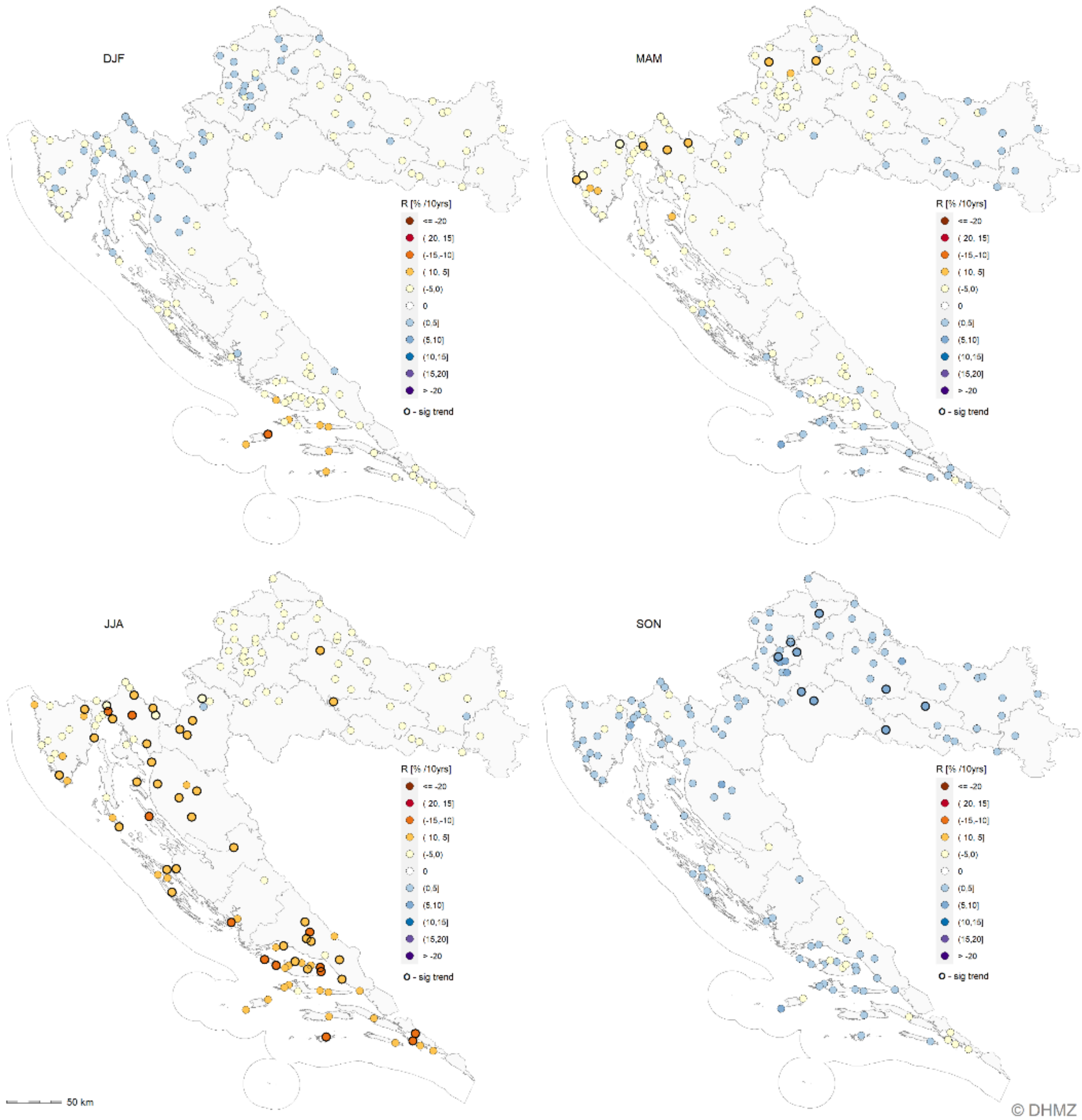

Figure 6.1.3.4. *Decadal trends in seasonal precipitation (R; in %/ 10 years with reference to 1981–2010 period) in Croatia during the period 1961–2020. Statistically significant trends at meteorological stations are denoted by bolded circles.*

Future changes in seasonal and annual precipitation

The change in the precipitation amount in the period 2041 - 2070 compared to the period 1981 - 2010 was observed with respect to relative amount ((P1-P0)/P0) and is expressed in percentages.

Total annual precipitation amount during the P1 period shows relatively small, spatially variable, changes compared to the P0 period (Figure 6.1.3.5). An increase in the precipitation amount is expected in the areas along the Adriatic coast from 3 to 4%. A smaller part of the Lika and Gorski kotar area and the Dalmatia inland will have 1 to 2% less precipitation, while the change will be negligible over most of the aforementioned area (in the range of -1 to 1%). Projected changes of precipitation amount over the country mainland increase from west to east, so the precipitation amount increase, from 3 to 5%, is expected over the easternmost regions.

Changes in seasonal total precipitation amounts during the 2041 – 2070 period are showing a decrease in summer precipitation over the entire country, and a predominantly weaker increase of precipitation amount in other seasons. An increase is expected for winter over all areas, and in autumn over the majority of Croatia. In the winter (Figure 6.1.3.5), the increase is most intense over the eastern regions - between 10 and 15%, while over the mountainous area and the Dalmatia inland it is least intense (between 1 and 5%). The autumn increase is from 1 to 5% over the largest part of the country (Figure 6.1.3.5), and from 5 to 10% over the coastal area and isolated areas of the mainland. Negative changes in autumn precipitation amount are projected for a narrow strip of the mountainous littoral (Velebit). Changes in spring precipitation amounts (Figure 6.1.3.5) in terms of sign and spatial distribution mostly agree with changes at the annual level. The area of the eastern parts of central Croatia and eastern Croatia itself, as well as coastal areas show an increase in precipitation amount, up to a maximum of 10% (eastern Slavonia). The areas of Lika, Gorski Kotar and Dalmatia inland are characterized by a negative change in the precipitation amount of 1 to 5%. The only season in which the amount of precipitation is expected to decrease throughout the country is summer (Figure 6.1.3.5). The largest decrease (between 15 and 20%) is possible over the mountainous littoral, central Dalmatia and mountainous areas, and the smallest in the northernmost and easternmost regions (between 5 and 10%). In all other regions, the projected summer decrease of total precipitation amount is between 10 and 15%.

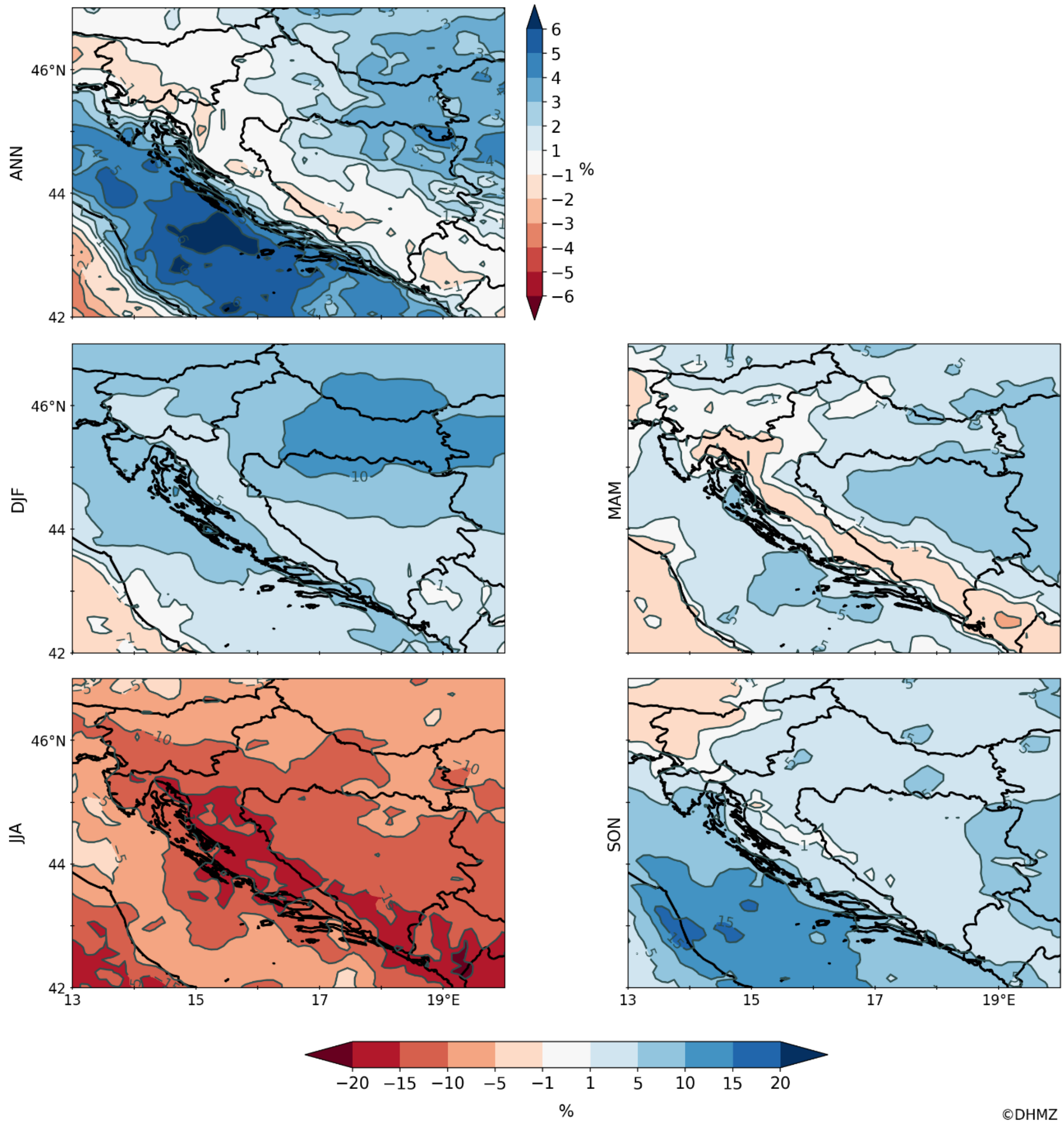

Figure 6.1.3.5. *Relative change in the total precipitation amount of the ensemble mean for selected models for the period 2041 – 2070 compared to the reference period 1981 – 2010 for RCP4.5. Annual change (ANN; top left), change in winter (DJF; middle left), spring (MAM; middle right), summer (JJA; bottom left) and autumn (SON; bottom right).*

Table 6.1.3.1. *Temperature and precipitation indices and their definitions used to analyze climate changes in this report*

Abbreviation	Name	Definition
Indices of cold temperature extremes		
FD	cold days (absolute threshold)	Number of days with a daily minimum temperature <0°C
Tn10	cold nights (percentile threshold)	Number of days with a daily minimum temperature lower than the threshold, determined as the calendar day 10th percentile of daily minimum temperature in the reference period (1981 - 2010)
Tx10	cold days (percentile threshold)	Number of days with a daily maximum temperature lower than the threshold, determined as the calendar day 10th percentile of daily maximum temperature in the reference period (1981 - 2010)
CSDI	cold spell duration index	Number of days in a span of at least six days with a daily minimum temperature lower than Tn10
Indices of warm temperature extremes		
Tn90	warm nights (percentile threshold)	Number of days with a daily minimum temperature higher than the threshold, determined as the calendar day 90th percentile of daily minimum temperature in the reference period (1981 - 2010)
Tx90	warm days (percentile threshold)	Number of days with a daily maximum temperature higher than the threshold, determined as the calendar day 90th percentile of daily maximum temperature in the reference period (1981 - 2010)
WSDI	warm spell duration index	Number of days in a span of at least six days with a daily maximum temperature higher than Tx90
SU	warm days (absolute threshold)	Number of days with a daily maximum temperature ≥25°C
Dry and wet indices		
DD	dry days	Number of days with a daily precipitation amount R_d<1.0 mm
SDII	standard daily intensity index	Total annual precipitation amount divided by the number of wet days (R_d≥1.0 mm)
R75	moderately wet days	Number of days with a daily precipitation amount $R_d > R_{75\%}$, where $R_{75\%}$ is the 75th percentile of precipitation on all days in the reference period (1981 - 2010)
R95	very wet days	Number of days with a daily precipitation amount $R_d > R_{95\%}$, where $R_{95\%}$ is the 95th percentile of precipitation on all days in the reference period (1981 - 2010)
R95T	precipitation due to very wet days	Sum of daily precipitation greater than the 95th percentile of precipitation on very wet days ($R_{95\%}$) in the reference period 1981 – 2010 divided by the total annual/seasonal precipitation amount
Rx1d	maximum one-day precipitation	The highest precipitation amount in one-day period
Rx5d	maximum five-day precipitation	The highest precipitation amount in five-day period
CDD	consecutive dry days	The maximum length of dry days. Dry day is determined as a day with daily precipitation < 1 mm (CDD1) and < 10 mm (CDD10)
CWD	consecutive wet days	The maximum length of wet days. Wet day is determined as a day with daily precipitation ≥ 1 mm (CWD1) and ≥ 10 mm (CWD10)

Observed trends of temperature extremes

Warming in Croatia is associated with significant trends in all indices of temperature extremes. There is an increase in the number of summer days up to 8.3 days / 10 years (Figure 6.1.3.6). There is an increase up to 3 and 5 days/10 years in spring and summer, respectively. Along the Adriatic, an increase in warm summer nights (up to 6 days / 10 years) was found and a trend toward longer warm spell durations. A prevalent decrease in the annual number of cold days is particularly pronounced in the mainland and northern Adriatic (up to 8 days / 10 years) accompanied by a decreasing number of cold nights (up to 10 days / 10 years). A decreasing trend in the cold spell duration was detected along the Adriatic coast (up to 2 days / 10 years).

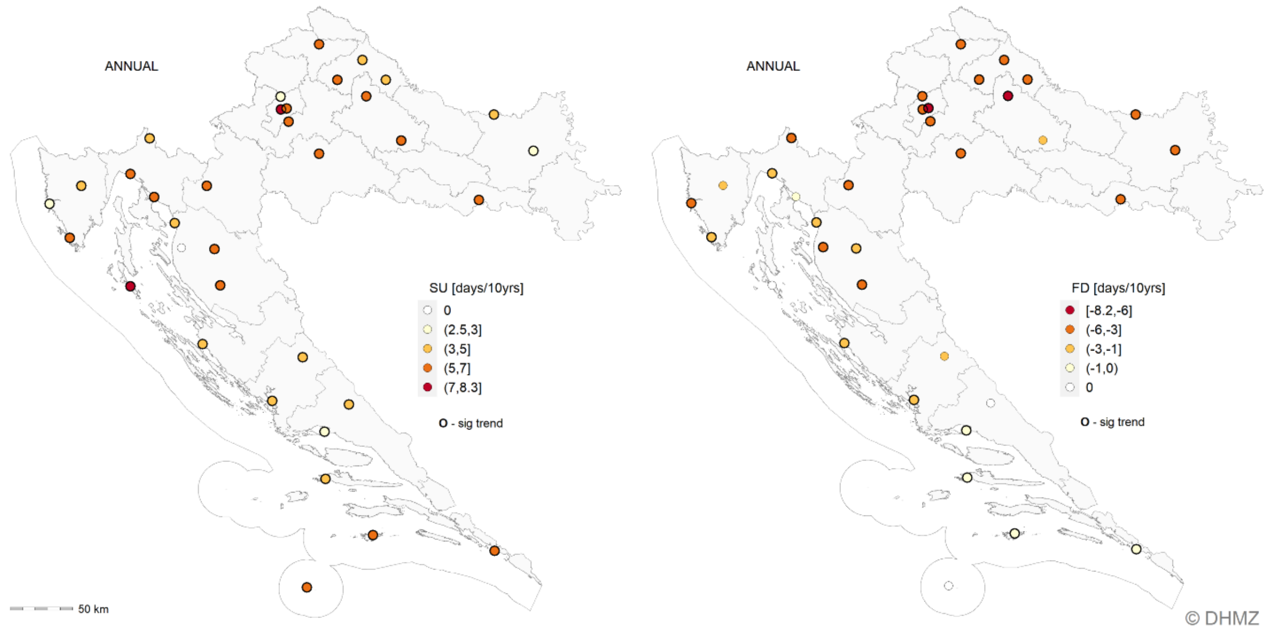

Figure 6.1.3.6. *Decadal trends in the number of summer days (SU) and frost days (FD) (days / 10 years) in Croatia during the period 1961–2020. Statistically significant trends at meteorological stations are denoted by bolded circles. SU - number of days with maximum air temperature >= 25°C; FD - number of days with minimum air temperature below 0°C.*

Strong warming in continental Croatia can be noticed in the area of the capital Zagreb, which points to a strong urban warming effect. Detailed local analysis of changes in extreme air temperatures for the Zagreb region showed stronger warming of the city centre compared to the outskirt and the mountain site (Nimac et al. 2021). The number of frost days (Tmin < 0 °C) decreased and the number of tropical nights (Tmin > 20 °C) increased due to nocturnal heating from highly built concrete surroundings. With the increase (decrease) in cooling (heating) degree days in Zagreb, the obtained results imply a potential increase in risk associated with warm, and a decrease in the risk associated with cold events, especially in cities (Cvitan and Sokol Jurković, 2016).

