CLIMATE

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Analysing past, present and future climates demands two fundamentally different methodological approaches. The past and the present can be described by mathematical statistical analyses of observations, while understanding the future climate requires numerical modelling based on the physical processes of the climate system.

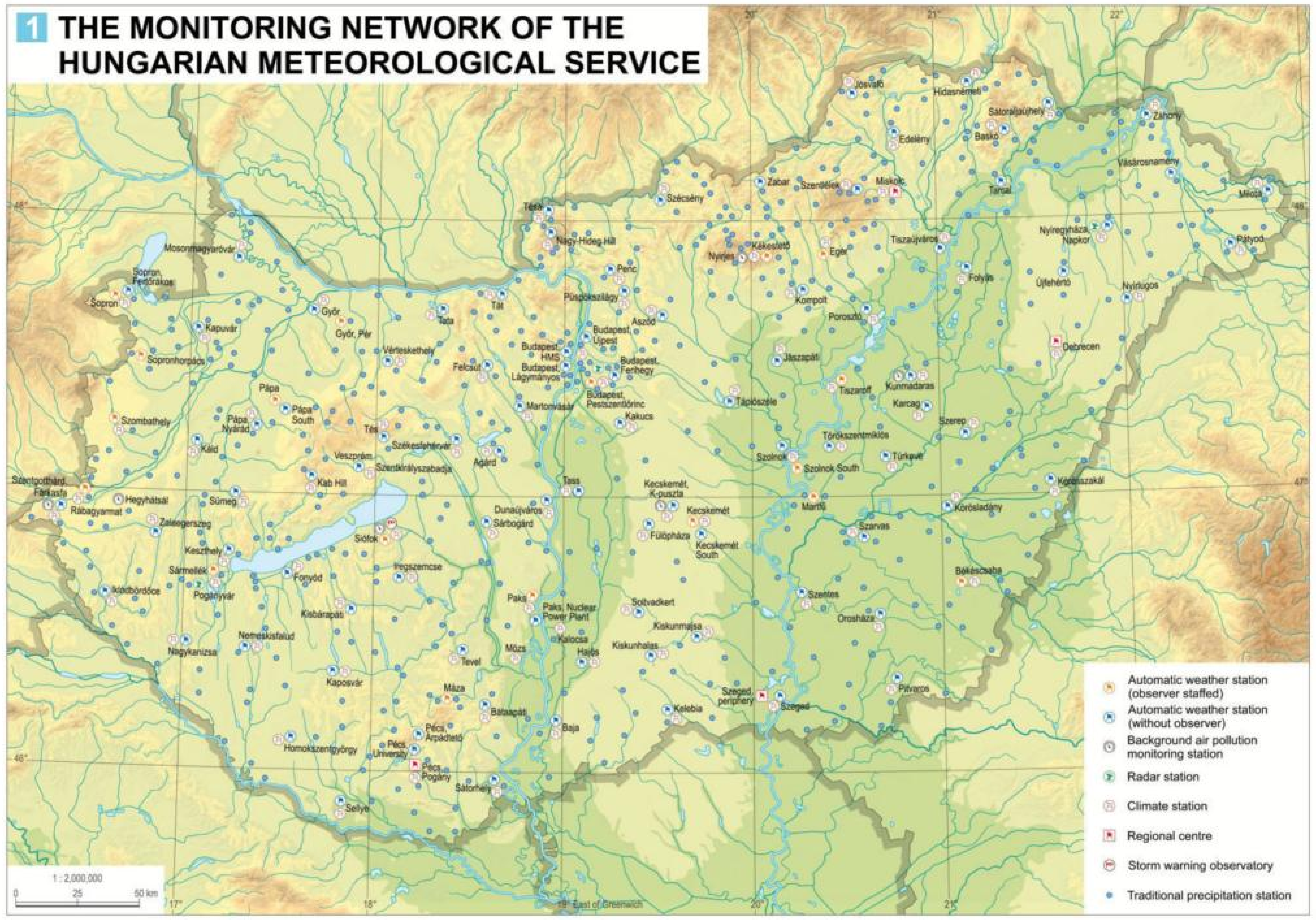
Methods of statistical climatology

Long-time averages and the analysis of climate element changes (e.g. temperature, precipitation) enable us to characterise the climate. The controlled and homogenised data sets obtained from some 100 climate and 400 traditional precipitation stations of the Hungarian Meteorological Service (OMSZ) are used to investigate the climate of Hungary 1. Though these stations have various measuring protocols and designations, an observation site is called a climate station if it collects temperature, precipitation and relative humidity data. Moreover, most of these climate stations also measure wind speed, and one third of them additionally detect sunshine duration. The automation of climate station operation started in the 1990s, which increased the frequency of observation, meanwhile some observations that required human intervention were no longer made. For example, the observation of sunshine duration was changed to automatic measurement of global radiation. Precipitation stations collect data on the amount and type of precipitation. These observations are carried out by voluntary observers, who do this work in addition to their own everyday occupations. Observations are carried out all over the world according to strict, uniform rules, which are determined by the World Meteorological Organization (WMO), thereby ensuring the appropriate data quality. However, these rules cannot eliminate errors caused by changes in the conditions of long-term measurements, as the type or position of the instrument, the location and surroundings of the site or the timing of observations may change over the years. In addition, spatially detailed data are also needed to characterise the climate.

Two mathematical methods have been developed by the OMSZ to produce climate data that are reliable in both space and time. One of these methods is homogenisation, which eliminates data set errors caused by changes in measurement conditions. The essence of this procedure is to detect and correct station data series that have a statistically significant break compared to the data of surrounding stations. Datasets used in long-term climate studies are homogenised by the mathematically established MASH process *(Multiple Analysis of Series for Homogenisation)* developed by the OMSZ, which is a prominent method throughout the world.

The other basic method is interpolation. As surface meteorological parameters are measured at discrete points in space, in order to generate maps these parameters also have to be interpolated to points between the observation sites. Through interpolation, meteorological parameters can be estimated at any point on the map, or a map covering the whole country can be drawn, as in the case of the climate atlas. To obtain an interpolation closest to the real state, the geographical factors that affect the estimated meteorological parameter have to be considered. First of all, the effect of elevation above sea level and other topographical factors, e.g. slope aspect, described in detail in the *Relief* chapter, have to be taken into account. The accuracy of interpolation can be improved when, apart from spatial characteristics, the information content that can be derived from the statistical characteristics of the long-term series of climate variables is also considered. The MISH (*Meteorological Interpolation based on Surface Homogenised Data Basis*) system developed and used by the OMSZ uses all the above-mentioned factors, moreover, it is able to use other background information (like forecasted values, satellite and radar observations) which are available on grids with a sufficiently dense spatial resolution. To obtain a more accurate approach to the real situation, the countrywide mean values presented in the atlas were determined as the averages of the values interpolated to the grid, instead of determining them directly from the changing observation sites.

1 THE MONITORING NETWORK OF THE HUNGARIAN METEOROLOGICAL SERVICE



In climatological practice, 30-year averages are used for analyses as far as possible. In most cases, maps and graphs representing the climate of Hungary show the data of the last three whole decades, the period of 1981 to 2010 (exceptions are always indicated). In addition to the average and extreme values, so-called climate indices also illustrate the climate.

> *A **climate index** is a diagnostic quantity that characterises the climate by the number of hours or days in which a specific threshold value is exceeded, which value is determined according to a particular practical aspect. Thus, a climate index, like the number of frost, winter, summer or hot days, makes comparison easier between the weather of a particular period and the average climatic conditions.*

Methods of climate modelling

To analyse the climate of Hungary, in addition to describing the current situation, the future evolution of the climate also has to be characterised. Numerical modelling is used to understand the complex operation and future behaviour of the climate system, during which the system of mathematical equations of physical processes is solved by numerical approximation. Global climate models are capable of describing the behaviour and interactions of the elements of the system (atmosphere, hydrosphere, lithosphere, cryosphere, biosphere), moreover, they are able to provide the global-scale response of the climate system in a hypothetical climate forcings.

One of the most important and most uncertain elements of climate forcing is human activity. Because its changes in the 21st century cannot be quantified, scenarios that provide different estimations for anthropogenic emission tendencies are used in global model simulations. These simulations are called projections, their result depends on the scenario used in the calculations.

> ***Climate forcings** are natural or anthropogenic processes, such as fluctuations in the orbit and rotation of the Earth or anthropogenic emissions of pollutants, that are continuously influencing the climate. According to one of the most important findings of the fifth assessment report of the leading intergovernmental climate change research review body, the IPCC (Intergovernmental Panel on Climate Change), 'it is extremely likely that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in GHG concentrations and other anthropogenic forcings together'.*

The resolution of the horizontal grid of global climate models (i.e. the distance between grid points) is generally 100 to 500 km, which is not enough to describe local features. For this purpose, regional climate models are used that are capable of making the large-scale results more accurate and detailed. The regional simulations use large-scale global simulation results over the area of interest as information on their lateral boundaries.

Four *regional climate models* are used for simulations in Hungary, two of them, the *ALADIN-Climate* and the *RegCM*, together with their results, are presented in this atlas. The joint presentation of the results of the two models analysing the period of 1961 to 2100 (with a 10 km resolution assuming average anthropogenic emission) makes the simple quantification of uncertainties possible.

General characteristics of the climate

Climate of Hungary is basically determined by its geographical location: the country is situated in the northern temperate climatic zone, whose main characteristics are the alternation of the four seasons and the dominance of westerly winds. Considering that most precipitation is transferred by these westerly winds, distance from the Atlantic Ocean is an essential factor. Another characteristic of the climate is its great variability over time, which is mainly caused by the weather of Hungary being equally affected by three climatic zones: oceanic, continental and Mediterranean. Any of these types can become prevailing for shorter or longer periods.

The other main determinant is topography. The country is situated in the central, deepest region of the Carpathian Basin and 84% of its surface is below 200 metres, so the effect of the Carpathian Mountains is prominent.

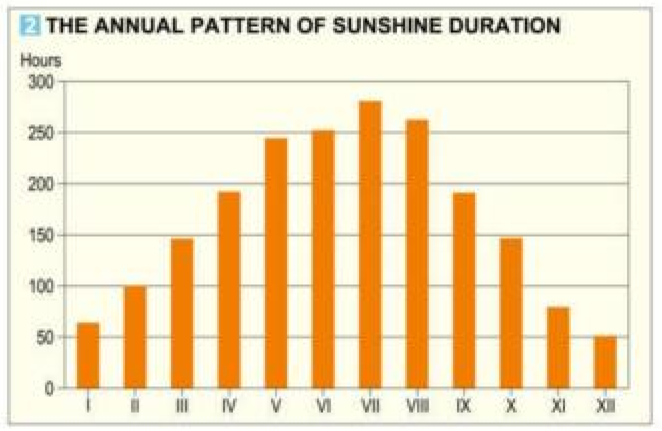
1 *Cold air pool in the Mátra Mts. Because of the clear air, the Börzsöny Mts. can be seen on the horizon 80 km away*

Sunshine duration

Radiation from the Sun is the basic forcing of the Earth's climate, and its amount can be described by various parameters. One of the simplest methods is measuring sunshine duration, which is the length of the period of sunshine in hours.

Two factors influence the amount of sunshine duration. Primarily it is determined by 'the astronomically possible sunshine duration', which is the possible amount in the case of cloudless weather, depending on the latitude and the angle between the rotational axis and the orbital plane of the Earth. This amount is modified by the other factor, the prevailing amount of cloud. A special case of this modification is the so-called 'cold air pool' 1. This phenomenon can be observed in winter: a cold, foggy, cloudy air mass fills the bottom of the Carpathian Basin, with only higher altitude areas rising above it and getting much more sunshine than the lower regions.

2 THE ANNUAL PATTERN OF SUNSHINE DURATION



The average monthly sunshine duration is between 50 and 280 hours in Hungary. Although the longest daytime is in June, because of the effect of clouds, July is the richest in sunshine. We receive the least amount of sunshine in December, when the daytime is the shortest as well 2.

The annual sunshine duration over the country fluctuates between 1900 and 2100 hours, with a spatial increase existing from the northwest to southeast. The highest values can be observed in the south, while the lowest are prevalent in the northern-north-eastern areas of the country 3.

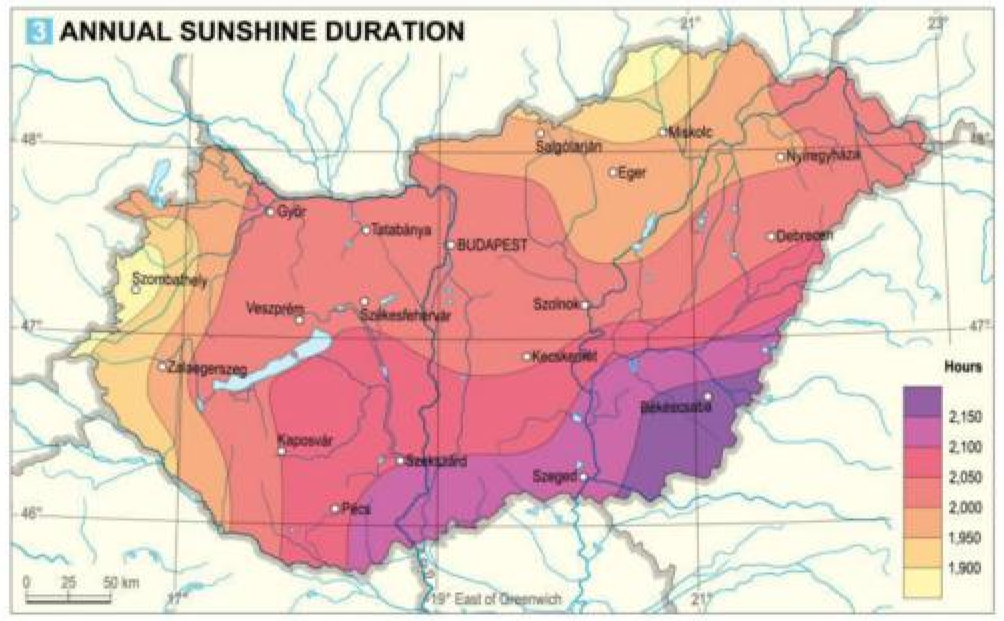
Temperature

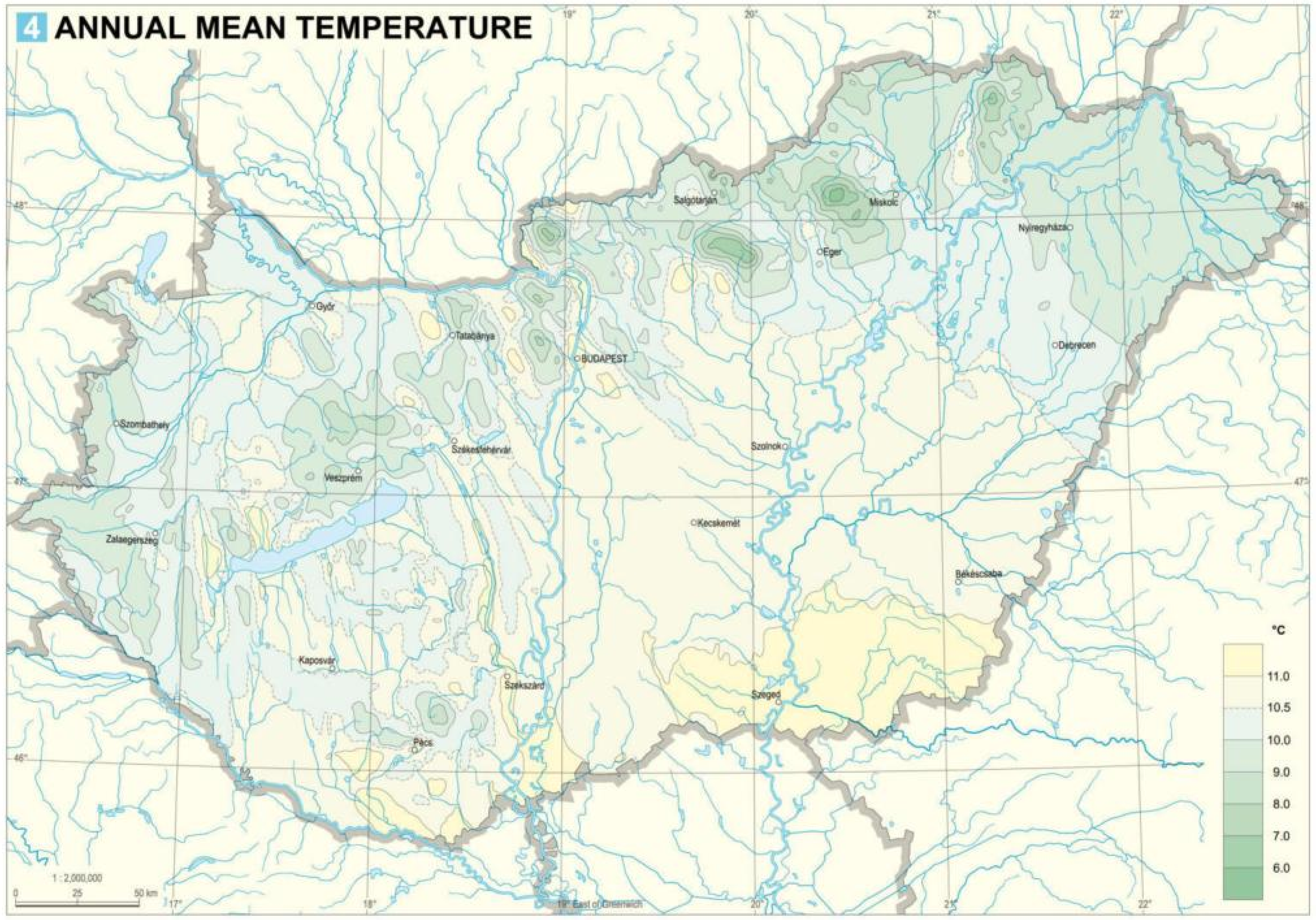
The main factors influencing the distribution of air temperature in Hungary are latitude, altitude and distance from the seas.

