Estimated change of hydrology of Lake Balaton for the impact of climate change

Research Report

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EXECUTIVE SUMMARY

The climate of planet Earth has warmed up by about 1.0 °C in the past one and half centuries. It is very likely that warming was caused partly by the increase of emission of greenhouse gases (carbon-dioxide, dinitrogen-dioxide, methane) started after the industrial revolution and accelerating in the recent decades (IPCC 2007). Warming is not extraordinary in climate history, the current warming is made extraordinary by its anthropogenous origin and its all-time high rapid rate. Regardless of the rate of continuing emission of the greenhouse gases in the 21st century, the global temperature may rise by 2–5 °C until the end of the century.

A multitude of uncertainties hinder the analysis of hydrological impacts of climate change:

- uncertainties of socio-economic development and emission
- uncertainties of global climate models
- uncertainties of regional climate models
- uncertainties of hydrological models

The large lakes in Hungary (Lake Balaton, Lake Velence, Lake Fertő, Lake Tisza) are, without exception, typical shallow lakes with their average depth remaining below 5 m. An important feature of the shallow lakes in the moderate climate zone is the high quantitative and qualitative sensitivity to the changes of environmental factors (including climate factors) in space and time.

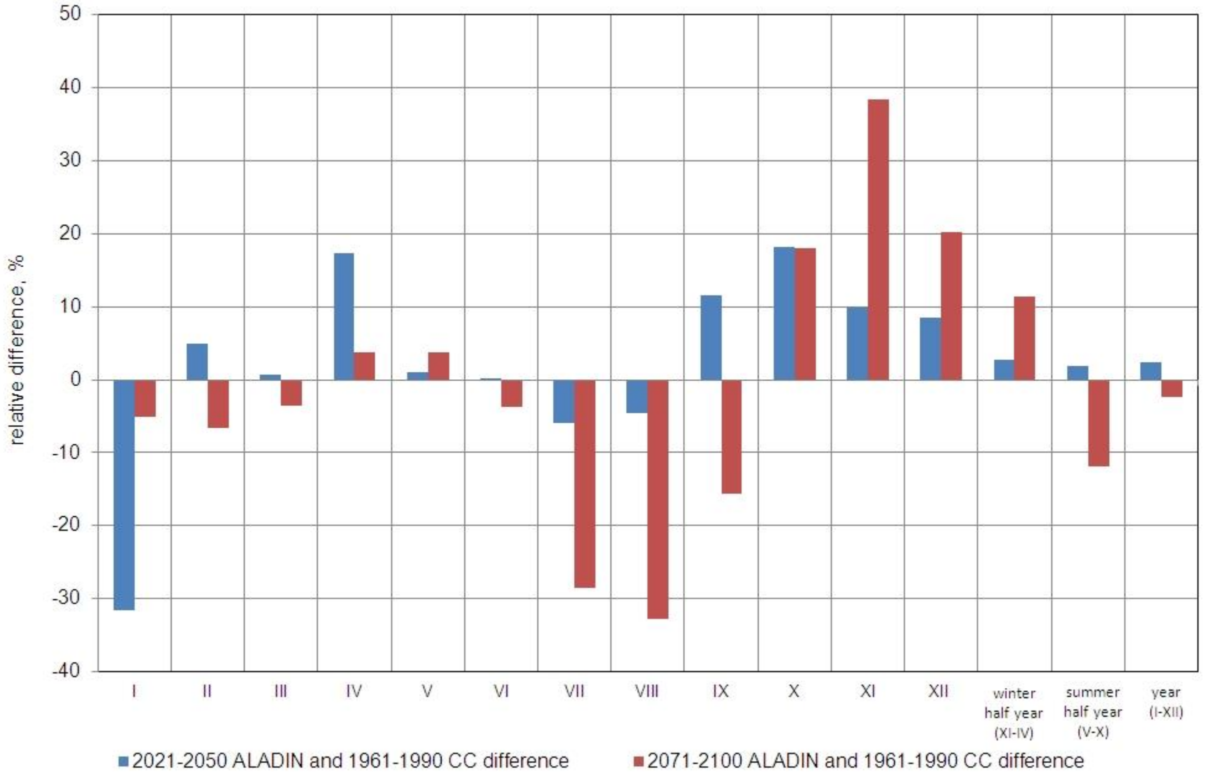
Quantitative sensitivity is manifest in the water balance (typical water turnover) of the lake, consequently in its typically unidirectional change of its water level, water reserve and water surface.

This study deals with the direction and extent of estimated changes in the hydrology of our largest lake, Balaton, for the impact of climate change.

The study includes the estimated trends in the water balance relations of Lake Balaton – the natural factors defining its water turnover (the natural water reserve change interpreted as the algebraic total of precipitation, in-flow and evaporation), the results of the hydrological calculations completed based on the ALADIN-Climate-Hu model results of the Hungarian Meteorological Service covering the reference period of 1961–1990 and the 30-year time periods of 2021–2050 and 2071–2100, respectively.

Reviewing the data concerning the time period of 2021–2050 it is found that considerable changes (exceeding ±10%) are not likely in the estimated trends of precipitation in the watershed (catchment area) of the Lake relative to the average values of the reference period over semi-annual and annual time horizons. In accordance with the relative variances applicable for the specific months, an increase above 10% is manifest in April and in the period of September to November, whereas, a decrease by 32% is recorded for January.

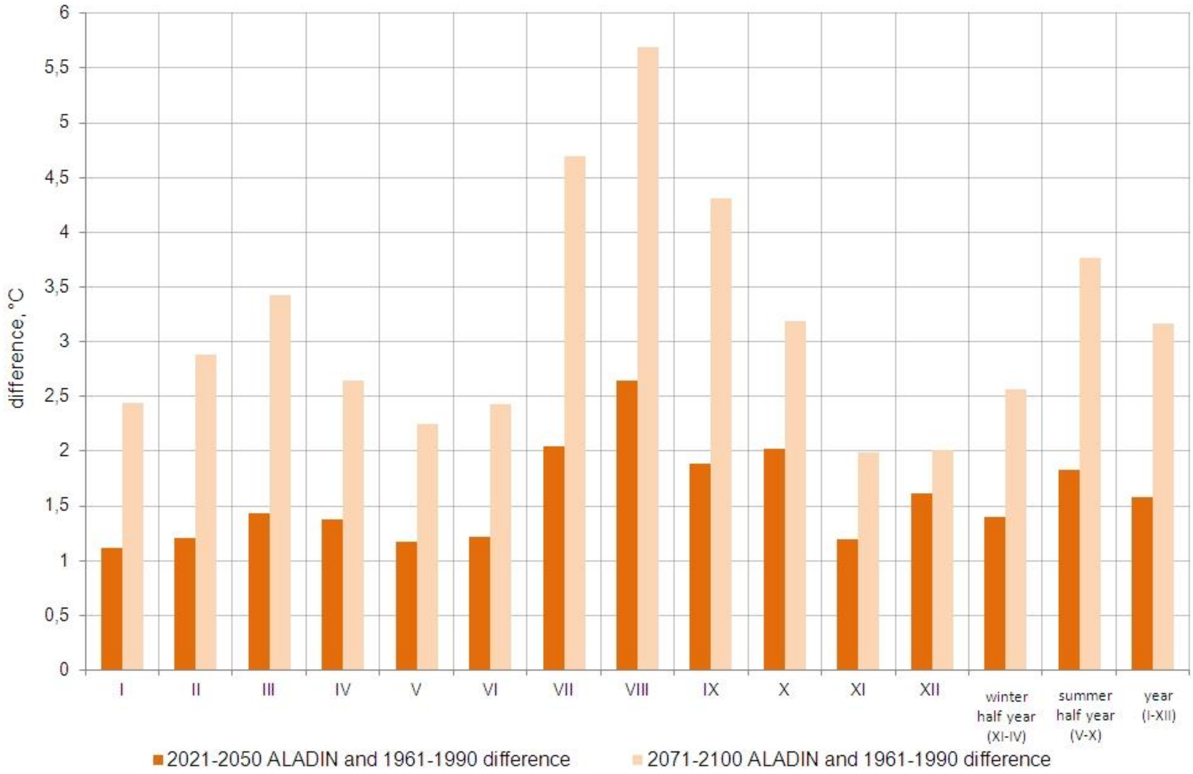
Reviewing the data concerning the time period of 2071–2100 it is found that considerable changes (exceeding ±10%) are not likely in the estimated trends of precipitation in the watershed of the Lake relative to the average values of the reference period of time over annual time horizons. The result concerning the decrease above 10% in summer and the increase above 10% in winter over the semi-annual time horizon related to the values of the reference period refers to the rearrangement of the annual total precipitation in time. The summer semi-annual estimated precipitation decrease is concentrated in the period of July–August, while the focus of the winter semi-annual precipitation increase is concentrated in November–December.



30-year territorial average (mm) of the precipitation in the Balaton watershed and the relative differences there at the time of the future climate windows (2021–2050 and 2071–2100) (%)

Reviewing the data concerning the time period of 2021–2050, it is found that considerable change (above 1 °C) is expected in the trends of mean temperature of the Balaton watershed related to the average values of the reference period over the semi-annual and annual time horizons. Warming up by a higher rate (1.8 °C) is estimated in the summer half of the year. The most powerful temperature increase within the calendar year is focused on the period of July– October.

Reviewing the data concerning the time period of 2071–2100, it is found that considerable change (above 2 °C) is expected in the trends of mean temperature of the Balaton watershed related to the average values of the reference period over the semi-annual and annual time horizons. Warming up by a higher rate (3.8 °C) is estimated at the summer half of the year. The most powerful temperature increase within the calendar year is focused on the period of March and July–October.



Absolute variances of the monthly, semi-annual and annual mean temperatures from the average of the reference period in the Balaton watershed at the time of the future climate windows (2021–2050 and 2071–2100) (°C)

The estimated average annual precipitation in the watershed related to the average of the reference period forecasts a change not exceeding ±2% in the periodical average of the future climate windows. This shows that the estimated increase of the actual evaporation is not caused fundamentally by the change of precipitation volume.

The real explanation, by all certainty, should be sought in the estimated temperature rise – the remarkable rate of warming. The ALADIN-Climate model predicts an average warming by 1.6 °C on the territory of the Balaton watershed related to the average of the reference period in 2021–2050, and an average of 3.2 °C between 2071–2100.

In the period of future climate windows, according to the estimate, with a hardly variable annual average precipitation volume the significant increase of evaporation is expected. This predicts the decrease of difference between the precipitation and the actual evaporation on the watershed area, which may result in a significant reduction of in-flow concerning the water budget of Lake Balaton.

Within the climate windows of 30 years, the number of years which can be characterized with negative annual precipitation evaporation provided the picture below:

- in the period of 1961–1990 1 year
- in the period of 2021–2050 6 years
- in the period of 2071–2100 13 years

In the years when the precipitation-evaporation difference is negative in the watershed area, there is still an out-flow, however, this derives overwhelmingly from the sub-surface water reserves. In the years with more precipitation, the precipitation arriving at the watershed in the beginning replenishes these missing reserves under the surface and only when it is done, the surface out-flow is expected to appear.

As the water turnover of the sub-surface water reserves, and as a result their regeneration, take place much more slowly than those of the surface water reserves, the impact of changes on the sub-surface reserves – as a protracted impact – may also cover several subsequent years.

Reviewing the data concerning the time window of 2021–2050, it is found that considerable changes (exceeding 10%) are probable in the semi-annual and annual time horizons in the evaporation trends of Lake Balaton compared to the average values of the reference period. At the monthly level, the difference above 15% can be observed in July– September.

