Research in Marine Sciences
Volume 9-Issue 3- 2024
Pages 510-536


# Analysis of climate and climate changes in the City of Zagreb

Diana Soric*
University of Zadar, Maritime Department, Mihovila Pavlinovića, Zadar, Croatia

*Received: 2024-07-13* *Accepted: 2024-08-28*

## Abstract

This study conducts a risk analysis and assessment of the vulnerability of individual sectors in Zagreb to the impacts of climate change. By examining key sectors such as infrastructure, agriculture, and public health, the research identifies potential risks and susceptibility associated with climate change in the region. The findings aim to inform policymakers and stakeholders about the specific challenges faced by Zagreb and suggest strategies to enhance resilience and adaptability in the face of changing climatic conditions.

**Keywords:** Risk analysis; Climate change; Zagreb.

## 1. Introduction

### *1.1. Climate and climate system*

Climate in the narrower sense represents average weather conditions expressed by means of means, extremes and variability of climatic variables over a longer, usually 30-year period. At the global level, the climate is determined by the radiation balance, which takes into account all forms of received and lost electromagnetic radiation energy. Roughly, 30% of the solar radiation that reaches the Earth is reflected on clouds, on particles in the atmosphere and on the Earth's surface into interplanetary space, while the remaining radiation is absorbed by the Earth's surface and atmosphere. By absorbing short-wave solar radiation, the Earth's surface heats up and radiates back into the atmosphere, and this return radiation takes place in the long-wave part of the spectrum. Part of the long-wave radiation is absorbed by the atmosphere and radiates back towards the surface, and part goes outside

* Corresponding Author's Email: diana-Soric@unizd.hr

it. Globally and for the whole year, the incoming solar radiation at the top of the atmosphere is in balance with the radiation that leaves it in the interplanetary space.

On smaller spatial scales, the climatic characteristics of certain areas on Earth are primarily determined by their geographic location, due to the spherical shape of the Earth, the solar radiation that reaches the surface depends on the geographic latitude. Furthermore, the climate of an area is also determined by atmospheric circulation, altitude as well as the interaction between the atmosphere and the ocean and the atmosphere and the soil, whose characteristics such as albedo, soil moisture and vegetation have an impact on the climate (Shrestha and Singh, 2014). From all of the above, it can be said that climate in a broader sense refers to the average state of the climate system, which consists of a number of components and their interactions, and the components of the climate system are as follow:

- Atmosphere - the envelope around the Earth's surface consisting of gases and solid and liquid particles (aerosol);
- Hydrosphere - oceans, seas, rivers, lakes, surface and underground waters;
- Cryosphere - glaciers, sea ice, ice in rivers and lakes, frozen ground, snow;
- Soil - whose characteristics such as relief, soil type and vegetation define the interaction with other components of the climate system and,
- Biosphere - living beings on Earth.

## 2. Climatic variations and climate changes

Climate changes in space and time. Inter-seasonal differences in climate are noticeable, as well as climate variations on an annual and multi-year scale, but also during long periods such as ice ages, which are caused by astronomical factors that change the incoming solar radiation on the Earth's surface. Climate variations are visible in changes in the mean state of the climate, changes in the inter-annual variability of climate parameters, and other statistical quantities that describe the state of the climate, such as the occurrence of extremes. By the term climate change, we mean statistically significant changes in the mean state or variability of climate variables that last for decades or longer.

Climate variability is influenced by natural and anthropogenic factors. Natural factors are divided into internal and external. An example of internal factors is, for example, the occurrence of El Niño - the Southern Oscillation, which is the result of the interaction between the atmosphere and the ocean in the tropical part of the Pacific Ocean, or the North - Atlantic Oscillation, which represents atmospheric pressure variations at sea level in the area of Iceland and the Azores, which affects the strength of the westerly current and storm tracks over the North Atlantic and part of Europe (Von der Heydt *et al*., 2021).

The natural variability of the climate can also be caused by external factors, for example a large amount of aerosol thrown into the atmosphere by a volcanic eruption or a change in the solar radiation that reaches the atmosphere and the Earth's surface. On an annual scale, the incoming solar radiation changes due to the motion of the Earth around the Sun. On long time scales, incoming solar radiation changes due to changes in parameters in the Earth's orbit around the Sun. This includes a change in the eccentricity of the path (with a period of 100,000 years), a change in the angle of inclination of the Earth's axis in relation to the plane in which the path lies (with a period of 41,000 years) and a change in the direction of the inclination of the Earth's axis in relation to the path (period of 19,000 up to 23,000 years) (Chapin *et al*., 2011).

In addition to the mentioned natural climate variations, anthropogenic factors are of great interest, i.e. climate changes caused by human activities that release greenhouse gases into the atmosphere, and they play a key role in warming the atmosphere (fossil fuels, urbanization, deforestation and agriculture).

## 3. Warming of the atmosphere and the greenhouse effect

Natural warming of the atmosphere takes place in such a way that the atmosphere, including clouds, absorbs long-wave radiation from the Earth's surface and emits it in all directions, and the part of this radiation that is directed towards the Earth's surface causes further warming of that surface and the lower layer of the atmosphere - the greenhouse effect. The most important gases (greenhouse gases) that are naturally present in the atmosphere and that absorb the Earth's long-wave radiation are:

- Water vapor and carbon dioxide ($CO_2$)
- Methane ($CH_4$)
- Nitrous oxide ($N_2O$)
- Ozone ($O_3$)

In the second half of the 18$^{th}$ century, with the beginning of the industrial revolution, man's influence on the climate increased sharply. Combustion of fossil fuels, changes in the type of substrate that is created, urbanization, cutting down of forests and the development of agriculture led to a change in the chemical composition of the atmosphere, i.e. to an increase in the concentration of greenhouse gases in the atmosphere compared to the pre-industrial era. From the beginning of industrialization to the present day, the concentrations of carbon dioxide, methane, nitrous oxide and halogenated hydrocarbons in the atmosphere have increased significantly, which has caused a stronger greenhouse effect and greater warming of the atmosphere than occurs naturally (Le *et al*., 2007).

## 4. Measured global warming in the Republic of Croatia

According to the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) from 2007, the global concentration of carbon dioxide ($CO_2$) in the atmosphere increased from 280 ppm (ppm - proportion of greenhouse gas molecules per million molecules of dry air) in the pre-industrial age to 379 ppm in 2005. The highest rate of increase in carbon dioxide concentration was measured in the time period from 1995 to

2005. The global atmospheric concentration of methane ($CH_4$) and nitrogen oxide ($N_2O$) increased from 715 and 270 ppm respectively in the pre-industrial age to 774 and 319 ppm respectively in 2005 in IPCC reports (Solomon *et al*., 2007).

According to a 100-year series of measurements (1906-2005), the increase in global surface air temperature, estimated from the linear trend, was 0.74 °C. If we look at the last 50 years of that period, the increase was almost twice as high as in the entire 100-year period and even higher in the last 25 years, which was contributed to by the fact that, since instrumental measurements of air temperature have existed, the warmest years were 1998 and 2005, and then in 2002, 2003 and 2004. The warming of the Earth is of a global character, but it is not uniform in all parts of the Earth. Thus, the warming of the land masses is greater than the warming of the oceans, especially in the period after 1970. Therefore, due to the distribution of land and sea on Earth, warming is more pronounced in the northern than in the southern hemisphere, with a double increase in the average air temperature in the Arctic compared to global warming over the past 100 years (Juszczak *et al*., 2013).

The trend of increasing air temperature in the $20^{th}$ century was also recorded at stations in the Republic of Croatia. Centuries-old series of air temperature measurements point to an increase between 0.02 °C and 0.07 °C per 10 years, as well as on a global level, the trend of increasing air temperature is particularly pronounced in the last 50 and 25 years. The consequences of global warming are the reduction of snow cover, especially in spring and summer, and the melting of ice. A rise in global sea level caused by the melting of land ice and the thermal expansion of the oceans due to warming has also been recorded (Kitoh *et al*., 2007). Global climate change is associated with changes in the Earth's energy balance. In the Figure1, it is visible that the total solar energy entering the atmosphere must be in balance with the total output energy, otherwise the Earth's energy balance will be disturbed. Local climate change can be attributed to local changes, i.e. varies on a smaller spatial scale, such as, for example, the reduction of forest cover.

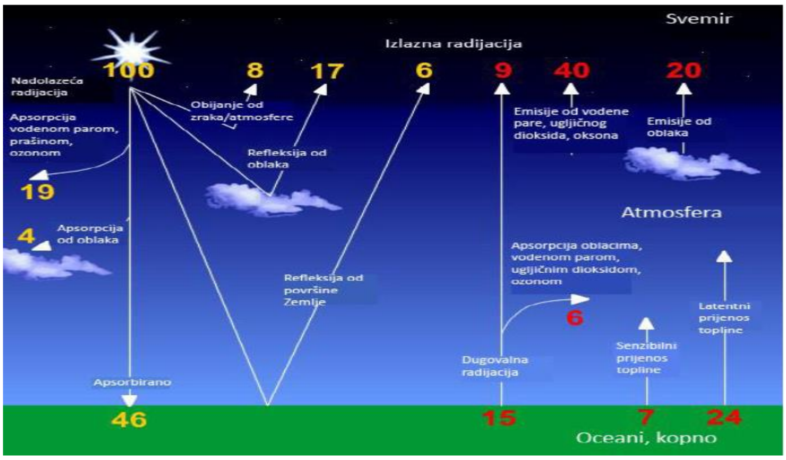


Figure 1. Earth's energy balance (%). In addition to directly reflected solar energy (yellow), the rest of the energy is reflected in the form of thermal long-wave (IR) radiation (red), and part of this radiation is absorbed by clouds, water vapor, carbon dioxide and ozone.
Source: Earth-Atmosphere Energy Balance Diagram (Blunden *et al*., 2017).

The climate change in the last hundred years is shown below (Figure 2) on the example of surface temperature anomalies in various areas (Kennedy, *et al.*, 2016). The increase in temperature since the 1970s is extremely pronounced, especially in the northern hemisphere, and coincides with the increase in the concentration of carbon dioxide, the most important greenhouse gas (Figure 3). The IPCC attributes this rise in $CO_2$ with high confidence to human activity (Putman *et al*., 2016).