In most of the country, the annual mean temperature is between 10 and 11 °C 4, the countrywide average is 10.4 °C based on the data from 1981 to 2010. The lower values appear in the higher altitudes (the Bakony Mts, around the western border, and in the North Hungarian Range), where the mean temperature usually does not exceed 8 °C. In the coldest areas, in the Mátra and Bükk regions, values below 6 °C are characteristic. Values above 11 °C occur in the southern-southeastern regions of the country on the southern exposed slopes, and in the area of Budapest caused by the urban heat effect. Note that the increasing appearance of areas with an annual mean temperature of 11 °C or above is only a recent phenomenon.

During the year, the spatial distribution of monthly mean temperature can significantly differ from the annual distribution. Considering the long-term average, the mean temperature in January decreases from the southwest to northeast 5, with the countrywide average being −1.0 °C based on the data of 1981 to 2010. Except for the warmest areas, values are below 0 °C everywhere, and drop below −5 °C in the coldest areas of the North Hungarian Range. The January mean temperature and the seasonal winter mean temperature display large fluctuation year by year, and

3 ANNUAL SUNSHINE DURATION





4 ANNUAL MEAN TEMPERATURE

the difference between individual years is much higher than in summer. Although the impact of topography on temperature is obvious, inversion is common in winter, when the temperature increases with altitude instead of decreasing. It can happen that higher altitude areas can be warmer as they rise above the cold air mass that fills the bottom of the Basin 1.

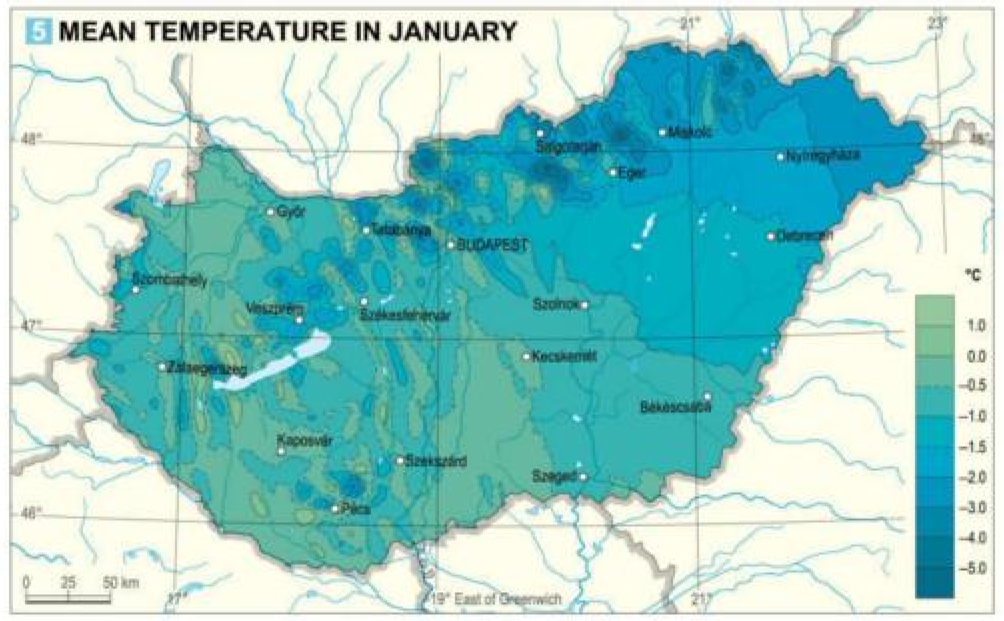
The warmest period of the year is the end of July and beginning of August, the warmest month is July in long-term average 6, however, August overtakes it in some years. In July, the mean temperature increases from north to south and towards the centre of the Basin, the countrywide average is 21.2 °C. The July mean temperature is 20–21 °C in the Transdanubian region, which is 1–1.5 °C cooler than in the areas of the Alföld (Great Hungarian Plain), where it is above 21 °C. In the warmest areas, in the vicinity of the Tisza River between Szolnok and Szeged, the mean temperature is above 22 °C, while in higher altitudes in the Mátra and Bükk region, it does not even reach 16 °C.

In the transition periods, spatial distribution displays an intermediate pattern compared to those of the two extreme months. Both distribution and temperature values are similar on the mean temperature maps of April 7 and October 8. The countrywide average temperature is 11.2 °C in April and 10.5 °C in October.

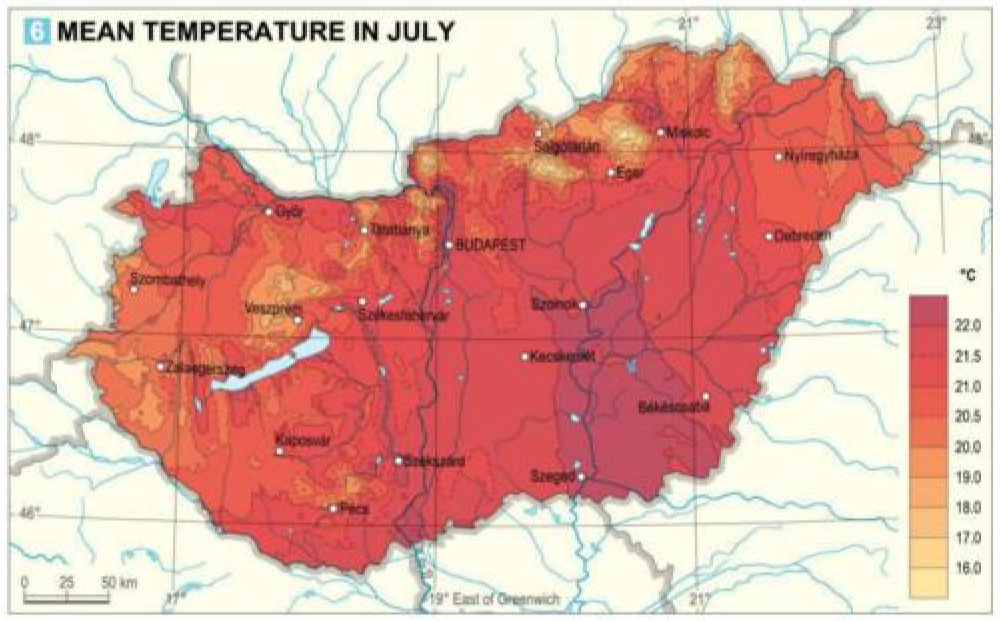
Of the climate indices mentioned earlier, the atlas presents the average number of summer and winter days as well as the average date of the first and last frost days. A *summer day* is a day when the daily maximum temperature reaches 25 °C, while on a *winter day* the daily maximum temperature does not rise above 0 °C. Apart from the effect of topography, the number of summer days 9 increases from north to south, while winter days become more frequent from west to east 10.

Knowledge on the frost periods is important mainly for agriculture, but it has a role in engineering planning processes as well. A *frost day* is a day when the daily minimum temperature is 0 °C or below. Naturally, the first and last appearances do not mean that there are no frost-free periods between these two dates. Days with a positive temperature can interrupt the cold weather even in the coldest winter periods. The first frost days 11 appear between 18 October and 1 November in most areas of the country. These can occur earlier in areas with higher altitudes, while on southerly slopes they may appear only in November. Frost days disappear between 3 and 10 April in most areas of the country 12, while they can occur even in May in areas with higher altitude. Lakes and rivers can freeze during longer frost periods 2.

The annual course of temperature, i.e. the monthly mean temperatures can be followed in two 30-year periods: the first period is the 1981 to 2010 period, which is the most typical for the present climate, the other period is between 1961 and 1990 13. The 1961 to 1990 period has a prominent role, since it is often considered as reference period in modelling future climate. In both periods, the January means are the lowest and the July means are the highest. All of the monthly means are higher throughout 1981 to 2010 than in the 1961 to 1990 period. This difference is the highest in January and August when it is above 1 °C, and warming also reaches 1 °C in July.

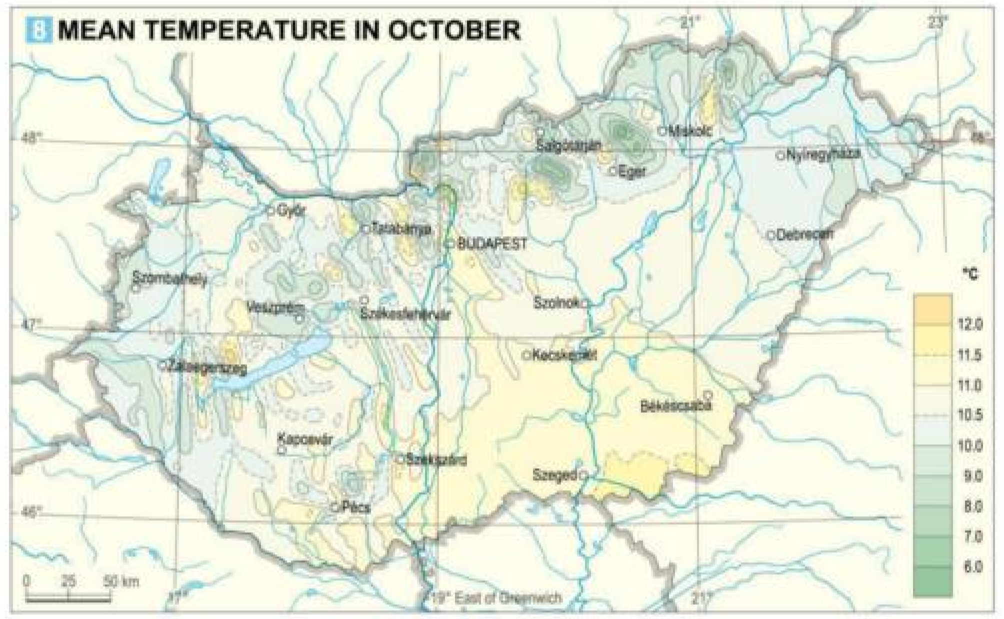


5 MEAN TEMPERATURE IN JANUARY

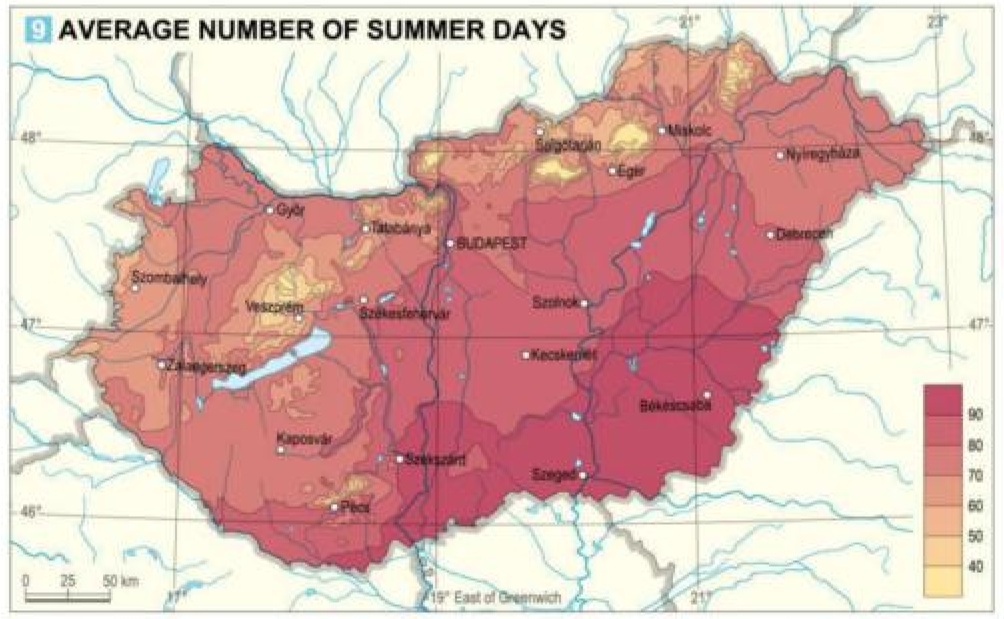


6 MEAN TEMPERATURE IN JULY

7 MEAN TEMPERATURE IN APRIL



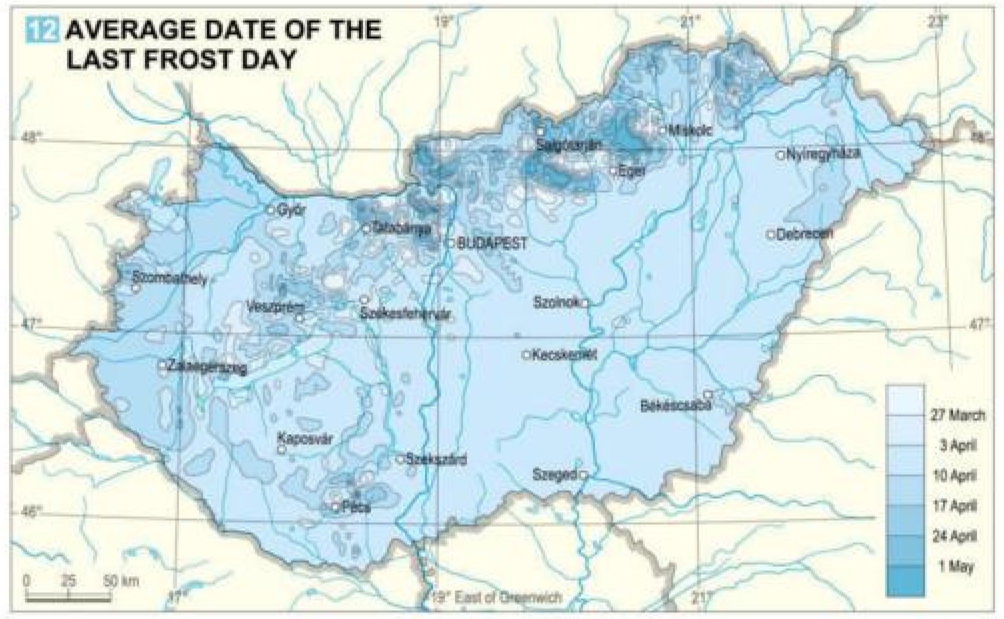
8 MEAN TEMPERATURE IN OCTOBER



9 AVERAGE NUMBER OF SUMMER DAYS

10 AVERAGE NUMBER OF WINTER DAYS

11 AVERAGE DATE OF THE FIRST FROST DAY



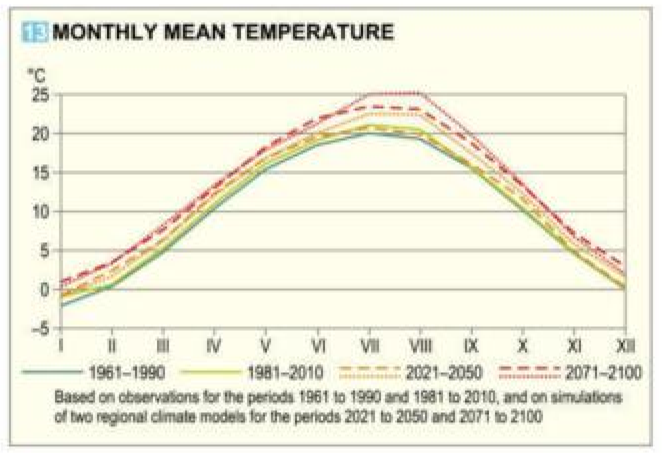
12 AVERAGE DATE OF THE LAST FROST DAY

Compared to the long-term averages, there are big differences in individual years. Year-by-year variability is smaller in the summer half year than in the winter half year. The scattering of monthly mean temperature is around 1.5 °C from April to October and reaches 3 °C in February. The course of the January monthly mean temperatures is the most extreme, the difference between the mildest and most extreme January values is 5.4 °C. July is the most balanced month regarding its temperature, with the difference being only 2 °C based on the observations of the 1981 to 2010 period.