A brief overview of future changes in warm and cold extreme temperature indices

Changes in extreme temperature conditions were analysed considering the change in the annual number of days in which the condition used to define a certain event, i.e. the climate index, is met (Table 6.1.3.1). The occurrence of temperature extremes strongly depends on the part of the year (warm indices rarely occur in the cold part of the year and vice versa), but also on the area observed (e.g. cold indices are rarer in the coastal area).

Cold temperature indices were analysed considering changes in total annual number of cold days (FD) and the changes in autumn, winter, and spring seasons (only the winter change is shown in figure). Changes in the duration of cold periods (CSDI), the number of cold nights (Tn10) and cold days (Tx10) were analysed for winter season and annually. In the P1 period, compared to the P0 period, a decrease in the number of days with cold temperature indices is expected.

In winter, the most pronounced decrease in the number of cold days (FD, Figure 6.1.3.7) is expected over central and eastern Croatia (11 to 12 days less), while over mountains the decrease is mostly up to 10 days less, only in some places 8 to 9 days less. The decrease in the number of cold days in the autumn and spring season is between 3 and 7 days in the entire observed area, with a smaller decrease over the coast and a larger decrease over the mainland. The decrease in the annual number of cold days is the sum of seasonal contributions and for most of the country it is between 18 and 21 days. Only in the north-western regions (along the Slovenian border) and in the narrow area of western Slavonia, a reduction of more than 21 days is possible. In the coastal area, the decrease intensity drops rapidly as we approach the Adriatic. The reason for this is the small number of cold days in the observed area even in the P0 period.

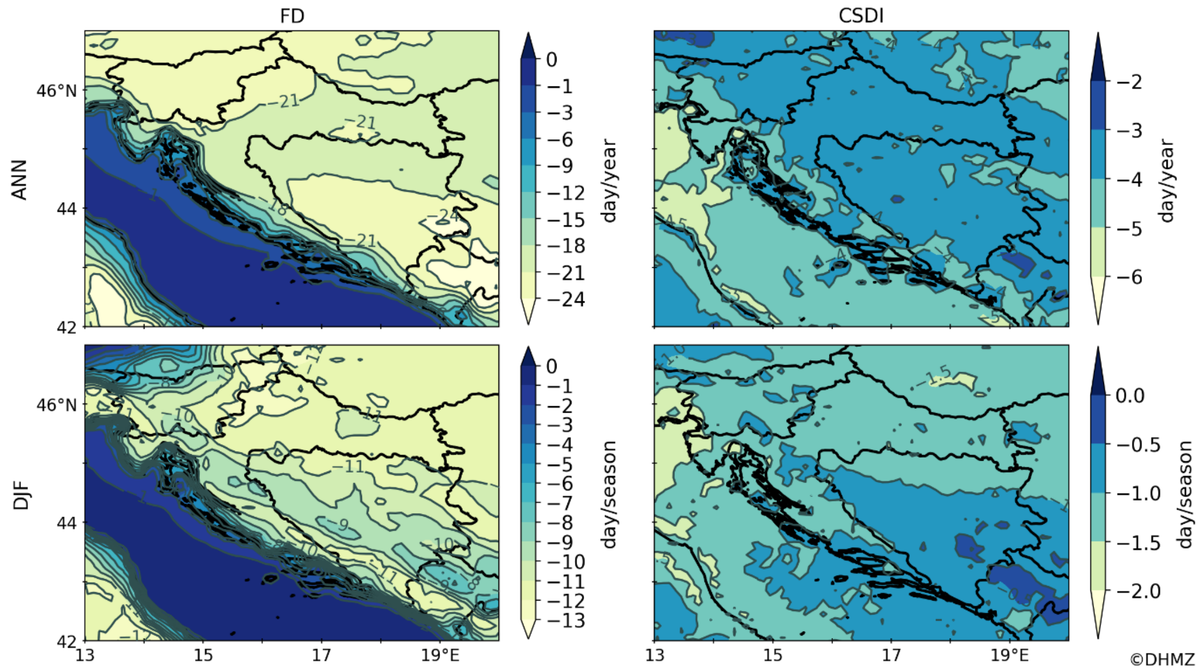

Figure 6.1.3.7. *Change in the number of cold days (FD; first column) and cold spell duration index (CSDI; second column) of the ensemble mean for selected models for the period 2041 – 2070 compared to the reference period 1981 – 2010 for RCP4.5. Annual change (ANN; first row) and change in winter (DJF; second row).*

The cold spell duration (CSDI, Figure 6.1.3.7) decreases in the winter season by at least 0.5 days (southern Adriatic and part of Gorski Kotar and Lika), and by a maximum of 1.5 days (rest of the country). On an annual basis, the cold spell duration is expected to decrease by 3 to 4 days in majority of the country. A greater decrease (4 to 5 days) is expected only in Istria and the mountainous coastal area.

Decrease in the number of cold nights (Tn10, Figure 6.1.3.8) in winter ranges from 4.5 to 5.0% in the majority of the mainland, in Istria and part of the northern Adriatic. A slightly smaller decrease is projected for the mountainous area, greater part of the central and southern Adriatic (from 4.0 to 4.5%). The smallest changes are expected in part of the central Adriatic area (decrease of 3.5 to 4.0%). On an annual level, a decrease in the number of cold nights is expected from 5.0 to 5.5% in most of the country. In the north-western regions (along the Slovenian border) and in the coastal regions, the decrease will be between 5.5 and 6.0%.

Changes in the number of cold days (Tx10, Figure 6.1.3.8) in winter indicate a decrease of 4.0 to 4.5% in the narrow coastal area and most of the mainland (central and eastern Croatia), and slightly less (from 3.5 to 4.0%) in the other parts of the country (mountainous area, mountainous littoral and the inland part of Dalmatia). Decrease in the annual number of cold days is largest over the Adriatic and coastal areas (6.5%), and it gradually decreases towards the mainland - the greater part of the mainland expects a decrease of 4.0 to 4.5%.

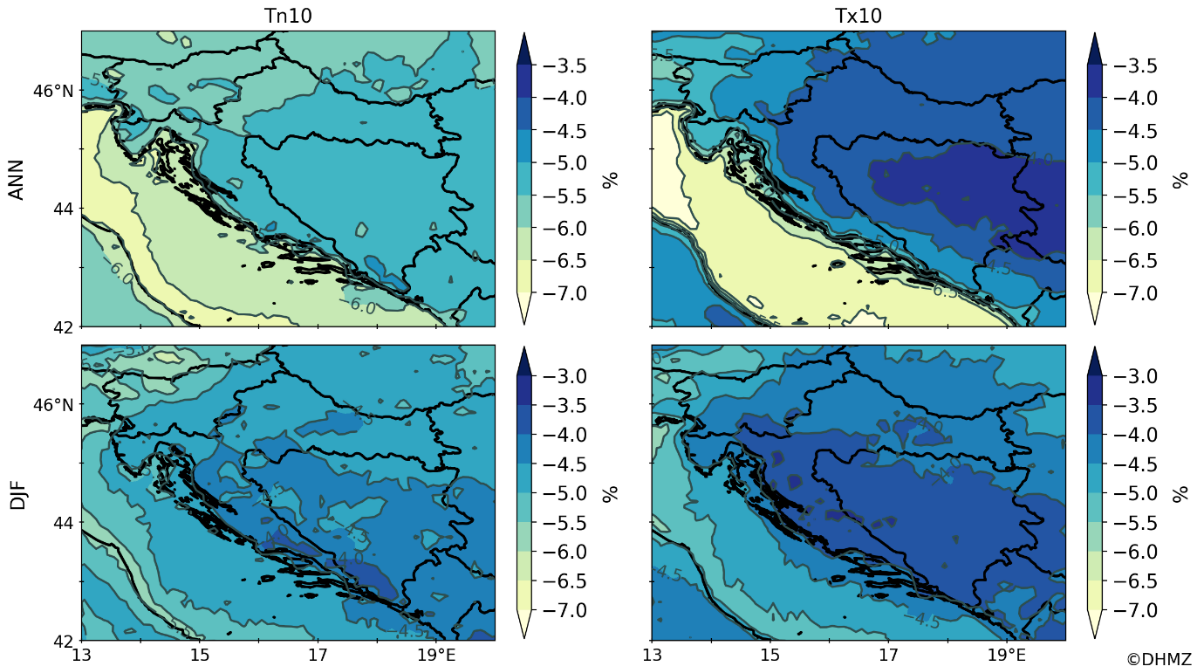

Figure 6.1.3.8. *Change in the number of cold nights (Tn10; first column) and cold days (Tx10; second column) of the ensemble mean for selected models for the period 2041 – 2070 compared to the reference period 1981 – 2010 for RCP4.5. Annual change (ANN; first row) and change in winter (DJF; second row).*

Changes in warm extreme temperature indices (Table 6.1.3.1) were analysed based on annual changes and seasonal changes for summer, spring and autumn, except warm spell duration index (WSDI) which was also analysed for winter season. Indices defined by absolute thresholds usually occur in the warmer part of the yeas, in contrast to the indices and warm periods, defined by percentiles on individual days, which can be recorded at any time of the year. In the future (P1) period, for all considered warm temperature indices, we can expect an increase in the number of days that meet the criteria for a particular index.

Annually the entire Republic of Croatia, in period P1 will experience at least 12 warm days more than in period P0 (SU, Figure 6.1.3.9). The far east of the country expects from 12 to 15, and the area of central Croatia between 15 and 18 warm days more. Mountainous area, Dalmatia and Istria inland will have up to 21 more warm days, while the narrow coastal area in the P1 period will have up to 24 more warm days compared to the P0 period. The summer season contributes the most to the annual increase in the number of warm days. The expected summer increase is between 5.0 and 7.5 days for eastern Croatia, 7.5 and 10.0 days for majority of central Croatia, and between 10.0 and 17.5 days for the wider mountainous and coastal areas. With an increase smaller than 10.0 but greater than 5.0 days, individual Dalmatian areas stand out. During the spring season, warm days can increase to a maximum of 5.0 days. It is interesting that the largest spring increase, from 2.0 to 5.0 days, can be expected over areas where the summer increase is smallest (parts of central and eastern Croatia, but also areas of Dalmatia). The increase in the number of warm days in the autumn season is greatest (between 5.0 and 7.5 days) over the coastal Adriatic area, and decreases towards the mainland, the largest part of which (mountains, large parts of central and eastern Croatia) is characterized by 2.5 and 5.0 warm days more.

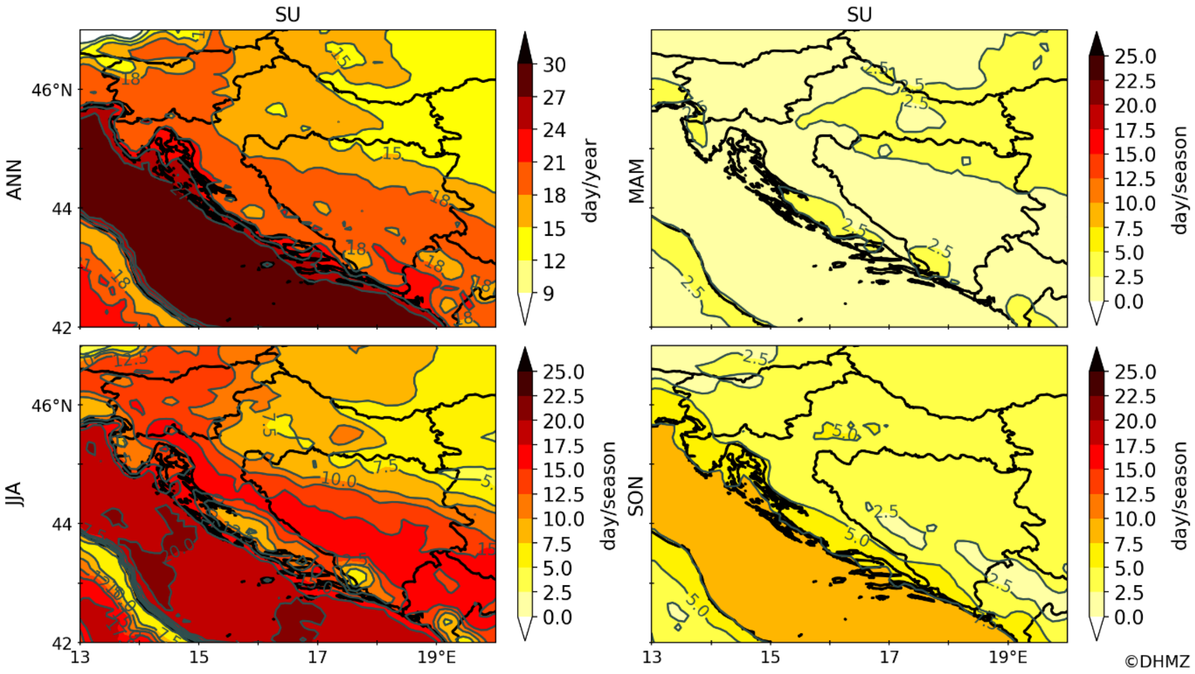

Figure 6.1.3.9. *Change in the number of warm days (SU) of the ensemble mean for selected models for the period 2041 – 2070 compared to the reference period 1981 – 2010 for RCP4.5. Annual change (ANN; top left), change in spring (MAM; top right), summer (JJA; bottom left) and autumn (SON; bottom right).*

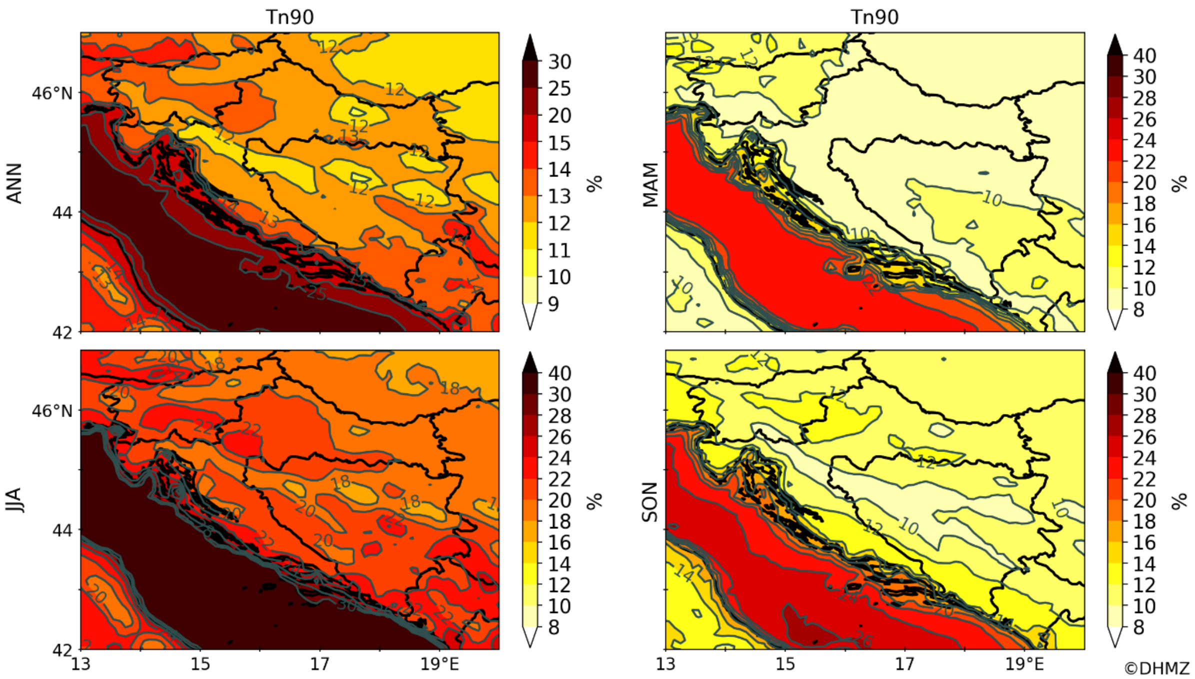

Figure 6.1.3.10. *Change in the number of warm nights (Tn90) of the ensemble mean for selected models for the period 2041 – 2070 compared to the reference period 1981 – 2010 for RCP4.5. Annual change (ANN; top left), change in spring (MAM; top right), summer (JJA; bottom left) and autumn (SON; bottom right).*

Annual change in the number of warm nights (Tn90, Figure 6.1.3.10) is largest over the narrow coastal area (greater than 13%), while the expected changes over the mainland are between 10 and 14%. Summer changes in the number of warm nights are also largest (greater than 22%) over the coastal area, between 20 and 22% in the majority of central Croatia and less than 18% over the rest of the country. Changes in the number of warm nights in both, the spring and autumn seasons, are also largest over the areas near the sea - in spring more than 10%, in autumn more than 14%. Spring changes over the rest of the country are between 8 and 10%. Autumn changes are between 8 and 10% over the mountains, between 12 and 14% over the western parts of central Croatia, and between 10 and 12% elsewhere.