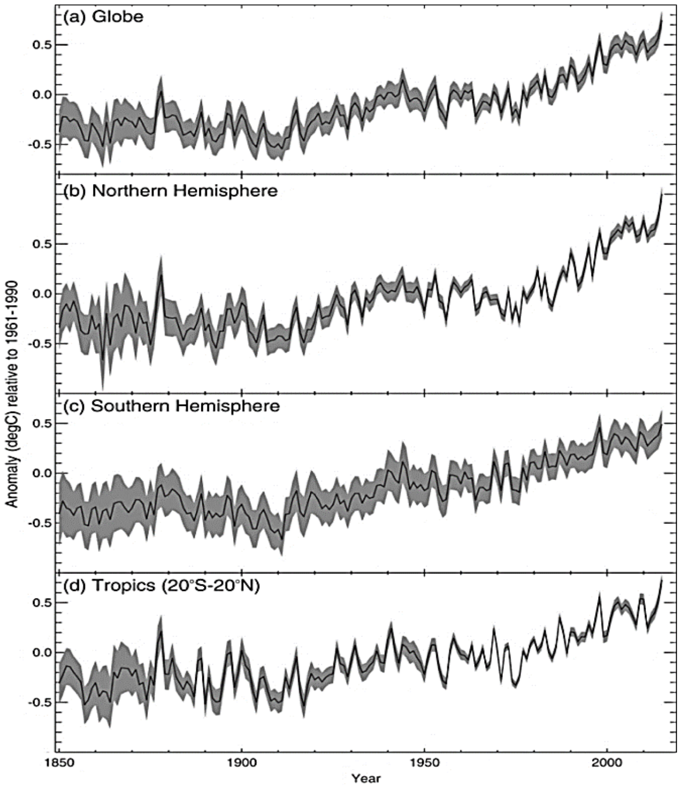


Figure 2. Annual mean temperature anomalies (relative to 1961–1990) from 1850 to 2015 for (a) the globe, (b) the Northern Hemisphere, (c) the Southern Hemisphere, and (d) the tropics (20°S–20°N). The black curve is the best estimate and the shaded area gives the 95% confidence interval of the estimate.
Source: Global and regional climate in 2015 (Kennedy, *et al*., 2016).

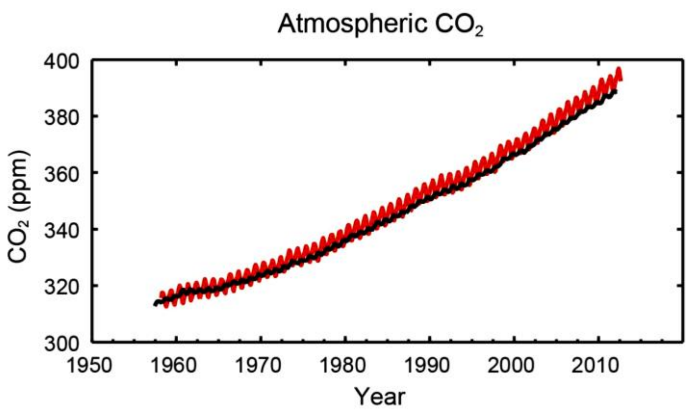


Figure 3. Atmospheric $CO_2$ concentration at Mauna Loa observatory, Hawaii (red) and South Pole (black).
Source: (Putman *et al*., 2016)

## 5. Climate modeling

The atmosphere is a fluid governed by the physical laws of hydrodynamics and thermodynamics, which can be described by mathematical nonlinear differential equations, and a set of such equations constitutes an atmospheric model, with the most complex atmospheric model being the set of equations that describes the general circulation of the atmosphere. The general atmospheric circulation model can be "joined" with the ocean circulation model, the ice sheet model, the soil process model, the vegetation model and can include various chemical processes within the components of the climate system. Then we are talking about a climate model that, on the basis of applicable physical laws, calculates the quantitative state of climate elements obtained by the interaction of the components of the climate system. The Global Climate Model (GCM) or the Earth System Model (ESM) takes into account a multitude of complex processes in various components of the climate system on Earth (*Lupo et al*., 2013). Due to the non-linearity of the processes taking place in the climate system, for future climate projections it is not possible to extrapolate the trends of changes in climate parameters that have been observed in the past, and for this reason, global climate models are used to display the components of the climate system and their interactions, i.e. climate simulations with climate models. The global climate model consists of atmosphere, ocean, soil and ice models and includes the carbon and sulfur cycles. The model is based on the laws of physics represented by mathematical equations that describe the processes in individual components of the climate system, taking into account their interactions, and therefore it is talking about a combined system.

In the atmospheric model, the Earth is divided into three-dimensional cells. Equations that define, for example, motion, conservation of mass, energy and moisture are solved in each cell, and the obtained solutions refer to the entire area that it covers. The total number of cells on the surface of the Earth defines the resolution of the model, and the more cells there are, the higher the resolution of the model. The characteristic resolution of the atmospheric model is 150-200 km in moderate latitudes. Vertically, the atmosphere is divided into layers, the resolution of which is higher near the Earth's surface than that in the upper layers of the atmosphere. A schematic representation of the three-dimensional network of the atmospheric global model is given below (Figure 4)

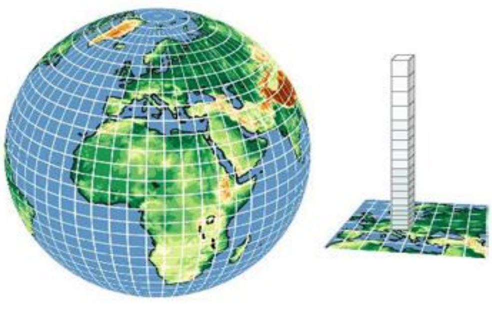

Figure 4. Schematic representation of the three-dimensional network of the atmospheric global model. (Source: official website of the State Hydro-meteorological Institute)

In ocean model - horizontal and vertical division, where the horizontal resolution is higher than in the atmospheric model, for example, currents in the ocean can be resolved. Vertically, the ocean model can have, for example, 40 levels. The dynamic combination of the atmosphere and the ocean is extremely important because the interaction of these two components of the climate system is observed in phenomena that cause the internal variability of the system, such as El Niño - the Southern Oscillation.

Soil model contains information about soil and vegetation types and soil properties such as albedo. In order to take into account, the exchange of energy and water between the soil and the atmosphere, for example, soil temperature, soil moisture that depends on precipitation and evapotranspiration, runoff, and snow cover are considered. Sea ice is also an important component of the climate system, since ice surfaces have a high albedo, so the reflection of solar radiation is high on them. By reducing the sea ice, the reflection decreases, the ocean absorbs more solar radiation and heats up, which causes a stronger warming of the atmosphere. As a result, along with the interaction between the atmosphere and the ocean, the global climate model also includes the relation between the atmosphere and sea ice (Seneviratne *et al*., 2010).

As well as the spatial division into cells, the integration time of the model is also divided into steps. In the model, in order to start with simulations, it is necessary to have the initial state of the components of the climate system, and then the values of the variables in the next time step are calculated with equations, which is repeated until the simulations are finished. Since the equations are solved in each cell of the model for a period of at least 30 years, powerful computers are required for climate simulations using the climate model. A schematic representation of climate modeling with a climate model is given in Figure 5.

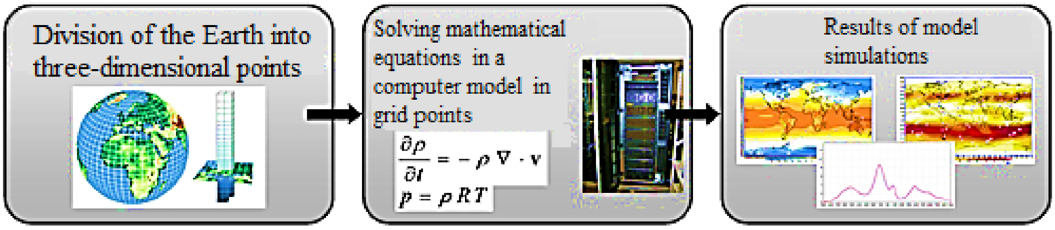


Figure 5. Schematic representation of climate modeling with a climate model.
(Source: State Hydro-meteorological Institute)

## *5.1. Simulations of the current climate by global climate models*

The influence of man on the warming that was measured in the second half of the 20$^{th}$ century is clearly seen if two climate simulation experiments are done with climate models in the previous 100 years.

1) Experiment - Climate models take into account only natural external factors that affect the climate, i.e. solar and volcanic activity. The air temperature values obtained in that experiment are lower than those measured in the second half of the 20$^{th}$ century.

2) Experiment - In addition to natural factors, climate models also include which increased the levels of greenhouse gases caused by human activity. In such simulations, the modeled air temperature follows the measured warming in the second half of the 20$^{th}$ century.

In this way, the possible predominant influence of man on the increase in air temperature was confirmed after the pre-industrial period (Figure 6).

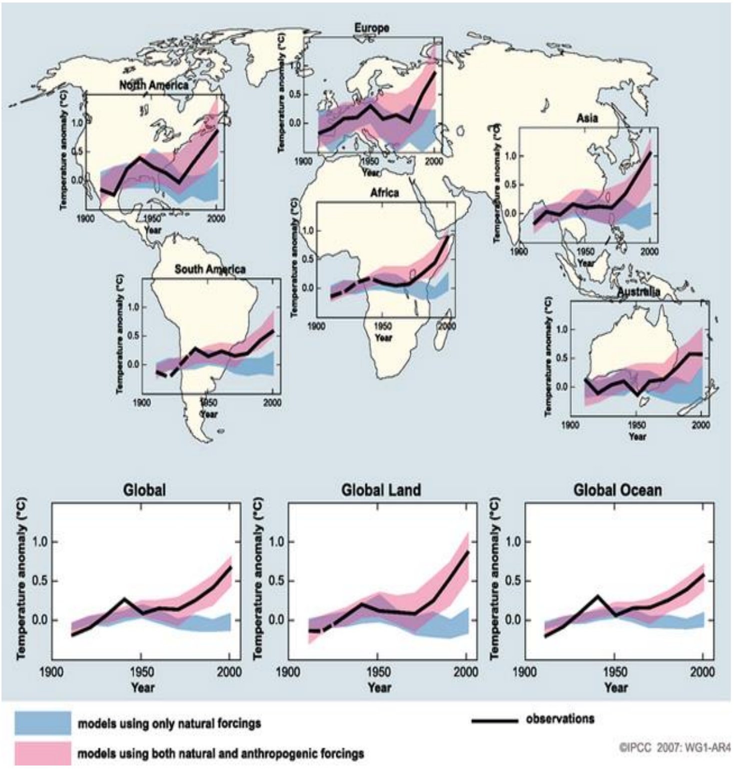


Figure 6. Comparison of measured changes in surface air temperature on continents and globally with the results of climate model simulations that take into account natural and anthropogenic influences. Source: IPCC reports (Solomon *et al*., 2007)

In the previous picture, the black line represents the decadal means of the measured air temperature anomalies in the period 1960-2005, in relation to the average air temperature from the period 1901-1950. The line is drawn in areas where the spatial coverage of the measured data is less than 50%. The blue shaded series shows the range (90%) of temperatures from 19 climate simulations obtained using five climate models that only consider natural factors influencing the climate (Solar and volcanic activity). The red-shaded arrays indicate the range of temperatures (90%) from 58 climate simulations obtained using 14 climate models that use both natural and anthropogenic factors influencing the climate.