2 *The frozen Szinva Waterfall, Lillafüred*

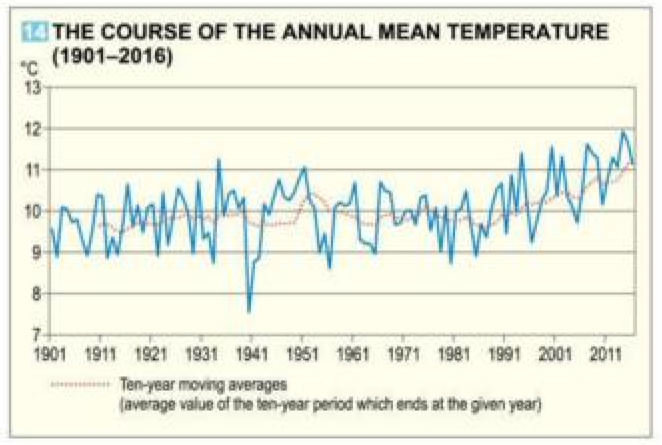
The mean annual *temperature range*, which is the difference between the mean temperatures of the warmest and coldest months, is 22.1 °C countrywide, based on the observations of the 1981 to 2010 period. This value increases from the oceans towards the interior of the mainland, thus expressing the extent of continentality. In Hungary, this value is around 23 °C in the middle and eastern parts of the country, while it is a bit lower, 22–23 °C in Transdanubia.

The characteristics of the Hungarian temperature time series fit the global temperature tendencies well, meanwhile they show greater variability. Extensive instrumental measurement was started in the second part of the 19th century in Hungarian territories. Based on the available sources, in the elapsed period, the millennium and the years following were the warmest years on the Earth, and in this region as well. The 20th century started with a period of warming, following which the 1930s saw a period of cooling, then



13 MONTHLY MEAN TEMPERATURE

Based on observations for the periods 1961 to 1990 and 1981 to 2010, and on simulations of two regional climate models for the periods 2021 to 2050 and 2071 to 2100



14 THE COURSE OF THE ANNUAL MEAN TEMPERATURE (1901–2016)

Ten-year moving averages (average value of the ten-year period which ends at the given year)

Future temperature change in Hungary

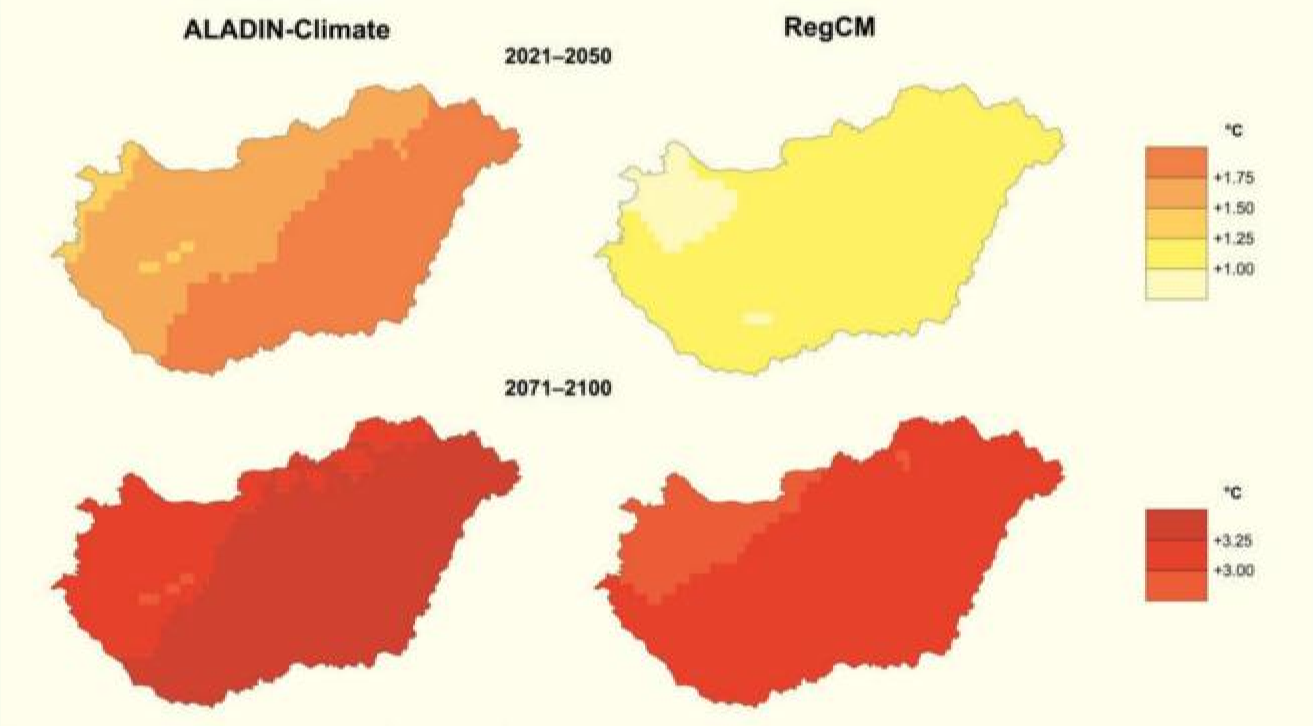
The ensemble method is use for quantification of uncertainties in climate projections for the future, during this process the results of different simulations (all providing a possible future path of evolution of the Earth System) are treated in together. The uncertainties for the next few decades originate mainly from natural climate variability and the approximations of the climate model used. The choice of scenario used to describe future anthropogenic activity up until the end of the 21st century can generate remarkable differences in the model outputs. The large-scale atmospheric forcings used for the ALADIN-Climate and RegCM regional climate models are provided (through boundary conditions) by two different global climate models using the same emission pathway. Consequently, the differences in the following assessment of the two models arise from the model formulations.

Climate models are able to describe the statistics of a longer period of time (usually 30 years). In the Atlas, the changes are evaluated for two future periods with respect to a past reference period (1961 to 1990). The period 2021 to 2050 is important for the adaptation strategies, while 2071 to 2100 was selected for the reason that by then the climate change signal will surpass natural variability.

Following the results of the two models, it can be concluded that mean temperature will continue to increase both annually and seasonally in the 21st century. Annual means are expected to change by 1 to 2 °C for 2021 to 2050 and by 3 to 4 °C for 2071 to 2100 15 with the temperature increase over east-southeast Hungary being higher than over west-northwestern areas. Based on the results of the two model simulations, it is not clear which season will have the most intense warming by the middle of the century: one projection estimates it for spring with around a 1.5 °C increase, while the other indicates summer warming with a signal above 2 °C. However, both simulations are consistent with the highest rise in temperature being in summer (3.5 to 4.5 °C) by the end of the century, meaning that August could possibly be an average of 6 degrees warmer in the future than in the past.

The coldest month on average will still be January in the future, but the monthly mean temperature is anticipated to be above zero (from below zero). This does not mean that frost days cannot occur in the coming decades but their frequency will be significantly lower. In autumn, particularly in September and October, a slightly lower temperature increase is foreseen than for summer (meaning above 3 °C by 2071 to 2100 13).

15 EXPECTED ANNUAL MEAN TEMPERATURE CHANGE



For 2021–2050 and 2071–2100 with respect to the reference period of 1961–1990 based on two regional climate model simulations

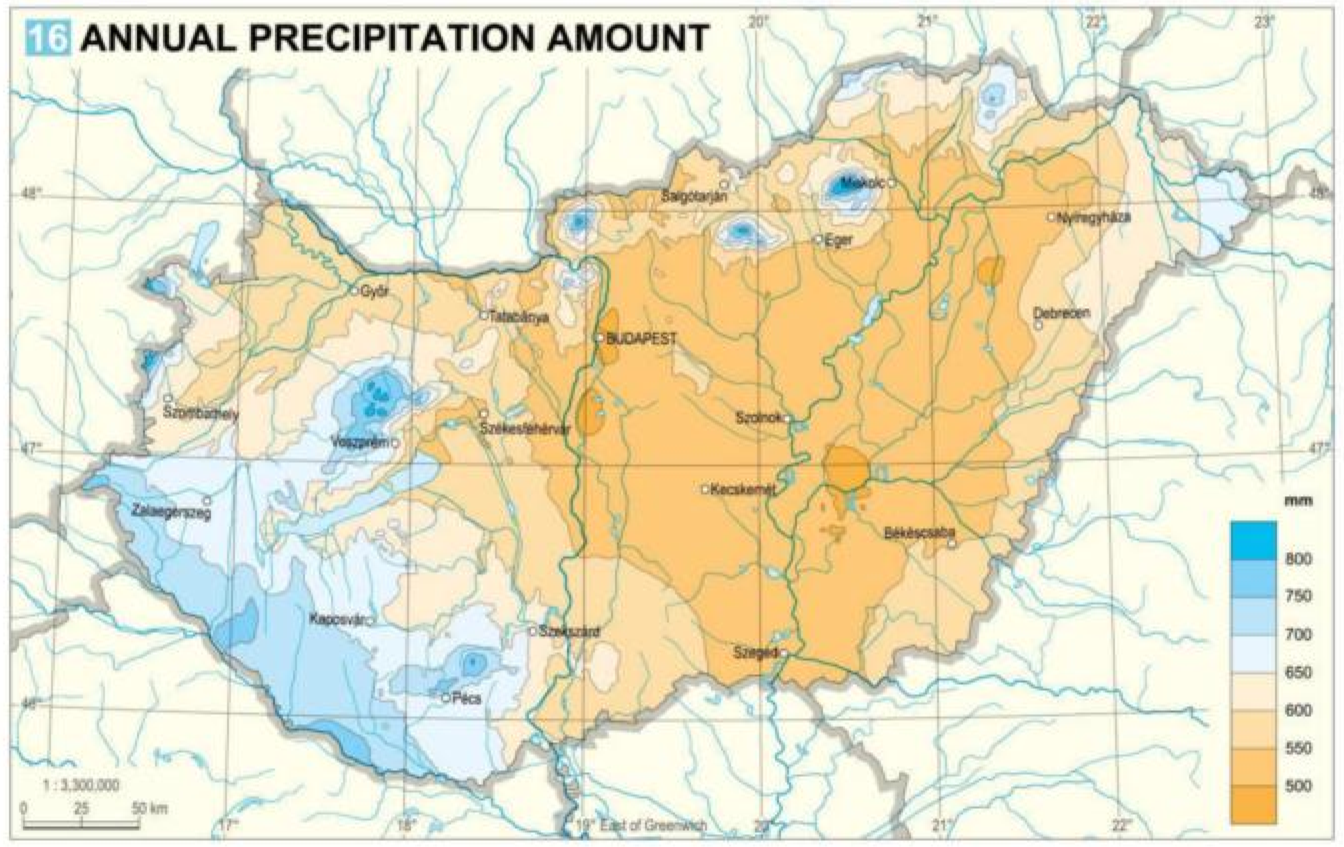
the warm period of the middle of the century changed direction to cooling, with a third warming period being seen from the 1980s 14. In the period of 1901 to 2016, the year 2007 was the warmest, and the ten warmest years (with two exceptions) occurred after 1994, mainly in the 21st century. Although, the course of the ten-year moving averages shows short cool periods, a definite period of warming does actually start in the 1980s, which can also be seen in the yearly values, even if striking year-by-year variations are accompanied by the one way warming.

The temperature conditions of the present can be characterised by the mean temperature of the 1981 to 2010 period, which is 10.35 °C. Among the years after the millennium, only the temperature of 2005 is considerably lower (by 0.59 °C) than the average, the other years have average or higher temperature.

The annual mean temperature shows a 1.1 °C increase calculated by the linear trend model, which used the countrywide averages calculated from homogenised and interpolated data. The trend is steeper in the last decades, and is 1.6 °C in the period of 1981 to 2010.

In addition to the yearly change, every season also displays remarkable warming, however the most evident warming occurs in spring and summer. Between 1901 and 2016, the spring temperature became 1.27 °C higher, with the same value for summer being 1.2 °C. In the same period, the autumn became 0.83 °C warmer, while the same value for winter is 0.8 °C. From 1981, the rise is steeper and more marked in every season, approaching the value of 2 °C in summer. Thus, global warming is obviously reflected in the Hungarian time series.

16 ANNUAL PRECIPITATION AMOUNT



Precipitation

Precipitation is a climate parameter with high temporal and spatial variability in Hungary. Its spatial distribution is determined by distance from the seas, continentality and topography. Topography also plays a role in the modification of the air flows in the Carpathian Basin.

In the period of 1981 to 2010, countrywide average precipitation was around 580 mm 16, with the annual mean being below 500 mm in the driest region of the Alföld, and between 500 and 550 mm in large areas around this driest region. At the southwestern border and in the mountains, annual mean precipitation is above 700 mm. Higher values (above 800 mm) appear only in small patches near to the peaks of the Mátra and Bükk and in the Kőszeg Mts.

The spatial characteristics of the seasonal precipitation amount differ from those of the annual values to greater and lesser extents. Though the effect of continentality and topography can be observed in every period of the year, their influence prevails to different degrees in the individual seasons. Countrywide spring precipitation is almost 140 mm, which can even be above 200 mm at higher altitudes 17. Summer has the highest seasonal precipitation, when 200 mm falls countrywide, which is one third of the annual value; again during this season the driest areas are on the Alföld, while there is also a high amount of precipitation along the southwestern border and in the northeastern parts of the country 18, in addition thunderstorms are a frequent phenomenon 3. Autumn precipitation is 145 mm, which is close to the spring value, meanwhile spatial differences are more considerable in autumn as the extent of both the driest and wettest areas are greater. In autumn, the rainiest area is obviously the southwestern part of the country 19. Winter is the driest season, as the countrywide average does not reach 110 mm. The rainiest areas are the southwestern regions, the Bakony Mts. and, with a smaller extent, the northeastern border with 160 mm in seasonal precipitation, meanwhile there are large patches with precipitation below 100 mm 20. It is worth examining the high spatial variability in the North Hungarian Range, because besides having the highest values, the driest area (the Sajó Valley) is also located in this area.