Annual changes in the number of warm days (Tx90, Figure 6.1.3.11) show a continuous increase from the far east of the country (between 9 and 10%), across the central parts (between 10 and 11%) and relatively rapid spatial changes in the mountainous area (between 11 and 15%), to coastal areas characterized by changes greater than 15%. Spring changes in the number of warm days are less than 8% over the country mainland, and over the coastal areas they spatially rapidly increase towards more than 16%. Autumn changes in the number of warm days over the mainland are between 8 and 10%, over mountain areas between 10 and 14%, and in coastal parts of the country they reach values of 22%. Summer changes in the number of warm days have a similar spatial distribution - the smallest increase is over eastern and central Croatia (from 14 to 16%), from 16 to 20% in the mountain areas, reaching a maximum from 20 to 24% over coastal areas.

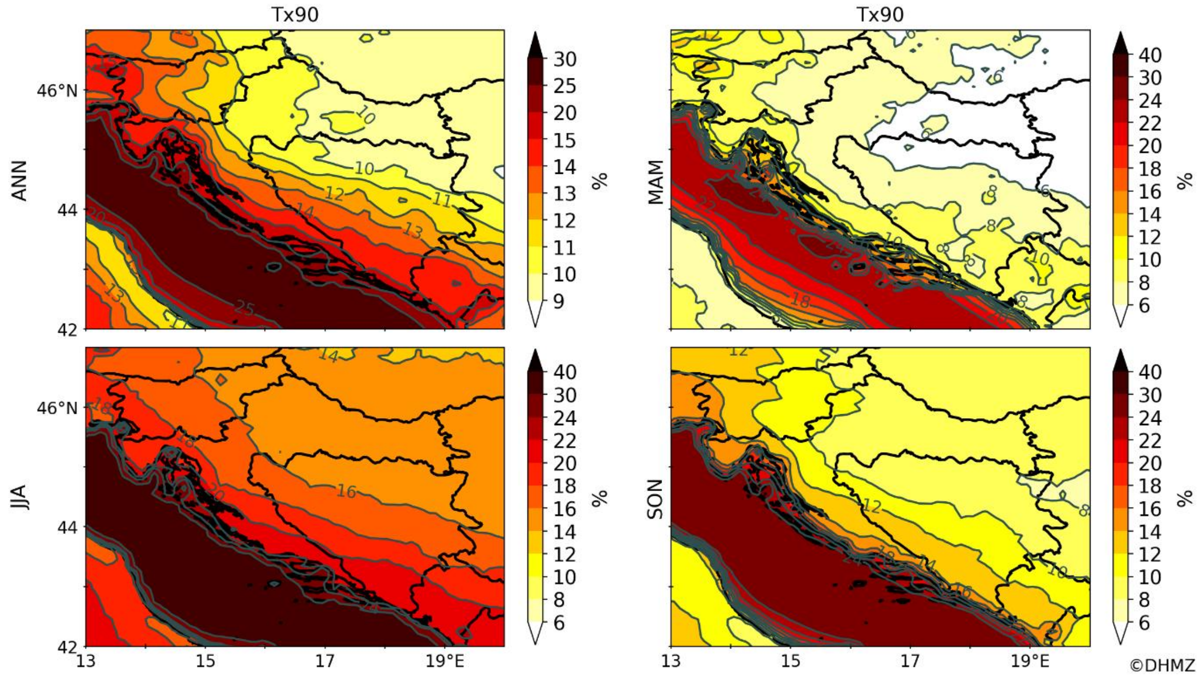

Figure 6.1.3.11. *Change in the number of warm days (Tx90) of the ensemble mean for selected models for the period 2041 – 2070 compared to the reference period 1981 – 2010 for RCP4.5. Annual change (ANN; top left), change in spring (MAM; top right), summer (JJA; bottom left) and autumn (SON; bottom right).*

Annual changes in warm spell duration index (WSDI, Figure 6.1.3.12), in accordance with changes in the number of warm days, gradually increase from the eastern (increase from 17.5 to 20.0 days) through the central and mountainous regions (20.0 to 32.5 days) and reach maximum over the coastal areas (up to 50.0 days). The aforementioned spatial increase, from the east through the central and mountainous areas towards the coast, is visible for all four seasons. It is most pronounced in the summer (from 8 to 10 days over the eastern and central regions to more than 16 days over coastal areas), and the least pronounced in the winter (2 to 4 days in the eastern regions, 4 to 8 days in mountainous Croatia, 8 to 10 days over the northern Adriatic coast and 10 to 12 days over the southern Adriatic coast). Autumn and spring changes in the warm spell duration are the same for the mountainous area and the area of central and eastern Croatia (in the spring between 2 and 6 days, in the autumn between 4 and 8 days), but over the coastal areas, they rapidly progress to 10 or more days in both seasons.

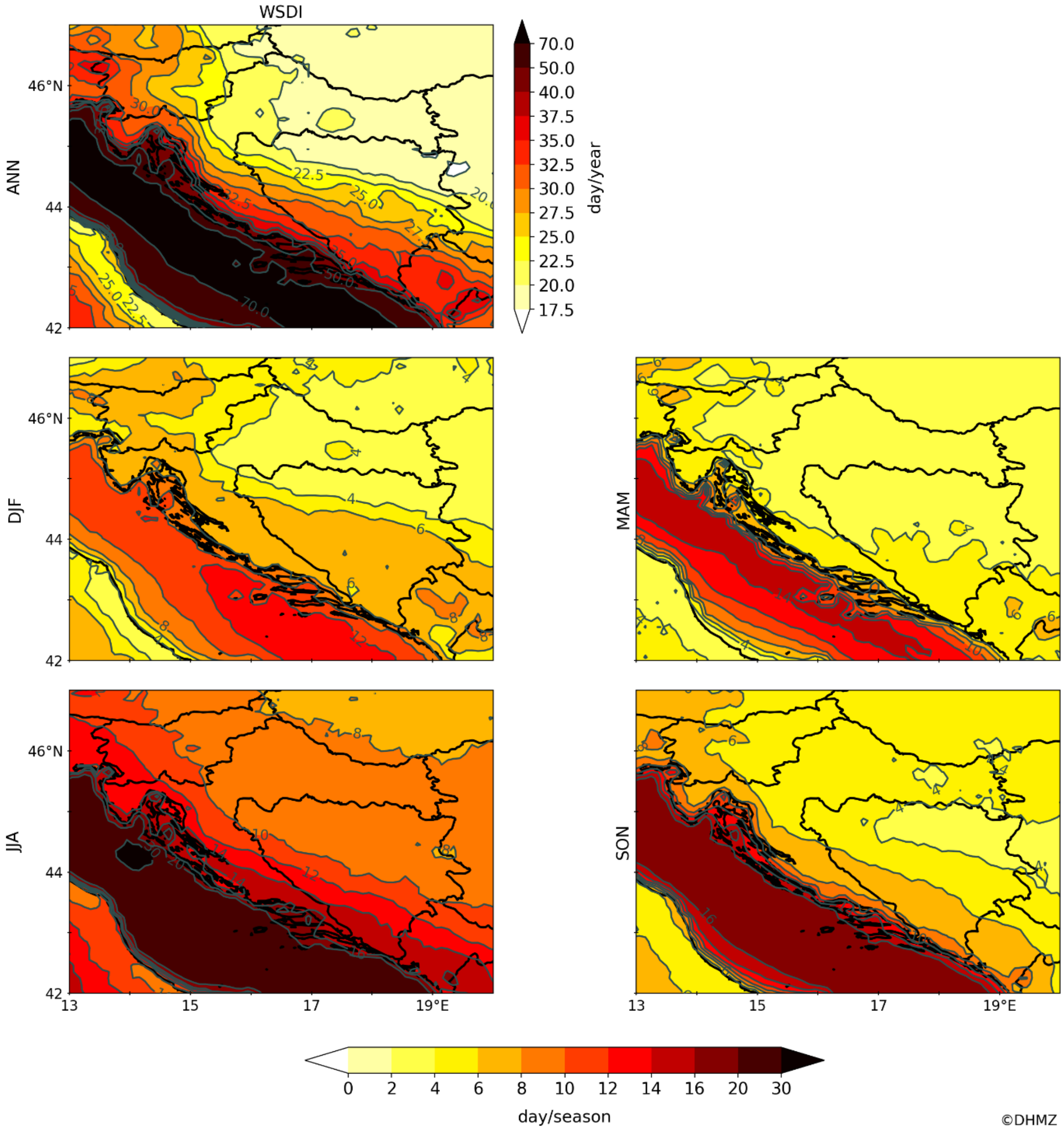

Figure 6.1.3.12. *Change in the warm spell days index (WSDI) of the ensemble mean for selected models for the period 2041 – 2070 compared to the reference period 1981 – 2010 for RCP4.5. Annual change (ANN; top left), change in winter (DJF; middle left), spring (MAM; middle right), summer (JJA; bottom left) and autumn (SON; bottom right).*

Observed trends of precipitation extremes

Changes in seasonal precipitation amounts are associated with observed changes in the frequency and magnitude of precipitation indices of extremes. The summer drying in the Adriatic was mainly contributed by a significant increase in the frequency of dry days (up to 5% / 10 years) and a decrease in the number of moderately wet days (at few stations up to 20% / 10 years in terms of the reference mean 1981–2020). In addition, maximum daily and multi-daily precipitation amount has been reduced (up to 10% / 10 years).

The autumn wetting trend is a consequence of a significant increase in the number of very wet days and the maximum daily precipitation amounts, particularly in the mainland (Figure 6.1.3.13), as well as a decrease in the duration of dry spells along the Adriatic.

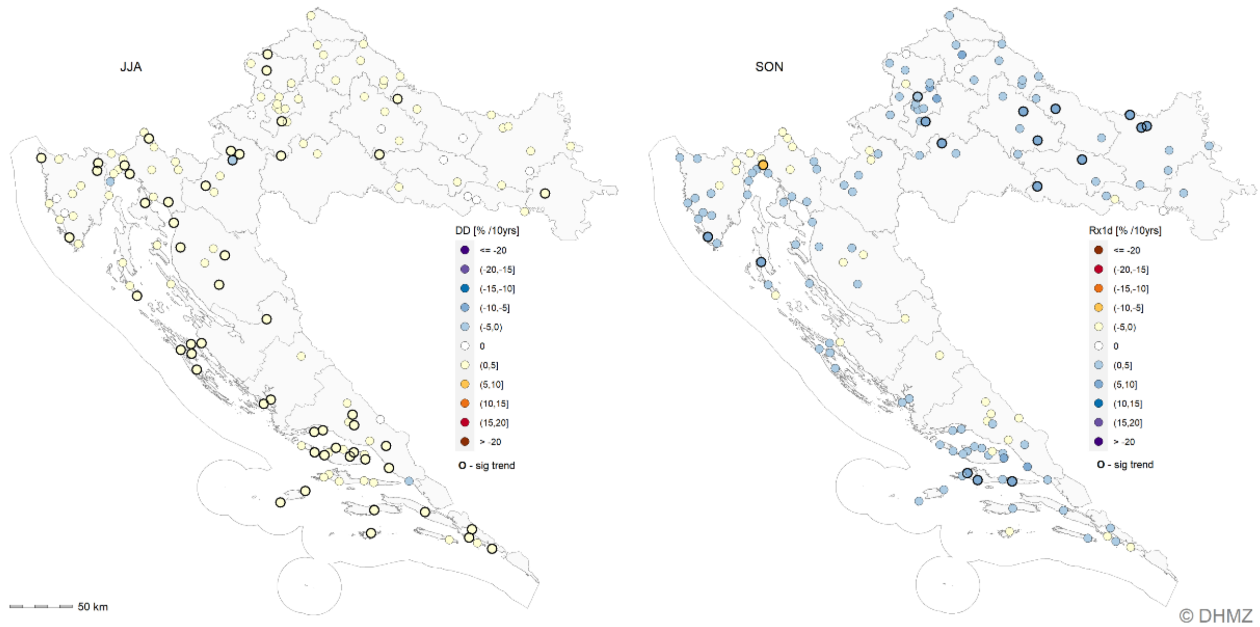

Figure 6.1.3.13. *Decadal trends in the number of dry days (DD) during summer (JJA) and maximum daily precipitation amounts (Rx1d) in autumn (SON) season (in % /10 years with reference to 1981–2010 period) in Croatia during the period 1961–2020. Statistically significant trends at meteorological stations are denoted by bolded circles.*

Future changes in dry and wet indices

The change in precipitation indices in the future (Table 6.1.3.1) was analysed on annual level and by seasons, while the figures show the change for the year and the two main seasons (winter and summer). The number of dry days (DD, Figure 6.1.3.14) on annual level in period P1 over the entire country will increase compared to the number of dry days in period P0. Projections indicate that the biggest increase will be over the mountainous regions and Dalmatia inland (up to 5%), while for the rest of the country there is an increase from 1 to 3%. An increase in the number of dry days is expected in all seasons throughout the country, except in winter. In winter, an increase in the number of dry days is expected in the southern Adriatic, while the change over the other parts of the country is mostly negligible - in the narrow area of the northern regions along the border with Hungary and the far east of the country, a decrease in the number of dry days of 1 to 2% is possible, elsewhere between -1 and 1%. The increase in the number of dry days is greatest in summer over the mountains and Dalmatian hinterland (from 5 to 7.5%).

Annual changes of both indices of consecutive dry days (CDD1, Figure 6.1.3.14 and CDD10, not shown) for the majority of the Republic of Croatia show that in the future period a longer series of consecutive dry days can be expected, up to 20% (mountainous areas). An exception are consecutive dry days when precipitation is less than 10 mm (CDD10), where projections show a possible shortening of the series, up to 5%, for eastern Croatia. Projections for both indices in the summer season indicate a lengthening of the series, while projections for the winter season mostly show a shortening of these series. Although the projections predict predominantly longer series of both indices in the spring and autumn seasons, a shortening of the series is also possible, more pronounced for the CDD10 index in the eastern and central parts of Croatia. All reductions are up to 10% and increases up to 15%.