## *5.2. Greenhouse gas emission scenarios*

With the aim of making an assessment of climate change in the future, the IPCC in its Special Report on Emission Scenarios (SRES) defined greenhouse gas emission scenarios taking into account taking into account assumptions about future demographic, social, economic and technological development at the global and regional level, and the scenarios are divided into four groups of possible world development in the future (Table 1).

Table 1. Defined possible scenarios of greenhouse gas emissions at the global and regional level

| **A1** | **A2** | **B1** | **B2** |
|---|---|---|---|
| The world in the future is characterized by very rapid economic growth and global population growth, which will be the largest in the middle of the 21st century. This group of scenarios envisages the rapid introduction of new and more efficient technologies and a significant reduction of regional differences in the income of residents. A1 scenario develops into three groups that describe alternative directions of technological changes in the energy system.<br>A1FI - the emphasis is on intensive use of fossil energy sources<br>A1T - the absence of fossil energy sources dominates<br>A1B - predicts a balanced use of energy sources. | The world in the future is characterized by great heterogeneity with a constant increase in world population. Economic development, as well as technological changes, are regionally oriented and slower than in other groups of scenarios. | This scenario envisages the introduction of clean technologies with an emphasis on global solutions for economic, social and environmental sustainability. The population is the most numerous in the middle of the 21$^{st}$ century, and after that it declines (similarly to the A1 group). | In the future, the world is oriented towards environmental protection and social equality, but the emphasis is on local solutions for economic and social sustainability and environmental sustainability. Economic development is of a medium level, and technological changes are slower and more varied than in the B1 and A1 groups of scenarios. This scenario predicts a continuous increase in the world population at a rate lower than in the A2 group. |

In order to create an assessment of climate change in the future, changes in the concentration of greenhouse gases in the future are calculated for the selected scenario using biogeochemical models. For example, according to the B1 scenario, the predicted $CO_2$ concentrations until the end of the 21$^{st}$ century are the lowest among the four described groups, while in the A2 scenario, a continuous increase in the $CO_2$ concentration in the 21$^{st}$ century is predicted, with the highest rate of increase in the second half of the century. Presentation of total annual $CO_2$ emissions in the period 1990-2100.

## *5.3. Projections of future climate by global climate models*

In order to assess climate change, it is necessary, in addition to the simulation of the climate model in the current climate in which the concentrations of greenhouse gases are based on measured values, to make simulations in the future climate when the model takes into account the concentrations of greenhouse gases in the atmosphere derived from various scenarios of the emission of these gases. Concentrations of greenhouse gases are included in the climate model in such a way that, using radiation schemes, their influence on the change in the balance of radiation coming into the atmosphere and that leaving it is calculated, then the climate model simulates the response of the climate system to this change. From such experiments, the values of climate parameters in the future and present climate can be calculated, and their difference expresses climate change. When simulating the future climate with climate models, it is important to note the difference between forecast and projection because it determines the interpretation of climate model results.

Weather forecast models, based on the current state of the atmosphere, predict the weather several days in advance, while for climate projections in the future, the climate model simulates the response of the climate system to a given external action in a longer period. For these simulations, unlike weather forecasts, the sequence of weather events is not important, but their long-term statistics.

## *5.4. Sources of uncertainty in climate change assessments*

Several sources of uncertainty are associated with climate modeling and climate change projections, and an overview of them is as follow:

1) The imperfection of climate models is the biggest source of uncertainty. Although models are today the best tool for assessing the future state of the climate, due to the exceptional complexity of the climate system, simplifications are introduced into the models and they cannot perfectly describe all processes and interactions in the climate system.
2) The uncertainty of emission scenarios and concentrations of greenhouse gases that cannot be predicted with certainty represents an additional source of uncertainty in climate change projections.
3) The internal variability of the climate system is also an important source of uncertainty. It is a consequence of the non-linearity of the processes in the climate system, due to which small changes in the initial conditions can produce different results of climate simulations.

In order to take into account, the uncertainty that comes from different configurations of climate models, it is desirable to repeat climate simulations with different models. The uncertainty associated with the greenhouse gas emission scenario is investigated by climate simulations based on different scenarios. Also, model simulations according to the same greenhouse gas emission scenario can be repeated several times with different initial conditions in order to take into account the internal variability of the climate system. In this way, a set of simulations is created that enables the evaluation of the variability of the model results with regard to slightly changed initial conditions. In this way, a range of possible climate conditions is obtained, which serves to assess the uncertainty of the future climate. Information about uncertainty can then be included in research on the impact of climate change on the economy and in decision-making on adaptation to climate change. The set of climate simulations also represents the basis for estimates of the probability of changes in climate parameters in the future.

## *5.5.Projected changes in ground air temperature and precipitation on a global scale*

According to the latest report of the Intergovernmental Panel on Climate Change, global climate models predict an increase in global surface air temperature in the last decade of the 21st century compared to the last 20 years of the 20th century by 1.8 °C to 4 °C, depending on the greenhouse gas emission scenario. According to the projections of the concentration of carbon dioxide ($CO_2$) in the atmosphere in different scenarios of greenhouse gas emissions in the future climate, the expected increase in global surface air temperature obtained by a set of simulations of global climate models is higher in A2 compared to B1 scenario. The global means of the increase in ground air temperature (°C; in relation to the period 1980-1999) based on the A2, A1B and B1 scenarios of greenhouse gas emissions are presented as a continuation of the simulations of several models in the 20th century (Figure 7).

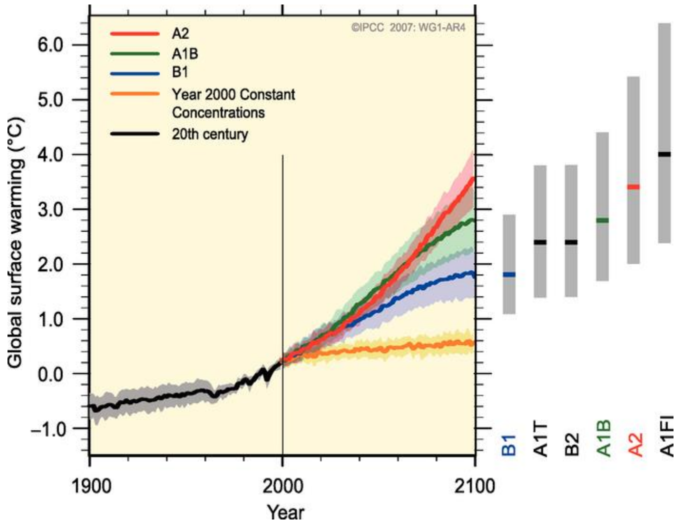


Figure 7. Global means of increase in surface air temperature (relative to the period 1980-1999; °C) according to A2, A1B and B1 greenhouse gas emission scenarios are shown as a continuation of multi-model simulations in the 20th century (solid lines).
Source: IPCC reports (Solomon *et al*., 2007)

The shaded areas visible in the figure indicate ± 1 standard deviation of the mean annual modeled air temperatures, and the orange line represents an experiment in which greenhouse gas concentrations are constant after the year 2000, while the gray bars represent the possible range of warming with the most likely value (horizontal line within each bar) for six greenhouse gas emission scenarios.

## *5.6. Expected changes in air temperature in the 21st century*

The predicted increase in air temperature in the 21st century is global in nature. The greatest warming is expected over land and in the high latitudes of the Northern Hemisphere in winter. The amplitude of warming is the smallest over the oceans in the southern hemisphere, Figure8.

## *5.7.Expected changes in precipitation in the 21st century*

In contrast to the global increase in surface air temperature, the precipitation change signal is not spatially coherent. For example, according to the A1B scenario, an increase in precipitation is very likely in the tropical Pacific and in high latitudes, while a decrease in precipitation is expected in most terrestrial subtropical areas. There is a tendency for extreme daily precipitation to increase even in areas where total precipitation is projected to decrease. The precipitation changes in percentage is shown in Figure 9.

The figure shows the average values obtained from several models according to the A1B scenario of greenhouse gas emissions for winter (December-February; left picture) and summer (June-August; right picture). Areas where less than 66% of the models agree on the sign of the change in precipitation are colored white, while areas where more than 90% of the models agree on the sign of the change are marked dotted.

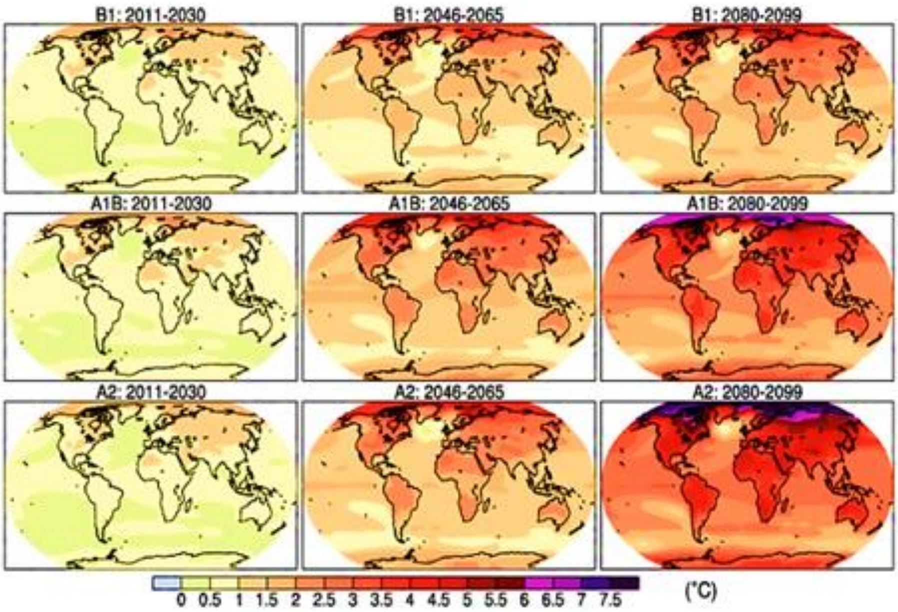


Figure 8. Mean annual warming from multi-model simulations under B1 (top), A1B (middle) and A2 (bottom) scenarios for three periods: 2011-2030 (left), 2046-2065 (middle) and 2080-2099 (right). (Source: Meehl *et al.*, 2007)

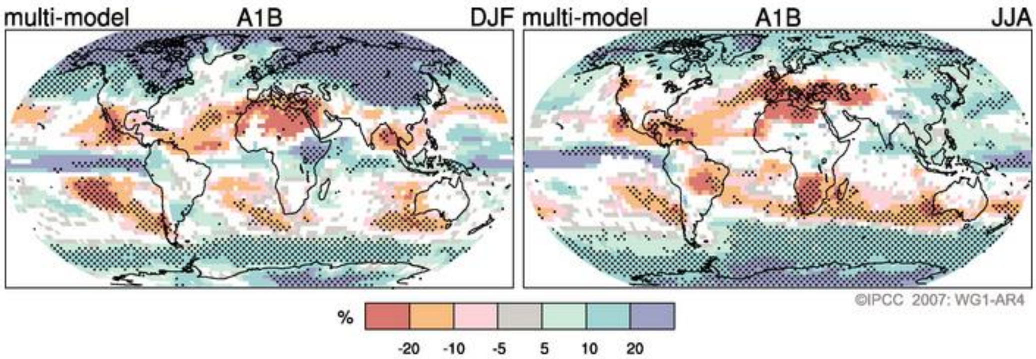


Figure 9. Percentage change in precipitation in the period 2090-2099. compared to the period 1980-1999. Source: IPCC reports (Solomon *et al*., 2007).