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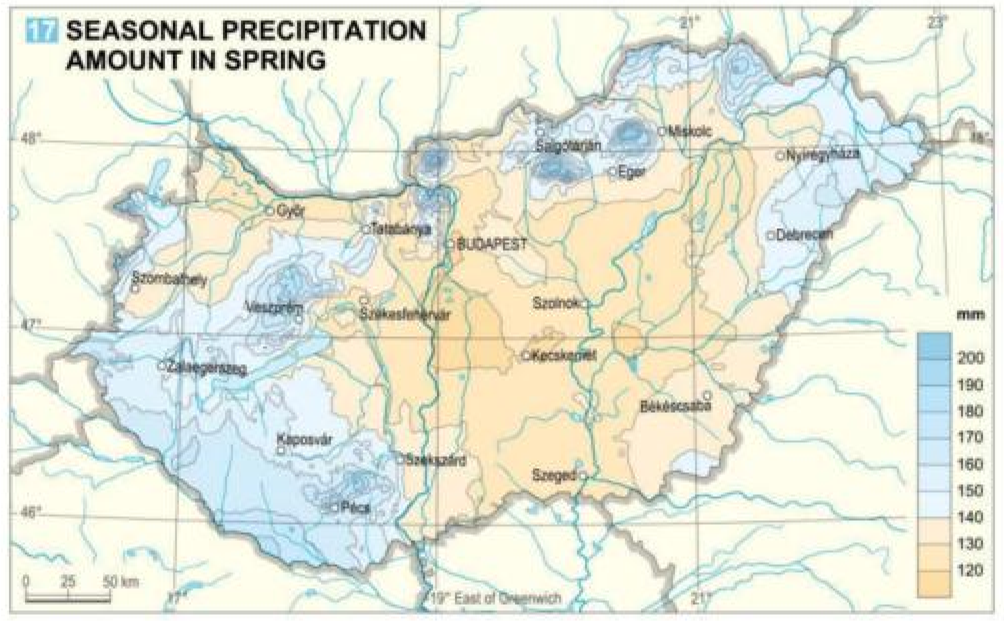
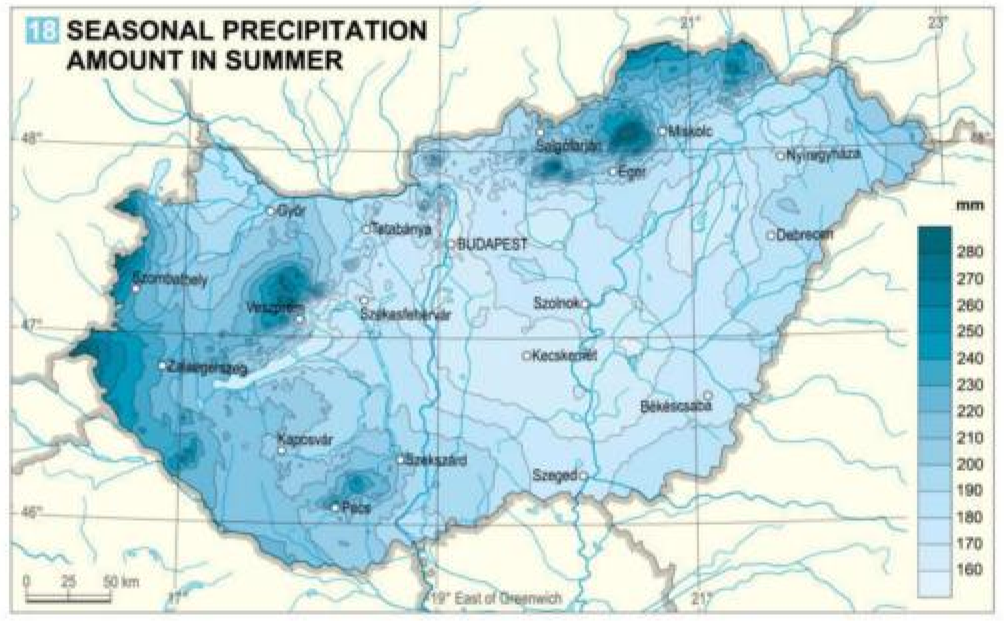
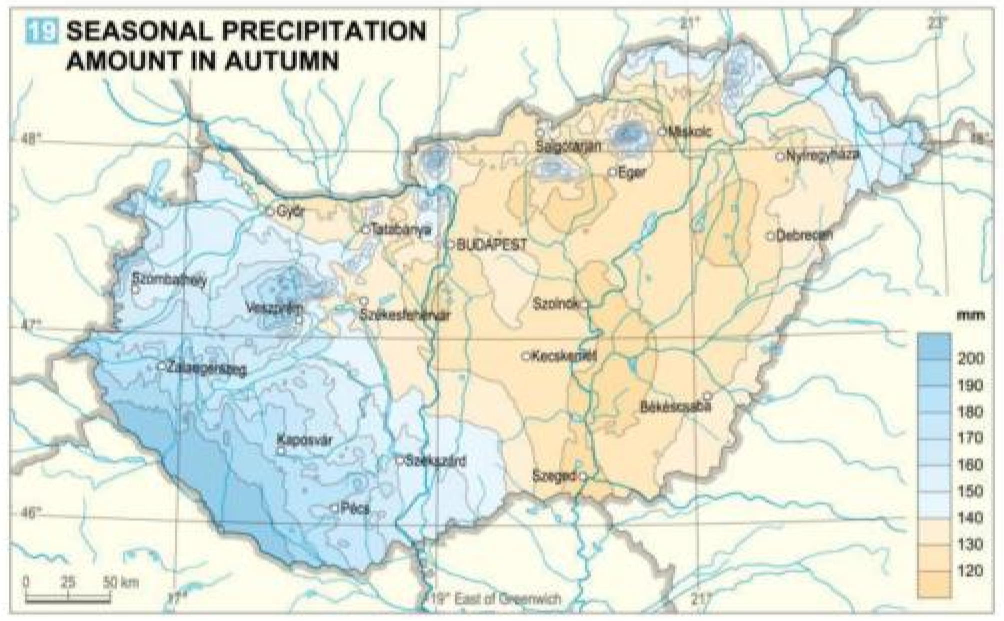
17 SEASONAL PRECIPITATION AMOUNT IN SPRING



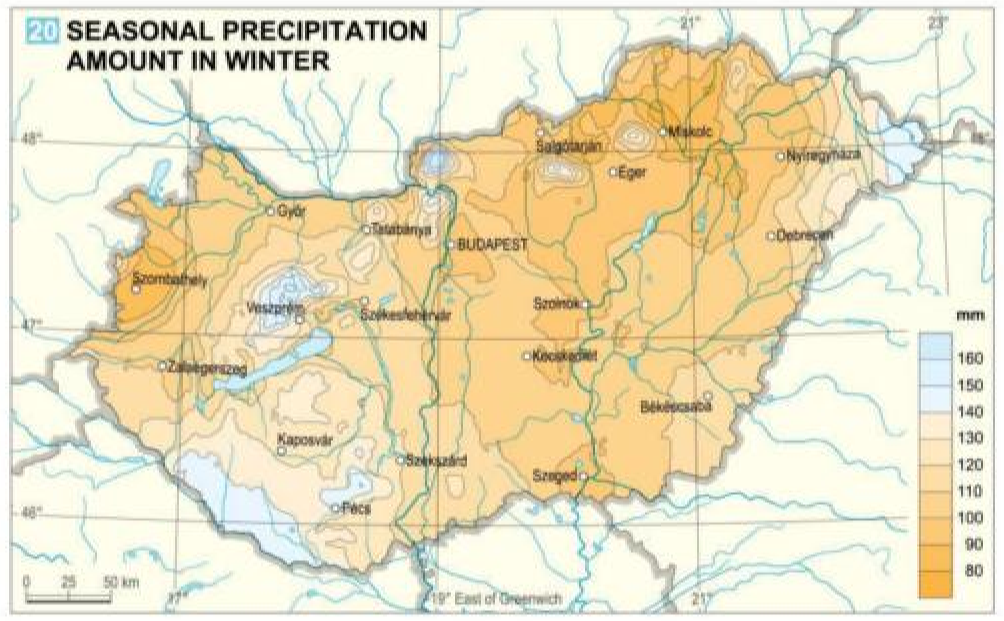
18 SEASONAL PRECIPITATION AMOUNT IN SUMMER



19 SEASONAL PRECIPITATION AMOUNT IN AUTUMN



20 SEASONAL PRECIPITATION AMOUNT IN WINTER



Considering the annual course, less precipitation falls in the winter half year (from October to March), about 40% of the countrywide average. This means that Hungary belongs to the continental climate zone characterised by drier winters and wetter summers, i.e. the continental characteristics of precipitation distribution are stronger than its oceanic or Mediterranean features. Observed monthly precipitation is presented for two periods 21: the period of 1981 to 2010, which describes the present situation better, and the period of 1961 to 1990. (The latter period is of special importance in climate evaluation as it is used as the reference period when modelling the future climate.) Precipitation is a highly variable parameter in the region, as its countrywide monthly amount can be three times higher than, or one third of the long-time average. For example, in the rainiest month of the later period, in May of 2010, the countrywide average was 172 mm, while in the driest month, in February of 1998, the countrywide average did not reach 2 mm.

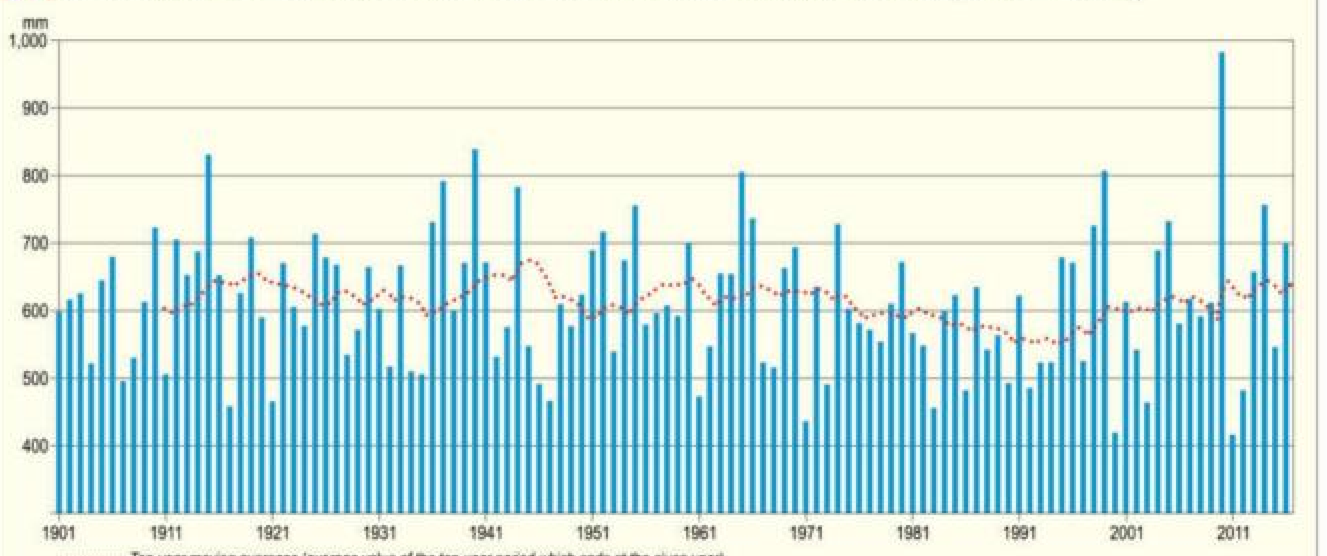
3 *Air flowing out of a summer thunderstorm (straight-line wind) and stripe of precipitation above Lake Balaton*

21 MONTHLY MEAN PRECIPITATION

Based on observations for the periods 1961 to 1990 and 1981 to 2010, and on simulations of two regional climate models for the periods 2021 to 2050 and 2071 to 2100

Among the seasons winter precipitation is the lowest, it was only 19% of the annual value in the period of 1981 to 2010. December is the wettest winter month in this period, and the January average has dropped, so in January and February almost the same amount of precipitation falls countrywide. The precipitation supply gradually increases during the spring months, the countrywide average rises from 34 mm (in March) to 61 mm (in May). The wettest month in summer and also in the whole year is June, though the average monthly amount for June is lower during 1981 to 2010 than in 1961 to 1990. Comparing these two standard periods we can say that more precipitation fell in July in the later standard period, while the amount in August did not change remarkably. In its annual course the amount of precipitation decreases during the autumn until October, then in the wettest autumn month, in November, the countrywide average approaches 50 mm. In the period of 1981 to 2010, the monthly means of September and October increased, while that of November slightly decreased, meaning that the secondary, autumn maximum is not as significant as it was in the previous standard period.

22 COURSE OF THE ANNUAL PRECIPITATION AMOUNT (1901–2016)



Ten-year moving averages (average value of the ten-year period which ends at the given year)

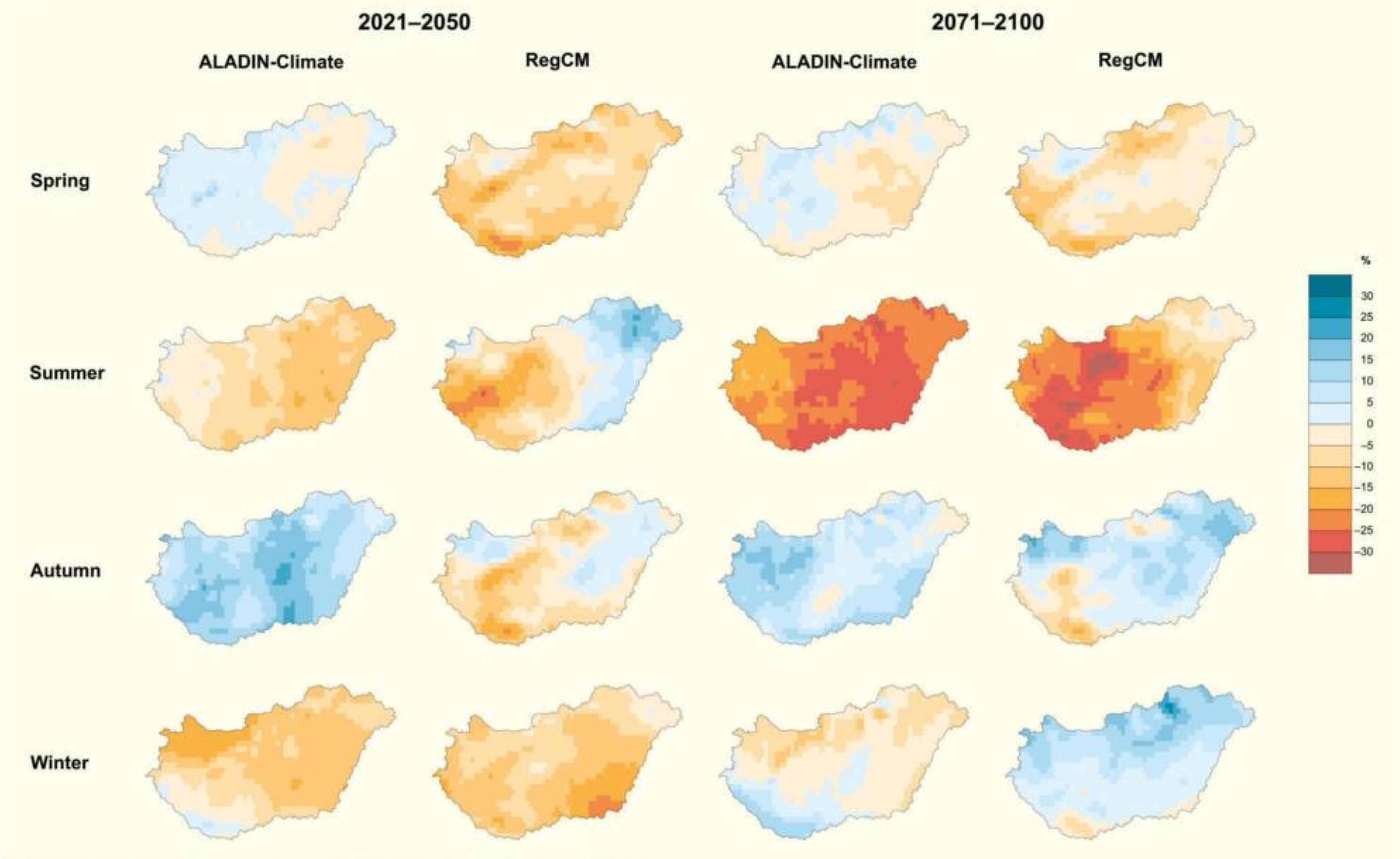
Future precipitation change in Hungary

Similarly to temperature, uncertainties of the future precipitation results can also be quantified by the ensemble method, meaning that the results of multiple simulations (all providing a possible future path of evolution of the Earth System) are investigated together. The uncertainties of precipitation projections are assigned principally to natural climate variability and the various approximations used in the climate models for describing precipitation formation processes. Future changes are evaluated for two 30-year periods compared to a past reference period (1961 to 1990). The period of 2021 to 2050 is important for the adaptation strategies, while 2071 to 2100 was selected for the reason that the changes are more robust (i.e. statistically more significant) since the projected climate change signals exceed natural climate variability more often.