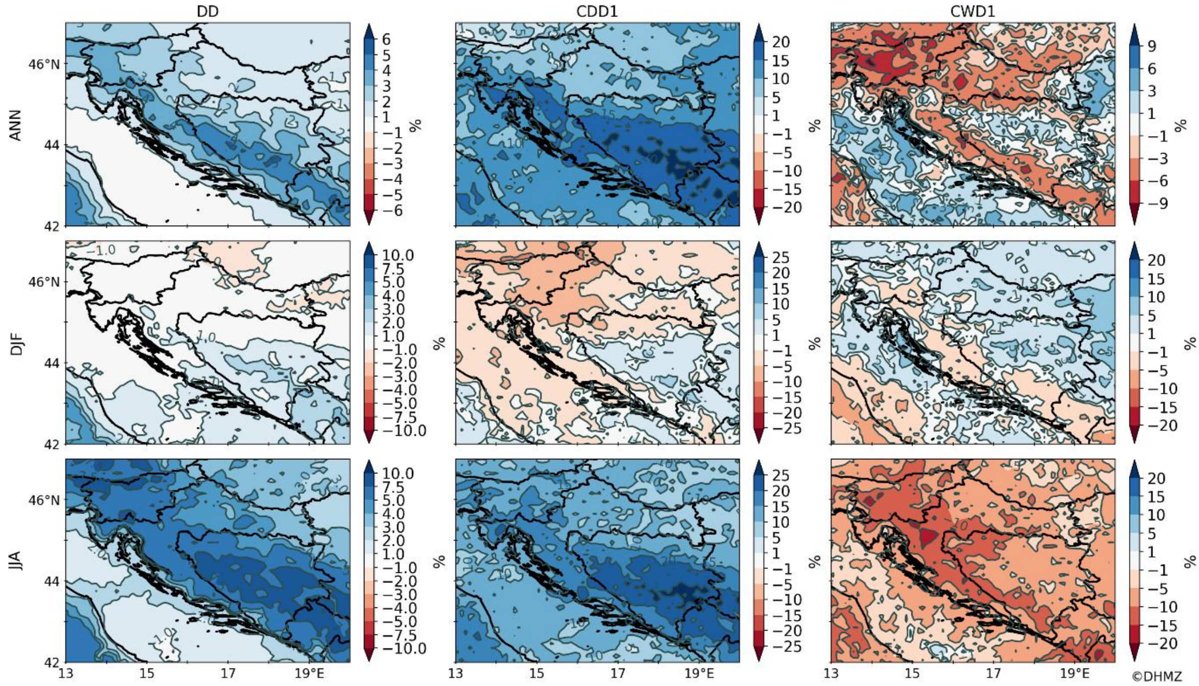

Figure 6.1.3.14. *Change in the number of dry days (DD; first column), consecutive dry days (CDD1; second column) and consecutive wet days (CWD1; third column) of the ensemble mean for selected models for the period 2041 – 2070 compared to the reference period 1981 – 2010 for RCP4.5. Annual change (ANN; first row), change in winter (DJF; second row) and summer (JJA; third row).*

Projections of both consecutive wet days indices (CWD1, Figure 6.1.3.14 and CWD10, not shown) are largely, as expected, in contrast to changes in the consecutive dry days index (CDD1 and CDD10). Over most of the country, the projections indicate a shortening of the series of consecutive wet days with precipitation greater than or equal to 1 mm (CWD1) on an annual level, except isolated areas of the far east of the country, and the coastal areas. The most common changes are in the range of -6 to 3%. Projections of the number of consecutive wet days with precipitation greater than or equal to 10 mm (CWD10) indicate a shortening of the series in the mountains, the inland of Istria and Dalmatia, and a lengthening of the series for the rest of the country. Analysis of the change in the CWD1 index indicates a shortening of the series of consecutive wet days during the summer over the entire Croatia, and in spring and autumn almost all over the country. In winter, the prolongation of the series is expected for the mountainous area and the Dalmatia inland (up to 5%), while in other areas, the prolongation of the series of consecutive wet days is projected, up to a maximum of 10% compared to the P0 period. The largest decrease for the CWD10 index is expected in the summer season, throughout the country. The changes in the spring and autumn will be spatially equally distributed as on the annual level, while the CWD10 index is mainly projected to increase for the winter.

Annual changes in the standard daily intensity index (SDII, Figure 6.1.3.15) in the P1 period indicate the largest increase over the coastal area, between 7.5 and 10.0%. Projections for the narrow areas of eastern Croatia along the border with Hungary and Bosnia and Herzegovina indicate possible changes of the same amount. Changes over Gorski Kotar and Lika are the smallest, but also positive, between 2.5 and 5.0%. In the rest of the country, an increase in the standard daily intensity index is also expected, from 5.0 to 7.5%. A possible decrease in the standard daily intensity index is projected only in the summer, and it is most pronounced over the coastal mountainous areas (from 3 to 9%). In other parts of the country and in other seasons, changes in the standard daily intensity index in the P1 period compared to the P0 period, are positive - mostly pronounced over the eastern regions in winter and in the autumn over the Adriatic coast (between 9 and 12%).

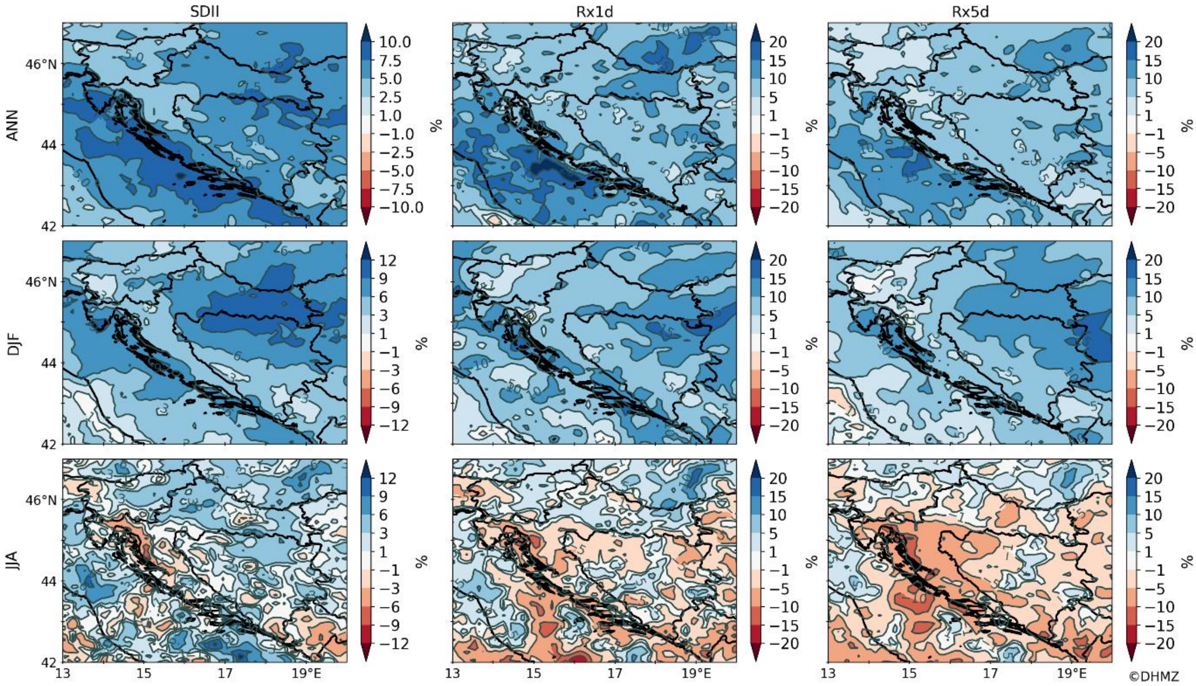

Figure 6.1.3.15. *Change in the standard daily intensity index (SDII; first column), maximum one-day precipitation amount (Rx1d; second column) and maximum five-days precipitation amount (Rx5d; third column) of the ensemble mean for selected models for the period 2041 – 2070 compared to the reference period 1981 – 2010 for RCP4.5. Annual change (ANN; first row), change in winter (DJF; second row) and summer (JJA; third row).*

An increase in the annual maximum one-day precipitation amount (Rx1d, Figure 6.1.3.15) is expected in the period P1 compared to the period P0 over the entire Republic of Croatia. The increase over most of the country will be between 5 and 10%, while over the eastern part of central Croatia and the western part of eastern Croatia, as well as the inland of Istria and parts of Dalmatia, it will be between 10 and 15%. The greatest contribution to the described annual increase is due to the autumn changes, which are very similar to the annual change both in terms of amount and spatial distribution. Spatially somewhat different and somewhat smaller in amount, the spring also shows a positive contribution over the entire country. The winter mainly indicates an increase in the maximum one-day precipitation amount - only a small part of Kvarner area indicates a possible decrease (up to 5%). The reduction of the maximum 1-day precipitation amount in the summer is expected over a much larger area than in winter. It covers almost the entire coastal area, mountains and the northern parts of the mainland and it is most pronounced over the mountainous littoral, where it reaches a value of 10 to 15%. However, central and eastern Croatia are characterized by an increase in the maximum one-day precipitation amount, mostly up to 5%.

The maximum five-day precipitation amount (Rx5d, Figure 6.1.3.15) annual change is similar to changes in the maximum one-day precipitation amount and over the entire Republic of Croatia it shows a positive change - over the majority of area from 1 to 5%, less in mountainous Croatia, and more over certain coastal areas. Like the seasonal changes of the maximum one-day precipitation amount, the changes of maximum five-day precipitation amount in the winter, spring and autumn seasons are mostly positive, and in the summer mostly negative. The increase in five-day precipitation in spring and autumn is, compared to the changes in one-day precipitation, less pronounced. Winter changes in maximum five-day precipitation amount are positive over the entire country. Projections show that changes of 5 to 10% will be the most spatially represented over the Dalmatia, Lika and the western part of central Croatia, 10 to 15% over the eastern part of the country and only over the part of the coast and the nearby highlands they are less than 5 %.The summer decrease of the maximum 5-day precipitation covers most of Croatia and over mountainous littoral it reaches values from 10 to 15%.

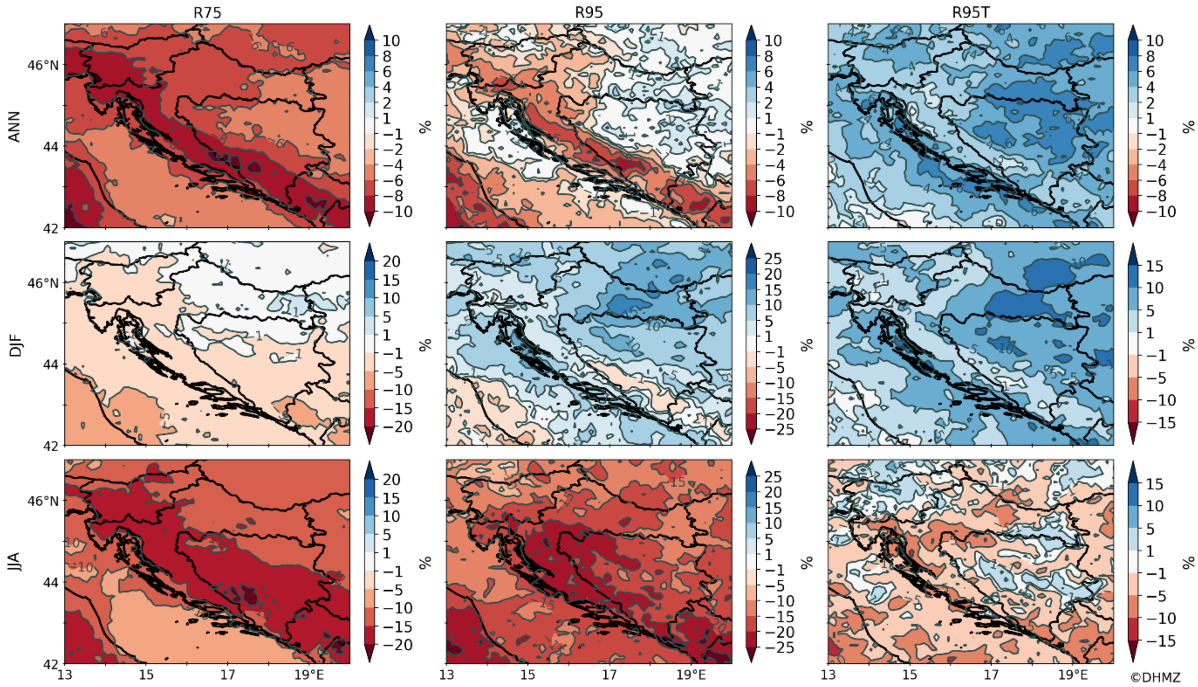

Figure 6.1.3.16. *Change in moderately wet days (R75; first column), very wet days (R95; second column) and precipitation due to very wet days (R95T; third column) of the ensemble mean for selected models for the period 2041 – 2070 compared to the reference period 1981 – 2010 for RCP4.5. Annual change (ANN; first row), change in winter (DJF; second row) and summer (JJA; third row).*

The number of moderately wet days (R75, Figure 6.1.3.16) in the P1 period will be lower than in the P0 period throughout the country. The largest changes, a decrease of 8 to 10%, are projected for the Istria inland, the mountainous Croatia (including mountainous littoral), and the Dalmatia inland. For the coastal area and central Croatia, the decrease is from 6 to 8%, and over eastern Croatia from 4 to 6%. Looking at the seasons, the smallest changes are expected in winter, when the number of moderately wet days in the central and eastern Croatia will increase (up to 5% in the far east) and decrease over the rest of the country (from 1 to 5%). In all other seasons over the entire Croatia, the number of moderately wet days decreases in the P1 period. Projections indicate a possible decrease from 1 to 5% for eastern Croatia, part of central Croatia and the coastal area of central Dalmatia in the spring. A reduction of 5 to 10% is projected for most of the coastal and mountainous areas in spring, also over the entire country in autumn. A decrease of more than 10% is projected only for the summer season - between 10 and 15% for the coastal area, central and eastern Croatia, and between 15 and 20% for the mountainous area and the inland of Istria and Dalmatia.

The change in the annual number of very wet days (R95, Figure 6.1.3.16) is spatially similarly distributed as the change in the number of moderately wet days. Exception is the sign of change, which alters from negative to positive over the eastern parts of the country and the change amounts to 2%. The largest changes (a decrease from 6 to 8%) are projected for the coastal area and the Dalmatia inland. A smaller decrease (4 to 6%) is expected in mountainous Croatia. For the central

Croatia, the reduction amounts from 1 to 4%. Projections for the summer over the entire Republic of Croatia indicate a decrease in the number of very wet days, the smallest over the far east and north of the country (10 to 15%), and the largest over mountainous area and the Dalmatia inland, mostly between 20 and 25%. Projections for the spring give the same spatial distribution of change as the annual change. A positive change (up to 10%) in the spring is projected for the eastern Croatia and the western part of Istria, while for the rest of the country the change is negative - the biggest over the mountains and Dalmatia inland (up to 10%). Autumn changes also indicate both, a possible decrease and a possible increase, and the changes are small ranging from -5% to 5%. In winter, we expect an increase in the number of very wet days and it is largest over western Slavonia, from 15 to 20%.

Unlike the change in the number of moderately wet days and very wet days, which mainly indicate a decrease in the period P1 compared to the period P0, the projections of precipitation due to very wet days (R95T, Figure 6.1.3.16) over the entire country indicate an annual increase in the precipitation amount due to very wet days, i.e. more intense extremes in the precipitation regime. The largest increase (from 6 to 8%) is expected for the Slavonian area and coastal parts. An increase between 4 and 6% in the precipitation due to very wet days covers a wider area of eastern and parts of central Croatia and the rest of the coast. Changes of less than 2% are projected for the rest of the country (mountainous Croatia, Dalmatian hinterland). The winter and autumn seasons also indicate an increase in precipitation due to very wet days throughout the country (highest during winter in Slavonia - between 10 and 15%). Even though the projections indicate an increase in the precipitation due to very wet days in largest part of the country during spring (up to 10% in the eastern areas, Istria and in several places along the coast), for the part of the mountainous area, central Croatia, and the hinterland of Dalmatia the projections show a possible decrease, up to 5%. The summer mainly shows a decrease in precipitation due to very wet days, at most between 5 and 10%, while for the narrower area of Slavonia an increase of 1 to 5% is projected in the summer as well.

6.3 Climate change impacts on nature, society and economy

6.3.1 Impacts of climate change of agriculture and wildfire risk

The negative impact of climate change has been registered in almost every sector of human activity, especially in the highly vulnerable sector - agriculture. Food production is an extremely complex process that depends on numerous factors and represents a great challenge that is even more challenging in terms of climate change. Numerous studies carried out in different countries indicate reductions in the yield of different crops due to extreme heat and drought events (e.g. Wang et al. 2018, Kumar et al. 2021). Such extreme weather events additionally create a favorable conditions for the occurrence and spread of forest fires.