## *5.8.Projected changes in ground air temperature and precipitation in the Republic of Croatia*

Climatic changes in the future climate in the Republic of Croatia obtained by climate simulations using the regional climate model RegCM according to the A2 scenario were analyzed for two 30-year periods:

1. The period from 2011 to 2040 represents the near future and is of greatest interest to users of climate information in long-term planning of adaptation to climate change.
2. The period from 2041 to 2070 represents the middle of the 21st century, in which, according to the A2 scenario, a further increase in the concentration of carbon dioxide ($CO_2$) in the atmosphere is predicted, and the signal of climate change is stronger.

According to the results of the RegCM for the Republic of Croatia, the mean of the set of simulations indicates an increase in air temperature in both periods and in all seasons. The amplitude of the increase is greater in the second period than in the first period, but it is statistically significant in both periods. The increase in average daily air temperature is greater in summer (June-August) than in winter (December-February).

In the first period of the future climate in Croatia, a temperature increase of up to 0.6 °C is expected in winter, and up to 1°C in summer. Presentation of changes in ground air temperature (in °C) in the Republic of Croatia in the period 2011-2040. in relation to the period 1961-1990. according to the results of the ensemble mean of the regional climate model RegCM for the A2 scenario of greenhouse gas emissions for winter (left) and summer (right) are shown in Figure 10 and Figure 11.

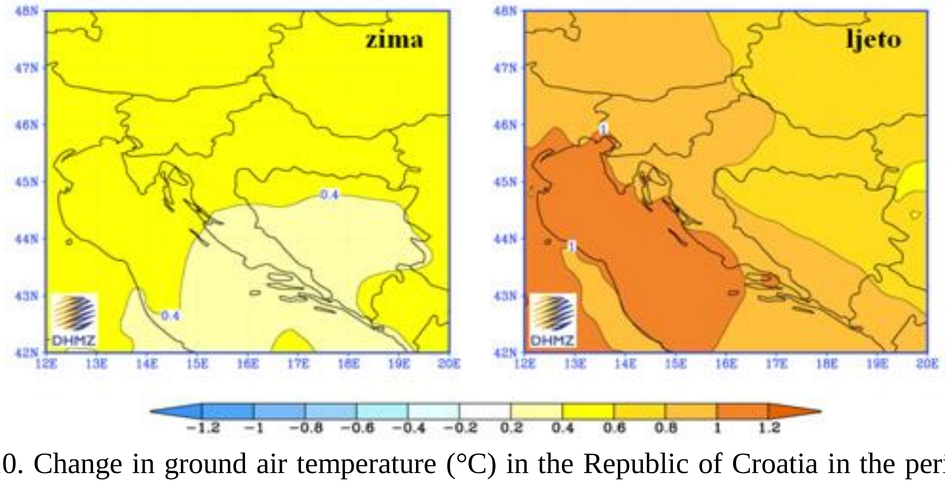


Figure 10. Change in ground air temperature (°C) in the Republic of Croatia in the period 2011-2040 in relation to the period 1961-1990 according to the ensemble mean results of the regional climate model RegCM for the A2 scenario of greenhouse gas emissions for winter (left) and summer (right). (Source: State Hydrometeorological Institute)

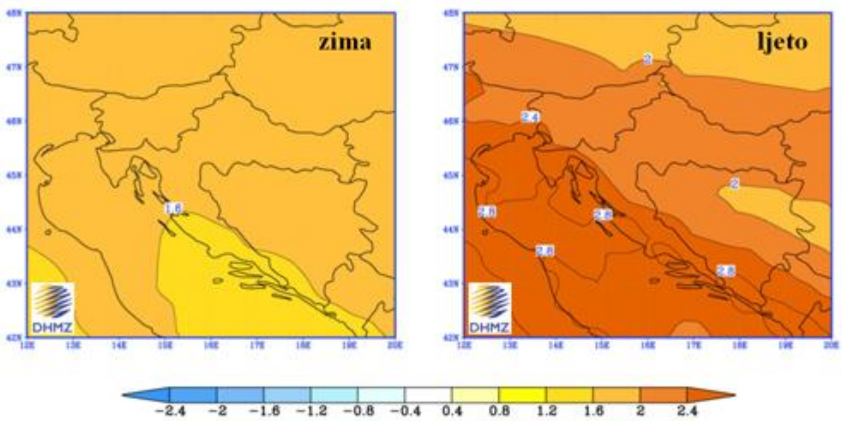


Figure 11. Change in ground air temperature (°C) in the Republic of Croatia in the period 2041-2070. in relation to the period 1961-1990. according to the ensemble mean results of the regional climate model RegCM for the A2 scenario of greenhouse gas emissions for winter (left) and summer (right). (Source: State Hydrometeorological Institute)

In the second period of the future climate, the expected amplitude of increase in the Republic of Croatia in winter is up to 2 °C in the continental part and up to 1.6 °C in the south, and in summer up to 2.4 °C in the continental part of the Republic of Croatia, i.e. up to 3 °C in the coastal zone (Branković *et al*., 2012).

## 6. Analysis of climate changes in the Zagreb

### *6.1. Observed climate changes*

The most important meteorological elements that define the climate are solar radiation (insolation), air temperature, pressure, wind direction and speed, humidity, precipitation, evaporation, cloudiness, and snow cover.

Diagnosing climate changes in the area of the City of Zagreb was carried out according to the data of long-term meteorological measurements of the Zagreb-Grič Meteorological Observatory:

- Analysis of air temperature and precipitation in the period of 1862-2015;
- Analysis of monthly and annual values of meteorological data for 30-year periods since 1871 and;
- Analysis of the number of days with certain meteorological characteristics in the last ten years.

### *6.2. Analysis of air temperature and precipitation in the period 1862-2015. according to the measurements of the Zagreb-Grič Meteorological Observatory*

According to the available measurement data of the Zagreb-Grič Meteorological Observatory in the period 1862-2015, the display of recorded temperature and precipitation extremes with the day of occurrence is given below, Table 2.

Table 2. Presentation of the recorded measurements of the Zagreb-Grič Meteorological Observatory in the period 1862-2015.

| | Parameter value | Year | Day |
|---|---|---|---|
| Highest temperature (°C) | 40,3 | 1950 | 05.07 |
| Lowest temperatures (°C) | -22,2 | 1942 | 24.01 |
| Maximum 24-hour precipitation (mm) | 118,8 | 1926 | 09.08 |

Furthermore, below is a graphical presentation of air temperatures and precipitation in the period 1862-2015, according to the measurements of the Zagreb-Grič Meteorological Observatory. Figure 12 is a graphic representation of the average daily air temperature (° C) by month, Figure 13 is a diagram of the highest air temperature (°C) in the period 1862-2015, Figure 14 is a graph of the lowest air temperature (°C) in the period 1862-2015, and Figure 15 is a graphic representation of the highest 24-hour precipitation amount in the period 1862-2015.

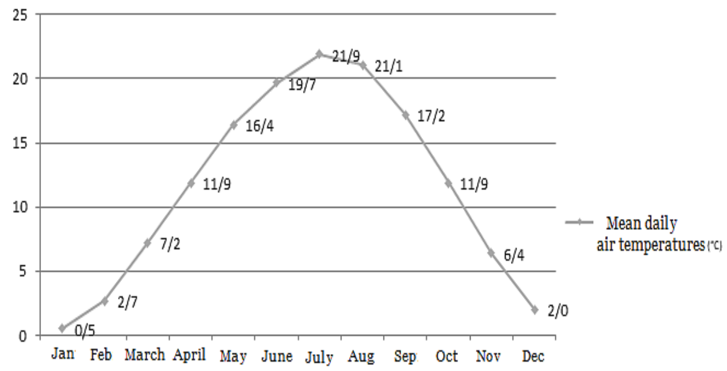


Figure 12. Average daily air temperature (°C) by month. (Source: State Hydrometeorological Institute)

According to the data of the State Hydro-meteorological Institute, in the observed time period from 1862-2015, in Figure 14, the lowest air temperatures (°C) were recorded on January 24, 1942. Furthermore, the data of the State Hydrometeorological Institute, in the observed time period from 1862-2015., the highest 24-hour rainfall (Figure 15) was recorded on August 9, 1926.