Precipitation change signals over Hungary are less clear than for temperature. Model results show an ambiguous direction of change in some seasons as the Carpathian Basin is located in a zone where global and regional simulations indicate very little change for the annual sums. North of Hungary precipitation increase, while south of it precipitation decrease is more likely, consequently the location of the area where the climate change signal turns from positive to negative is not straightforward. Moreover, due to the naturally high precipitation variability, results are often not statistically significant or the simulations do not even share the same sign. Current observed trends may not necessarily continue in the future. Annual sums are projected to increase over eastern Hungary in the next few decades according to both model results, while the changes over western Hungary are less clear since one simulation shows a slight precipitation increase while the other one portrays a 10% reduction. By the end of the 21st century, both models indicate an annual decrease over most parts of the country, although there may be growth in precipitation in the northeastern and northwestern regions. Changes are, in general, within the magnitude of 10% and not statistically significant.

In the last few decades the wettest season has been summer, while the driest has been winter on average in Hungary. Even though these main features will not change in the future, some variations in the intra-annual distribution are likely to occur. Based on the results of the two models, the average amount of precipitation in summer and winter is expected to drop by 2021 to 2050, particularly in July–August and January–February 21. Seasonal changes are between 10 and 20% over a large part of Hungary and only a few gridpoints have values notably higher than 20% 23. The previously mentioned decrease is compensated by a positive change in spring and autumn in the ALADIN-Climate model, while the RegCM model mainly supports the negative direction in these seasons as well. Therefore, simulation uncertainty is the largest in these months, possibly reaching a 15–20 mm deviation between the precipitation amounts in the 2021 to 2050 period. By the end of the 21st century both models indicate stronger summer drying. These results are statistically significant and the magnitude of change can reach –20% over a large part of the country, while in certain areas even –30% is possible. At the same time, the precipitation increase in autumn could be so large that the secondary annual peak could even approach the magnitude of the summer peak. In the past June was clearly the wettest month on average, while November may achieve similar amounts by 2071 to 2100 21. Whereas spring precipitation is not expected to change remarkably, winter changes are more relevant but, at the same time, ambiguous in the model simulations: while the ALADIN-Climate model shows a precipitation decrease, the RegCM model renders an increase for 2071 to 2100 (opposed to the decrease for 2021 to 2050).

23 **EXPECTED SEASONAL PRECIPITATION CHANGE**



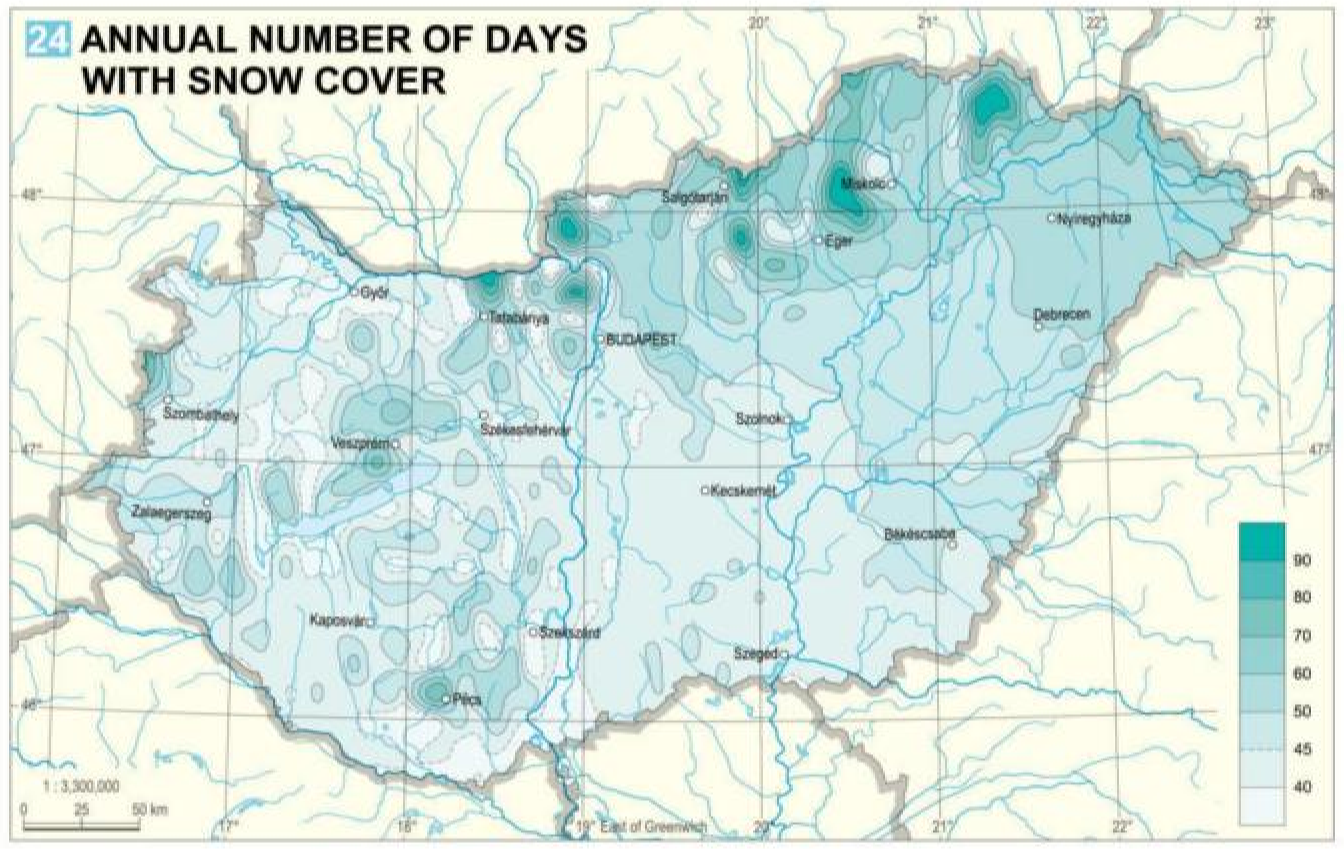
For 2021–2050 and 2071–2100 with respect to the reference period of 1961–1990 based on two regional climate model simulations

The countrywide annual mean precipitation varies greatly 22. The first half of the 20th century was wetter than the period starting in the 1970s, which was drier in total with high annual fluctuations. While earlier wetter and drier years appeared in groups, the period after the millennium is characterised by extremities. Consequently, drought is a recurring phenomenon of the region. (Drought is discussed in detail in the *Natural Hazards* chapter.) Drier years occurred in every decade, but they have become more frequent since the middle of the 1970s, although the mean precipitation of the last standard period (1981 to 2010: 587 mm) exceeds the previous values (1961 to 1990: 577 mm, 1970 to 2000: 568 mm).

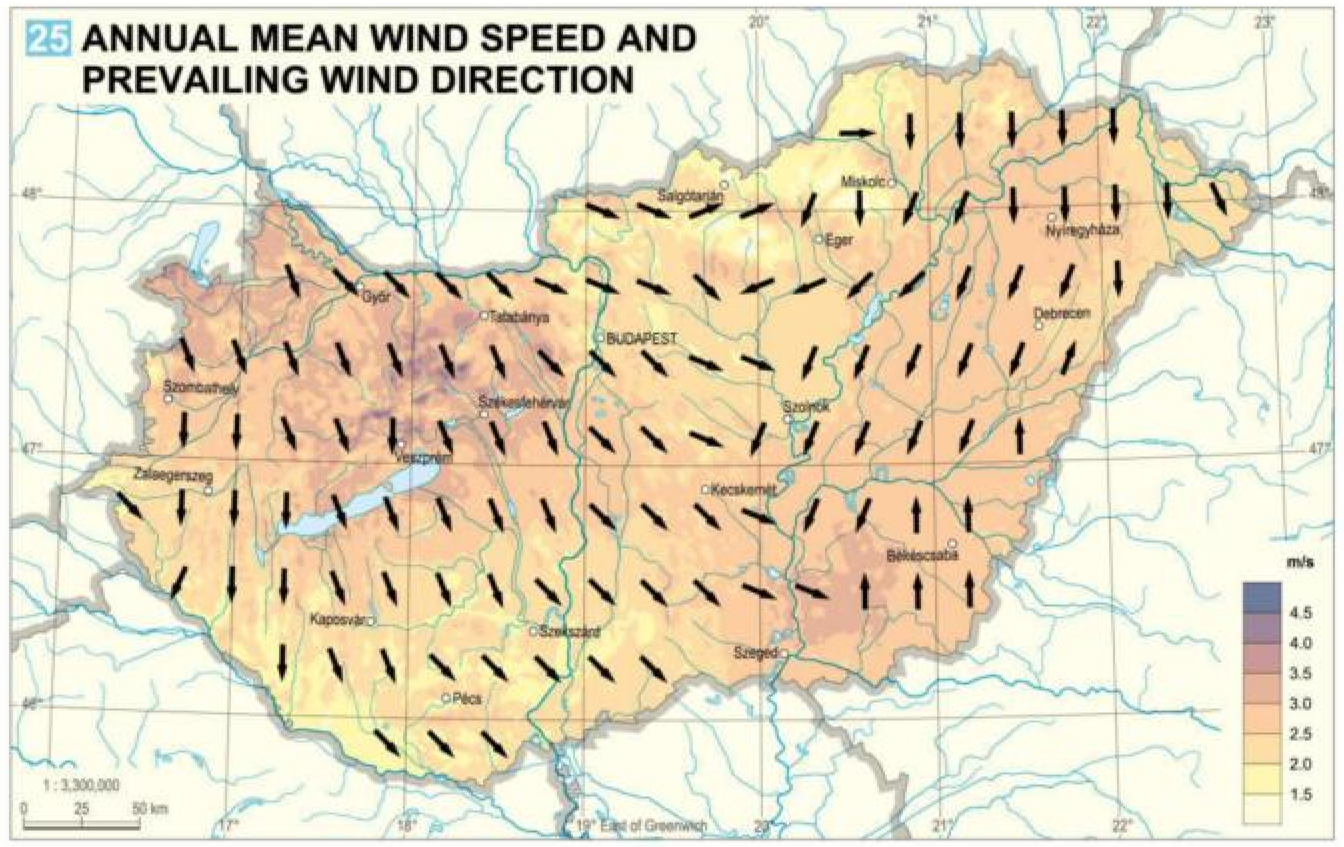
While in northern and western Europe there is more precipitation due to climate change, our region is beginning to resemble the Mediterranean region since it has fewer days with precipitation and the annual amount also displays a decreasing tendency. Precipitation fluctuates greatly both in space and time, thus one-way changes are harder to detect than in the case of temperature. Although its annual amount saw only a 5% decrease from 1901 to 2016, its annual distribution changed remarkably: spring precipitation significantly decreased (by 17%), the secondary, autumn maximum is disappearing due to the 12% drop, while summer precipitation increased by about 6%.

4 *The condition of poplar trees after a wind storm indicating the strength and direction of the wind*

24 **ANNUAL NUMBER OF DAYS WITH SNOW COVER**



25 **ANNUAL MEAN WIND SPEED AND PREVAILING WIND DIRECTION**



From the beginning of the 1990s, precipitation amounts have been increasing both on annual and seasonal scales, however this rise is not significant. Recent years have been dominated by extremes.

Snow cover

Of the climate characteristics related to snow, the most expressive is the number of days with snow cover. Knowledge of it is important in many areas, e.g. in agriculture, tourism and transport. The duration of snow cover is determined by the joint effect of several factors, the most important of which are the amount and accumulation of the fallen precipitation and the temperature of the air and the soil surface; the spatial distribution of these factors is reflected on the map presenting the number of snow cover days 24. The longest snow cover durations occur in the mountains with 90 days or above, while the effect of the southwest–northeast decrease in winter temperature can be observed in lower lying areas. The long-term countrywide average is 47 days, however there is a great fluctuation in individual years, when double–triple differences can occur. In the period of 1980 to 2010, the smallest value, occurring in 2007, was just 18 days, while the greatest value, in 1996, was 89 days. Since the winter precipitation amount and mean temperature have slightly increased in recent decades, due to these two opposite effects, the countrywide average number of days with snow cover does not show unidirectional change.

Wind

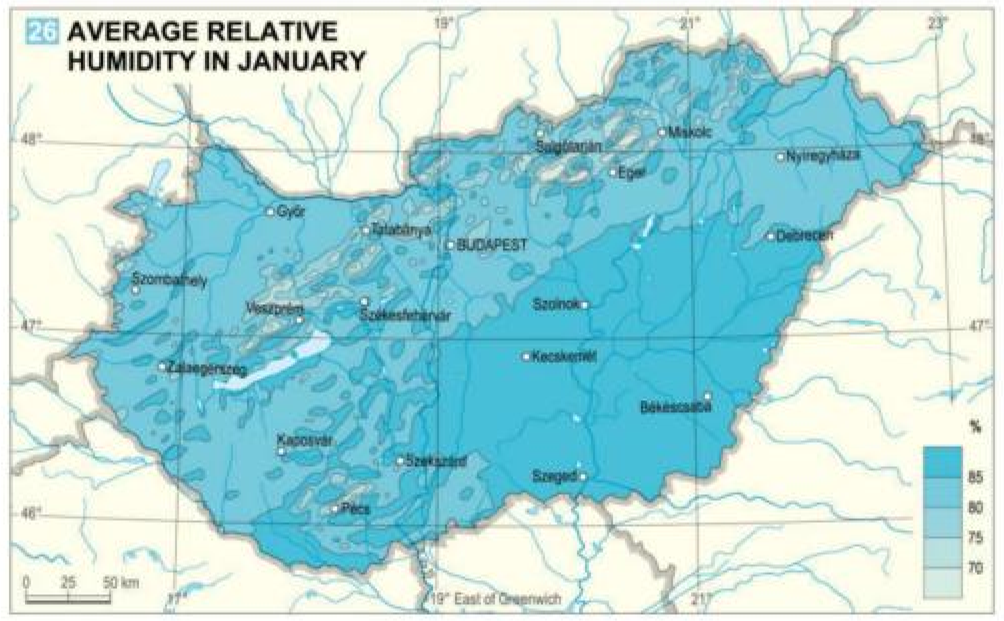
Due to the geographical location of Hungary, the prevailing wind direction is northwestern 25 4 while the southern winds are the secondary maxima. Northwestern airflow is emphasized in most areas of Transdanubia and between the Danube and Tisza rivers, while due to its location in the basin, east of the Tisza the prevailing wind is northeastern.

In areas with varied terrain, in mountains and hills, a deviation from these two directions can be experienced. It is worth noting that the relative frequency of the most frequent, i.e. prevailing wind is generally 10–15%, with the secondary maximum being barely different.