Reviewing the data concerning the time window of 2071–2100, it is found that a remarkable change (an increase exceeding 40%!) is probable on the summer semi-annual and annual time horizons in the evaporation trends of Lake Balaton compared to the average values of the reference period. On a monthly level, the biggest differences related to the reference period (57–73%!) were manifest in July–September.

The estimated large-scale increase of evaporation of Lake Balaton in actual fact can be explained by the higher value of saturation vapour pressure, which belongs to the higher air temperature with warming, at the same time, the climate model predicts a diminishing relative humidity concerning both future climate windows (and within that, for the half-year summer period). Jointly, this means that the material increase of saturation shortage of the air – the difference between the saturation and actual vapour pressure – is expected. The saturation deficit is included in the empirical formula applied for the calculation of Balaton's evaporation, it is particularly sensitive to that parameter.

The water budget of Balaton is defined as the algebraic total of the natural change of water reserves and of those factors of water budget, whose evolution in space and over time is determined by the natural factors only. These are: precipitation falling on the surface of the Lake, runoff into the Lake and evaporation from the surface of the Lake.

According to the calculations completed, the number of years which can be characterized by annual natural water reserve change with a negative sign within the 30-year climate windows resulted in the picture below:

- in the period of 1961–1990 7 years
- in the period of 2021–2050 9 years
- in the period of 2071–2100 19 years

In accordance with the estimates of ALADIN-Climate model for future climate windows significant climate change may occur on the watershed of Lake Balaton in the periods of 2021–2050 and 2071–2100 in comparison with the climate data measured in the reference period (1961–1990). The most remarkable and robust change is manifest in the estimated rise of temperature. The rise of temperature supplies additional energy for evaporation, as a result of which increased evaporation is expected both on the watershed and the free water surface. The territorial evaporation on the watershed (the joint process of evaporation and transpiration) is expected to increase even if the water reserve available for evaporation is typically limited. The water budget pattern of the watershed changes due to the increasing territorial evaporation, which results in a significant decline of runoff as a consequence of increased evaporation.

The decrease of runoff leads to a deficit on the in-flow side of water budget of Balaton and enhances the deficit nature of the water budget.

The increase of evaporation is even more remarkably present on the free water surface of unlimited water supply. The weight of the out-flow side of the balance of water budget increases, the evolution of the water budget is determined by the out-flow side.

Altogether, the decline of the in-flow side and the increase of the down flow side can be predicted for the water budget of Balaton. This double effect will fundamentally change the hydrology of the Lake compared to the average conditions of the reference period – particularly in the second future climate window (2071–2100). The water exchange activity of the Lake will substantially deteriorate, here will be more frequent and longer periods without down flow and what is more, by the last decades of the 21st century, Lake Balaton may become practically a lake without down flow.

It is also important to heed the fact that because of the permanent deficit in the water budget, the Lake gradually shifts towards a new hydrological equilibrium. In addition to the decrease of water level, this also means a reduction of the surface area. As a result of this change, the extreme values of the water balance elements may become more moderated, however, the sustainable satisfaction of the demands concerning the use of the Lake will no longer be possible with the contents and in the form known today.

Estimating the expected change of climate – and within that the estimated changes of values of the specific climate elements – are burdened by faults and uncertainties which inevitably enhance the uncertainty of hydrological calculation results – in addition to the faults, uncertainties and generalization existing in the methodology of hydrological calculations.

Estimated annual average values of water budget factors determined by the natural factors of Lake Balaton and of the derived natural water reserves (lake mm/year)

Period	Precipitation	Inflow	Evaporation	Natural water reserve change
1961–1990 CC	609	1001	807	803
2021–2050 ALADIN	631	725	926	430
2071–2100 ALADIN	602	224	1137	–311

Note: 1 lake mm is equivalent about 600,000 m^3 water.

In the trends of the total water turnover – which ultimately in aggregation leads to the change of water level – the anthropogenic effect may not be ignored, in addition to the role of natural factors.

Of these impacts, the most important ones are as follows.

Balaton is a lake regulated from the bottom, which means that its down flow is regulated through the canal Sió. The principles and practice of water level regulation are adjusted to the water level variability of the Lake and its future changes are not known. These days efforts are made to raise the level of low water periods arising as a result of negative water budget extremes by increasing storage in the basin (elevating the upper limit of the water level regulating range by 5–10 cm). This is a good solution, however, it is a question whether this solution may prove adequate over a period of several decades to satisfy the demands of the sustainable lake use. Based upon the results of this study, the answer to this question is a clear no.

The cases of water use existing on the watershed and with direct impact on the Lake (water off takes, water inlets in the water system) also have an effect on the water turnover. We must also heed the area use of the watershed, its natural and human-induced changes (afforestation, change of cultivation sectors and methods, regulation of run-off, change of expansion of free water surfaces, etc.).

It is practically impossible to estimate the long-term change (for the next 6–8 decades) of the anthropogenic factors listed. This fact burdens the results of the ‘water management sector’ with additional uncertainties and at the same time it warrants great caution and highlighting the uncertainties concerning their use.

INTRODUCTION

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A multitude of uncertainties hinder the analysis of hydrological impacts of climate change:

- uncertainties of socio-economic development and emission
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- uncertainties of hydrological models

The uncertainties of modelling grow in the direction of decreasing the scale in space and time and they are the greatest if they are aiming at the prediction of extremes.

On the basis of past hydrological surveys and processing of data as well as the results of water budget evaluations over several decades, it is known that our waters – depending on the type of water – are sensitive to the changes of the environment and within this, in particular, of the climate elements, over time and space. This can be established particularly in case of the precipitation and air temperature.

The large lakes in Hungary (Balaton, Lake Velence, Lake Fertő, Lake Tisza) are, without exception, typical shallow lakes with average depth remaining below 5 m. An important feature of the shallow lakes in the moderate climate zone is the high quantitative and qualitative sensitivity to the changes of environmental factors (including climate factors) in space and time.

Quantitative sensitivity is manifest in the water balance (typical water turnover) of the lake, consequently in its typically unidirectional change of its water level, water reserve and water surface.

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1 CHARACTERISTICS OF WATER BUDGET FACTORS OF BALATON IN THE ANALYSIS

An important feature of the Lake's water budget is the natural water reserve change, the difference between the natural water input and water output of the Lake over a specific period of time. Water input is the total of precipitation over the surface of the Lake (P) and of the value of runoff from the watershed of the Lake (R_{vgy}) converted to the Lake surface in the ratio of the watershed (F) and lake surface (f) in the F/f ratio, whereas the water output is the evaporation from the water surface (R_H) (E_w).

The natural water reserve change can be calculated by the formula

$$\Delta S_T = P + R_{vgy}(F/f - 1) - E_w \qquad (1).$$

The value of natural water reserve change depends on the size of lake surface, from time to time. The lake surface changes only slightly between 590 and 610 km^2 in the water level range of 40 cm to 120 cm, which is typical of the water level regime of the lake (OVH 1968), accordingly, the value of the F/f multiplier ranges from 8.79 to 8.47. In the calculation of the natural water reserve change by formula (1), the F/f value is adopted at 8.70, which results in a relative error of about (–2) – 1% in converting the in-flow, which is of negligible extent.

1.1 *Characteristics of precipitation, in-flow and evaporation time series available under the closed water balances of the Lake for the period of 1921–2014*

The precipitation arriving on the surface of the Lake (Figure 1) was calculated up to 1970 by means of the arithmetic averaging of data provided by the monitoring stations located directly on the waterfront of the Lake and by means of the weighted averaging of the Thiessen method after 1971.

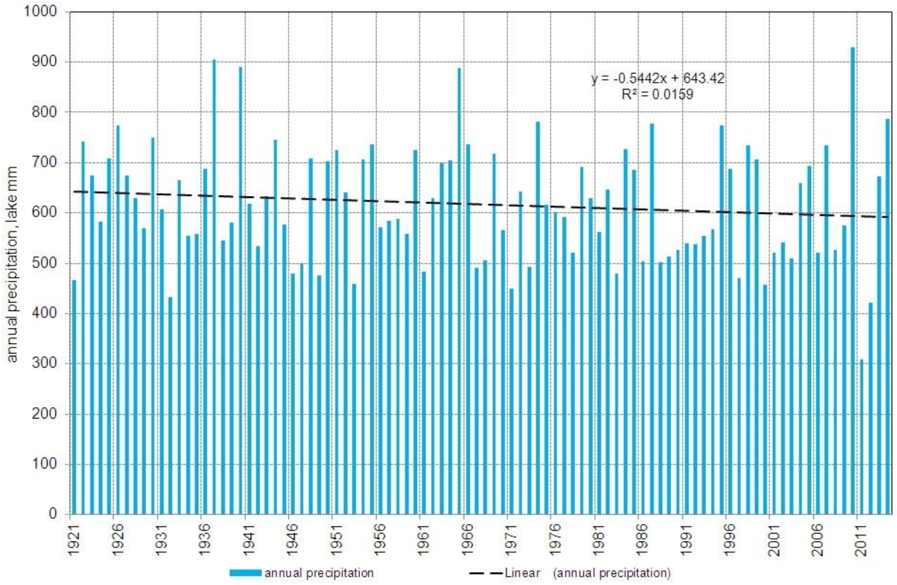

Figure 1. Annual area average values of precipitation falling on the surface of Balaton

The number of stations considered was 12 up to 1970, their number grew from 1971 first to 25 and later decreased to 19 and then again to 12. The decrease of number of the stations considered had no material impact on the amount of precipitation calculated with the average for the area (Varga B. 2011).

The problem of calculating the in-flow (Figure 2) is that it covers only the surface streams and only a part thereof, while by and large, the direct runoff into Balaton and the supply under the surface are missing. The proportion of the total in-flow from the watershed included in the measurements amounted to about two-thirds in the 1970s and 80% in the mid-1980s, accounting for only 60% of the northern watershed, while the Zala catchment area was completely covered (Bratán 1988). The number of water in-flow measurements also changed with some variability. Most complete are the flow rate measurements of the Zala River providing the largest in-flow into the Lake, where continuous daily flow rate data have been available since mid-1975. At this time the ratio of the area continuously monitored by flow rate measuring is above 90% in the watershed. The in-flow from the catchment areas not covered by metering was calculated by the method of analogy with time variable (Virág 1997).

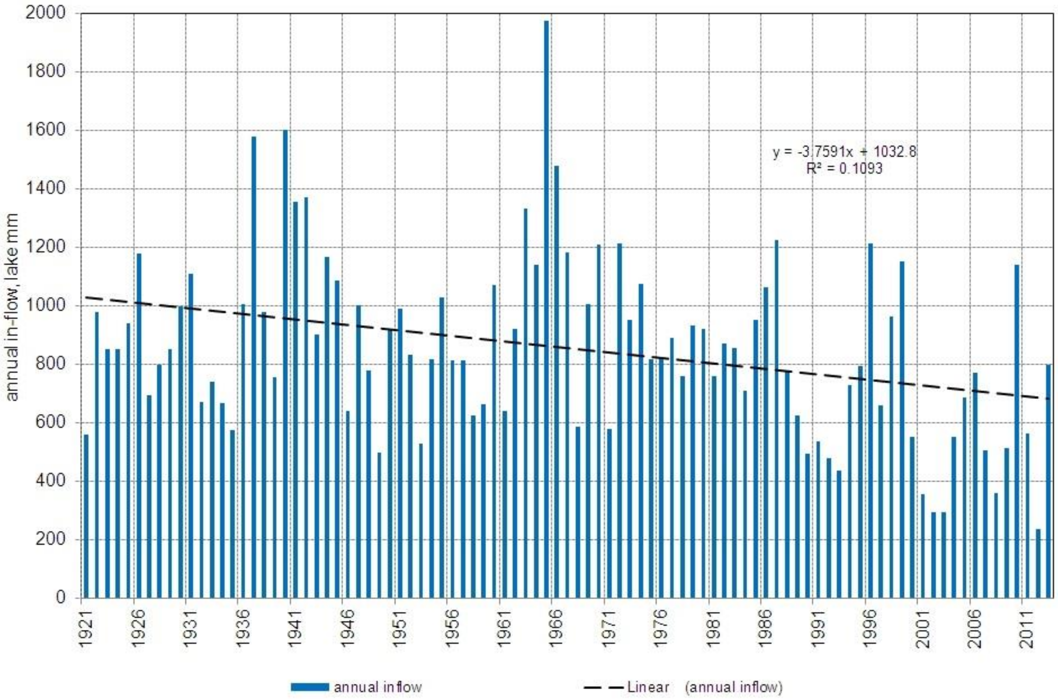

Figure 2. Annual in-flow in Lake Balaton

Evaporation from the water surface (Figure 3) was determined by calculations from the data measured by the meteorological stations (air temperature, saturation deficit calculated as the difference of saturation and actual vapour pressure, wind speed). The Meyer-formula was used for the calculations in 1921–1974, followed by the Antal-formula generated from the experimental measurements conducted over several years by the Central Atmospheric Physical Institute of the Hungarian Meteorological Service and VITUKI in 1974–1986 (Antal et al. 1971), and finally its upgraded version since 1986 (Varga B. 2011).