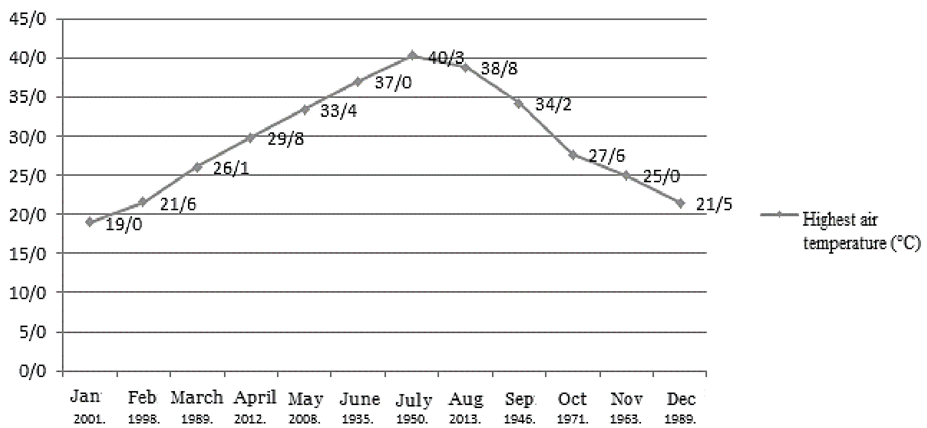


Figure 13. The highest air temperature (°C) in the period 1862-2015. (Source: State Hydrometeorological Institute)

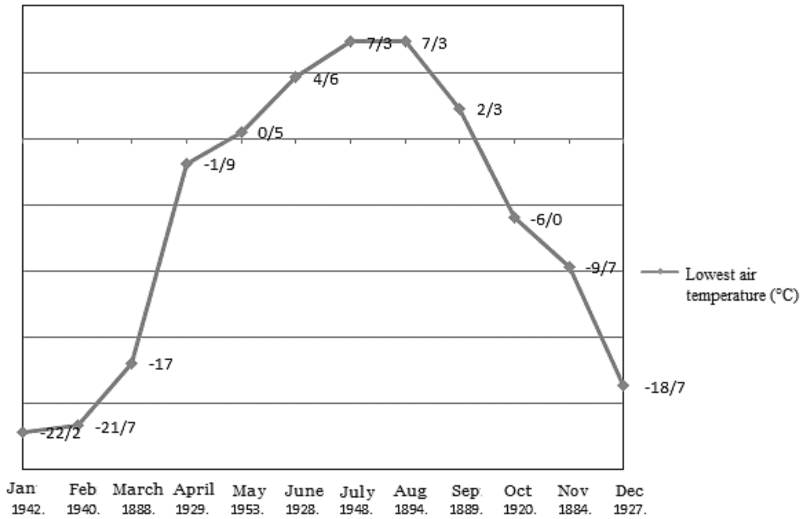


Figure 14. The lowest air temperature (°C) in the period 1862-2015. (Source: State Hydro-meteorological Institute)

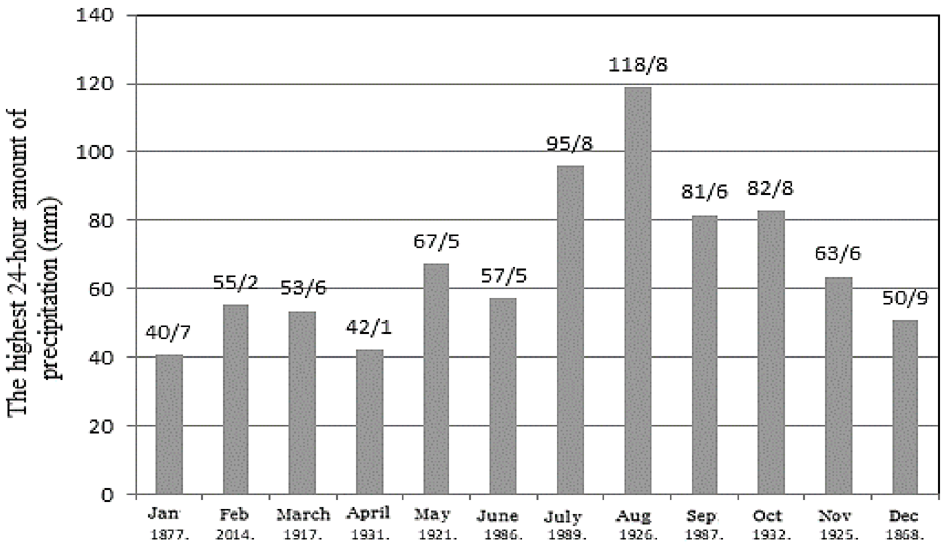


Figure 15. The highest 24-hour precipitation amount in the period 1862-2015. (Source: State Hydrometeorological Institute)

### *6.3. Analysis of monthly and annual values of meteorological data for 30-year periods since 1871 according to the measurements of the Meteorological Observatory Zagreb – Grič*

Diagnosing climatic variations and changes in air temperature and precipitation in the area of the City of Zagreb was carried out according to the data of long-term meteorological measurements of the Meteorological Observatory Zagreb - Grič for 30-year periods, starting in 1871. Decadal trends of mean annual and mean monthly values as well as indices of temperature and precipitation extremes were analyzed.

The presentation of the results of the annual values of meteorological data for 30-year periods since 1871, according to the measurements of the Zagreb-Grič Meteorological Observatory, is given in the Figures 16 - 19.

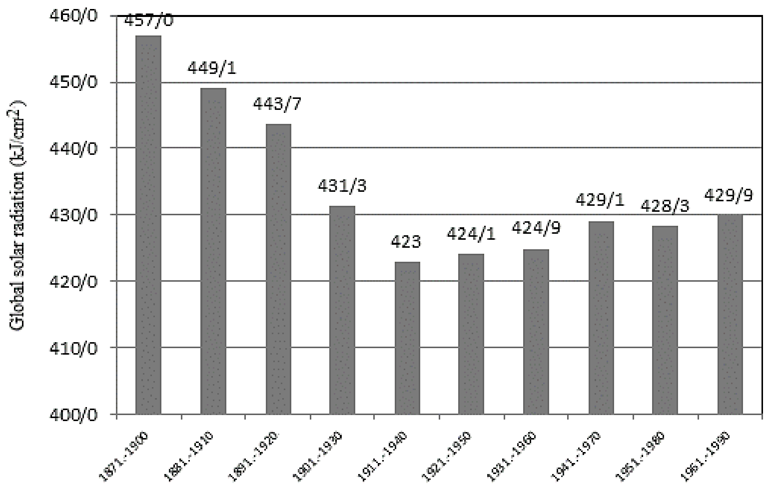


Figure 16. Global solar radiation (Kj/cm$^2$) for 30-year periods since 1871. (Source: State Hydrometeorological Institute)

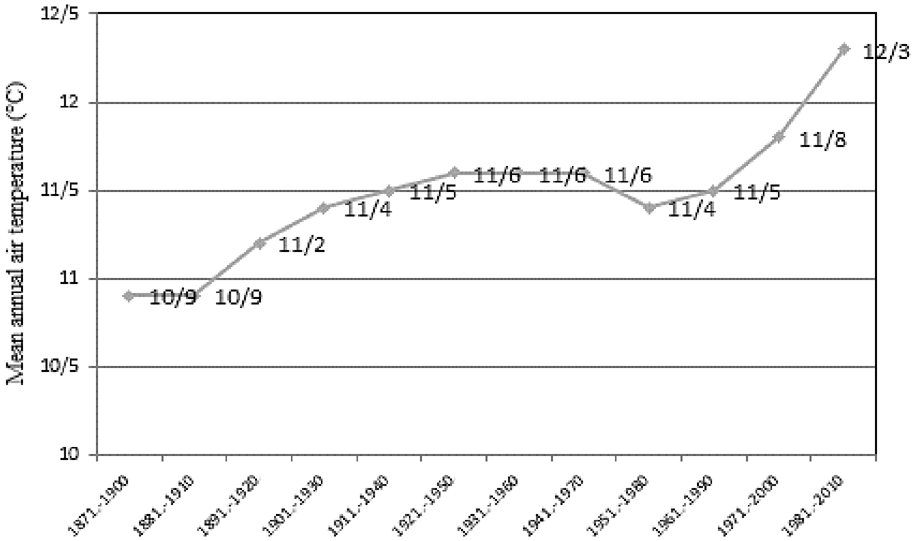


Figure 17. Graphic representation of average annual air temperature (°C) for 30-year periods since 1871. (Source: State Hydrometeorological Institute)

For the observed 30-year time periods, since 1871, an increase in the mean annual air temperature (°C) in the City of Zagreb is noticeable, while it is noticeable that in the last observed 30-year period, from 1981 to 2010, the trend of increasing average annual air temperature (°C) significantly more pronounced.

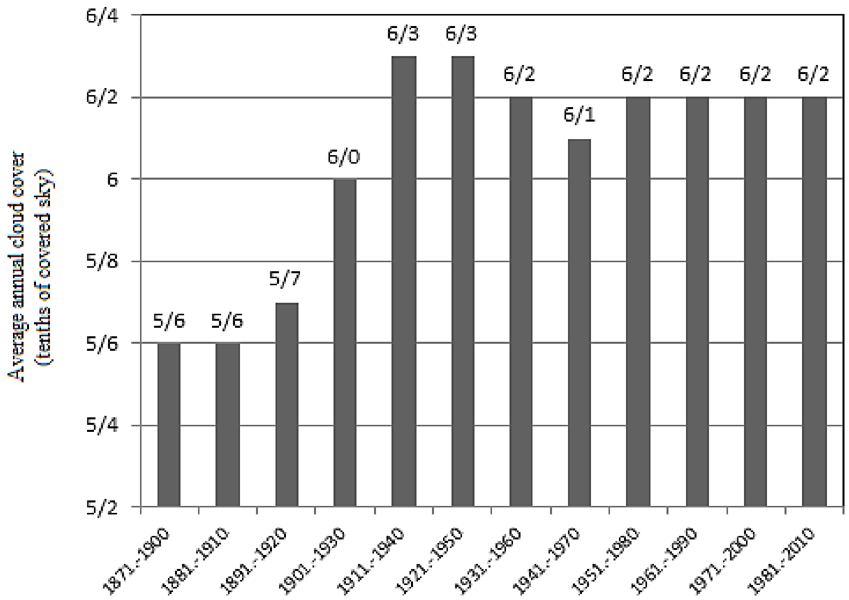


Figure 18. Graphic representation of cloud cover (tens of veiled sky) for 30-year periods since 1871. (Source: State Hydrometeorological Institute)

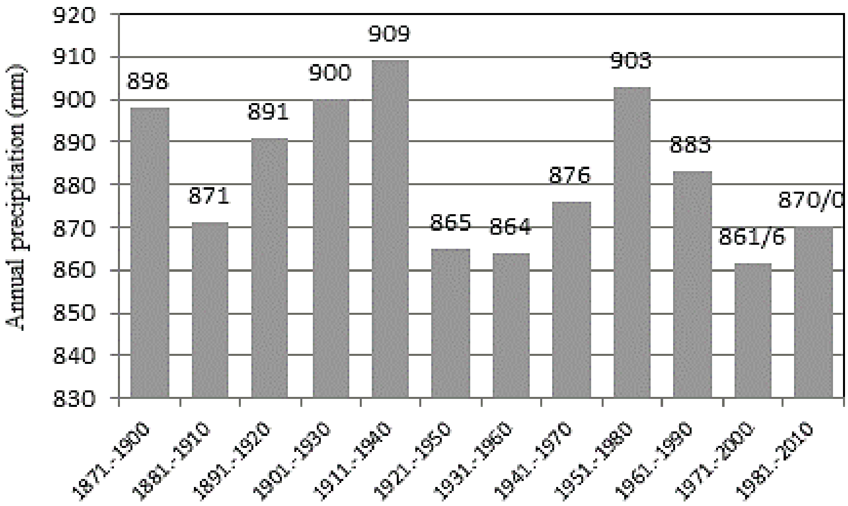


Figure 19. Precipitation for 30-year periods since 1871. (Source: State Hydrometeorological Institute)

## *6.4. Analysis of monthly and annual values of meteorological data for ten years, from 2006-2015. according to the measurement of the Meteorological Observatory Zagreb – Grič*

Analysis of monthly and annual values of meteorological data in the last ten years, from 2006-2015. year according to the measurements of the Meteorological Observatory Zagreb - Grič is given below graphically in Figures 20 -25.