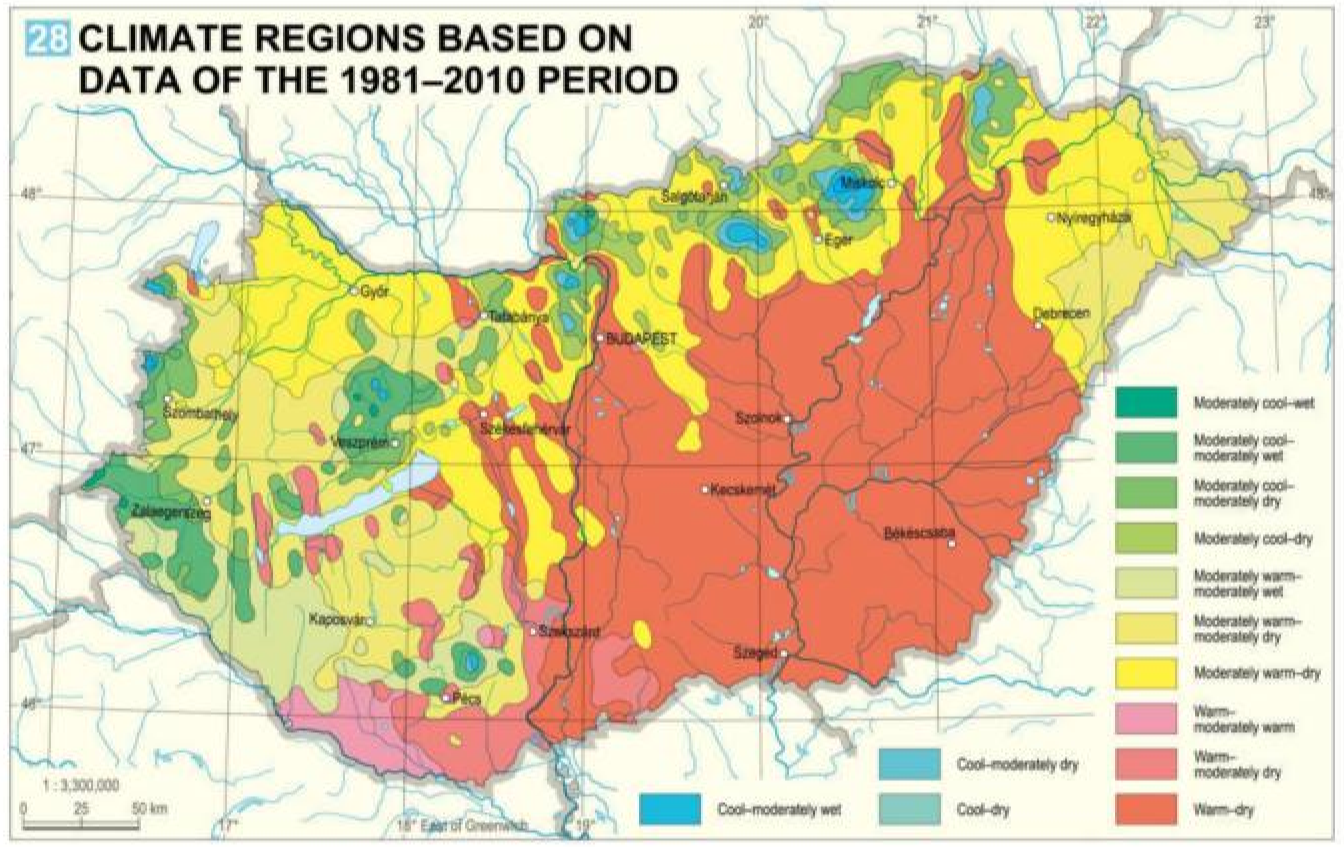
Wind speed is determined considerably by local effects like the relief, land cover and other obstacles in the vicinity of a given location (buildings, trees, etc.). The roughness parameter is used for quantifying the latter effects. The roughness parameter for low vegetation sporadically interrupted by higher obstacles is 0.1 m, the map of wind speed and direction 25 was made with this assumption, because this roughness type is characteristic for the most areas of the country. Based on wind speed, Hungary belongs to the moderately windy regions. The annual mean wind speed is around 2.5 m/s in most areas of the country, however higher values can be observed in the middle of the Alföld and in the Transdanubian Range. Due to local effects, the strongest winds are measured in the Bakony Mts., while south of the North Hungarian Range and in the southwestern part of Transdanubia, the shading effect of the mountains can be observed.

Wind speed has a characteristic annual course. Generally, March and April are the windiest months

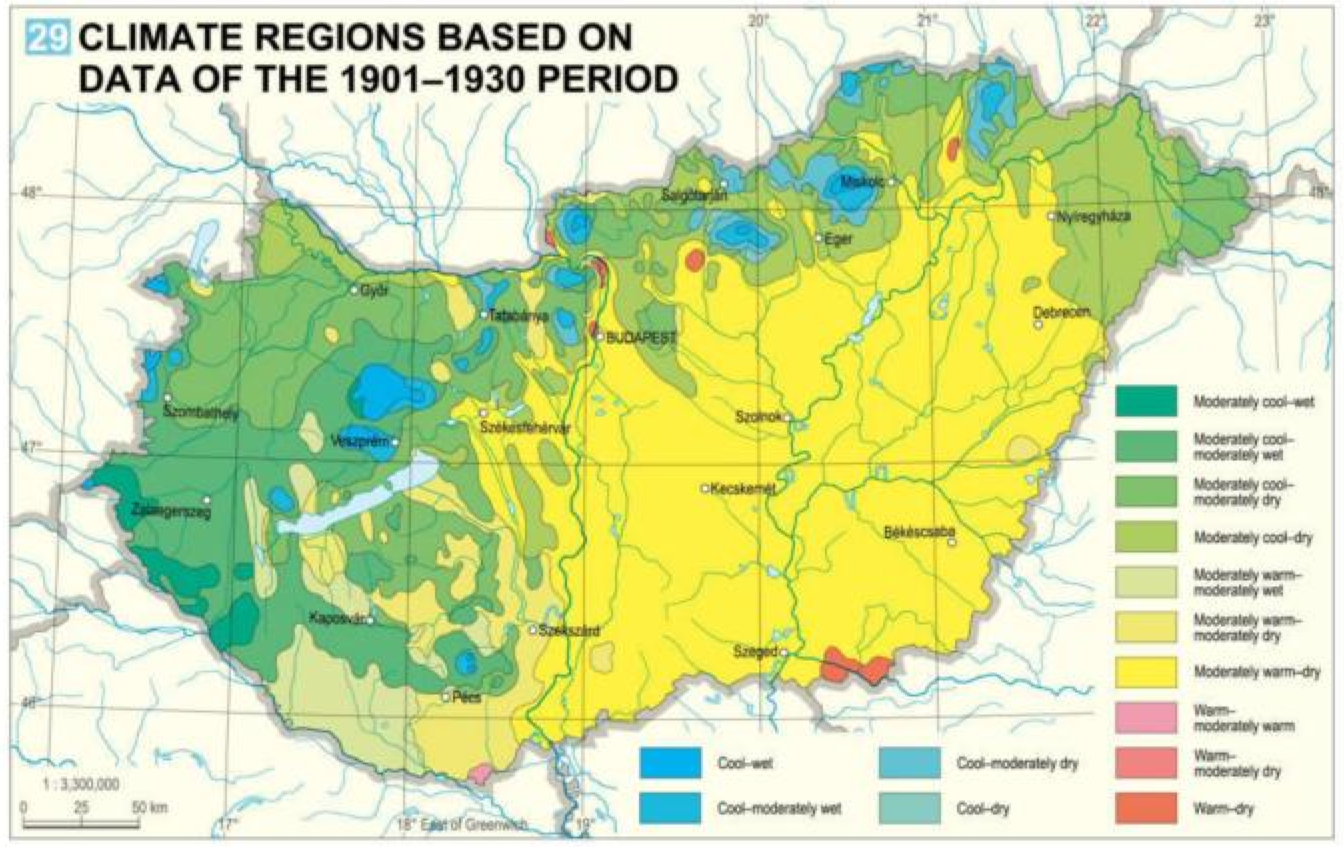
26 **AVERAGE RELATIVE HUMIDITY IN JANUARY**



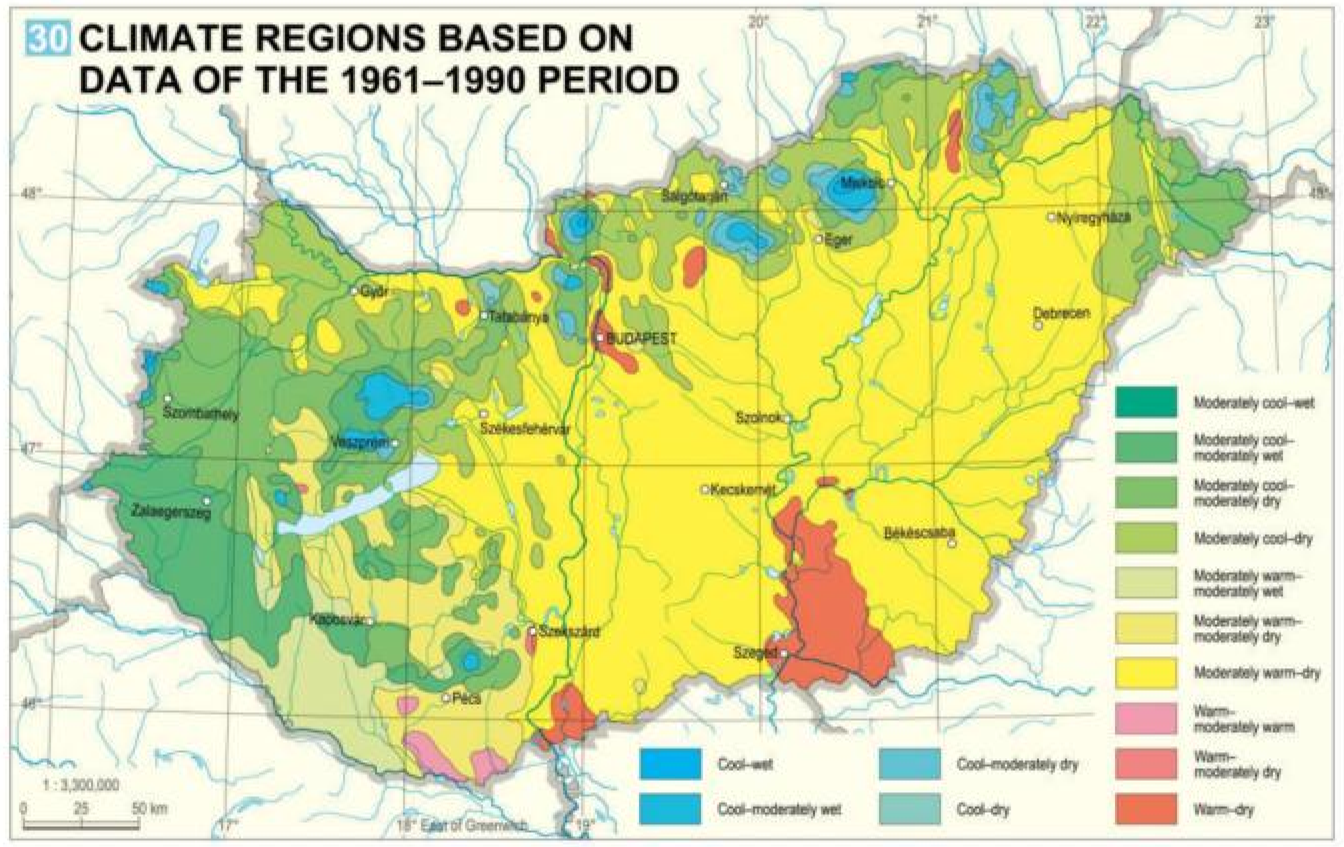
27 **AVERAGE RELATIVE HUMIDITY IN JULY**



28 CLIMATE REGIONS BASED ON DATA OF THE 1981–2010 PERIOD



29 CLIMATE REGIONS BASED ON DATA OF THE 1901–1930 PERIOD



30 CLIMATE REGIONS BASED ON DATA OF THE 1961–1990 PERIOD

with countrywide mean values of 3.2 to 3.3 m/s (for example the so-called fasting winds before Easter), while the lowest values (2.5 m/s) can be observed between August and October. The countrywide mean number of windy days (when the speed of the strongest wind gusts reaches or exceeds 10 m/s) is 133 days, of which 38 days are stormy (when the strongest wind gust is above 15 m/s).

Relative humidity

One of the most well-known measures of the amount of water vapour present in air is relative humidity, which expresses the ratio of the partial pressure of water vapour to the saturated vapour pressure of water at the given temperature. The annual course of relative humidity is roughly the mirror image of that of temperature, it has its maximum in December–January and minimum in July. Maps 26 27 show the differences that can be observed between the two extreme months, January and July. While in January the countrywide average is 83%, in July this value is just 67%. The two months differ not only in value but in spatial distribution as well: in January the most humid areas are located on the southeastern part (e.g. in the Alföld), while in July they are along the southwestern border of the country (e.g. in Zala, Somogy and Baranya counties).

Climate regions

In climate studies the practice of climate classification is based on the examination of the concomitance of different parameters, and using the existing similarities, the climate is classified into types. Some of these classification systems determine global types, other systems are capable of describing finer details. The most known classification in Hungary is associated with the name of György Péczely, therefore this system is applied in our climate region descriptions as well. Using the aridity index and the temperature of the vegetation period, this method identifies 16 climate regions, of which a total of 14 can be observed in the present area of Hungary 28. Based on this classification, it can be said that most of the country belongs to the warm – dry region classification, while the opposite, cool – wet regions can be found only at the highest parts of the mountain ranges.

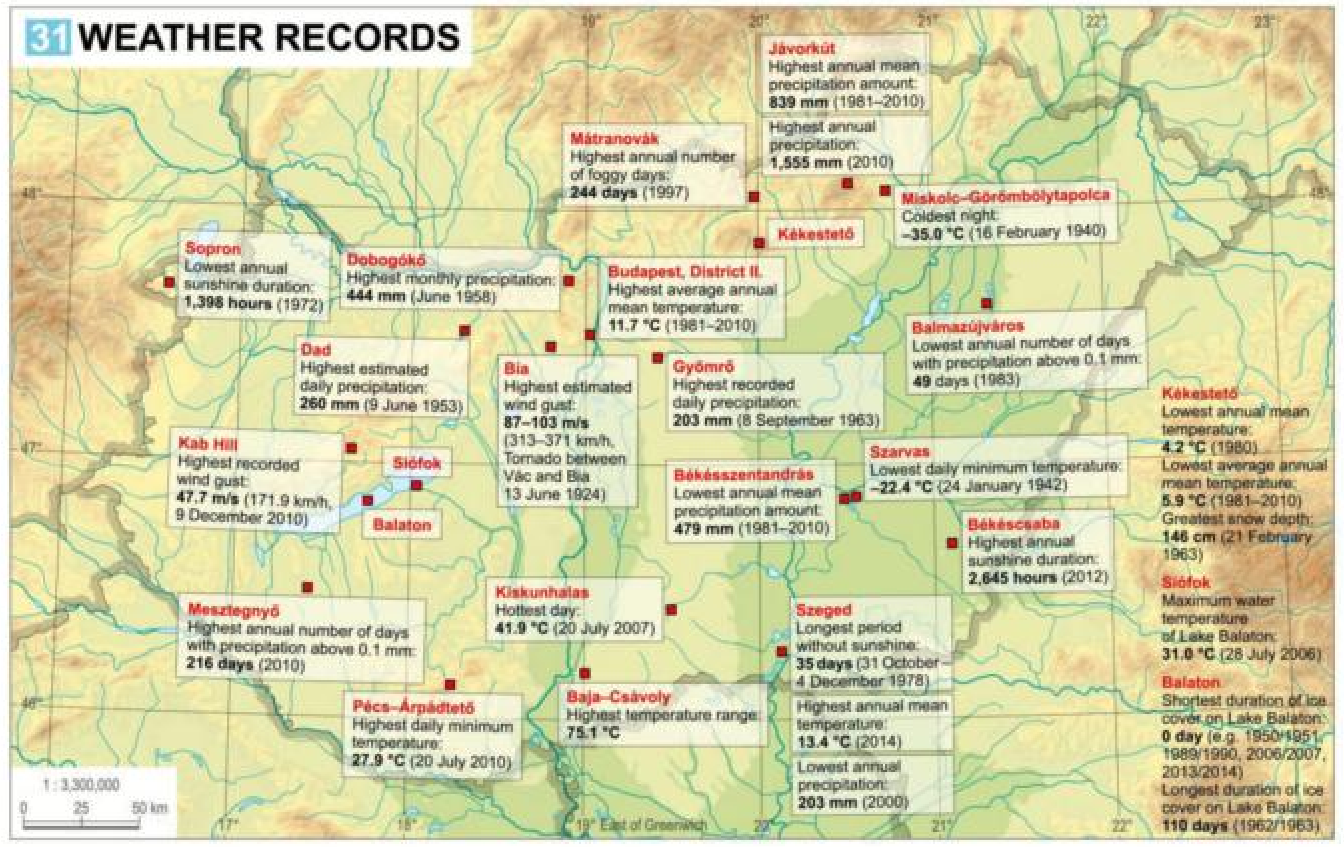
Because of climate change, the ratio of the areas of the various climate regions has remarkably changed compared to past periods. The most conspicuous change is the spread of warm – dry areas to the expense of moderately warm – dry regions. At the beginning of the 20th century 29 and even in the years of the 1961 to 1990 period 30, only very small areas belonged to this extreme category. The area of moderately cool regions has also decreased, with their place having been taken over by moderately warm areas.

Climate extremes

Weather records

The occurrence of extreme values, i.e. the highest or lowest ever observed values of climate elements or phenomena, is often a consequence of the random coincidence of different meteorological phenomena and strengthened local effects. The determination of extreme values is an essential task of a monitoring network. An extreme value observed at a particular geographical location is just an interesting thing in itself, but a detailed analysis of extreme values has practical implications.

The weather records of Hungary based on the data observed by the Hungarian Meteorological Service (OMSZ) and its predecessors are shown in map 31. The recording of extreme values and determining the absolute extremes has been performed since observations began, the values have been updated many times. Naturally, higher values may have occurred, but on the one hand data are available only at instrumental monitoring points, on the other hand not all data are available in digital form, especially from the first part of the 20th century.