The number of meteorological stations included in the calculation changed repeatedly over the period. The comparative review conducted for the period of 1931–1970 showed that the empirical formula yields a lower value for the average annual evaporation than the Meyer-formula.

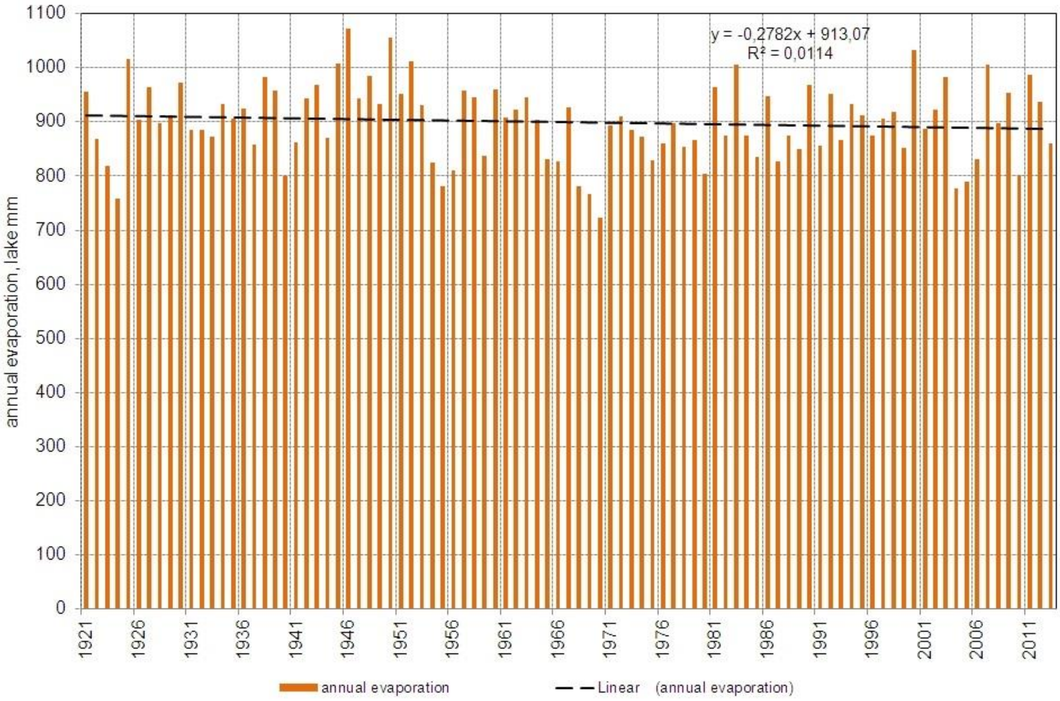

Figure 3. Annual evaporation of Lake Balaton

In the period under review, the precipitation falling on the Lake slightly declined, its rate was about 6 mm/decade, i.e. 1%/decade. The in-flow from the watershed decreased by a substantially greater rate, amounting to about 33 mm/decade, i.e. 3%/decade. This value corresponds to about 3.8 mm/decade on the watershed.

In aggregation, the precipitation falling over the Lake and the in-flow decreased by about 39 mm/decade, with the majority, 85%, accounted for by the declining in-flow. The Lake evaporation decreased slightly, its amount may be estimated at 3 mm/decade.

1.2 Interpretation and characterisation of the natural water reserve change – an integrated indicator which describes the water turnover of the Lake (tendencies, periodicity, steady state)

The time series of natural water reserve change (Figure 4) can be regarded as an approximation to the methodological changes in the calculation of precipitation, evaporation and runoff as well as in the stations used for the calculations (VITUKI 1990).

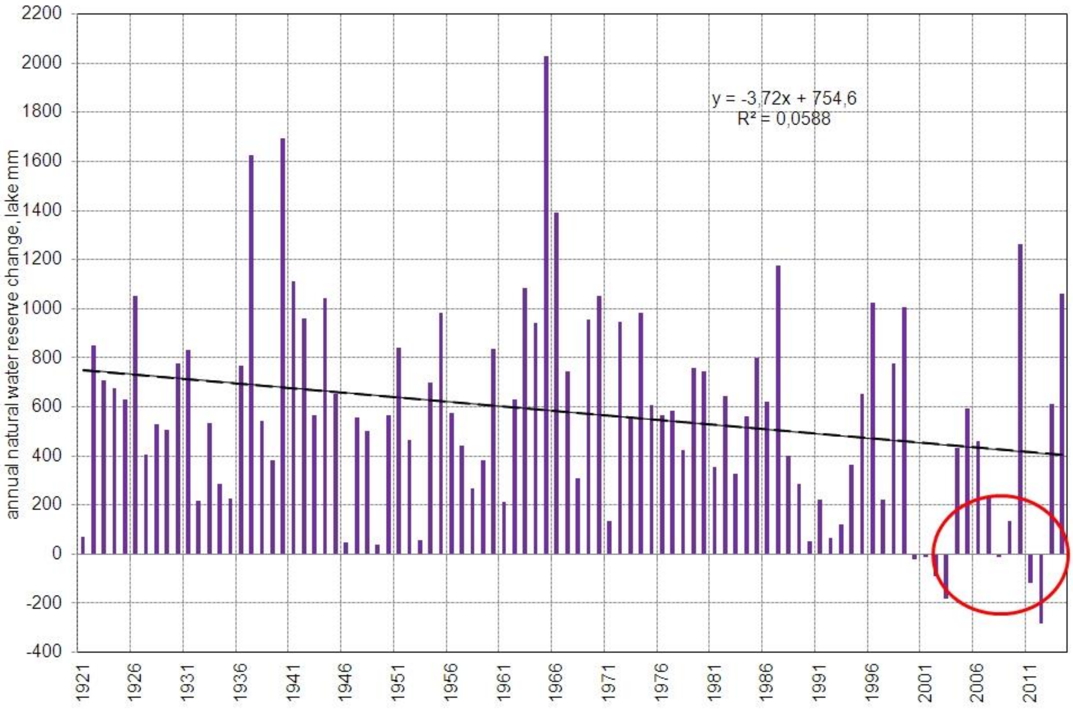

Figure 4. Annual natural water reserve change of Lake Balaton

A declining trend is presented by the time series of the annual natural water reserve change ($\mathrm{TVK}_{\text{év}}$) in 1921–2014, covering almost 100 years. According to the non-parametric test of Mann-Whitney widely used in the hydrological practice (Reimann and V. Nagy 1984) the tendency is significant at a probability level of 98%, that is, it is not random. Under an earlier analysis (Nováky 2013), no significant trend can be ascertained in the time series continuously growing from 1921 until 2000, however, following the year 2000, the trend becomes significant with a growing reliability. This process is reinforced by the behaviour of the 94-year time series. Moreover, the presence of a 24-year period and some shorter periods manifest as subharmonic to the former can be detected in the time series, which jointly explain about 12% of the variability of the annual natural water reserve change. Consideration of the periods provide only some slight explanation for the behaviour of the time series of annual natural water reserve change after 2000, the extremely low values in the 2000s are not justified by the periodicity alone.

The statistical indicators, expected value and variance of the annual natural water reserve change calculated with samples of adequate size show no statistically significant variance up to the 1980s, therefore, the time series can be considered steady state – in accordance with the definition of the steady state process (Reimann and V. Nagy 1984, Dévényi and Gulyás 1988). The time series changed after the 1980s: the expected value shows a definitive decline and the process which was stationary up to 1980s, transformed into a non-stationary process thereafter. Following the 1980s, a material change occurred in the probability distribution function of the annual natural water reserve change (Figure 3, Nováky 2013). From the comparison of the periods of 1921–1990 and of 1980–2009, it is seen that the probability distribution function of the latter period changed significantly, it ‘shifted’ to its earlier state to such an extent that it is outside the confidence range of 95% of the distribution function characterizing the earlier state calculated by the Kendal-method, what is more, even outside the confidence range of 70% reliability. This material variance also underpins that the process is not stationary, and a change occurred in the process of the annual natural water reserve change covering the complete period.

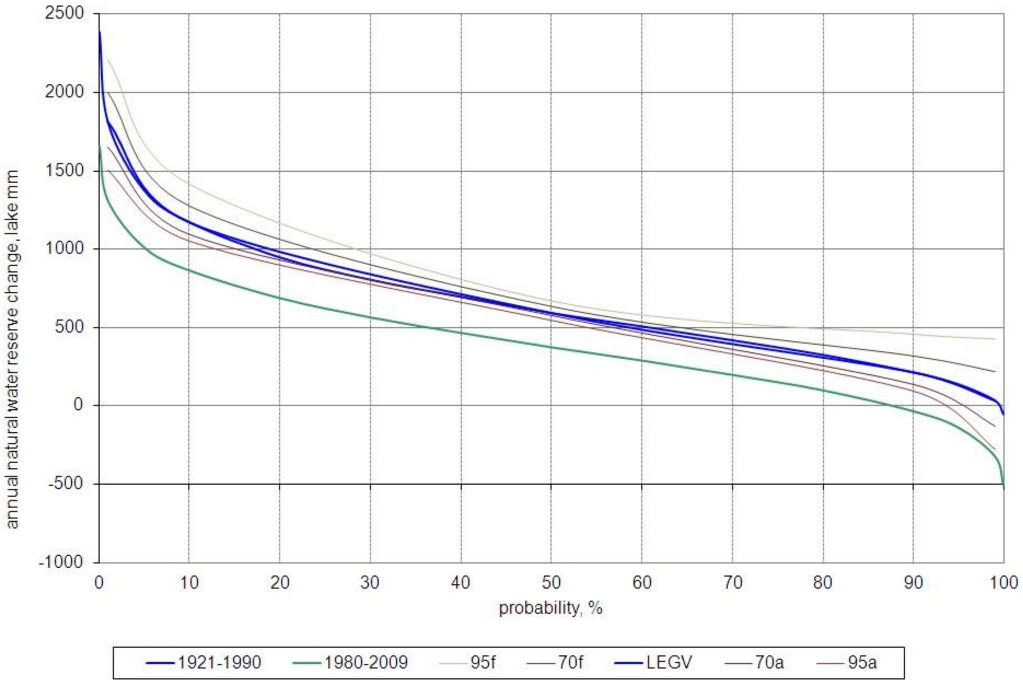

Figure 5. Distribution functions of the annual natural water reserve change in 1980–2009 (in green) and 1921–1990 (in blue, highlighting the reliability ranges of 70% and 95%, respectively) (NOVÁKY 2013)

The result of the statistical reviews is a signal alerting to the change of behavior in the annual natural water reserve change of Balaton in the last decades of the 20th century compared to the earlier years. The change in the time series is not justified by the steady and slight decrease of precipitation falling over the Lake and of the evaporation from the Lake surface, however, at the same time, a significant change can be detected in the in-flow (runoff from the watershed), which is comparable to that of the natural water reserve over time (HONTI 2013, in NOVÁKY et al. 2013).