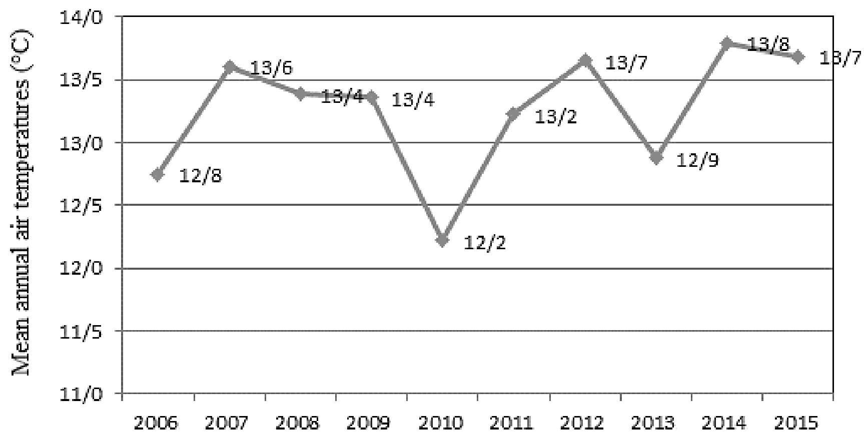


Figure 20. Mean annual air temperatures (°C) for ten years, from 2006 to 2015. (Source: State Hydrometeorological Institute)

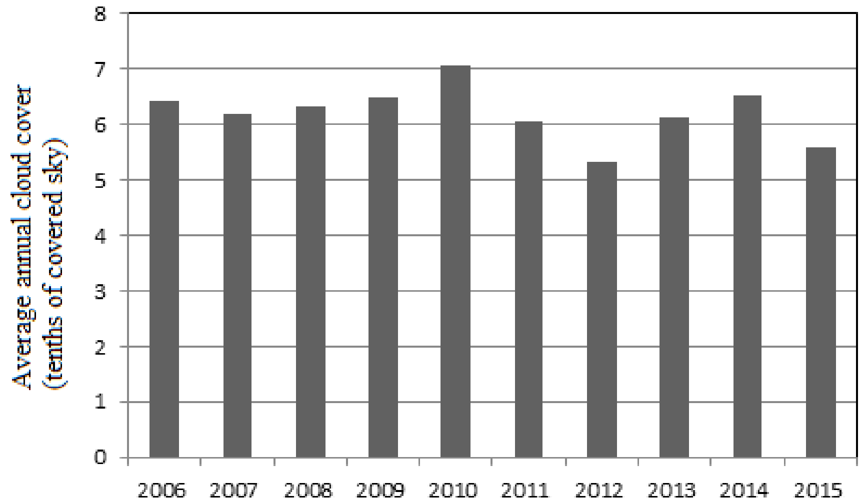


Figure 21. Average annual cloud cover (tenths of covered sky) for ten years, from 2006 to 2015 (Source: State Hydrometeorological Institute)

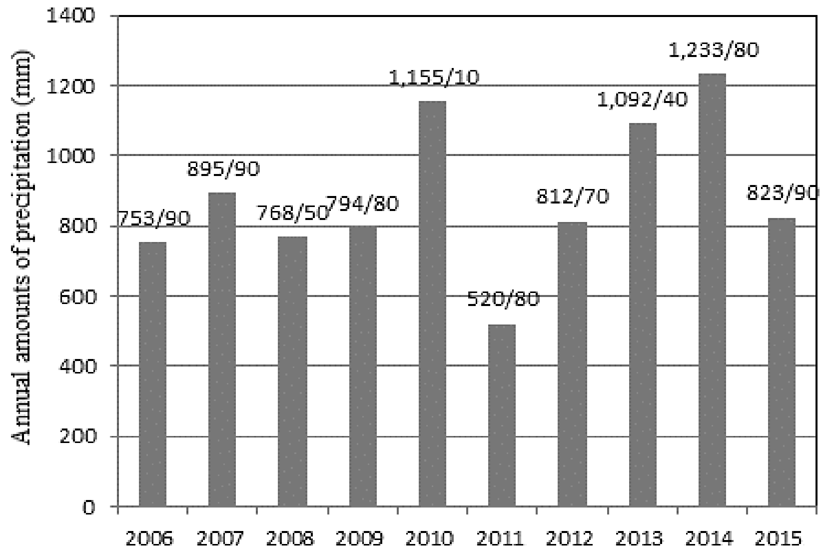


Figure 22. Annual amounts of precipitation (mm) for ten years, from 2006 to 2015. (Source: State Hydrometeorological Institute)

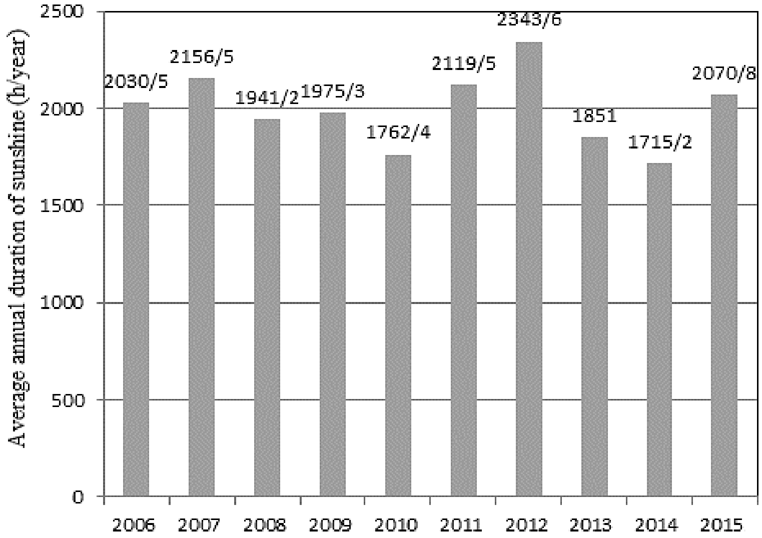


Figure 23. Average annual duration of sunshine for ten years, from 2006 to 2015. (Source: State hydrometeorological office)

In the observed time period, from 2006 to 2015, the average monthly wind strength in the area of the City of Zagreb ranges from 1.4 to 1.9 Bouf (Figure 24). The display of the Beaufort scale table is given in Table 3. The Beaufort scale is an experimental measure that relates wind speed to observed conditions at sea or on land.

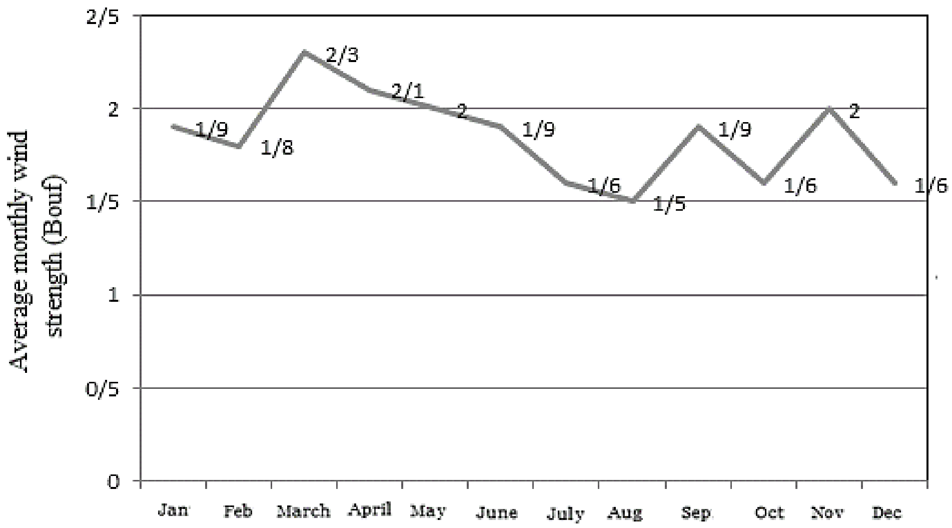


Figure 24. Average monthly wind strength (Bouf) for ten years, from 2006 to 2015. (Source: State hydrometeorological office)

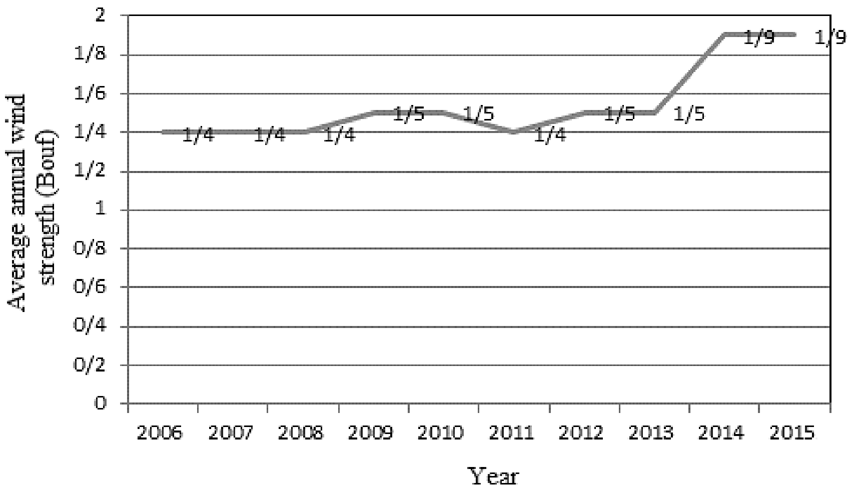


Figure 25. Average annual wind strength (Bouf) for ten years, from 2006 to 2015. (Source: State hydrometeorological office)

Table 3. Table of the Beaufort scale

| | | | Speed | | Maximum wave height (m) | |
|---|---|---|---|---|---|---|
| Strength (Bf) | Name | km/h | m/s | knot | Inland sea near the coast | Open sea |
| 0 | Calm | <1 | 0-0,2 | <1 | - | - |
| 1 | Breeze | 1-5 | 0,3-1,5 | 1-3 | 0,1 | 0,1 |
| 2 | Sea breeze | 6-11 | 1,6-3,3 | 4-6 | 0,2 | 0,3 |
| 3 | Light wind | 12-19 | 3,4-5,4 | 7-10 | 0,6 | 1 |
| 4 | Moderate wind | 20-28 | 5,5-7,9 | 11-16 | 1 | 1,5 |
| 5 | Moderately strong wind | 29-38 | 8-10,7 | 17-21 | 2 | 2,5 |
| 6 | High wind | 39-49 | 10,8-13,8 | 22-27 | 3 | 4 |
| 7 | Strong wind | 50-61 | 13,9-17,1 | 28-33 | 4 | 5,5 |
| 8 | A stormy wind | 62-74 | 17,2-20,7 | 34-40 | 5,5 | 7,5 |
| 9 | Strong storm wind | 75-88 | 20,8-24,4 | 41-47 | 7 | 10 |
| 10 | Hurricane wind | 89-102 | 24,5-28,4 | 48-55 | 9 | 12,5 |
| 11 | Strong Hurricane wind | 103-117 | 28,5-32,6 | 56-63 | 11,5 | 16 |
| 12 | Hurricane | >118 | 28,5-32,6 | >64 | 14 | - |

## *6.5.Modeling of climate change in the area of the City of Zagreb*

### *6.5.1 Assessments of climate change in the area of the City of Zagreb in the future*

Estimates of future climate change are based on the definition of future greenhouse gas emissions that take into account certain parameters about future demographic, social, economic and technological development at the global and regional level, after which estimates can be obtained by integrating global climate models that include the components of the climate system parameters in the future. Integrations of global models are also carried out for periods in the current climate in which the concentrations of greenhouse gases correspond to measured values and in the future when they are defined by the emission scenario of these gases, then the values of climate parameters in the future and current climate can be calculated from such experiments, and their difference gives climate change.