31 WEATHER RECORDS

Heat wave days

Changes in the extreme temperature values suggest that climate change in our region involves a clear increase of the warm extremes. Not only the temperature values but other derived climate indices (see the above previous text box) indicate the changes to the climate. Considering the tendencies of the latest decades, the sharpest growth in the number of heat wave days (when the daily mean temperature is above 25 °C) can be observed in the central parts of the country and in the southern parts of the Alföld 32. The extent of the increase exceeds two weeks in many areas in the intensive warming period after 1981. In our higher mountains, heat waves were not typical in the beginning of the period, and their number did not increase either in the temperature increasing period, but today we have to count on them occurring in the Alpokalja region and the Transdanubian Range.

Because of the cooler summers, there were only a few heat wave days in the beginning of the 20th century 33, then an increasing tendency appeared until the beginning of the 1950s followed by a cooler period. After that, from the 1980s, the intense warming can be also seen in the increasing frequency of heat wave days, which is obvious from the 1990s. In the last decade ending in 2016, as many as 14 heat wave days were detected on countrywide average. The growth is 6 days from the beginning of the last century, which significantly indicates the increasing tendency of warm extremes.

Precipitation extremes

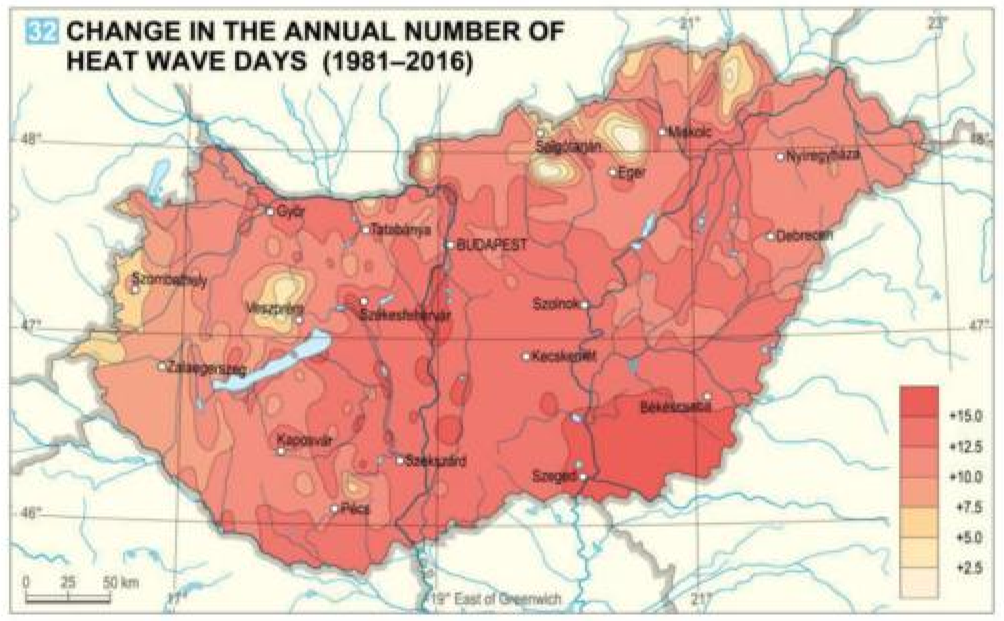
Climate change is manifested in more extreme rainfalls, but these do not equally affect the regions. Changes in the precipitation extremes are less obvious, however, based on observations, tendencies can be determined. The countrywide average increase in the number days when the precipitation amount is high (above 20 mm) is 1.8 days, however there are regions where it shows a decrease in the 1981 to 2016 period 34. The spatial distribution is very diverse, the highest rise (6 days) occurs in the vicinity of the Bükk Mts., while a decrease is apparent in the Zala Hills and in Nyírség.

The countrywide average of the number of days with high precipitation (above 20 mm) shows high temporal variation in the data series of 116 years covering the whole 20th century and extended to 2016 35. In the 20th century, there was an increasing tendency until the beginning of the 1940s, then it turned to decrease till the end of the 1990s, with by an extremely high number of days with precipitation above 20 mm occurring in many of the following years. The greatest number of such days was 9 on countrywide average in 2010, which was the wettest year concerning the precipitation amount as well.

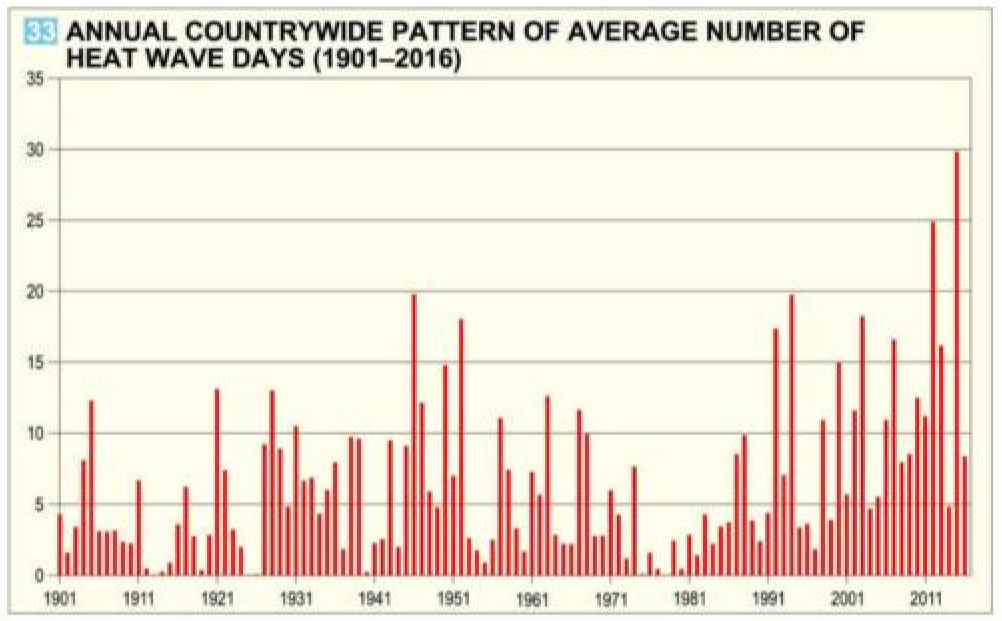
Effects of extremities on the human body

Thermal comfort affects human health and well-being. The most well-known measure of this is the *physiological equivalent temperature (PET)*, which is defined as a fictional, meteorologically standard indoor air temperature at which the human body has the same physiological responses (e.g. sweating) as under complex outdoor conditions.

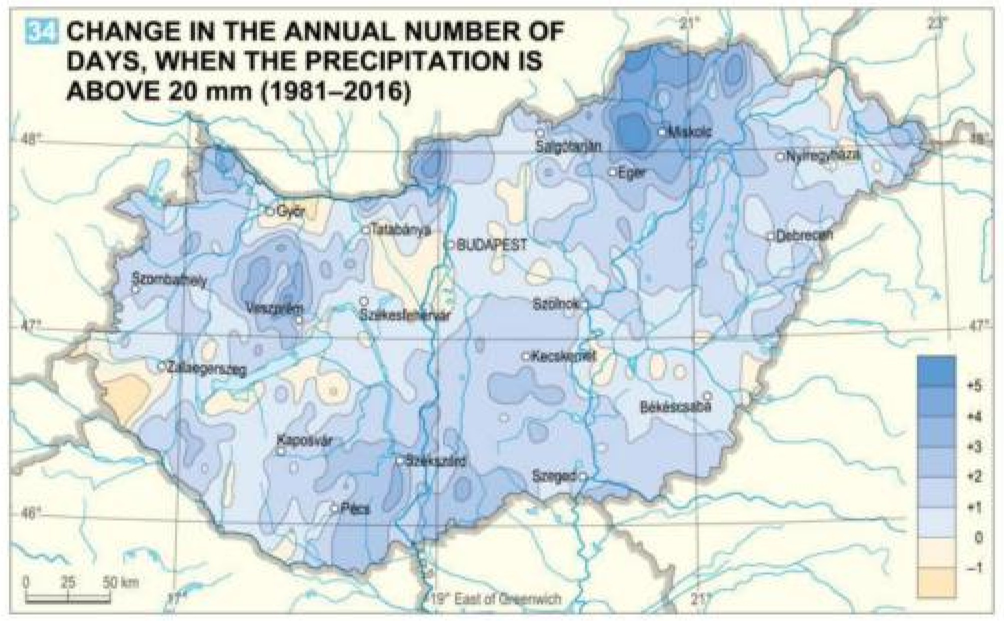
The relative frequency of thermal perception categories is shown by the so-called bioclimatic diagram 36. We can count on days causing warm or slightly warm stress from the third part of March to the beginning of October. Days with hot stress can occur from June to the middle of September, however their relative frequency does not reach 10% anywhere. The most stressful thermal comfort period of the year is the first part of August. During December and January, our bodies are affected by cold stress to lesser or greater extents; there are no neutral days in these two months. Spatial differences are very small in the country, while



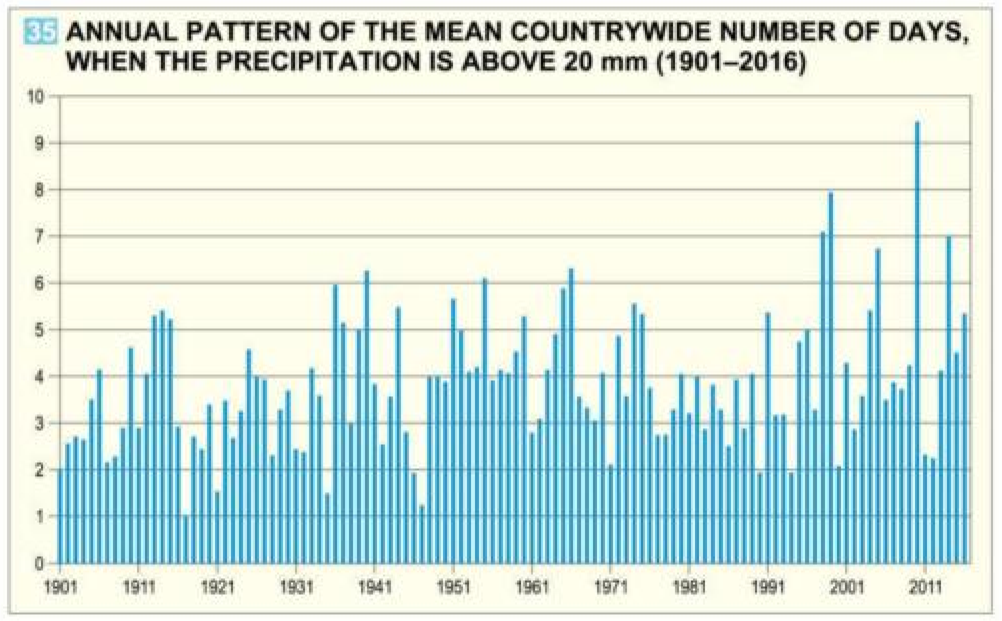
32 CHANGE IN THE ANNUAL NUMBER OF HEAT WAVE DAYS (1981–2016)



33 ANNUAL COUNTRYWIDE PATTERN OF AVERAGE NUMBER OF HEAT WAVE DAYS (1901–2016)

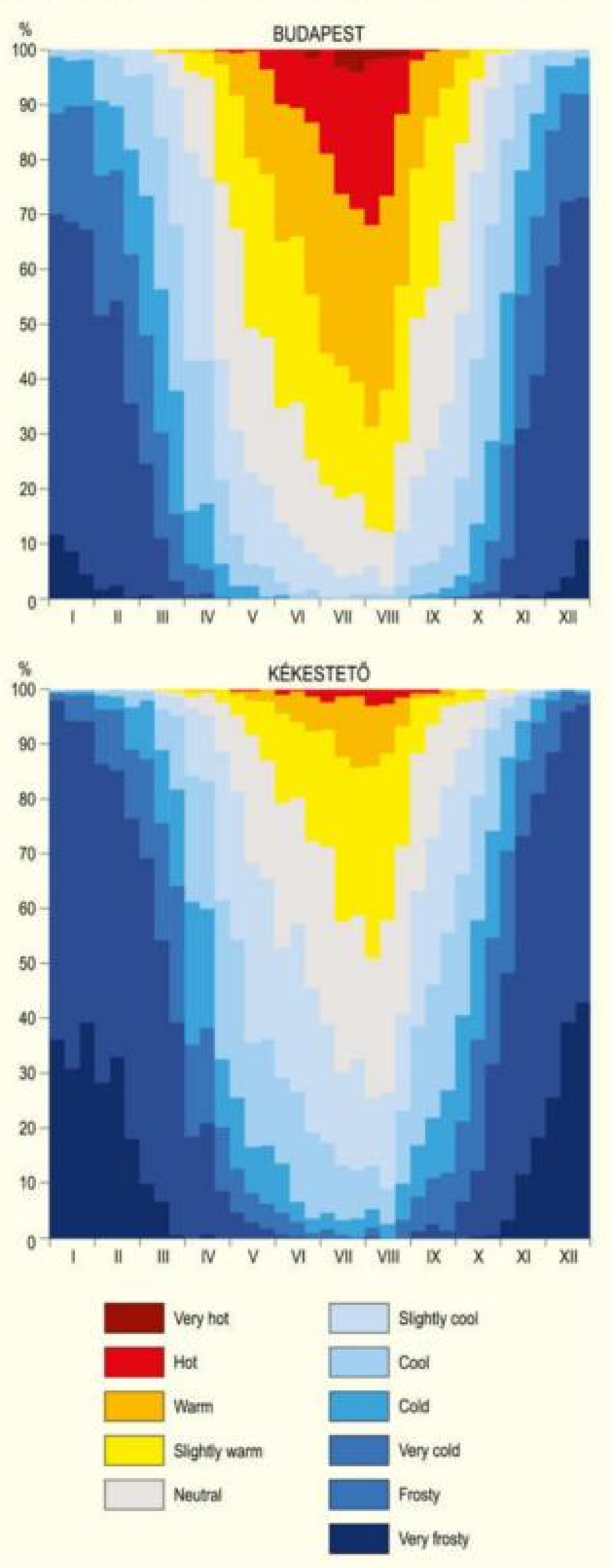


34 CHANGE IN THE ANNUAL NUMBER OF DAYS, WHEN THE PRECIPITATION IS ABOVE 20 mm (1981–2016)



35 ANNUAL PATTERN OF THE MEAN COUNTRYWIDE NUMBER OF DAYS, WHEN THE PRECIPITATION IS ABOVE 20 mm (1901–2016)

36 BIOCLIMATIC DIAGRAM OF BUDAPEST AND KÉKESTETŐ

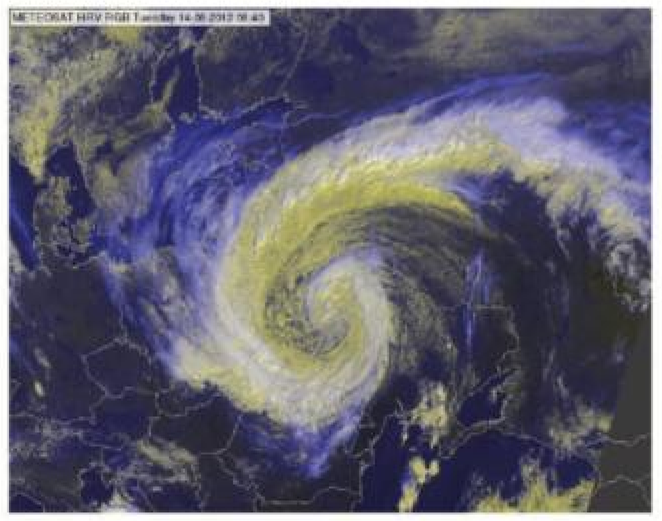


the role of altitude is more significant; however the diagram of Kékestető (highest point in Hungary) clearly indicates that in the summer period we can count on serious heat stress even at higher altitudes.