The rate of decrease of in-flow accelerated after 1980, similarly to the rate of the annual natural water reserve change. The decrease of in-flow is partly explained by the decrease of precipitation falling over the watershed and mainly by the decrease of the runoff proportion (Figure 6).

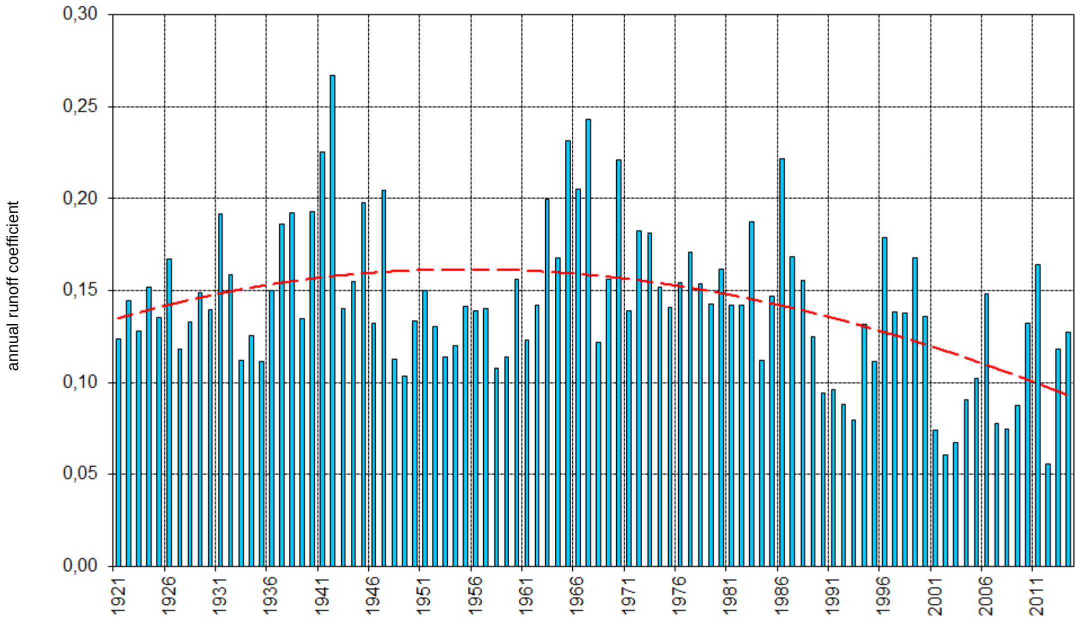

Figure 6. Change of annual runoff factor on the Balaton watershed in 1921–2014

Seeking the cause of decreasing runoff factor, the question presents itself, whether the decrease of the water amount stored naturally in the watershed could play a role in this. According to a correlation edited with a condition of intensive approximation, there is a good relationship between the runoff factor and the stored amount of water (HONTI in NOVÁKY et al. 2013). This study selected the clarification of this relationship as an objective.

The change of water volume stored in the watershed in the i-th year ($\Delta S_{vgy,i}$) can be calculated from the total of input into the watershed from precipitation ($P_{vgy,i}$) and the output of evaporation in the area ($E_{vgy,i}$) and down flow ($R_{vgy,i}$) using the formula

$$\Delta S_{vgy,i} = P_{vgy,i} - (E_{vgy,i} + R_{vgy,i}) \qquad (2)$$

and the annual stored amount of water – starting from an initial year – can be generated through the continuously aggregated summary of the annual reservoir change. For the calculation of the stored amount of water, it is necessary to know the annual evaporation over the area, which was calculated by the Turc method and the relevant values have been available since 1951 (VARGA GY *2015*). The evaporation includes also the evaporation values of the fishponds and the Kis-Balaton commissioned into service in 1986. The change of the water stored in the watershed over time without the evaporation of Kis-Balaton and the fishponds and with the consideration of the additional evaporation of these latter water bodies, are shown in Figure 7. The additional evaporation of the fishponds and mainly of Kis-Balaton decreased the water amount of the watershed after 1986, virtually superimposed on the impact of the more arid climate and contributed considerably to the 'drying out' of the catchment area.

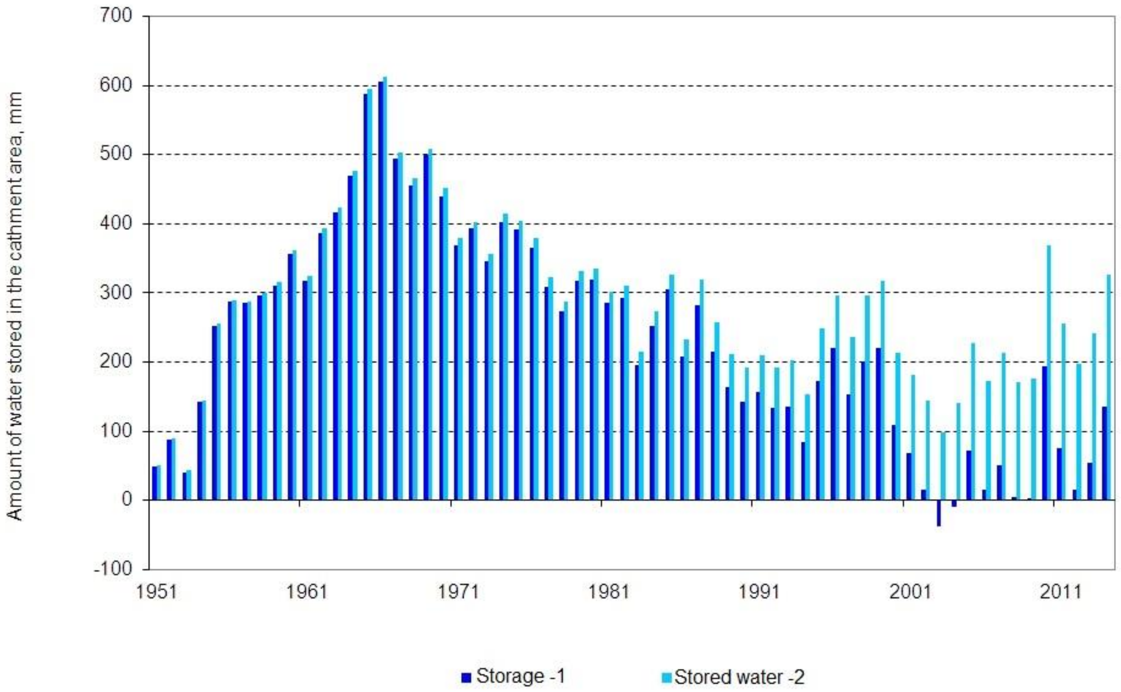

Figure 7. The stored water amount of the watershed without the evaporation from Kis-Balaton and the fishponds (light blue), and with the consideration of the additional evaporation (dark blue)

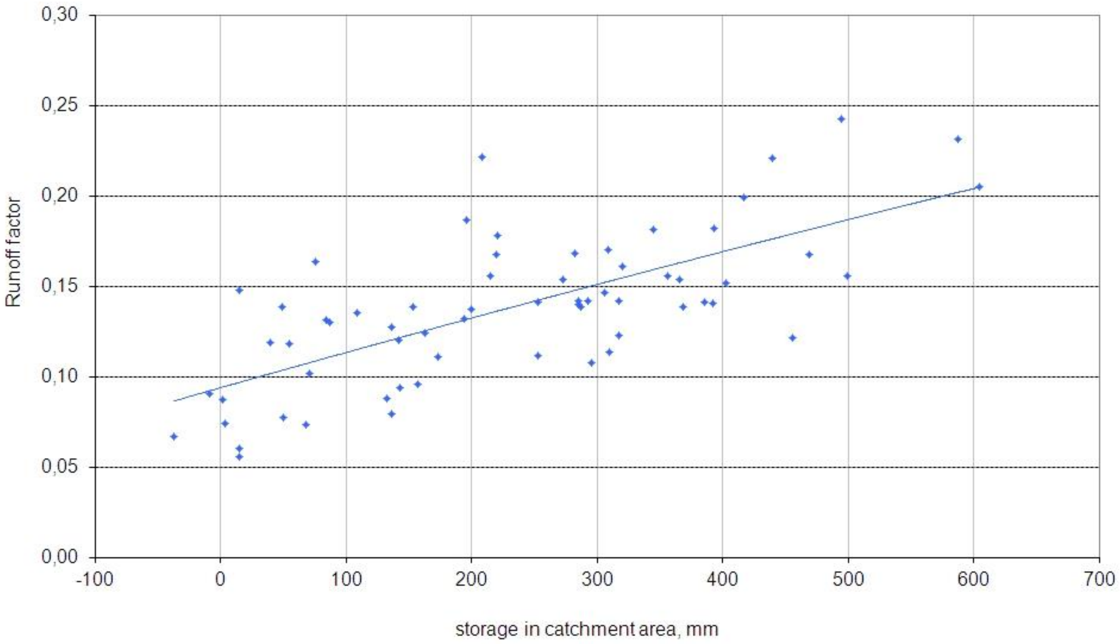

Figure 8. Correlation of water amount stored in the watershed with the runoff factor

The runoff factor correlates well with the stored water amount of the catchment area (Figure 8), and follows the decrease of the stored water amount.

The additional evaporation of the Kis-Balaton and the fishponds decreased the stored waters of the watershed by close to 200 mm in the recent decades, gaining momentum particularly in the 1980s, which, however, contributed to the decrease of the runoff proportion of precipitation in the catchment area (runoff factor) and through that to the decrease of in-flow in Lake Balaton. In addition to the additional evaporation from the Kis-Balaton and the fishponds, the increase of climatic aridity of the watershed experienced in the recent years had also a role in the reduction of the runoff factor.

1.3 Characterising the relations between the annual climatic elements and the natural water reserve change

The annual natural water reserve change is closely related to the change of precipitation and of the temperature fundamentally determining evaporation during the year. The relations can be modelled based upon the past observation data, through linear regression in a simpler case. In the models presented, the input data included the precipitation falling on the Lake and the temperature of the Keszthely station, whereas the output data were the values of annual natural water reserve change in 1921–2002.

The first model (MODELL-1) does not analyze the behavior of variances between the modelled and observed values (the residual member), the second model (MODELL-2) complements the linear regression model based upon the behavior of the residual member with a single-step AR(1) model fitted to the time series of the residual member.

Both models well approximate the detected values: the closeness of relations can be described with a correlation factor exceeding 0.80, the residual member of the models – according to the peak test (Dévényi and Gulyás 1988) – can be considered as a white noise process. The good correlation of the modelled and detected time series as well as the good correlation of the time series modelled in two ways are obvious (Figure 9).