Growing season length

The duration of the growing season is an extremely important agroclimatic element. In fact, it is a limiting factor that regulates the success of growing certain plant species in a certain area. If the vegetation period is too short plants cannot complete vegetation cycle. In this report temperature threshold of 5 °C was selected to determine growing season length (GSL5). The annual GSL5 is defined as the number of days between the first span of at least 6 days with mean daily temperature above 5 °C and the first span of 6 days with mean daily temperature below 5 °C (Mueller et al. 2015). Spatial distribution of average GSL5 during recent climatological period 1991–2020 is showing that GSL5 is longest in coastal part of Dalmatia and shortest in the highlands. In lowland part of Croatia average duration of GSL5 is mainly between 265 and 280 days (Figure 6.3.1.1, left).

The map of anomalies (Figure 6.3.1.1, right), which was obtained by the difference of the average duration of GSL5 in the recent (1991–2020) and older (1961–1990) climatological period, indicates a significant prolongation of the vegetation period in the continental part of Croatia during the period 1991–2020. Prolongation of the growing season is a direct consequence of the increase in air temperature (see chapter 6.1.3) and can potentially lead to higher yields. However, this potential is limited by the amount of available water.

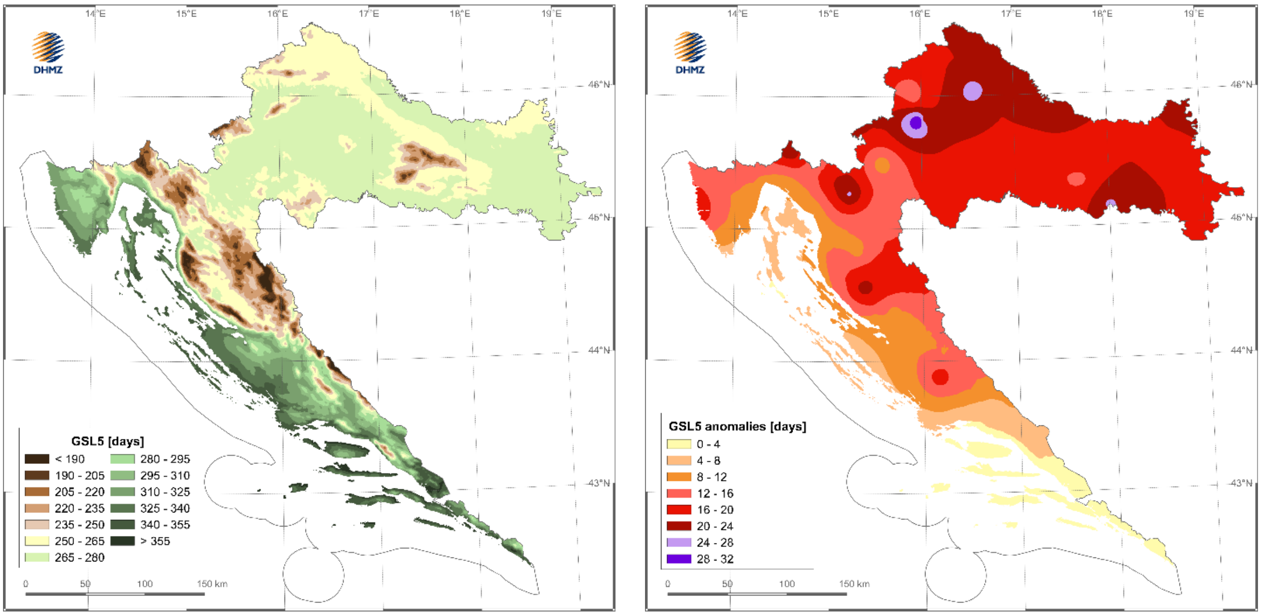

Figure 6.3.1.1. *Spatial distribution of average GSL5 during recent climatological period 1991–2020 (left); GSL5 anomalies calculated as difference between average GSL5 during the recent (1991–2020) and older (1961–1990) climatological period (right).*

Growing degree days

Growing degree days (GDD) are another limiting factor that regulates the success of growing certain plant species in a certain area. Plants need for the transition from one phenological phase to another, as well as for the completion of the vegetation cycle a certain amount of accumulated heat which is manifested through GDD. GDD can be calculated by subtracting the air temperature threshold from the mean daily air temperature, and positive daily values are then summed over the desired time period (e.g. Vučetić and Anić 2021). For the purposes of this report, a temperature threshold of 5 °C was used, while the summation was performed in the warm part of the year (1st of April – 30th of September). In average, the highest GDD5 are achieved in coastal Dalmatia, and the lowest in the highlands (Figure 6.3.1.2, left). GDD5 anomaly map indicates a significant increase in GDD5 during the recent climatological period 1991–2020. This increase of GDD5 is also a direct consequence of the increase in air temperature and is most pronounced in the central part of lowland Croatia (Figure 6.3.1.2, right). We can conclude that climate of Croatia is getting warmer and if such trends continue in the future, in absence of appropriate adaptation strategies, it may become unsuitable for the growing of some plant species that are traditionally cultivated in Croatia. On the other hand, the potential for growing species that are traditionally cultivated in more southern regions is slowly emerging.

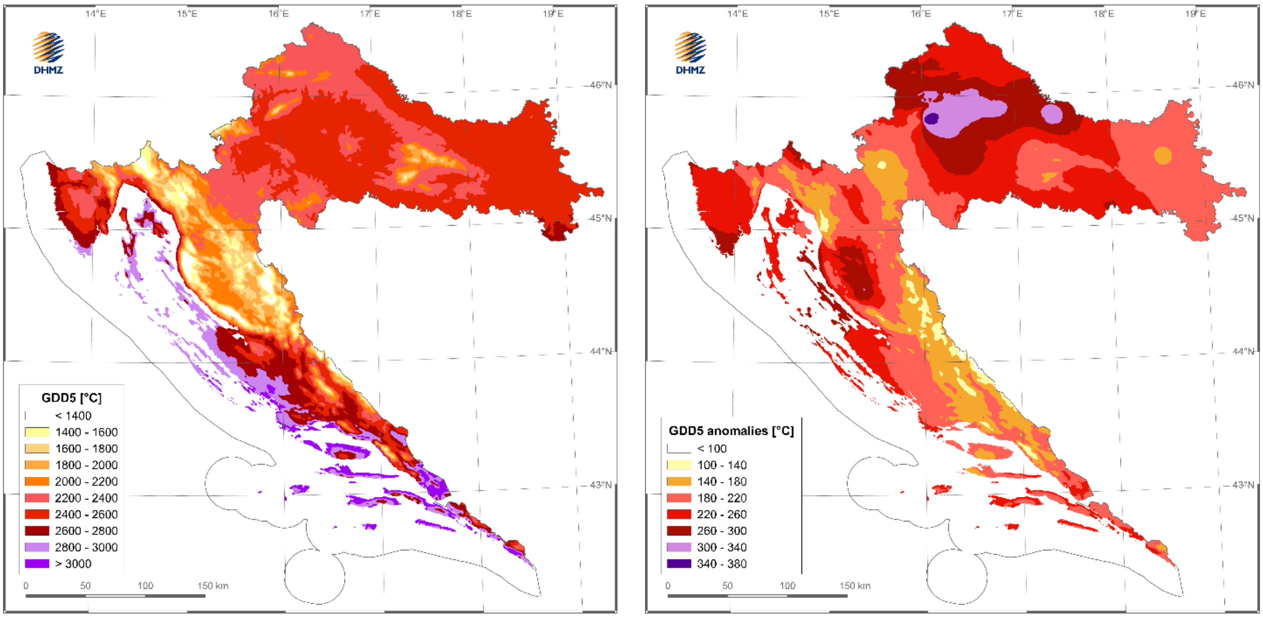

Figure 6.3.1.2. *Spatial distribution of average GDD5 during recent climatological period 1991–2020 (left); GSL5 anomalies calculated as difference between average GDD5 during the recent (1991–2020) and older (1961–1990) climatological period (right).*

Soil temperature

Soil temperature is a very important agroclimatic factor that affects germination and emergence of crops, root growth and water and nutrient uptake from soil. Combined with humidity, soil temperature initiates and determines the budding of trees and emergence of leaves (Lalić et al. 2018). For the purposes of the report trends in the average daily soil temperature at a depth of 10 cm were analysed. Cartographic representation was not possible due to the insufficient number of stations with a long-term (1961. – 2020.) soil temperature measurements, so trend analysis was performed on measurements from four stations which belong to different regions of the Republic of Croatia. The trend analysis showed significant increase in the mean daily soil temperature at a depth of 10 cm after year 1991 at all analysed stations. The statistically significant soil warming of 0.5 / decade was observed in central Croatia (station Bjelovar) and the highlands (station Gospić). In eastern Croatia (station Osijek) and in the northern part of the Adriatic (station Rab) statistically significant soil warming was slightly lower 0.3 °C / decade (Figure 6.3.1.3).

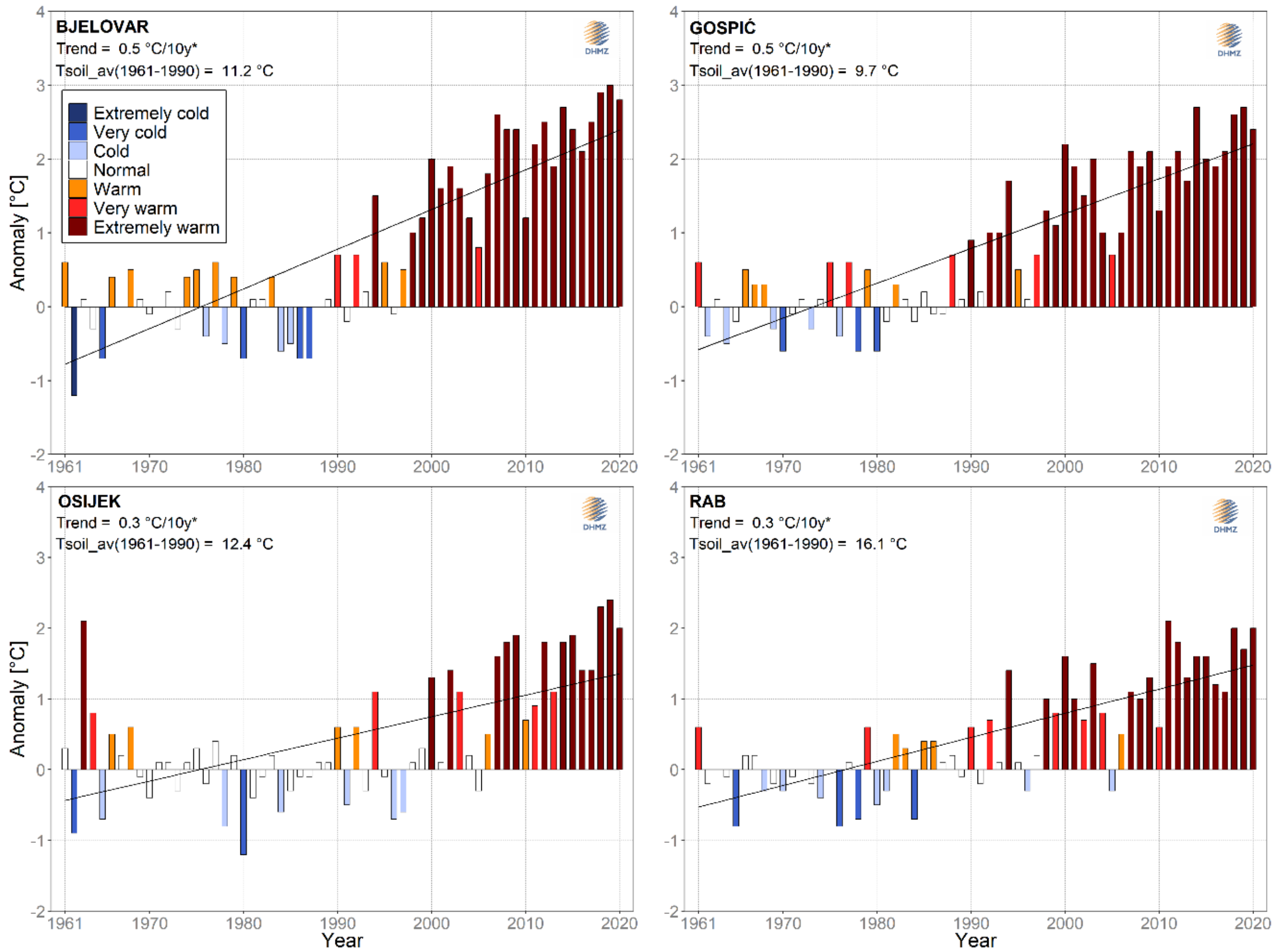

Figure 6.3.1.3. *Deviations of the average annual soil temperature at a depth of 10 cm from long-term average (1961–1990) and linear regression lines during the period 1961–2020 on four DHMZ stations (Bjelovar, Gospić, Osijek i Rab). Statistically significant trends are marked with *.*

Furthermore, the trend analysis of the annual number of days with maximum soil temperature above 30 °C at the same soil depth showed a significant increase in the number of such days in the last two decades (Figure 6.3.1.4). The statistically significant increase in number days of 5 days / decade was observed in central Croatia (station Bjelovar), eastern Croatia (Osijek) and northern part of Adriatic (Rab). In highlands (Gospić) increase in number of days is slightly lower 2 days / decade (Figure 6.3.1.4). Analysis showed that the soil in the Republic of Croatia is becoming warmer. Longer duration of high soil heating could threaten agricultural production. Also, high soil temperatures increase water loss from the soil.