Given that global climate models have a relatively coarse resolution (150-200 km), regional climate models whose resolution is usually 10-50 km are used to assess climate change on a finer network of points and are integrated over a smaller area. Regional climate models at the beginning of the simulations and at the edges of the area over which they are integrated use the results of the global climate model simulations. The State Hydro-meteorological Institute uses the RegCM regional climate model, and a detailed description is given in this paper. The assessment of climate changes in the area of the City of Zagreb until 2040 is also represented in the next section.

*6.5.2 Expected changes in climate parameters until 2040*

As previously stated, the most important meteorological elements that define the climate are solar radiation (insolation), air temperature, pressure, wind direction and speed, humidity, precipitation, evaporation, cloudiness and snow cover. At the same time, they are significant factors influencing risk events of natural or anthropogenic origin and risk management. The results of climate simulations using the regional climate model RegCM showed the following projections:

- Direct impact of extreme weather conditions – extended periods of high solar radiation were observed (Figure 26). The model shows extended periods of high solar radiation averaging around 0.21%.
- Increase in mean daily, maximum and minimum air temperature in all seasons. The Figures 27-29) from the model outcomes show an increase in average daily air temperature (°C) of around 1%, an increase of about 0.5% in the average maximum air temperature and an increase of around 2.51% in average minimum air temperature (°C) during the period, respectively.
- Future climate precipitation changes vary by season. In winter and spring, the model gives an average increase in precipitation of 3%, and in summer and autumn a decrease of 3%, Figure30.
- Direct influence of extreme weather conditions – humidity and evaporation. In the immediate future, until 2040, it is expected that the specific humidity will increase throughout the year, Figure 31. The model shows an average increase in precipitation of 3% in winter and spring, and a decrease of 3% in summer and autumn.
- Assessment of dry and wet years. The assessment is taken from the Climate Change Adaptation Strategy. Preparation of the Report on the estimated impacts and vulnerability to climate change by individual sectors. The model shows an increasing trend in the number of extremely dry, very dry or dry years, while the models indicate different results, a rise in the frequency of extremely rainy, very rainy and rainy years of project (Figure 32).

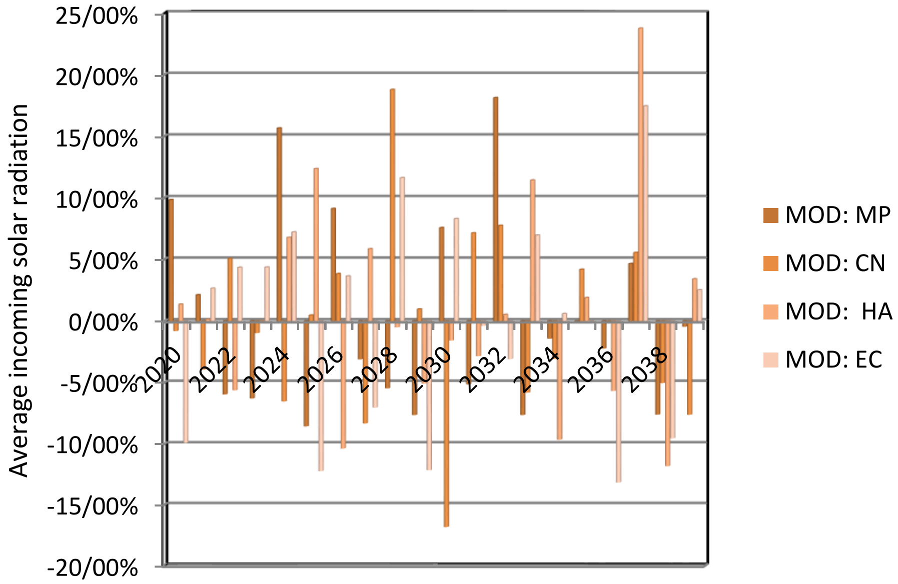


Figure 26. Projections of mean incoming solar radiation (W/m$^2$) for the City of Zagreb
(Source: Database: Energy_monthly_all_REGCM-GRELL-50km_HIST-RCP45)

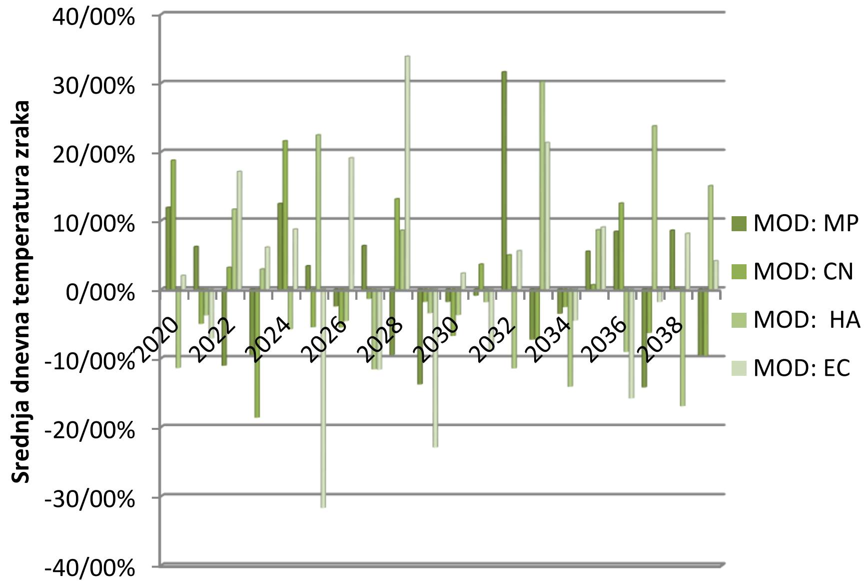


Figure 27. Projections of mean daily air temperatures for the City of Zagreb
(Source: Database: Energy_monthly_all_REGCM-GRELL-50km_HIST-RCP45)

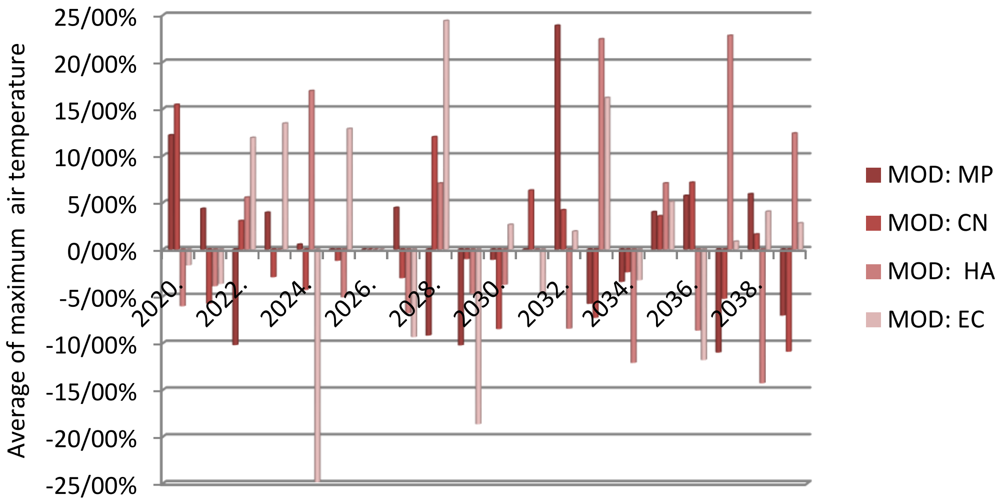


Figure 28. Average of maximum air temperature for the City of Zagreb
Source: Database: Energy_monthly_all_REGCM-GRELL-50km_HIST-RCP45

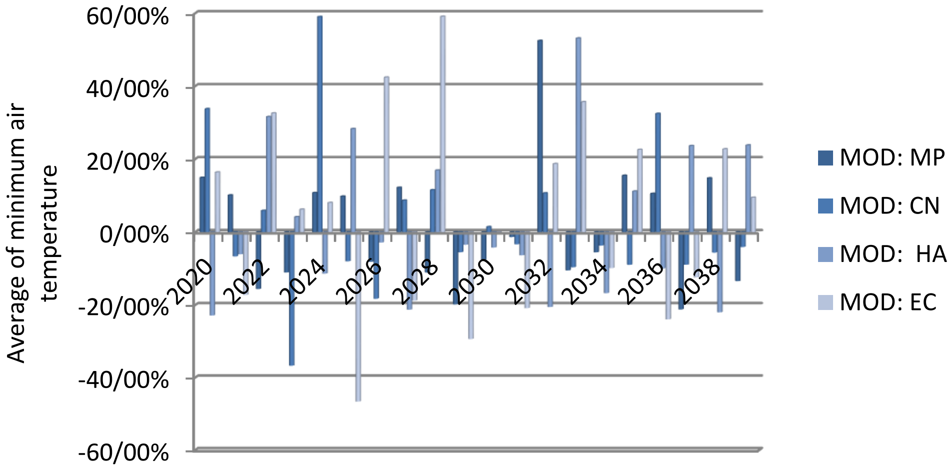


Figure 29. Average of minimum air temperatures for the City of Zagreb
(Source: Database: Energy_monthly_all_REGCM-GRELL-50km_HIST-RCP45)