Remote sensing in climate monitoring

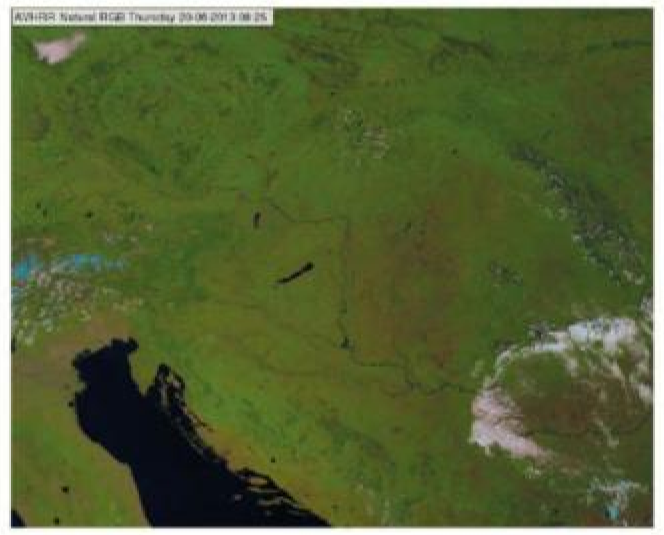
Meteorological remote sensing observations started more than fifty years ago. Since that time, the measuring instruments have developed a great deal, and the data can be used for an increasing number of purposes. Satellite observations have many benefits, since they can provide data for places where surface observation is difficult, moreover, the same instruments are used for the whole Earth. In Europe, the EUMETSAT *(European Organisation for the Exploitation of Meteorological Satellites)* organises and coordinates this activity.

Meteorological satellites measure radiation data in several wavelength ranges, and their purpose is to monitor the atmosphere, including the clouds and the Earth surface. This helps to diagnose (and, based on this, forecast) the weather, to observe the climate and to understand the atmospheric processes better. In addition to displaying the satellite data as images, many atmospheric and surface parameters (e.g. cloud top height and temperature, ground surface temperature, vegetation cover) can be calculated from the observations. Modern satellite images are not simple photos but numerical data that can be transformed to physical quantities, however the displayed images are still important in meteorology 5 6. Forecasters can examine dense (even 5-minute) series of satellite images, in which the movement of cloud patterns, the generation and evolution of thunderstorms, the dissipation of fog patches can be easily traced.



5 *Satellite image of a cyclone above Europe (14 August 2012)*

Satellite data also help forecasters make short and medium range weather predictions. An increasing amount of satellite data and derived parameters are used in numerical weather prediction models. The chemical composition of the atmosphere can also be observed by satellites, as it is particularly important to observe and trace the components affecting our health (e.g. ozone), air pollutants or gases influencing the climate (e.g. carbon dioxide, water vapour). Multidecadal, long-term satellite data series provide help in climate monitoring, giving information on numerous environmental elements and phenomena with climatic importance, like incoming and outgoing radiation, changes in temperature, precipitation and wind conditions, and vegetation coverage. Satellite data can also help identify drought phenomenon based on the analysis of the vegetation cover, calculating a so-called vegetation index (NDVI).

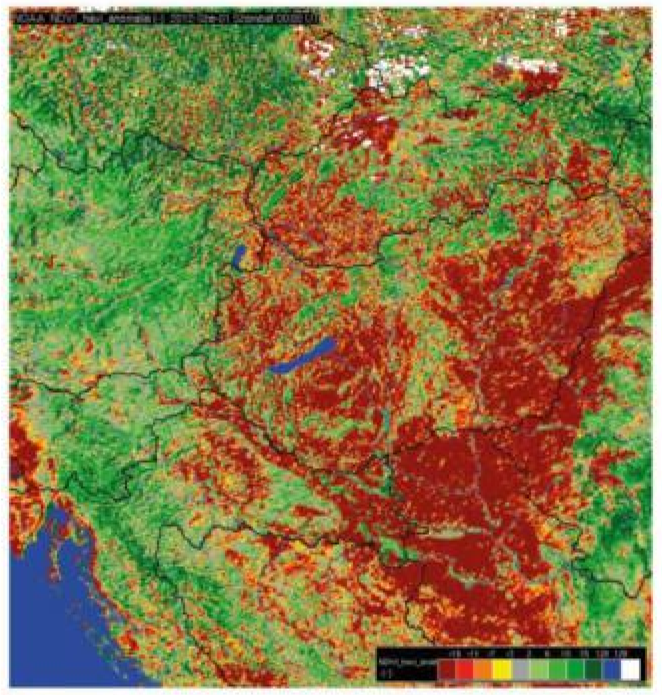


6 *Satellite image of the Carpatho–Pannonian Area in mainly clear weather (20 June 2013)*

Anomaly maps can be compiled based on monthly maps calculated from vegetation index images. The anomaly for a given month indicates how the monthly vegetation values differ from the long-term monthly average of the 2003 to 2012 period. Positive anomalies (green colours 7) show that in the given period the vegetation coverage was higher than in previous years, while negative anomalies (yellow and red colours 8) indicate weaker vegetation. In 2010, the annual precipitation amount remarkably exceeded the long-term average. It can be seen that in August the NDVI values were higher than the long-term average 7. In contrast, 2012 was a year with severe drought, the precipitation falling in the vegetation period was significantly lower than the long-term average in many months and there was a long heat wave period in summer. This extremely dry and warm period was also reflected in the growth of vegetation, in September the NDVI values were lower than the 10-year average in the whole country 8.

> ***Vegetation index** (Normalised Difference Vegetation Index) is a dimensionless number connected to the photosynthesis of plants, i.e. to the amount of chlorophyll produced. Satellite observation of vegetation is based on the fact that the radiance values reflected back from the vegetation and the ground surface differ in different wavelength ranges. Vegetation reflects only a small portion of visible light, while the reflection in the near-infrared intensifies in proportion to its development and chlorophyll content. When the vegetation suffers from water shortage or the end of vegetation period approaches, the chlorophyll content decreases and the measured proportion of reflectance in different wavelengths decreases.*

7 *Anomalies in the vegetation index in August of 2010*



8 *Anomalies in the vegetation index in September of 2012*

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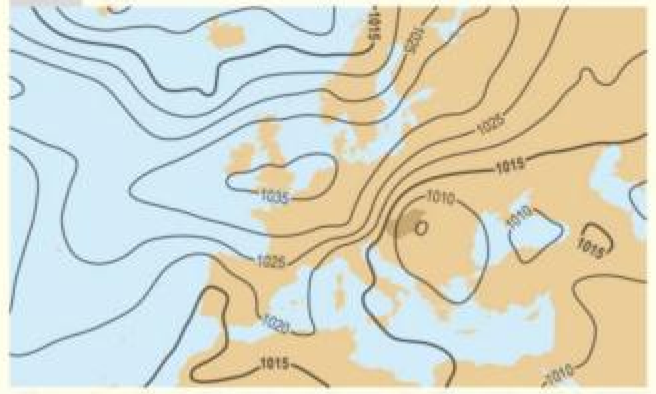
37 PÉCZELY'S MACROCIRCULATION CLASSIFICATION

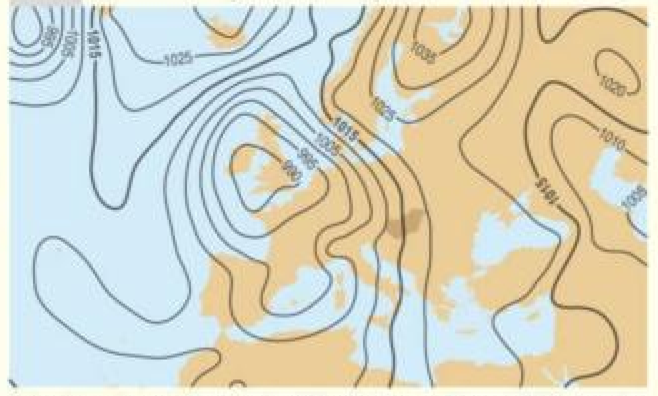
Maps display the lines of equal pressure (isobars) in hPa, the relative frequency of the annual occurrence is shown in brackets

C Cyclone above the Carpathian Basin



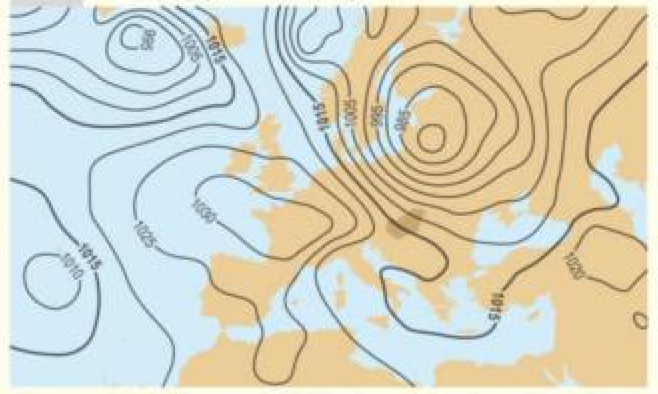
The centre of the cyclone is located above the Carpathian Basin (3%)

mCw Frontal flow system of the cyclone



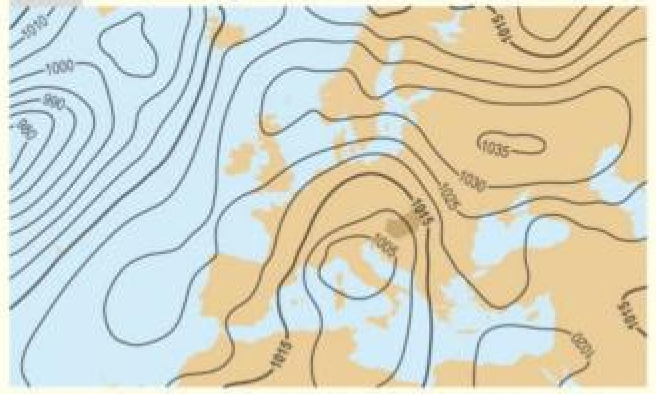
The flow above Hungary is defined by a cyclone with its centre above western–northwestern Europe, Hungary is affected by the warm front of the cyclone (15%)

mCc Rear flow system of the cyclone



Hungary falls in the rear, cold front current system of a cyclone, which stays east–northeast of Hungary above the Baltic region or Ukraine (3%)

CMw Frontal flow system of a Mediterranean cyclone

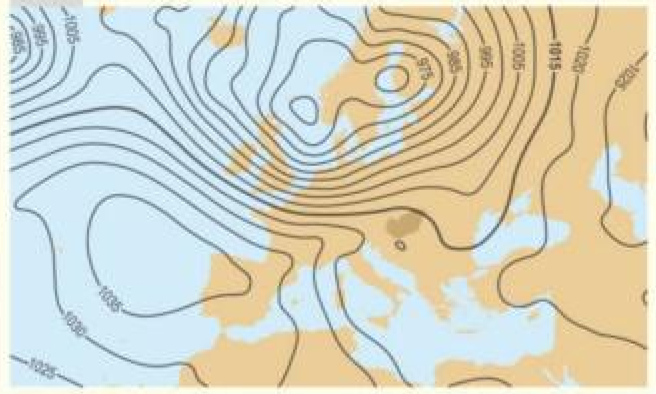


The flow above Hungary is defined by a cyclone which arose above the central part of the Mediterranean Sea and moved toward the Adriatic region (8%)

CMc Rear flow system of a Mediterranean cyclone

A Mediterranean cyclone moves toward the Balkan Peninsula and the region of the Black Sea, Hungary falls in the rear, cold front current system of the cyclone (4%)

zC Zonal cyclone

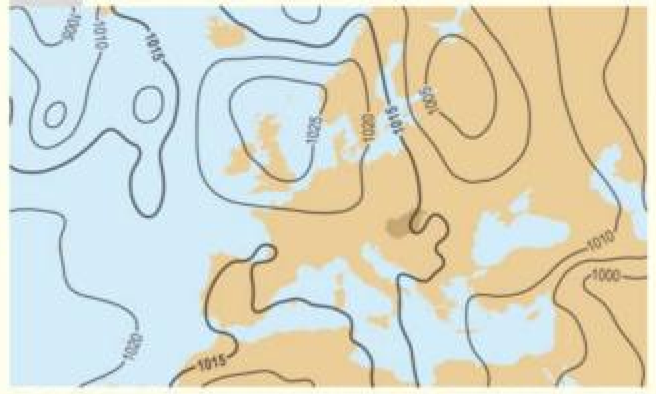


Cold fronts of northern European cyclones moving fast with the western–eastern flow reach the Carpathian Basin (6%)

A Anticyclone above the Carpathian Basin

The centre of the high pressure is located above the Carpathian Basin (8%)

AB Anticyclone above the British Isles

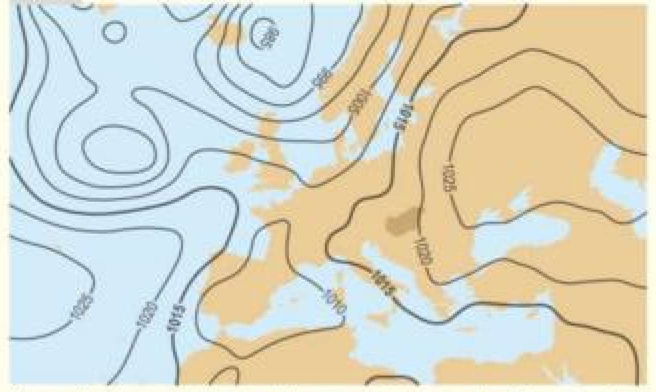


Partly because of the Azores anticyclone moving to the north or because of the anticyclone moving from the arctic basins to the south, high-pressure air masses develop above the British Isles or the North Sea (15%)

Aw Anticyclone located west of the Carpathian Basin

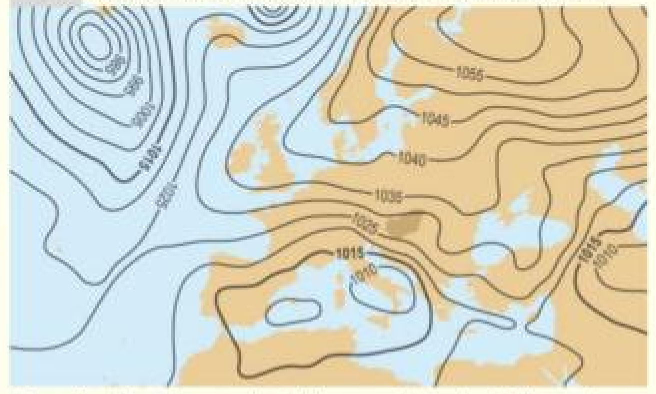
A protrusion of the Azores anticyclone advances as far as the central European region (5%)

Ae Anticyclone located east of the Carpathian Basin



A southerly or south–westerly current of an anticyclone located above Ukraine dominates the region of Hungary (8%)

An Anticyclone located north of the Carpathian Basin



An anticyclone stays north of Hungary above the Baltic region or Poland (8%)

AF Anticyclone above Fennoscandia

Weather of Hungary is defined by an anticyclone staying above Fennoscandia. The characteristic orientation of the longitudinal axis of the anticyclone has a north–easterly direction (8%)

Typical circulation patterns determining the weather

On the basis of the cyclones and anticyclones affecting Hungary, which decisively determine the weather, György Péczely defined 13 main, so-called macrosynoptic circulation patterns. Nowadays, Péczely's circulation types are used in synoptic-climatological studies through analysing the frequency of the studied weather phenomenon in the individual circulation pattern types. It is in this way that climate change can be detected, in some cases. Each type is described by a selected situation 37, and in addition to a short description, the annual relative frequency of the given type is presented for the 2003 to 2014 period. (The individual days were classified by the forecasters of the OMSZ.) The occurrence of the most frequent cyclonal and anticyclonal types (the *mCw* and AB types) is 15% each. It is worth noting that the frequency of periods affected by anticyclones (64%) is twice as great as the frequency of those affected by cyclones (36%).

As Anticyclone located south of the Carpathian Basin

The Carpathian Basin is located at the northern edge of an anticyclone above the Mediterranean Sea (9%)

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Cover design
Gáspár Mezei – Geographical Institute, MTA CSFK, Ildikó Kuti – Civertan Bt.

Design and typography
Ildikó Kuti – Civertan Bt.

Printing
Pannónia Nyomda Kft. (Budapest)

Publisher: László Szarka (Director general)
Hungarian Academy of Sciences (MTA), Research Centre for Astronomy and Earth Sciences (CSFK), www.csfk.mta.hu

The publication is supported by
Hungarian Academy of Sciences (MTA)
Ministry of Human Capacities (Emmi)

Closing date of editing: 31st October 2018

ISBN 978-963-9545-58-8ö
ISBN 978-963-9545-57-1

NATIONAL ATLAS OF HUNGARY
NATURAL ENVIRONMENT

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