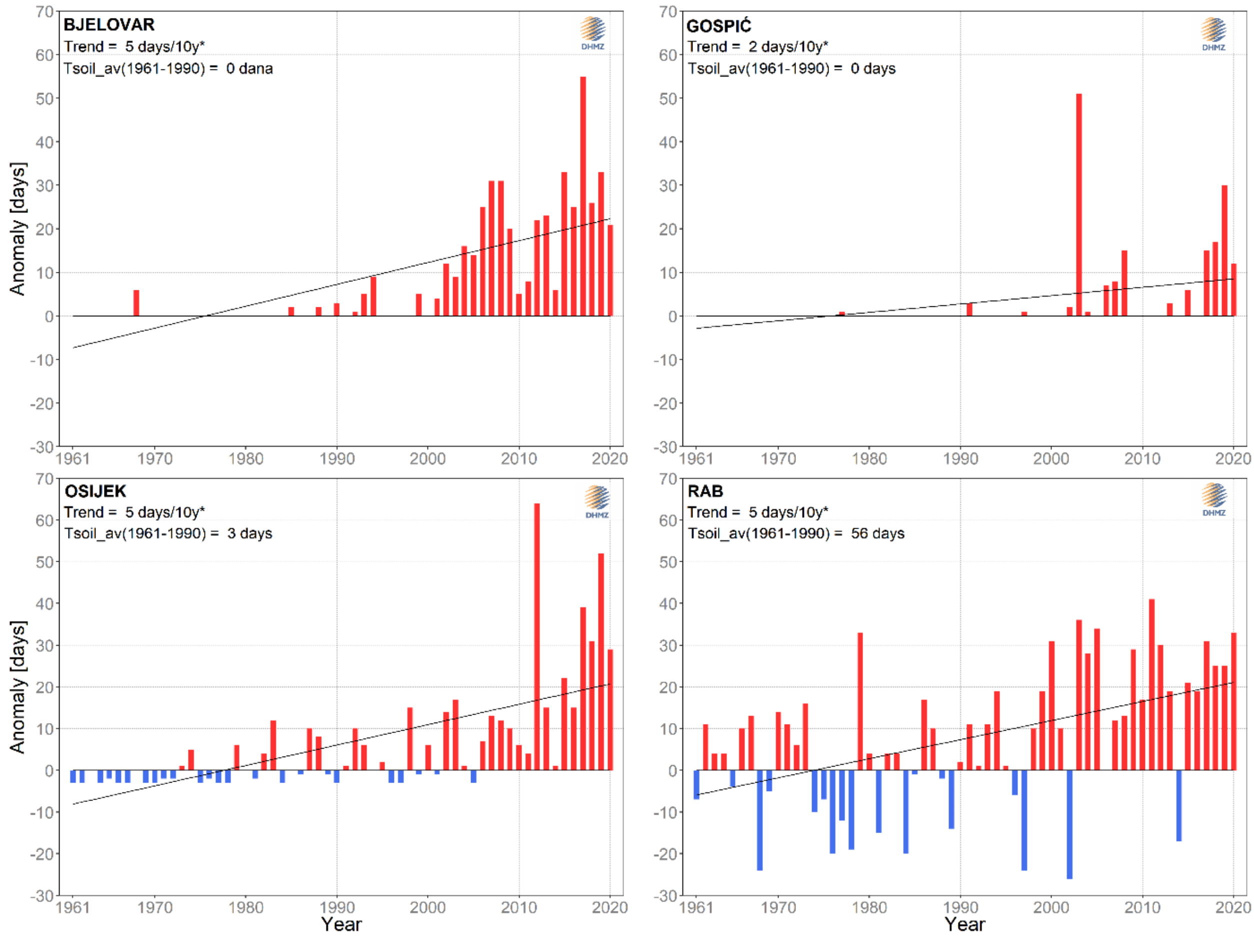

Figure 6.3.1.4. *Deviations od annual number of days with maximum daily soil temperature at a depth of 10 cm ≥ 30 °C from long-term average (1961–1990) and linear regression lines during the period 1961–2020 on four DHMZ stations (Bjelovar, Gospić, Osijek i Rab). Statistically significant trends are marked with *.*

Soil water

Water is the most limiting abiotic factor to plant growth and productivity (McElrone et al. 2013). The aridity index (AI) is used as one of the indicators of dryness of the climate (UNEP, 1992). AI is calculated as ratio between precipitation and potential evapotranspiration (PET, the maximum possible evaporation that would occur if there is no shortage of water), where precipitation represents the amount of available water, while PET indicates how much water is needed. Spatial distribution of the average AI during the warm part of the year (1st of April – 30th of September) in the period 1991–2020 shows that the largest part of Croatia belongs to the humid zone AI > 0.65 (Figure 6.3.1.5, left). Eastern part of Slavonia, the northern part of Adriatic and the continental hinterland of Dalmatia belong to the dry-subhumid zone (0.5 < AI < 0.65), while the coastal part of Dalmatia mainly belong to the semi-arid zone (0.2 < AI < 0.5). Anomalies of AI (Figure 6.3.1.5, right) indicate a decrease in the aridity index during the warm part of the year in recent climatological period 1991–2020 what means that the climate of Croatia is becoming more arid during the warm part of the year when the vegetation is developed.

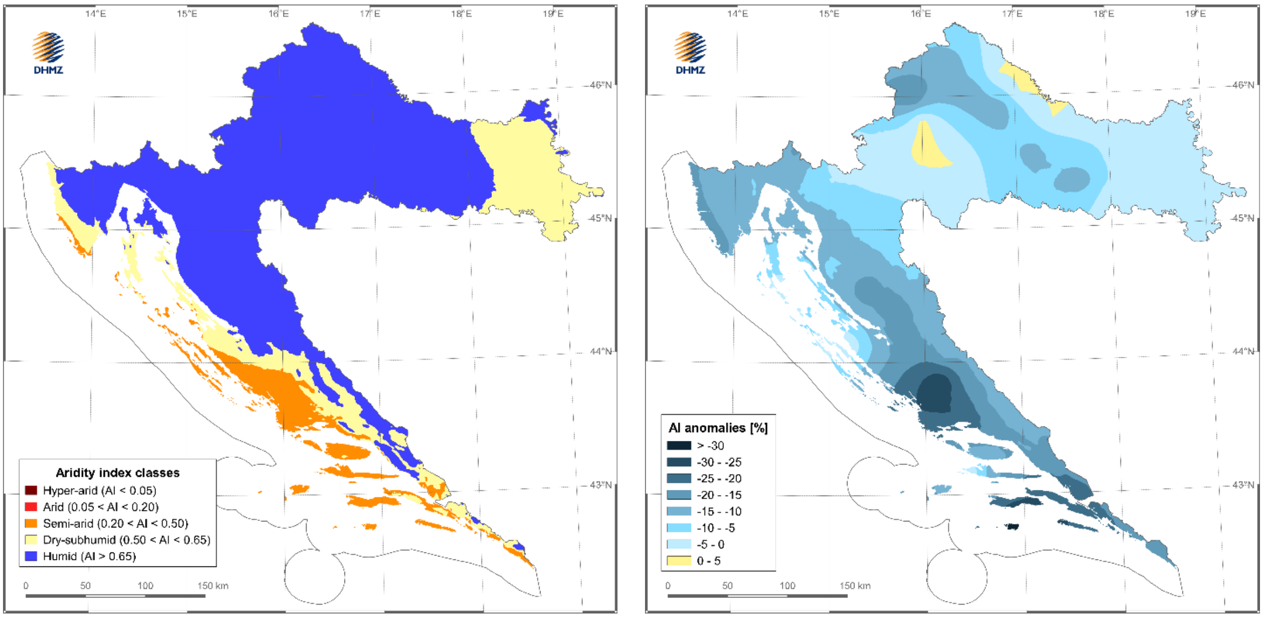

Figure 6.3.1.5. *Spatial distribution of average AI during the warm part of the year in the recent climatological period 1991 – 2020 (left); AI anomalies calculated as ratio between average AI during the warm part of the year in recent (1991 – 2020) and older (1961 – 1990) climatological period (right).*

Viticulture

Viticulture is a major economic activity in many regions around the world. In the Republic of Croatia, viticulture has a rich and long tradition, and the grapevine represents an important culture for agriculture and the economy of the state. Since climatic conditions in certain area largely determine the success of growing a certain grapevine variety, climate change could have a significant impact on the yield and quality of grapes in the future (Fraga et al. 2013). Studies have shown that increase in air temperature has a great influence on the phenological stages of the grapevine as well as grapevine yield and the quality (Webb et al. 2012, Fraga et al. 2016, van Leeuwen and Darriet 2016). Huglin heliothermal index (HI) is traditionally used for zoning of wine-growing regions (Tonietto and Carbonneau 2004). According to Huglin (1978), grapevine cultivation is not possible in regions where HI does not exceed 1500 °C, while in regions where HI exceeds 2400 °C heliothermal conditions are favourable for the cultivation of almost all grape varieties. Spatial distribution of HI in the period 1991–2020 shows that the heliothermal conditions are favourable for growing grapevines in larger part of Croatia (Figure 6.3.1.6, left). The HI anomaly map (Figure 6.3.1.6, right) indicates a significant increase in HI during the recent climatological period 1991–2020, what means that the heliothermal conditions in some areas are slowly becoming favourable for the cultivation of vines. In addition, in some areas a potential for cultivating vine varieties that did not prosper in the past because there was not enough heat is emerging. Climate change is expected to introduce new challenges in viticulture, and in order to ensure successful grapevine cultivation in regions where the suitability for grapevine cultivation is slightly declining due to climate change (Hall and Jones 2009), grapevine cultivation will have to be adapted to climate change in order to mitigate their impact (Metzger et al. 2008).

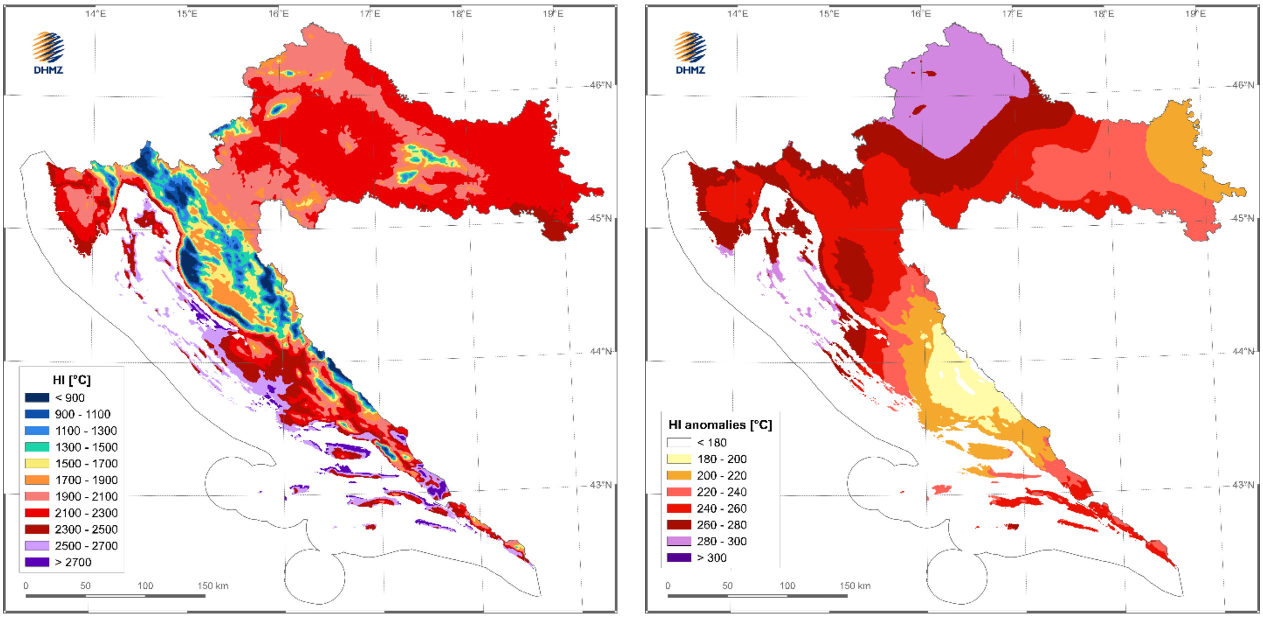

Figure 6.3.1.6. *Spatial distribution of average HI during recent climatological period 1991 – 2020 (left); HI anomalies calculated as difference between average HI during the recent (1991–2020) and older (1961–1990) climatological period (right).*

For the study of the dates of harvest and duration of ripening two varieties typical for Croatian region, „Graševina“ (station Daruvar, 1961–2020) and „Plavac mali“ (station Hvar, 1962–2016), were selected. The duration of ripening was calculated as the difference between two phenological stages - full ripening and the beginning of ripening. The analysis showed that the duration of ripening of both observed varieties decreased significantly in the recent climatological period 1991–2020 (Figure 6.3.1.7). Both observed varieties showed shifting trend of the duration of ripening and the decrease was more obvious in the case of “Graševina” (-6 days / decade) and less for “Plavac mali” (-3 days / decade).

Furthermore, the analysis showed that the harvest occurs earlier in the case of both analysed varieties (Figure 6.3.1.8.). Shifting trend in the date of harvest was greater for „Graševina“ (-3 days / decade) and somewhat less for „Plavac mali“ (-1 day / decade). Decreasing trend in the date of harvest of „Plavac mali“ was not statistically significant.

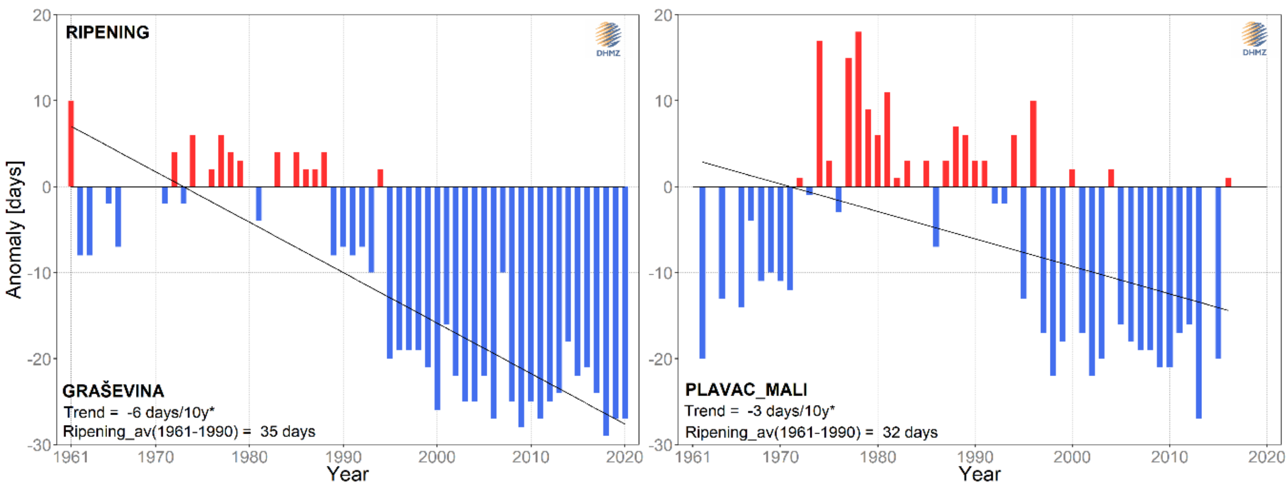

Figure 6.3.1.7. *Deviations of the duration of ripening from long-term average (1961–1990) and linear regression lines for two grapevine varieties „Graševina“ (left) and „Plavac mali“ (right).*

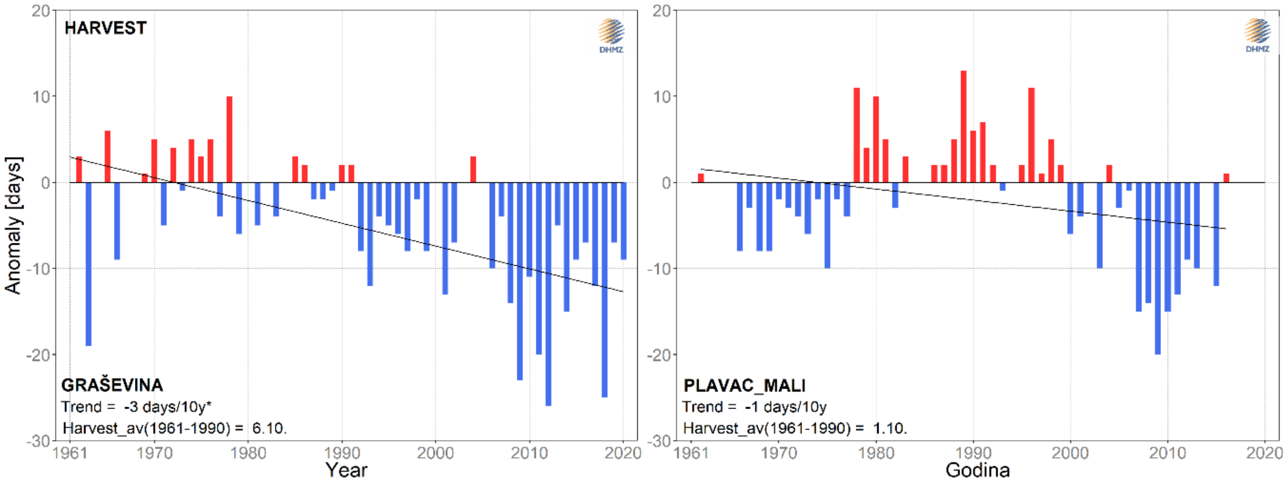

Figure 6.3.1.8. *Deviations of the date of harvest from long-term average (1961–1990) and linear regression lines for two grapevine varieties „Graševina" (left) and „Plavac mali" (right).*

The earlier onset of the development stages of the grapevine is a direct consequence of the increase in air temperature. More pronounced changes in the earlier onset of the development stages of the grapevine occur in the continental part of Croatia.