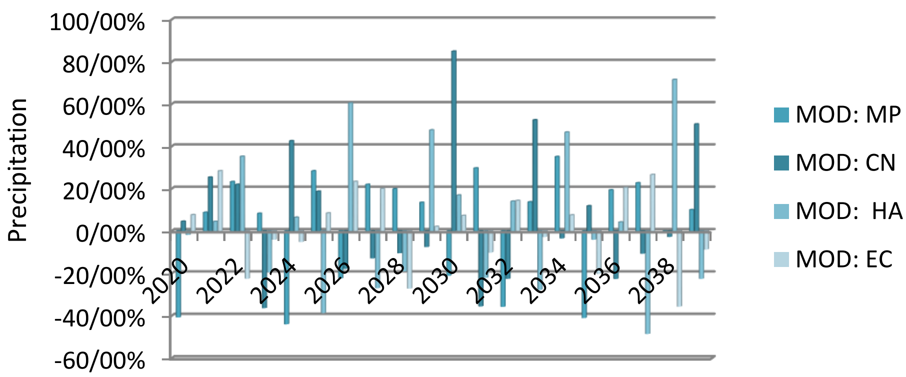


Figure 30. Precipitation for the City of Zagreb during 2020-2040
(Source: Database: Energy_monthly_all_REGCM-GRELL-50km_HIST-RCP45)

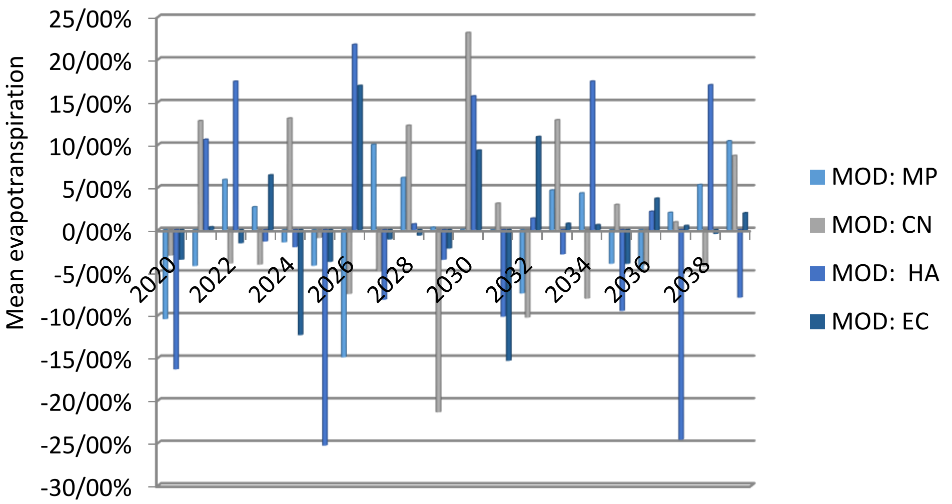


Figure 31. Projections of the frequency of extremely wet and extremely dry years for the City of Zagreb during 2020-2040

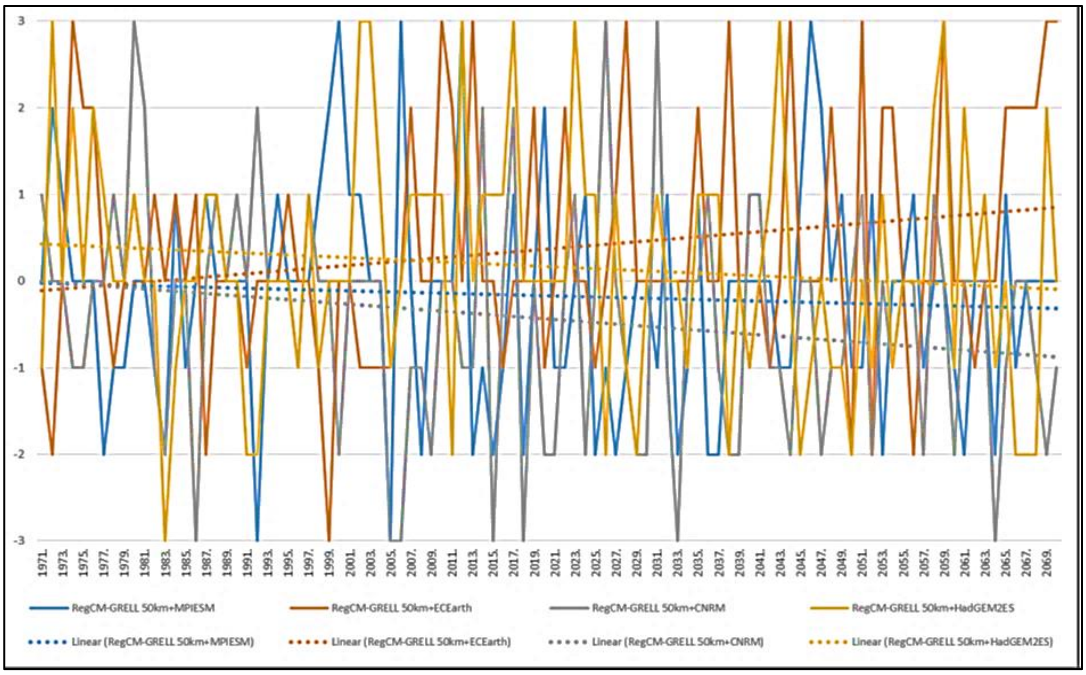


Figure 32. Projections of trends in the frequency of extremely wet and extremely dry years for the City of Zagreb

## *6.6.Assessment of risk and vulnerability of exposure to the effects of climate change*

The agreement of the mayors prescribed as one of the mandatory parts of SECAP the creation of a risk and sensitivity analysis from the effects of climate change. The complete analysis of the climate and climate changes in the area of the City of Zagreb was presented in the previous section, and in the continuation of this section Table 4 taken from the Reporting template of the Agreement of Mayors (Reporting template - SECAP) shows the status of the risk's levels.

Table 4. Qualitative assessment of the risk of exposure to climate change according to the instructions from the Form for reporting the Agreement of Mayors

| | Current risks | | Anticipated risks | |
|---|---|---|---|---|
| A type of climatic extreme | Current risk level | Expected change in intensity | Expected change in frequency | Period |
| Extreme heat | High | Increase | Increase | Current risk |
| Extreme cold | High | Increase | Increase | Current risk |
| Extreme humidity | Moderate | Increase | Increase | Current risk |
| Floods | Low | Increase | Increase | Risk in the long term |
| Sea level change | No risk | No change | No change | No risk |
| Droughts | High | Increase | Increase | Current risk |
| Storms | High | Increase | Increase | Current risk |
| Landslides | High | Increase | Increase | Current risk |
| Forest fires | Low | Increase | No change | Current risk |

## Conclusions

Risk analysis and assessment of the vulnerability of individual sectors to the impacts of climate change in Zagreb are crucial for effective adaptation planning and resilience building. By identifying the specific risks each sector faces, such as infrastructure, agriculture, water resources, and public health, policymakers can develop targeted strategies to mitigate these risks. Understanding the vulnerabilities of each sector allows for the prioritization of resources and efforts where they are most needed.

In Zagreb, a comprehensive risk analysis should consider factors such as extreme weather events, sea-level rise, temperature increases, and changes in precipitation patterns. By assessing how these factors will impact critical infrastructure like transportation networks, energy systems, and buildings, city planners can make informed decisions about investments in resilient infrastructure and emergency preparedness. Furthermore, understanding the vulnerability of sectors like agriculture and water resources is essential for ensuring food security and sustainable water management in the face of changing climate conditions. By identifying areas at high risk of droughts or floods, policymakers can implement measures such as improved irrigation systems or water conservation practices to enhance resilience.

In conclusion, conducting a thorough risk analysis and vulnerability assessment of individual sectors in Zagreb is essential for building a climate-resilient city that can withstand the challenges posed by climate change. By integrating this information into urban planning processes and policy decisions, Zagreb can proactively address climate risks and ensure a sustainable future for its residents.

## References

Blunden, J., Hartfield, G., Arndt, D.S., Dunn, R.J.H., Tye, M.R., Blenkinsop, S., and *et al*. 2018. State of the Climate in 2017. Bulletin of the American Meteorological Society, 99(8): Si-S310.

Branković, Č., Patarčić, M., Güttler, I., and Srnec, L. 2012. Near-future climate change over Europe with focus on Croatia in an ensemble of regional climate model simulations. Climate research, 52: 227-251.

Chapin, F.S., Matson, P.A., Vitousek, P.M., Chapin, F.S., Matson, P.A., and Vitousek, P.M. 2011. Earth's Climate System. Principles of Terrestrial Ecosystem Ecology, 2011: 23-62.

Juszczak, R., Kuchar, L., Leśny, J., and Olejnik, J. 2013. Climate change impact on development rates of the codling moth (Cydia pomonella L.) in the Wielkopolska region, Poland. International Journal of Biometeorology, 57: 31-44.

Kennedy, J., Morice, C., Parker, D., and Kendon, M. 2016. Global and regional climate in 2015. Weather, 71(8): 185-192.

Kitoh, A., Knutti, R., Murphy, J.M., Noda, A., and Raper, S.C. 2007. Global climate projections. Chapter 10.

Le, T.H., Somerville, R., Cubash, U., Ding, Y., Mauritzen, C., Mokssit, A., Peterson, T., and Prather, M. 2007. Historical overview of climate change science. In IPCC reports 2006.

Lupo, A., Kininmonth, W., Armstrong, J.S., and Green, K. 2013. Global climate models and their limitations. Climate change reconsidered II: Physical science, 9, p.148.

Meehl, G.A., Stocker, T.F., Collins, W.D., Friedlingstein, P., Gaye, A.T., Gregory, J.M., and *et al*. 2007. Global climate projections, in Climate Change 2007: The Physical Science Basis. Contribution of Working Group Ito the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by S. Solomon *et al*., chap. 10, pp. 747–845, Cambridge Univ. Press, Cambridge, U. K.

Official website of the State Hydro-meteorological Institute. Available at: https://www.shmu.sk/en/?page=1793 (Accessed date: 28/05/2023).

Putman, W.M., Ott, L., and Darmenov, A. 2016. A global perspective of atmospheric carbon dioxide concentrations. Parallel computing, 55: 2-8.

Seneviratne, S.I., Corti, T., Davin, E.L., Hirschi, M., Jaeger, E.B., Lehner, I., and *et al*. 2010. Investigating soil moisture–climate interactions in a changing climate: A review. Earth-Science Reviews, 99(3-4): 125-161.

Shrestha, S., and Singh, P. 2014. Global Climate System, Energy Balance, and the Hydrological Cycle. Climate Change and Water Resources. 2014 May 22:1.

Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K., and *et al*. 2007. IPCC fourth assessment report (AR4). Climate change, 374.

Von der Heydt, A.S., Ashwin, P., Camp, C.D., Crucifix, M., Dijkstra, H.A., and *et al*. 2021. Quantification and interpretation of the climate variability record. Global and Planetary Change, 197:103399.