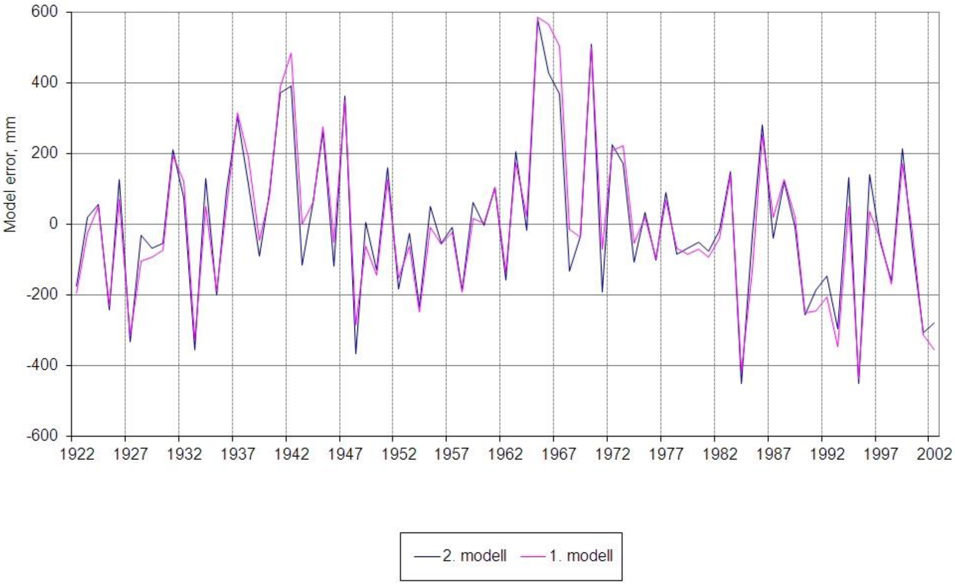

Figure 9. Time series calculated and modelled from the water balance of the annual natural water reserve change

The precipitation and the temperature are the two fundamental meteorological factors which shape the Lake's natural water reserve change by a decisive rate.

Integrating the two meteorological elements into the aridity indicator of the formula ARI = 100T/P, a quite clear relationship can be built between the comprehensive indicator of the character of climate and the values of annual natural water reserve change (Figure 10). From the figure it is clear that with the increase of aridity of climate (dry character) the annual natural water reserve change declines, it turns negative at the 2.3 value of the aridity index, i.e. the natural water reserve of the Lake decreases at an annual level.

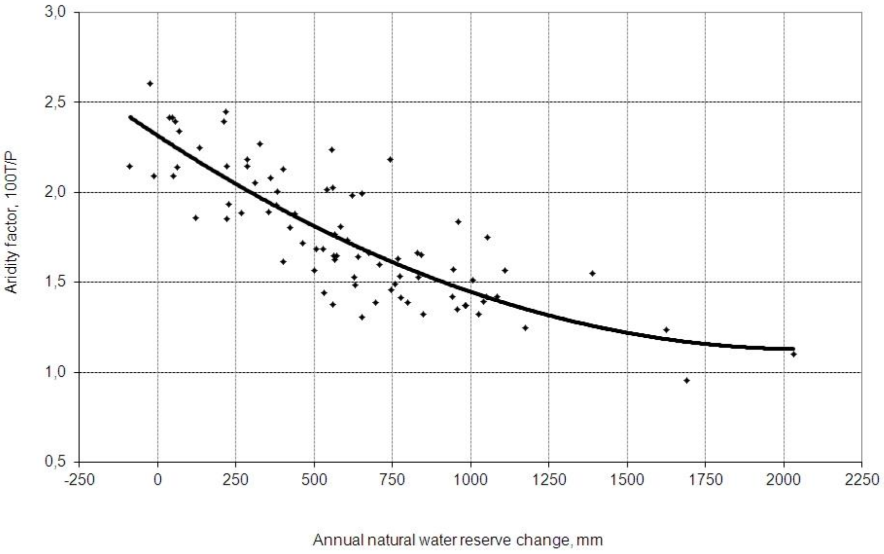

Figure 10. Relations of annual natural water reserve change and the aridity index

2 SUMMARY OF CLIMATIC IMPACT ANALYSIS CONDUCTED SO FAR FOR THE ANNUAL WATER BUDGET OF LAKE BALATON

2.1 Historical review

The climatic sensitivity of the lakes and particularly of the shallow lakes similar to Balaton have been known for a long time. Historical research pointed out that the water regime of the Lake and the surface of the Lake related to the water regime has changed several times in the past, from case to case, to a significant extent related to the variability of climate (VIRÁG 1997). For a given climate, the equilibrium lake surface can be determined, in which the lake evaporation totally consumes the water input of the lake from precipitation and in-flow, there is no out-flow from the lake, i.e. over an average of several years, the lake becomes a closed lake without down flow (SZESZTAY 1959).

The equilibrium surface is dependent on the climate, it follows the fluctuation of the climate. According to the calculations, its value was 1,730 km^2 in 1921–1950 (SZESZTAY 1959), 1,300 km^2 in 1921–2000 (NOVÁKY 2005b), 988 km^2 in 1921–2002 (KONCSOS et al. 2005). In accordance with the sensitivity test conducted for the water turnover of Balaton, the water turnover of the Lake, and particularly its out-flow is very sensitive even to the smaller changes of climate, its impact is reinforced in the out-flow (NOVÁKY 1985).

The impact tests related to the climatic scenarios of the total water balance of the Lake have started from the beginning of 1990s. Climate impact study was made concerning the lasting extremely low water level of the Lake as well as the phosphorus and nitrogen contents. The impact assessments have increasingly been conducted in the framework of international projects from the middle of the first decade of the 2000s – PRUDENCE/GEF/UNDF, CLIME-EVKI-CT, CLAVIER, EULAKES. The studies with a past of close to two decades have been characterized by the tendencies below.

– The impact assessments were based on different climate scenarios. The earliest study was based upon equilibrium climate models assuming the doubling of carbon-dioxide concentration in the atmosphere (BMO, GISS, GFDL, NCAR), by scaling them to the broader area of Balaton through regression relations. After the turn of the century, the impact assessments used regional climate scenarios, based upon tensioned climate models, mainly the HadCM3 of the U.K and ECHAM4 of Germany, as global models or their versions, which anticipated in general the medium rate of atmospheric emission of greenhouses gases (medium emission scenario A1B). The outputs of the early climate scenarios in most of the cases were limited to the average values of mean temperature and precipitation of longer time horizons (year, season, month), and a regional climate scenario may provide the time series of the two climate element with short time scales. As rare exceptions, the climate background was represented by the past time analogy of the climate expected in the future.

– In the beginning, the impact assessments were limited to the average annual water balance and used empirical-statistical models: regression correlations, empirical climate – downflow models of simple structure, like the Budyko-model also used in sensitivity analyses. The use of empirical models has not disappeared later either: the EULAKES project after the turn of the century calculated the runoff as the difference of precipitation and the evaporation from the area, this latter, by means of the empirical Turc formula requiring the knowledge of the annual mean temperature and precipitation, also considering the forest cover. The advantage of the empirical models is that they can be directly connected to the climate scenarios only providing average climate elements. The physical (conceptual) models appear only after the turn of the century, representing a change of era in the history of impact assessments. Several kinds of physical models have been applied, mainly of foreign origin (SWAT, GWFL or WetSpa down flow model), or eventually a local model (ARESZ). The physical models in general require the daily time series of temperature and precipitation, which can be provided by the regional climate scenarios.

– Both the statistical-empirical and physical models used in climate impact assessments are calibrated under the data observed and the stability of the model is accepted with the assumption that the model can also be used in case of climate change. The verification of models against independent data is practically not done; partial verification is carried out only seldom, primarily in case of the empirical-statistical models.

– The studies in general cover changes expected in two time horizons, a shorter (2020–2050) and a longer one (2070–2100), while the reference state was provided first by the years of 1961–1990 and later by the years 1971–2000. In the impact assessments, the total water balance and in specific cases only its specific elements were produced by the model both for the present and the future conditions, and the change was evaluated as a difference between the modelled future and present. The impact assessments in most of the cases cover the annual average water balance related to the specified time horizon, however, exceptionally the average monthly water balances are also analysed.

Table 1 provides a comprehensive summary of the impact assessments conducted in 1991–2012.

Table 1. Climate impact analyses of Balaton water balance in 1991–2012

Water balance element	Climate scenario		Impact assessment method		Author
	Global	Regional	Runoff	Lake evaporation	
Annual TVK	equilibrium models (BMO, GISS, GFDL, NCAR	GCM statistical (regression) scaling (*Mika 1988*)	Budyko model	regression	NOVÁKY (1991)
ANNUAL TVK	Not published	BALALONE BALACOOL	SWAT model		National Public Benefit Non-profit Ltd. for Employment 2004
Annual and monthly TVK		GCM statistical scaling (*Mika 1999*), and past analogue climate	Time series generation (Thomas-Fiering)	regression	KONCSOS et al (2005)
ANNUAL TVK	A2B2/ECHAM4 and HadCM3	Changes derived from global climate scenarios for the specific region	Budyko model with divided parameters	Regression	NOVÁKY (2006)

Water balance element	Climate scenario		Impact assessment method		Author
	Global	Regional	Runoff	Lake evaporation	
ANNUAL TVK		PRUDENCE project regional climate scenarios			PRUDENCE/GEF/UNDF KUTICS 2007
Annual TVK	HadAM3p and ECHAM4/OPYC3	Rossby Centre RCM (RCAO) and Hadley Center RCM (HadRM3p) Daily data: RCAO weather generator	GWLF AREsz WetSpa		CLIME-EVKI-CT Padisák (2006) KOVÁCS and CLEMENT 2009 PADISÁK 2006
Annual lake evaporation	A1B/ ECHAM/MPI-OM	REMO 5.0 and REMO 5.7		Modified Morton process	JACOB and HORÁNYI 2009 CLAVIER KOVÁCS and SZILÁGYI 2010
Annual water balance, TVK	Climate scenario based upon A1B SRES	EULAKES regional climate scenarios	Precipitation-area evaporation Area evaporation Turc formula	Balaton formula	EULAKES KRAVINSZKAJA (2012) VARGA (2012)

2.2 Brief presentation and summary evaluation of the impact assessments

2.2.1. Results of the specific impact assessments

The probably first climate impact assessment, which focused on the average annual water balance of Balaton, was considering in the lower stage of global warming, an increase of the annual mean temperature by 0.5 °C and a decrease of the annual precipitation by 5%, and in its higher stage, a temperature increase by 2 °C and the increase of precipitation by 5% (NOVÁKY *1991*). The model based on the Budyko climate – runoff relations was calibrated with past observations, and its partial verification was carried out over shorter time series obtained by cutting the past period of observation into two equal parts. Both climate scenarios predict the deterioration of the water balance of the lake resulting from the increase of lake evaporation and the reduction of runoff in addition to the decrease of precipitation. In case of global warming by 2 °C, the lake evaporation exceeds 10%, at a warming by 0.5 °C it is uncertain and even its slight increase may not be precluded either.

In both stages of global warming, the reduction of runoff is significant; its rate is estimated in a range from 6 to 27% – also considering uncertainty. As a consequence of all these points, the water turnover is expected to deteriorate, in case of a greater warm up, the out-flow of the Lake may decrease by even 60–70%, bringing the ratio of out-flow/evaporation closer to 0 the Lake may get closer to a (closed) state without out-flow.

The first known impact assessment based on physical models was made for a shorter period of time, 2011–2040, in the framework of the regional climate modelling PRUDENCE (Balaton Integrációs Közhasznú Nonprofit Kft. 2004). In the impact assessment, the watershed of the Lake was divided into 7 cells of 50x50 km each. The precipitation and temperature change was calculated related to the 1961–1990 reference period by cells, in accordance with two climate scenarios BALALONE and BALACOOL, not presented in greater detail. The scenarios expect the increase of annual mean temperature, the rate of which was 2.4 °C in case of BALALONE and 1.5 °C in case of BALACOOL. The scenarios anticipate a slight change of the annual precipitation: BALACOOL expects an increase by 0.6% and BALALONE a decrease by 1.4%. The changes expected in the water balance of the Lake can be interpreted by the middle of the period under review, 2026. Runoff was modelled by SWAT (Soil Water Assessment Tool), which model considers relief, land use and soil type. According to both scenarios, the decrease of runoff is expected, according to BALACOOL slightly in the winter and the spring, while in case of BALALONE, throughout the year with a possible range from 10–40%.