Forest fire risk

Fire represents one of the major disturbances in forest ecosystems around the planet. During the summer months, forest fires in the coastal part of Croatia frequently reach catastrophic proportions and destroy forests and agricultural lands and often pose a threat to populated areas and human lives. The *Canadian Forest Fire Weather Index* (FWI, van Wagner 1974, 1987) is used globally to assess the meteorological risk of forest fires. Seasonal severity rating (SSR) is a final component of a FWI system and serves as an indicator of the potential seasonal meteorological risk of forest fires. Spatial distribution of average SSR during the fire season (1st of June – 30th of September) in the period 1991–2020 indicates that Dalmatia is the most fire-prone region in the Republic of Croatia (Figure 6.3.1.9, left). Reason for this are prolonged dry spells during the summer months accompanied by high air temperatures and easily flammable Mediterranean vegetation cover. Conditions for the occurrence and spread of forest fires are becoming more favorable due to climate change. The SSR anomaly map (Figure 6.3.1.9, right) indicates a significant increase in SSR during the recent climatological period 1991–2020. The increase of SSR is more intense in the northern part of the Adriatic and in the continental part of Croatia where in some places SSR has doubled during the recent climatological period. This trend of SSR growth is a consequence of the increase in air temperature and the prolongation of dry spells during the summer months (see chapter 6.1.3).

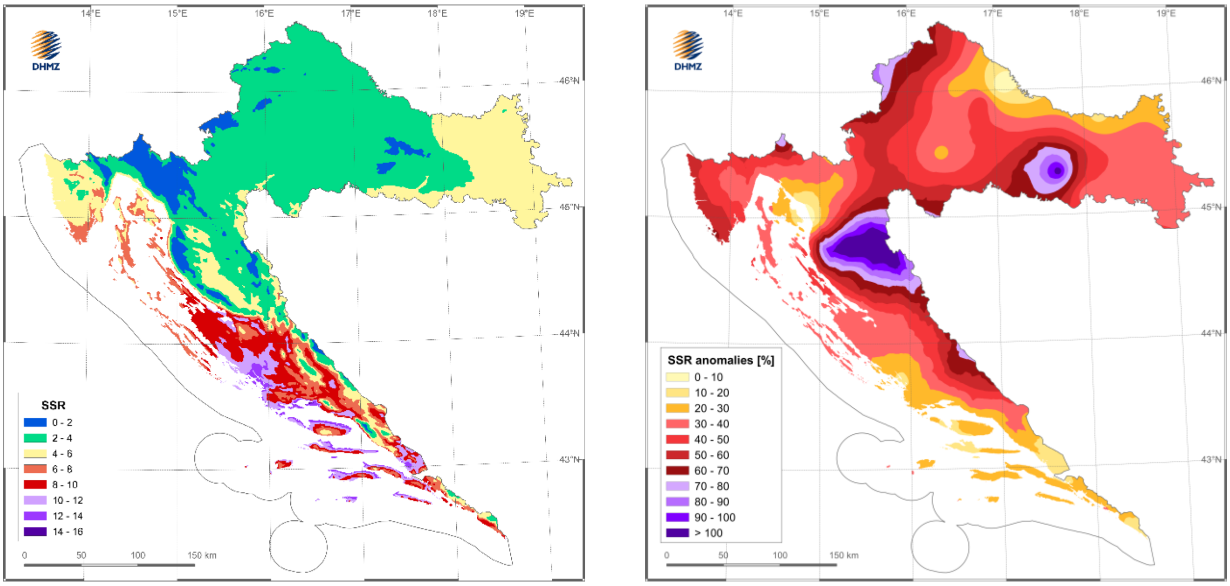

Figure 6.3.1.9. *Spatial distribution of average SSR during fire season in the recent climatological period 1991–2020 (left); The ratio of average SSR during the fire season in the period 1991–2020 with average SSR during the fire season in the period 1961–1990.*

6.3.2 Impacts of climate change on tourism

Weather and climate have a key role in choosing a tourist location, and climate change can significantly influence the usual tourist activities. Strategic planning of the tourism development, as one of the most important economic branches in Croatia, should definitely take into account the known facts about possible change in climatic elements important for tourism in Croatia.

The expected changes in temperature and precipitation conditions presented in the chapter 6.1.3 show that tourism will have to adapt to the upcoming changes in the future. This mostly applies to coastal tourism in the summer. High air temperatures with extended warm periods and more frequent heat waves, less precipitation and consequently a lack of drinking water, increased risk of fire will certainly not be suitable for coastal tourism in the form we have today. However, the temperature increase in spring and autumn, with smaller changes in the precipitation regime than in summer, is an opportunity to extend today's summer activities on these two seasons. Mountain tourism, hiking and green continental tourism will be possible in all seasons (to a lesser extent in summer compared to the remaining seasons). Ski tourism will weaken due to the lack of snow, but with adequate adaptation to other contents, winter tourism will be possible.

From 2022, the Croatian Meteorological and Hydrological Service has been supporting the Ministry of Tourism and Sports in holding workshops "Strengthening the resilience of tourism to climate change" across the Republic of Croatia by giving talks about the future changes in climate elements important for tourism of particular region.

8. Research and systematic observation

8.2 Research and development

Research on weather, climate and climate change based on data from Croatian Meteorological and Hydrological Service (DHMZ) and climate models is regularly conducted, and research results and published in scientific journals with international peer review. Data about the number of scientific papers and about number of projects being implemented are collected in the Report of the Croatian Committee of Geodesy and Geophysics of Croatian Academy of Sciences and Arts which is prepared for the International Union on Geodesy and Geophysics. According to last published report for meteorology in Croatia (2015-2018), Croatian meteorologists implemented 46 projects and annually published 27 scientific papers with international peer review. It should be mentioned that scientific papers of Croatian meteorologists and climatologists were cited also in the The Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change – IPCC.

One of the main goals of the conducted applied research activities is application of the research results which is done through preparing information for development of policies and implementation of measures of the climate change adaptation, as well as managing risks in current climate. Croatian Meteorological and Hydrological Service, besides its contribution to the Eight National Communication of the Republic of Croatia under the United Nation Framework Convention on the Climate Change (UNFCCC), contributes also to the following major reports and documents:

- Report on the state of environment in Republic of Croatia
- National report on climate change adaptation measures
- Disaster risk assessment in the Republic of Croatia

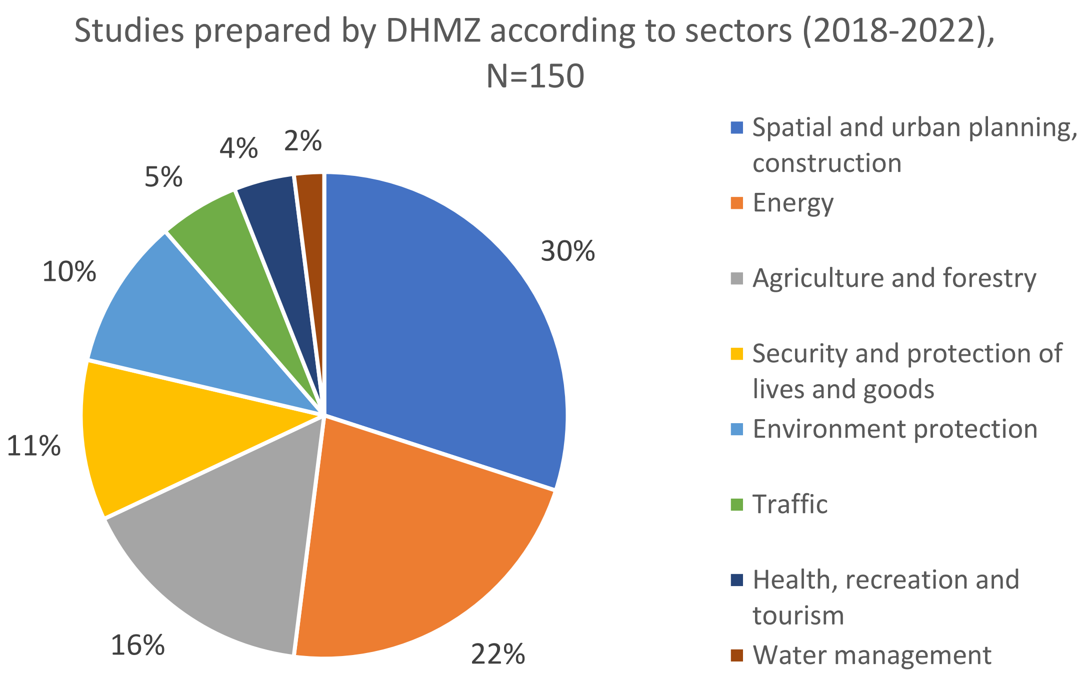

Figure 8.2.1. *Studies of the Croatian Meteorological and Hydrological Service according to sectors in period 2018-2022 (%, in total 150 studies). Source: DHMZ.*

Besides support to development of policies and action plans, applied research and translating research to society can be assessed from studies which are conducted for various purposes and stakeholders. For example, experts from the Croatian Meteorological and Hydrological Service prepared 150 meteorological studies in period 2018-2022 for different sectoral needs (Figure 8.2.1). Translation of applied research results to society through studies most directly enhances resilience and adaptation of the country to climate and climate change.

For the purpose of specific investors, Croatian Meteorological and Hydrological Service in recent years prepared climate assessments for SECAPs (Sustainable Energy and Climate Action Plan). For that purpose, climate information was prepared for cities of Rijeka, Zadar, Korčula, Osijek, municipalities of Mrkopalj and Ravna Gora, Brač island, and Split-Dalmatia and Primorje-Gorski Kotar counties. Climate projections are also prepared for development of SECAPs within the framework of the Interreg projects.

Description of several relevant projects is given below:

(1) Adriadapt - A Resilience information platform for Adriatic cities and towns

For two and a half years, Adriadapt project (https://adriadapt.eu/) has been working on harmonizing and expanding existing knowledge about climate change. DHMZ's greatest contribution was preparation and processing of meteorological data and the creation of documents about expected climate change in the Adriadapt domain as well as for the specific Italian and Croatian case study locations.

There are two main project outcomes: Prepared and updated adaptation plans to climate change for the local authorities involved in the project (the Union of the Municipalities of the Savio Valley, the cities of Udine and Cervia, in Italy; the county of Šibenik-Knin and the city of Vodice, in Croatia) and the multilingual platform (in English, Italian and Croatia) that can serve as a support to the municipalities of the Adriadapt region, but also more broadly, for alignment with the goals of the European Strategy for Adaptation to Climate Change[5].

DHMZ prepared two educational videos that are part of the video platform, together with other video materials that show the results achieved during the project. The one of the results is also published Coastal Resilience Handbook for the Adriatic (PAP/RAC, 2021).

(2) RESPONSe - Strategies to adapt to climate change in Adriatic regions

RESPONSe project (https://www.italy-croatia.eu/web/response) was initiate in early 2019. with the aim to make local communities ready for the climate change in the near decades and to have more harmonized approaches and share of data for the implementation of adaptation measures. RESPONSe project analysed and compared historical climate data over the Adriatic regions, identifying that majority of the temperature related variables and indices, including sea surface temperature, shows rising and statistically significant changes, while changes in precipitation related variables and indices are more local specific.

Adaptation and mitigation strategies and actions were aggregated in the Climate Menu supporting system tool (www.climatemenu.eu), with 160 actions at disposal of municipalities. Piloting projects for drafting Sustainable Action Plans were put in place in 6 coastal municipalities of both sides of Adriatic. A standardized methodology for Risk and Vulnerability analysis was developed to support the local policy makers in identifying main risks and vulnerabilities of their territories and in addressing mitigation and adaptation actions to be developed in the near future. Constant dialogue

[5] https://climate.ec.europa.eu/eu-action/adaptation-climate-change/eu-adaptation-strategy_en

with municipalities and participatory approach with local communities supported achievement of the results, and the possibility to close the project leaving local municipalities a concrete Action Plan to be implemented and climate smart governance approaches that could empower other decision makers towards climate resilient planning policies.

RESPONSe project improved monitoring system with meteorological and oceanographic stations acquired both in Italy and in Croatia by collecting, transferring and sharing the newly data and by integration with data coming from other collateral initiatives, such as the METMONIC project in Croatia. The improvement of the monitoring system allowed collection of climate information dispersed over different sources and developed focused products for each of the key pilot areas involved. The integration of data in the networks also supported the adoption and integration in the networks of newly methodological systems for prediction of scenarios and for identification of future projections contributing the overall knowledge on climate change adaptation methods.

(3) "UKV - Management of coastal karst aquifers threatened by climate change"

Investigating the impact of climate change on coastal karst aquifers and proposing adaptation measures to climate change were the goals of the scientific research project "Management of coastal karst aquifers threatened by climate change" (UKV, https://www.ukv-projekt.eu/). The role of DHMZ in the UKV project was to analyse the current climate and observed changes in air temperature and precipitation in three pilot areas, to compare the results of high-resolution regional climate models with measured data for the current climate, and to prepare future climate projections. All the above were analysed in the DHMZ report. One of the possible consequences of the impact of climate change is the salinization of coastal aquifers due to the disruption of the labile dynamic balance of fresh and salt water in them. These mechanisms of salinization have been investigated using advanced methods, and surface and underground water monitoring has been established. As part of the project, separate studies of the impact of changes in the state of water resources on the sectors of water and marine resource management, agriculture, tourism and health and proposals for adaptation measures were prepared.

(4) SEE-MHEWS-A - South-East European Multi-Hazard Early Warning Advisory System

Project SEE-MHEWS-A (https://public.wmo.int/en/projects/see-mhews-a) is implemented by the World Meteorological Organisation in collaboration with 17 partner national meteorological and hydrological services from partner countries from the southeast Europe. SEE-MHEWS-A project provides support to the national meteorological and hydrological Services in the southeast Europe in fulfilling their core function: providing timely and accurate warnings of hazardous weather and hydrological events in order to reduce loss of lives and other impacts on people, infrastructure and industry. The role of DHMZ was to evaluate the accuracy of the forecasting systems in all 17 partner countries, as well as development and testing of the common information platform for access to information about severe meteorological and hydrological conditions. Project established impact-based forecasts and risk-based warning capacities that contribute to better informed decision-making by national governments, disaster management authorities, humanitarian agencies, and NGOs.

8.3 Systematic observations

Global Climate Observation System

Global Climate Observation System (GCOS) was established in 1992 and the Republic of Croatia, represented by the Croatian Meteorological and Hydrological Service, has been its member since then. This system includes observations in all parts of the climate system – in the atmosphere, ocean, sea and land. It is intended to define and cover all the observations required for monitoring the climate system including satellite observations at the global, regional and national levels, and to create conditions for observation enhancement. Global Earth Observation System of Systems (GEOSS) is a new initiative taken with the objective to co-ordinate and enhance all current observing systems at the global level in support of the requirements of user areas: natural disasters, health, energy, climate, water, weather, ecosystems, agriculture and biodiversity. The Republic of Croatia joined the GEOSS in 2004.

Modernisation of the DHMZ measurement networks

The Republic of Croatia has a long tradition in monitoring of all segments of the climate system. The Croatian Meteorological and Hydrological Service (DHMZ) is a national institution for meteorology and hydrology and has been carrying out meteorological observations for operational needs since 1851. Today, DHMZ is modernized through three projects METMONIC, AirQ and VEPAR implemented through the EU financial envelope through Operational Programme Competitiveness and Cohesion 2014.-2020.

National Weather Observations Network

Meteorological observations include two types of data: visual observations of weather phenomena and instrumental measurements. Sporadic observations in the Republic of Croatia began in the middle of the 18th century, and in the middle of the 19th century systematic and continuous meteorological observation began on the entire territory of the Republic of Croatia. In DHMZ, mostly manual observations are still carried out by observers at: 40 synoptic stations (34 DHMZ + 6 locations of the Croatian Air Traffic Control), 98 climatological, 325 rain gauge stations and 22 totalizer rain gauges. Automated weather stations (AMP) are co-located with 34 synoptic stations, while there are 30 independent AMPs in other locations. The standard time resolution of AMP data is 10 minutes. Furthermore, at individual meteorological stations, monitoring of soil conditions and measurements of soil temperature and humidity, solar radiation and evaporation from the water surface are carried out. In order to obtain the vertical profile of the atmosphere, radiosonde measurements are performed in Zagreb and Zadar two times per day (00 and 12 UTC). Remote measurements of the atmosphere include 6 C-band meteorological radars (5 meteorological radars are in function at the beginning of 2023), 2 wind profilers (Dubrovnik and Monte Kope in Istria), one LIDAR in Slavonski Brod and one microwave radiometer (Monte Kope). In order to determine the physical characteristics of the sea, 5 moored buoys were installed in the eastern part of the Adriatic Sea, they include AMPs for measuring atmospheric parameters at buoys locations. A map of meteorological stations in Croatia si given in Figure 8.3.1. Analysis of costs and benefits show that the development and maintenance of the meteorological monitoring network is economically justified, i.e. investing 1 USD results in 7 USD of profit for society.