The extreme low water levels of the Lake in the early 2000s once again highlighted the necessity of climate impact assessment (SOMLYÓDY 2005). The impact assessment anticipated a decrease of the annual precipitation by 10% with the increase of the annual mean temperature by 1°C in the coming 30–35 years, approximately until 2040, with a considerable rearrangement of the precipitation within the year. The past analogue of the new climate was searched in the assessment, selecting such years, which have average climate properties equal to the ones expected in the future.

Climate analogy – accepting the hypothesis of similarity – can also be extended to the natural water reserve change (NOVÁKY 2005). Having selected the analogue climate, the monthly time series of natural water reserve change for 5,000-5,000 years were generated both for the current climate of the years 1921–2002 and the analogue years by means of time series generation under the Thomas-Fiering model, providing that the average monthly values of natural water reserve change must be equal to the ones calculated for the years selected for the analogue climate, and the other statistical characteristics (variance, correlation factors) are equal with the ones calculated according to the observations of the entire past period. Contrasting the time series of monthly natural water reserve change for future climate with the time series also created by generation for the current state characterized by the years of 1921–2002, the expected change can be predicted. Accordingly, the annual natural water reserve change will decline by 22%, with a significant re-arrangement within the year: their monthly value drops in April–November and increases in the winter months.

Each of the climate scenarios of the climate impact assessment made in the framework of the VAHAVA project expected temperature increase: by 1.5–2.0 °C over the short-term, and by 4–5 °C over the long-term, with greater variances among the scenarios. Regarding precipitation, in general, a decrease by 5–15% was expected in the short- to medium-term and by 25% over the longer-term, and an increase by a few per cents.

The impact assessment used the version of the modified Budyko model with parameters divided in space for the lake water catchment cells (grid). Under the modified Budyko correlation, the model first calculates the grid-runoff and then, by adding the runoff in the grid cells, the total catchment runoff. The model was calibrated by the data of the three flow rate measuring stations of the Zala River emptying into Balaton.

The model-constant is indeed not constant according to the test, it changes in the function of annual precipitation and the modelled change is apparently sensitive to the model-constant, much more so than to the climate proper. The impact assessment predicts the decrease of annual natural water reserve change in case of each climate scenario; however, with rates differing by scenarios (Figure 9), as a consequence of which the average water balance of the Lake may even turn to negative from the middle of the century. This should be interpreted so that there can/will be years when the water input of the Lake exceeds the water output, which ensures the survival of the Lake – with a smaller equilibrium surface than today.

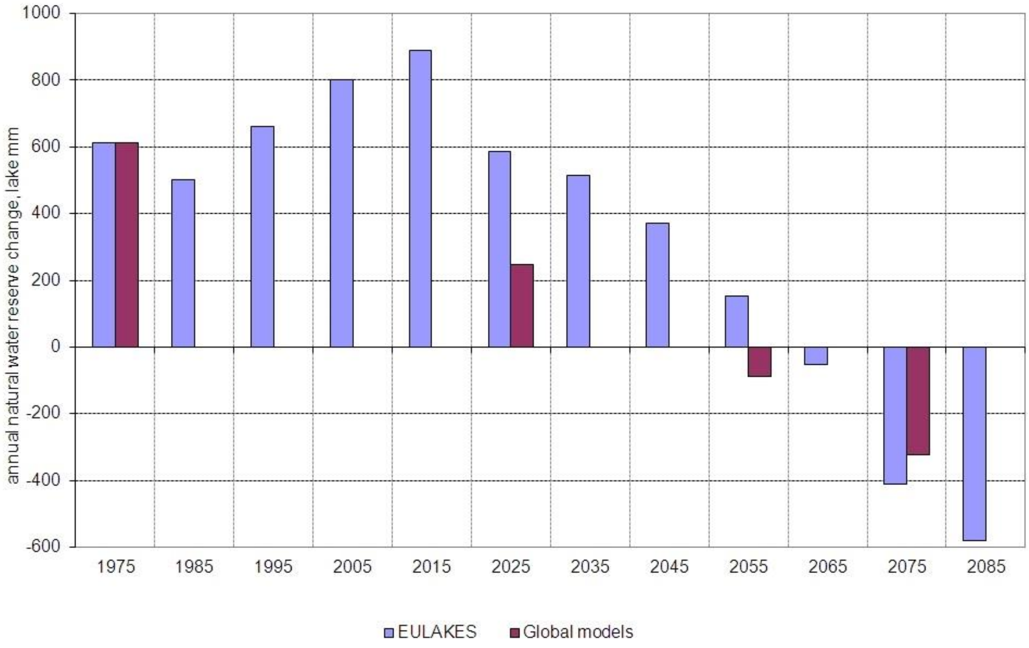

Figure 11.: Natural water reserve change of the Lake considering different climate scenarios

A climate impact assessment was made in the framework of the GEF/UNDF project for a longer-term, 2071–2100 (Kutics et al 2007). The impact assessment started from the regional climate scenarios based upon the emission scenarios A2 and B2 created in the course of the PRUDENCE project. The scenarios anticipated a decrease of precipitation in the summer (June–August) by up to 25% and an increase of the winter (November–January) precipitation by similar rate.

No detailed information is available about the temperature change. Runoff modelling was conducted based upon the SWAT model. In case of a more favorable emission scenario (B2), in most of the water flows, the average annual runoff increases in general, with the exception of a few small or periodical water streams in the northern catchment area of Balaton, where the decrease of annual runoff by maximum 20% is possible. In case of the emission scenario A2, a decrease by 50%, from case to case, is expected in the eastern half of the catchment area, which, however, is compensated by the powerful increase expected in the western half of the catchment area. In case of scenario A2, the increase can be as high as 50% on the River Zala and its tributaries, whereas, in case of scenario B2, the increase can be even above 200% on some tributaries.

In the framework of the international project CLIME EVKI-CT-2002-00121 covering several lakes in Europe (PADISÁK 2006, KOVACS and CLEMENT 2009) the expected impacts of climate change on the phosphorus and nitrate turnover of the lakes were investigated. The analysis used the Generalized Watershed Loading Functions (GWLF), the Hungarian ARES model (KONCSOS 2007) with a grid of 250 m × 250 m and the WetSpa model. Using the two scenarios of different emissions (A2 and B2) and the two types of climate models, a total of four types of climate scenarios were generated for 2070–2100. The scenarios anticipate the increase of the annual mean temperature by 3.6–5.7 °C, and a change in the annual precipitation between decrease by 4% and increase by 8.5%. Impact assessments were made for closer time horizons, for the years of 2025–2034, for which the rate of climate change was determined simply by splitting the values in half which were forecast in the CLIME model. The climate impact assessment predicts a relatively small decrease of the annual average runoff. In accordance with the calculations performed with the ARES model, the decrease may have a range of 6–16% and according to GWLF in the range of 2–18%, varying in accordance with the climate scenarios. The WetSpa model predicts the change of average annual runoff to be between a decrease by 4% and an increase by 12% (KOVÁCS and CLEMENT 2009).

In the framework of the CLAVIER project, the impact assessment made for the lake evaporation was based upon the regional climate scenarios using the regional climate models REMO 5.0 and REMO 5.7. Accordingly, in contrast with the current reference period (1961–1990), the increase of the annual mean temperature by 1.2–1.4 °C is expected in the future (in 2020–2050) in the area of the Lake. New empirical formula was elaborated by the combination of the evaporation calculating processes Penman- and Priestley-Taylor for the calculation of the lake evaporation (JACOB and HORÁNYI 2009, KOVÁCS and SZILÁGYI, 2010). Both climate scenarios forecast a slight increase of the average annual evaporation for the years of 2020–2050: an increase by 3.2% in case of REMO 5.0 and 1.0% in case of REMO 5.7. According to REMO 5.7, the increase of evaporation will not exceed 1% either in 2001–2050 (KOVÁCS and SZILÁGYI 2010). The increment is substantially smaller than the one obtained from the empirical formula, which predict an increase by 6.3–8.6% in case of a temperature rise considered in the REMO models.

In the framework of the EULAKES (2012) project, the Balaton water balance was studied based upon a regional climate scenario (KRAVINSZKAJA et al. 2012). Compared to the current period of 1971–2000, the regional climate scenarios assuming medium emission first predict the increase of temperature by a lower rate and later by a higher rate. In the last decades of the century, the annual mid-temperature can be 13.2 °C, 3.3°C higher than at present. The scenarios predict the increase of rainfall; its extent may even exceed 8% in the first decades of the 21st century, while in the last decades of the century it can be only 1%. The preliminary impact assessment performed in the framework of the project was based upon empirical correlations. In accordance with the impact assessment, the water balance, the natural water reserve of the Lake will not change in the short-term, in 2021–2050, what is more, it may even improve temporarily due to the increase of precipitation. The lake evaporation will slightly increase, by about 3%, until 2030, thereafter there will be a significant increase, and in the last third of the century, it will be 45% higher than at present (VARGA GY. and KRAVINSZKAJA 2012). Owing to the changes of precipitation and temperature forecast in the climate scenarios, the water balance of Balaton is expected to improve in the first decades of the 21st century and a steadily intensive deterioration after 2030. The natural water reserve change of the Lake may increase temporarily due to the increased precipitation in the short-term, however, it is expected to decline from the middle of the 21st century and in the last decades of the century, the Lake may enter into a state without down flow.

2.2.2. Summary evaluation of impact assessments

The assessments based upon various climate scenarios and made with different methods also offer a possibility for one kind of assessment comparison. The impact assessments agree that the water balance of the Lake will deteriorate due to global warming, and according to most of the impact assessments, the annual natural water reserve change will decrease. However, there are significant differences in the rate of deterioration; what is more, there are studies which even expect an improvement of the water balance in the coming decades. It is to be noted, that the rate of deterioration is closely related to the increase of aridity of the climate, which may be triggered by the declining precipitation, the increase of temperature and the joint occurrence of the two (Figure 12).

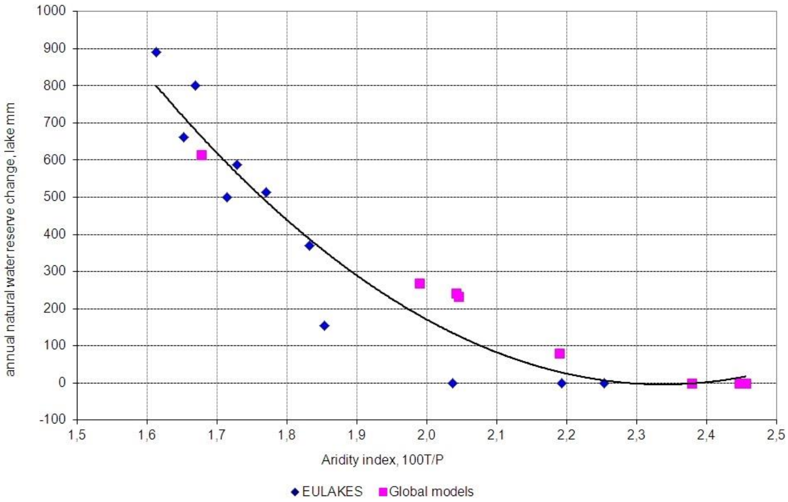

Figure 12. Decrease of natural water reserve change in the function of the climatic aridity index

The change of aridity of the climate may have a fundamental impact on the water balance of the Lake, however, the uncertainty of the change is an essential source of estimating the water balance for the future. Therefore, the change of climate is a key issue and it is a fundamental task to determine it more precisely, to reduce the relevant uncertainties as well as considering the uncertainties concerning the future of the Lake.