The implementation of the modernization of more than 400 meteorological stations in the Republic of Croatia began on October 1, 2017 with the implementation of the project Modernization of the National Weather Observation Network in Croatia - METMONIC, which is one of the strategic projects of DHMZ and MINGOR in the thematic goal of adapting to climate change in the EU- and in the financial period 2014-2020 from which the project is co-financed with the amount of 85%, while the contribution of the Republic of Croatia is 15%. The METMONIC project ends in 2023.

The data obtained by the modernized network of meteorological stations will serve many purposes; for climate monitoring and calibration of climate models, adequate environmental planning and management and for sustainable activities of the economy sector; obtaining more detailed measurements will result in better understanding of the impact of pollutants on the environment; development of an appropriate policy for climate change adaptation and mitigation including reducing the risk of natural disasters (for example floods or droughts) as well as other disasters; for the purpose of producing renewable energy. In addition to the above, it will be used for better monitoring and assessment of long-distance cross-border pollution, analysis and application of modeling techniques for the geographic distribution of pollutant concentrations (emissions), thus providing the necessary information to combat the risk of danger to human health due to exposure to pollution, especially for sensitive groups.

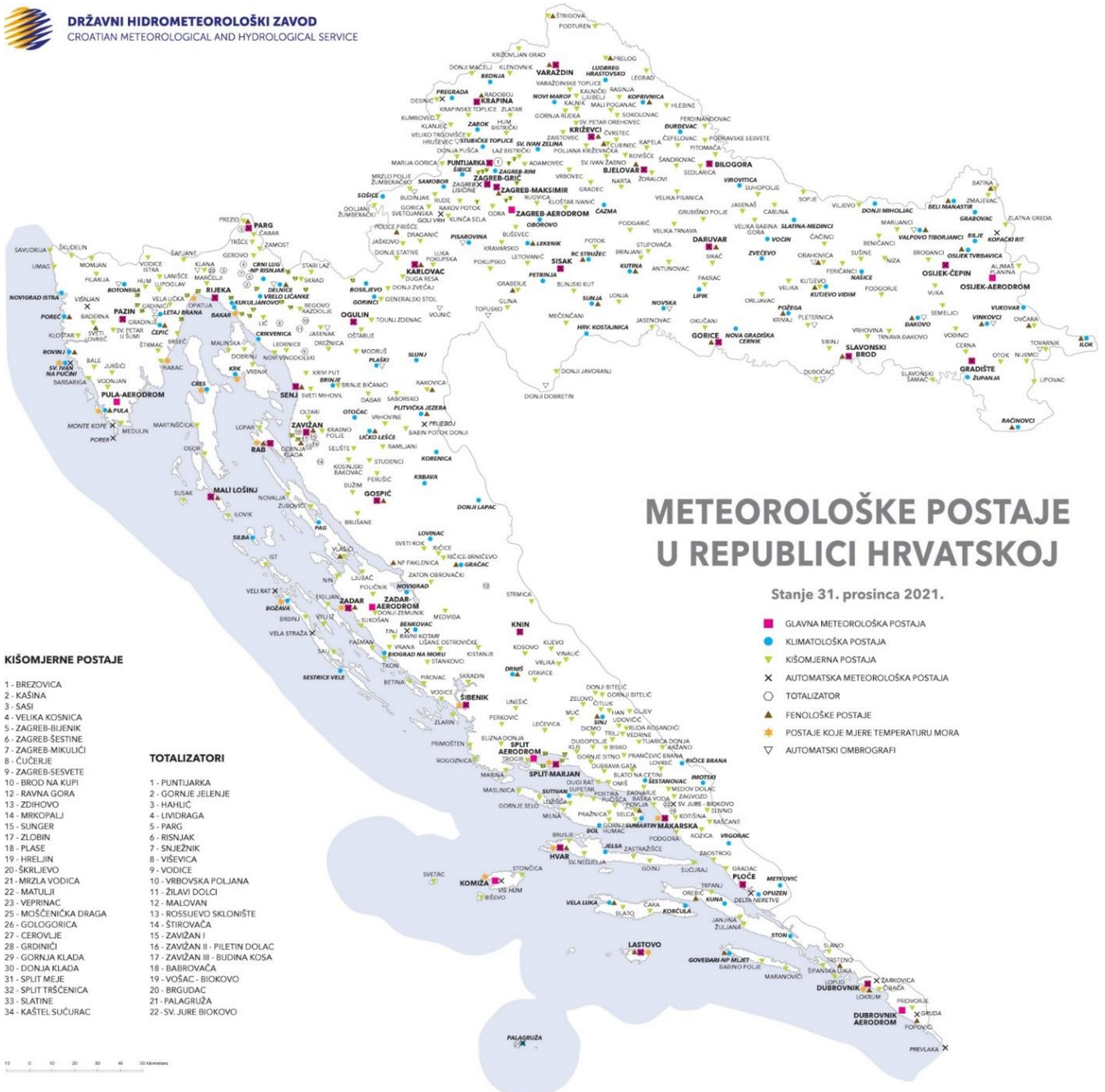

Figure 8.3.1. *Weather observation network – map of meteorological stations in Croatia.*

National Network for Continuous Air Quality Monitoring

Air quality and pollution levels in the Republic of Croatia are monitored at two levels, national and local. Monitoring of pollution levels at the national level takes place through the national network for continuous air quality monitoring and it is carried out by reference laboratories. The first station started operating in 2003. Monitoring of air pollution at the local level and measurements at special-purpose measurement stations are carried out by test laboratories. The national network is managed by the Croatian Meteorological and Hydrological Service, while counties, cities and municipalities are responsible for the measurements at the local level. Special-purpose measuring stations are located near the air pollution sources and these measurements should be ensured by the polluters themselves, in accordance with the environmental protection conditions.

To fulfil the obligations, set by EU legal regulations in the area of air quality protection, the Republic of Croatia is obliged to improve air quality monitoring in urban areas, zones and agglomerations, in accordance with the latest knowledge and best practice, through the development of sustainable integrated strategies and projects that create preconditions for adequate assessment, planning and implementation of appropriate measures in their area.

As a result, the beginning of the modernization and expansion of the state network for air quality monitoring started with the implementation of the EU project "Expansion and modernization of the state network for permanent air quality monitoring - AirQ" (through the Operational program Competitiveness and Cohesion 2014-2020, investment priority 6e Environmental protection and sustainability of resources and Specific objective 6e1 Improvement of the air quality management and monitoring system in accordance with Directive 2008/50/EC). The project started on May 1,

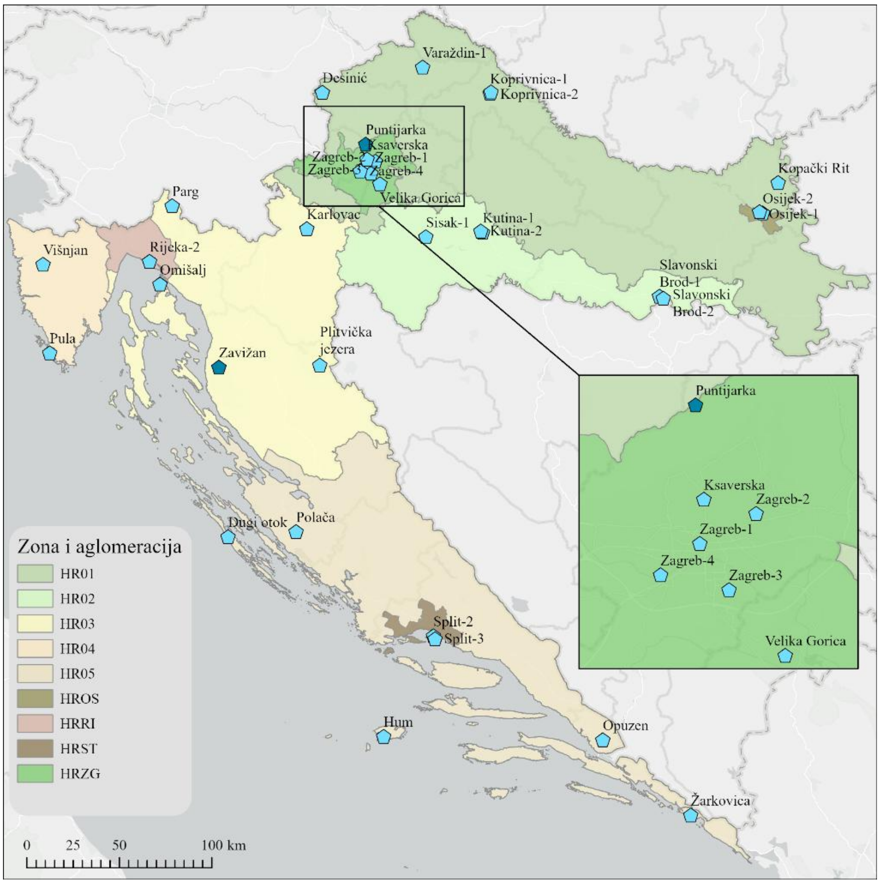

Figure 8.3.2. *Measuring stations of the state network for continuous air quality monitoring, distributed within zones (5) and agglomerations (4).*

2017, and the end is planned on September 30, 2023. The EU participates in the co-financing of project activities with 85% of the funds, while the Republic of Croatia's contribution is 15%.

For this purpose DHMZ, as the competent body responsible for the running of the state network for continuous air quality monitoring and for the implementation of the Air Quality Measurement Program, in cooperation with the Institute for Medical Research and Occupational Health (IMI) as a partner, the Ministry of Economy and Sustainable Development and the Fund for Environmental Protection and Energy Efficiency, establishes an adequate system for measuring and modelling air quality, as well as a system for analysing measurement and modelling results and a system for informing the public and state institutions. To achieve these goals, it was necessary to ensure the functionality of a sufficient number of measuring stations by modernizing and expanding the state network for continuous air quality monitoring, because the previous number of measuring stations was not sufficient, and the measuring equipment was outdated or inadequate. The construction of 5 new and the modernization of 19 stations is planned. A map of measuring stations of the state network for continuous air quality monitoring, distributed within zones (5) and agglomerations (4) is given in Figure 8.3.2. In addition, it was of strategic importance to upgrade the existing air quality modelling system to enable the development of activities and measures that will ensure positive results in terms of long term air quality improvement.

The planned result of these efforts is the establishment of an appropriate system for monitoring and managing air pollution in accordance with Directive 2008/50 EC. The existing measurement program is being upgraded to consider air quality and relevant climate parameters for the synergy of air quality and climate policy and to improve the monitoring program for short-lived climate forcers (SLCF) and introduce climate-sensitive measures against air pollution. The air quality data system is being upgraded to enable spatial display of all air quality data, emissions, and modelling results. The expansion and modernization of the state network will enable obtaining relevant data of the levels and atmospheric movements of individual pollutants, which will further enable the adoption of effective measures to improve air quality in urban areas where limit and target values of pollutant concentrations are exceeded.

The benefits of the project, manifested in the increase of air quality and in the reduction of the number of deaths, illnesses, medical treatments and all accompanying costs (e.g. sick leave), significantly exceed the investment costs.

Water Monitoring Network

Surface Water Monitoring Network

The first hydrological station in the Republic of Croatia began operating in 1817, and systematic collection and publication of hydrological data has been carried out since the beginning of the 20th century. The basic network of hydrological stations has the function of determining the water balance and statistical data analysis from continuous and long-term monitoring, under the expert supervision of the Croatian Meteorological and Hydrological Service.

In addition to the standard field collection of hydrological data in the form of direct field measurements of flow, profile recording, field observations and controls, there is also a system of automatic data collection from telemetry hydrological stations.

In 2021, discharge measurement of surface flows is monitored at 292 hydrological stations. DHMZ participates in various data exchange programs, including sending discharge data to international data centers: GRDC: 1 station, WISE-SoE: 19 stations and EFAS: 48 stations. Water monitoring network station map is shown in Figure 8.3.3 (left).

Despite a significant number of hydrological stations and data being collected, there is a need for a thorough modernization of the existing monitoring network, which includes the renovation of existing and the installation of new stations. The modernization began in 2021 with the implementation of the EU Project for the improvement of non-structural flood risk management measures in the Republic of Croatia - VEPAR, approved under Priority Axis 5 of the Competitiveness and Cohesion Operational Program 2014-2020. Through these activities, 136 existing hydrological stations will be modernized and 4 stations in the main national network will be renovated.

The main goal of the project is to establish a functional system for the implementation of non-structural flood risk management measures and to increase the accuracy and stability of hydrological monitoring and data reporting. The planned duration of the project is four years, until the end of December 2023.

Groundwater monitoring network

Systematic measurements of groundwater levels over a sufficiently long period allow for the understanding of the regime and state of groundwater, as well as aquifer parameters. Based on the analysis of collected measurement data, the state of groundwater and its relation to surface flows are defined, which is one of the useful bases for designing future hydraulic structures, as well as for predicting changes in the quantitative and ecological state of groundwater as a result of the construction of hydraulic structures.

Monitoring of groundwater levels in the Pannonian part of Croatia is carried out as part of the national monitoring network by the Croatian Meteorological and Hydrological Service. Monitoring is established on several hundred piezometers in the western part of the Drava and Sava basins. The entire network of stations that monitor groundwater levels is composed of nearly 700 stations which

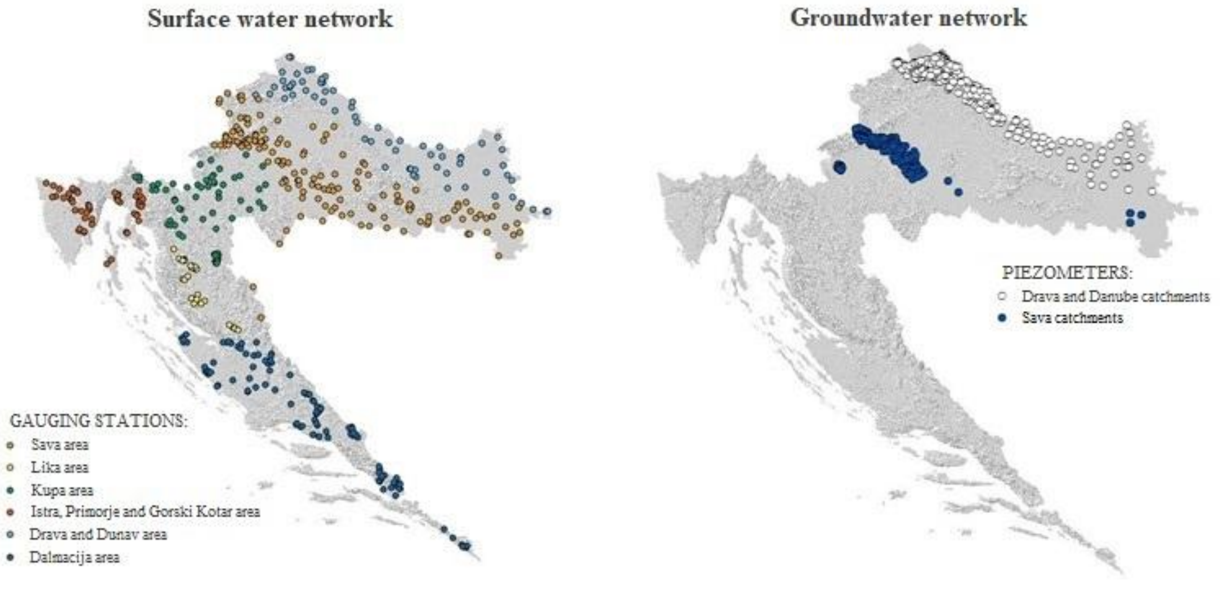

Figure 8.3.3. *Station map for surface water (left) and groundwater (right) monitoring networks.*

in the Drava and Danube catchments yield 44 limnigraphic stations and 306 piezometers and in the Sava catchment 52 limnigraphic stations and 294 piezometers. Groundwater station map is given in Figure 8.3.3. (right).

Limnigraphic stations provide data on groundwater levels every hour, and piezometer stations are monitored twice a week. Data on groundwater levels is sent from 15 stations to the WISE-SoE database of the European Environment Agency.

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