3 SCOPE AND USE OF MODEL DATA OF OMSZ ALADIN-CLIMATE AND CARPATCLIM-HU (CC)

Meteorological data were available for the hydrological calculations necessary for the estimates concerning the water turnover of Balaton related to the reference period (1961–1990) and the future periods (2021–2050 and 2071–2100) in accordance with the details below.

The CARPATCLIM-HU (CC) data were determined for the reference period (1961–1990) based upon actual measuring results, while the ALADIN-Climate data were determined for the climate windows by modelling (1961–1990, 2021–2050 and 2071–2100).

The data apply to the periods listed with monthly time horizons and represent weighted territorial average (catchment area, water surface of the Lake). Selection by areas and calculation of the weighted territorial averages were carried out by Emese Homolya (MFGI).

Data used in this research:

- weighted territorial averages for the catchment area of the Lake
- monthly total precipitation (mm) (1961–1990 CC; 1961–1990 ALADIN; 2021–2050 ALADIN, 2071–2100 ALADIN)
- monthly mean temperature (°C) (1961–1990 CC; 1961–1990 ALADIN; 2021–2050 ALADIN, 2071–2100 ALADIN)
- territorial weighted averages concerning the water surface of the Lake
- monthly total precipitation (mm) (1961–1990 CC; 1961–1990 ALADIN; 2021–2050 ALADIN, 2071–2100 ALADIN)
- monthly mean temperature (°C) (1961–1990 CC; 1961–1990 ALADIN; 2021–2050 ALADIN)
- monthly mean wind speed at 10 m (m/s) (1961–1990 CC; 1961–1990 ALADIN; 2021–2050 ALADIN, 2071–2100 ALADIN)
- monthly relative humidity (%) (1961–1990 CC; 1961–1990 ALADIN; 2021–2050 ALADIN)

We held regular consultations with the expert of OMSZ, Gabriella Szépszó about the use of the meteorological data listed above in the hydrology calculations (possibilities and limits), as well as the interpretation and evaluation of results in the course of elaborating the study.

As part of the professional cooperation, a summary study was made by Gabriella Szépszó and Anett Csorvási under the title 'Results of ALADIN-Climate model simulations', which is presented in its entirety in the annex of this study.

In the following, the details and findings of the study are summarized, which we used as professional compass in the application of the meteorological data, the hydrological calculations and the assessments of their results.

The analysis of the climate change is possible with the help of the climate models and four regional climate models are used in Hungary for mapping the changes expected in our region in the 21st century. Of these, in the current case, we summarize the possibilities and limits of using the ALADIN-Climate model employed at the Hungarian Meteorological Service.

Therefore, the ‘long-term predictability’ in the classic meaning cannot be implemented with the climate models. The global connected models can describe processes and interactions having slow enforcing impact on the circulation and the climate of the entire Earth, therefore, the asymptotic characteristics of the behavior of the climate system can be determined with their help. The results of the climate models on a climate time scale, therefore, must be considered as a statistical multitude, where no prognostic significance is attached to the specific moment in time to which the given forecast applies and the reliability of the models is classified according to the accuracy, by which they can reflect the statistical characteristics of a selected period.

As of necessity, the regional (and global) model results are burdened by a smaller or larger fault which must be taken into account while evaluating the projections for the future. This can be done by determining change values: the model results for the future are not interpreted in themselves, but related to the own reference period of the models, therefore, the systematic model faults concerning the future and the past partly eliminate each other by generating the difference; and the change values are added to the values calculated on the basis of measurements for the reference period (in case of a relative change, the values of measurement and change are multiplied).

Just like the past model results, the same way the data for the future cannot be interpreted as ‘predicted time series of climate change’, only as one possible realization of the meteorological variables. Within the periods of 30 years, the annual data constitute such statistical populations, which can be interchanged in time. This means that an arbitrary annual data line can be related to any year of the period.

It is impossible to match a trend to a data line within the period, and the data applicable for the specific year cannot be considered as a long-term weather forecast. The attention must also be directed to the point that the climate system is a system of non-linear evolution; therefore, it is impossible to draw conclusions from the trends of a specific period for the characteristics of another period.

No justified statements can be made concerning the uncertainty of results by analyzing the results of a single model simulation – ALADIN-Climate in this case. As noted earlier, there is no guarantee that the models well describing the past may give successful climate estimates for the future, therefore, the faults calculated in the validation and the changes estimated for the future cannot be ‘blended’. Uncertainties can only be described correctly by means of several model experiments. The application of two models already provides a good starting base for the fundamental quantification of uncertainties. Therefore, for the interpretation of future changes, it is necessary by all means to analyze the results of a suitably selected model experiment.

The calculations and evaluations described in detail in the sub-chapters 3.1–3.7 below were carried out by considering the points above.

3.1 Calculation of territorial average of the precipitation over the Balaton catchment area for the climate windows

As proposed by the experts of OMSZ – for the minimization of systematic model faults – the precipitation data concerning the periods of 2021–2050 and 2071–2100 were taken into account with the correction below:

ALADIN 2150 (corr.) = (CC 6190)×k, where k = (ALADIN 2150)/(ALADIN 6190 average)
ALADIN 7100 (corr.) = (CC 6190)×k, where k = (ALADIN 7100)/(ALADIN 6190 average)

The results are shown in Tables 2–5 and Figures 13–15.

Table 2. Monthly, semi-annual and annual fact (for the period of 1961–1990) and estimated (for the periods of 2021–2050 and 2071–2100) values of the 30-year territorial average of the precipitation over the Balaton catchment area (mm)

Period	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Winter half year (XI–IV)	Summer half year (V–X)	Year (I–XII)
1961–1990 CC	39	37	43	53	68	81	76	76	56	45	67	48	289	402	689
2021–2050 ALADIN (corr)	27	39	44	62	69	81	71	72	62	54	74	52	297	409	706
2071–2100 ALADIN (corr)	37	34	42	55	71	78	54	51	47	53	93	58	321	354	673

Table 3. 30-year territorial average (mm) of the precipitation over the Balaton catchment area and the absolute differences therefrom at the time of the future climate windows (2021–2050 and 2071–2100) (mm)

Period	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Winter half year (XI–IV)	Summer half year (V–X)	Year (I–XII)
1961–1990 CC	39	37	43	53	68	81	76	76	56	45	67	48	289	402	689
2021–2050 ALADIN (corr)	–12	2	0	9	1	0	–4	–4	6	8	7	4	8	8	17
2071–2100 ALADIN (corr)	–2	–2	–2	2	3	–3	–22	–25	–9	8	26	10	33	–48	–16

Table 4. 30-year territorial average (mm) of the precipitation in the Balaton watershed and the relative differences therefrom at the time of the future climate windows (2021–2050 and 2071–2100) (%)

Period	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Winter half year (XI–IV)	Summer half year (V–X)	Year (I–XII)
1961–1990 CC	39	37	43	53	68	81	76	76	56	45	67	48	289	402	689
2021–2050 ALADIN (corr)	–32	5	1	17	1	0	–6	–5	11	18	10	8	3	2	2
2071–2100 ALADIN (corr)	–5	–7	–4	4	4	–4	–29	–33	–16	18	38	20	11	–12	–2

Table 5: Statistical characteristics of the actual and estimated precipitation over the Balaton catchment area (mm) by climate windows

Period	Min	Average	Max	Variance
1961–1990 CC	481	689	988	115.72
2021–2050 ALADIN (corr)	418	706	911	125.81
2071–2100 ALADIN (corr)	430	673	905	131.58

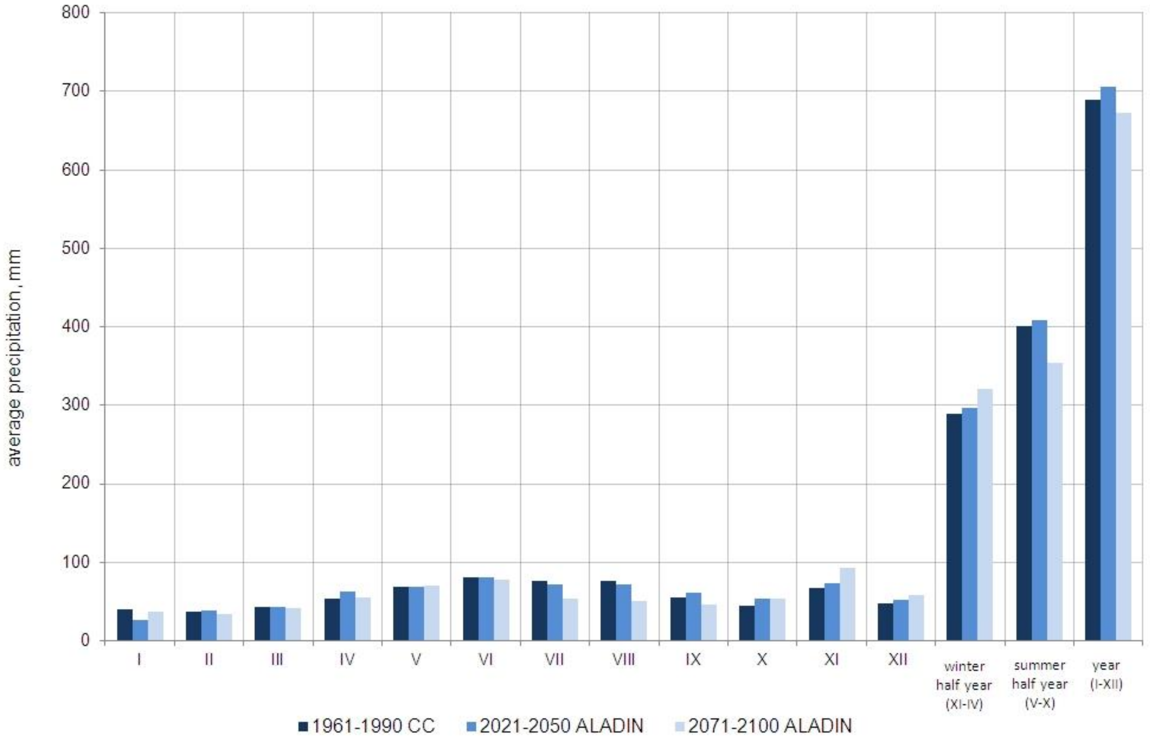

Figure 13. Monthly, semi-annual and annual fact (for the period of 1961–1990) and estimated (for the periods of 2021–2050 and 2071–2100) values of the 30-year territorial average of the precipitation over the Balaton catchment area (mm)

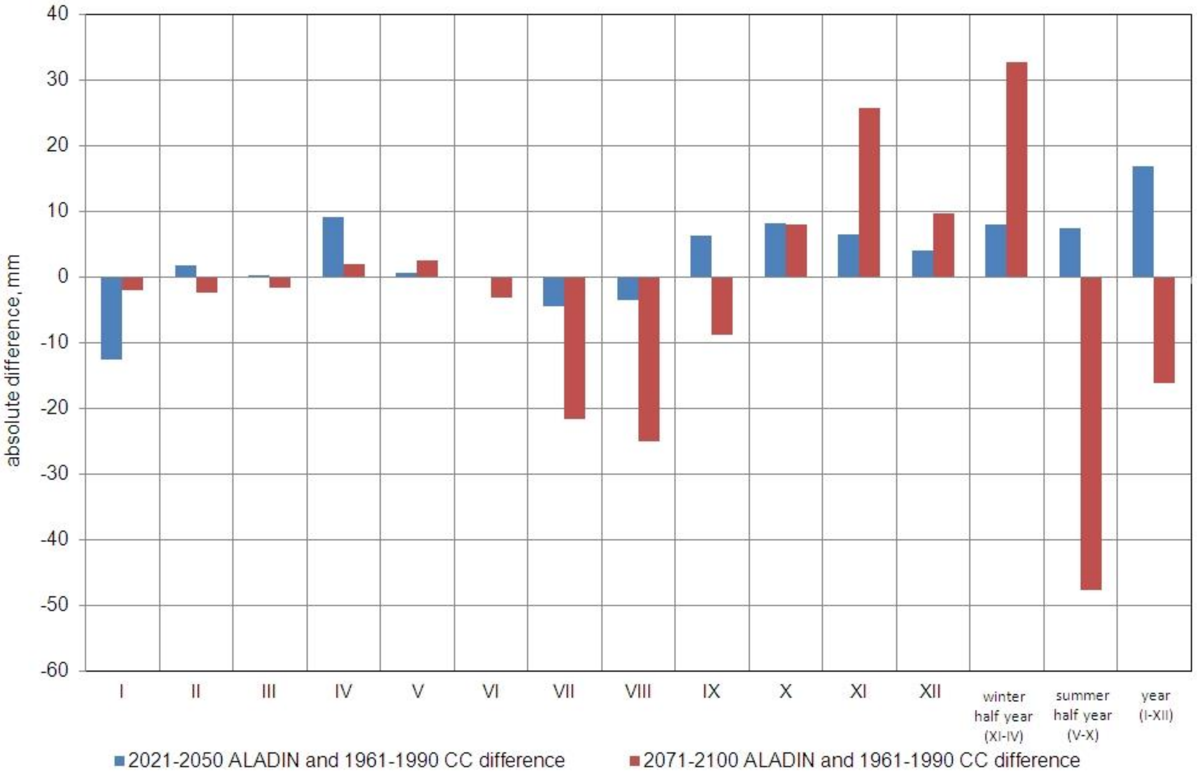

Figure 14. 30-year territorial average (mm) of the precipitation over the Balaton catchment area and the absolute differences therefrom at the time of the future climate windows (2021–2050 and 2071–2100) (mm)

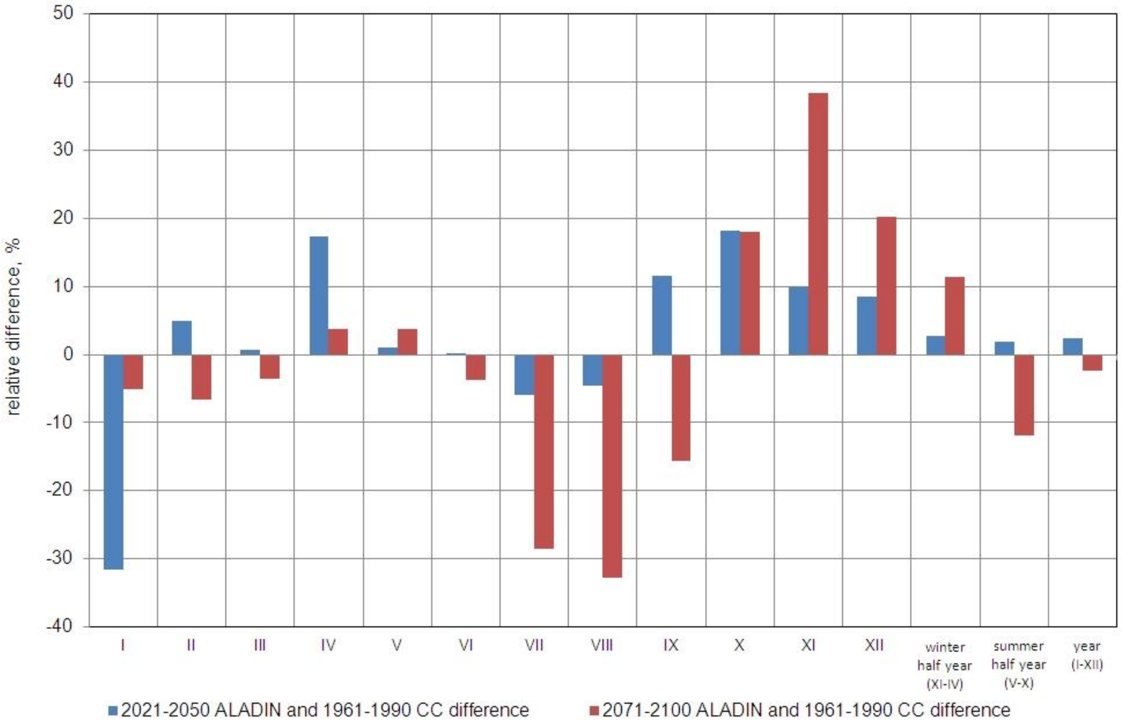

Figure 15. 30-year territorial average (mm) of the precipitation in the Balaton watershed and the relative differences therefrom at the time of the future climate windows (2021–2050 and 2071–2100) (%)

Reviewing the data concerning the time window of 2021–2050 it is found that considerable changes (exceeding ±10%) are not likely in the estimated trends of precipitation in the watershed of the Lake relative to the average values of the reference period of time over semi-annual and annual time horizons. In accordance with the relative variances applicable for the specific months, an increase above 10% is manifest in April and in the period of September to November, whereas, a decrease by 32% is recorded for January. It is noted, that the reduction of length of the period under review involves the uncertainty of the model results.

Reviewing the data concerning the time window of 2071–2100 it is found that considerable changes (exceeding ±10%) are not likely in the estimated trends of precipitation in the watershed of the Lake relative to the average values of the reference period of time over annual time horizons. The result concerning the decrease above 10% in summer and the increase above 10% in winter over the semi-annual time horizon related to the values of the reference period refer to the rearrangement of the annual total precipitation in time. The summer semi-annual estimated precipitation decrease is concentrated in the period of July–August, while the focus of the winter semi-annual precipitation increase is concentrated in November–December.

3.2 Calculation of territorial average of the precipitation over the Balaton water surface for the climate windows

As proposed by the experts of OMSZ – for the minimisation of systematic model faults – the precipitation data concerning the periods of 2021–2050 and 2071–2100 were taken into account with the correction below:

ALADIN 2150 (corr.) = (CC 6190)*k, where k = (ALADIN 2150)/(ALADIN 6190 average)
ALADIN 7100 (corr.) = (CC 6190)*k, where k = (ALADIN 7100)/(ALADIN 6190 average)

The results are shown in Tables 6–9 and Figures 16–18.

Table 6. Monthly, semi-annual and annual fact (for the period of 1961–1990) and estimated (for the periods of 2021–2050 and 2071–2100) values of the 30-year territorial average of the precipitation over the Balaton water surface (mm)

Period	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Winter half year (XI–IV)	Summer half year (V–X)	Year (I–XII)
1961–1990 CC	37	35	38	46	59	73	64	68	46	38	61	45	263	347	609
2021–2050 ALADIN (corr)	25	34	40	58	60	77	62	61	52	45	70	47	273	357	631
2071–2100 ALADIN (corr)	35	33	36	48	66	73	46	44	37	43	87	55	294	309	602

Table 7. 30-year territorial average (mm) of the precipitation over the Balaton water surface and the absolute differences therefrom at the time of the future climate windows (2021–2050 and 2071–2100) (mm)

Period	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Winter half year (XI–IV)	Summer half year (V–X)	Year (I–XII)
1961–1990 CC	37	35	38	46	59	73	64	68	46	38	61	45	263	347	609
2021–2050 ALADIN (corr)	–12	–1	2	12	1	5	–1	–7	6	7	9	1	10	10	21
2071–2100 ALADIN (corr)	–2	–2	–2	2	7	1	–17	–24	–10	5	25	9	31	–39	–7

Table 8. 30-year territorial average (mm) of the precipitation in the Balaton water surface and the relative differences therefrom at the time of the future climate windows (2021–2050 and 2071–2100) (%)

Period	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Winter half year (XI–IV)	Summer half year (V–X)	Year (I–XII)
1961–1990 CC	37	35	38	46	59	73	64	68	46	38	61	45	263	347	609
2021–2050 ALADIN (corr)	–32	–2	6	26	2	6	–2	–11	13	19	14	3	4	3	3
2071–2100 ALADIN (corr)	–6	–5	–5	5	11	1	–27	–36	–21	15	42	20	12	–11	–1

Table 9. Statistical characteristics of the actual and estimated precipitation over the Balaton water surface (mm) by climate windows

Period	Min	Average	Max	Variance
1961–1990 CC	459	609	877	105.61
2021–2050 ALADIN (korr)	386	631	847	122.35
2071–2100 ALADIN (korr)	349	602	808	117.01

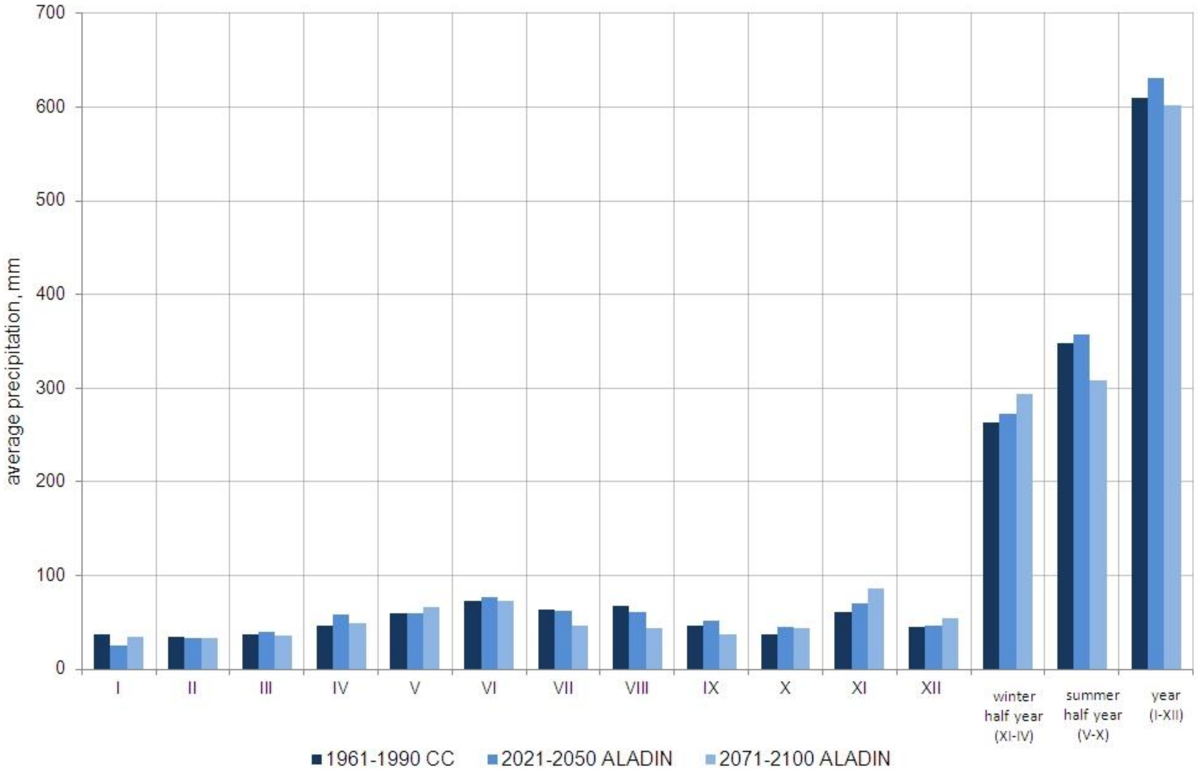

Figure 16. Monthly, semi-annual and annual fact (for the period of 1961–1990) and estimated (for the periods of 2021–2050 and 2071–2100) values of the 30-year territorial average of the precipitation over the Balaton water surface (mm)

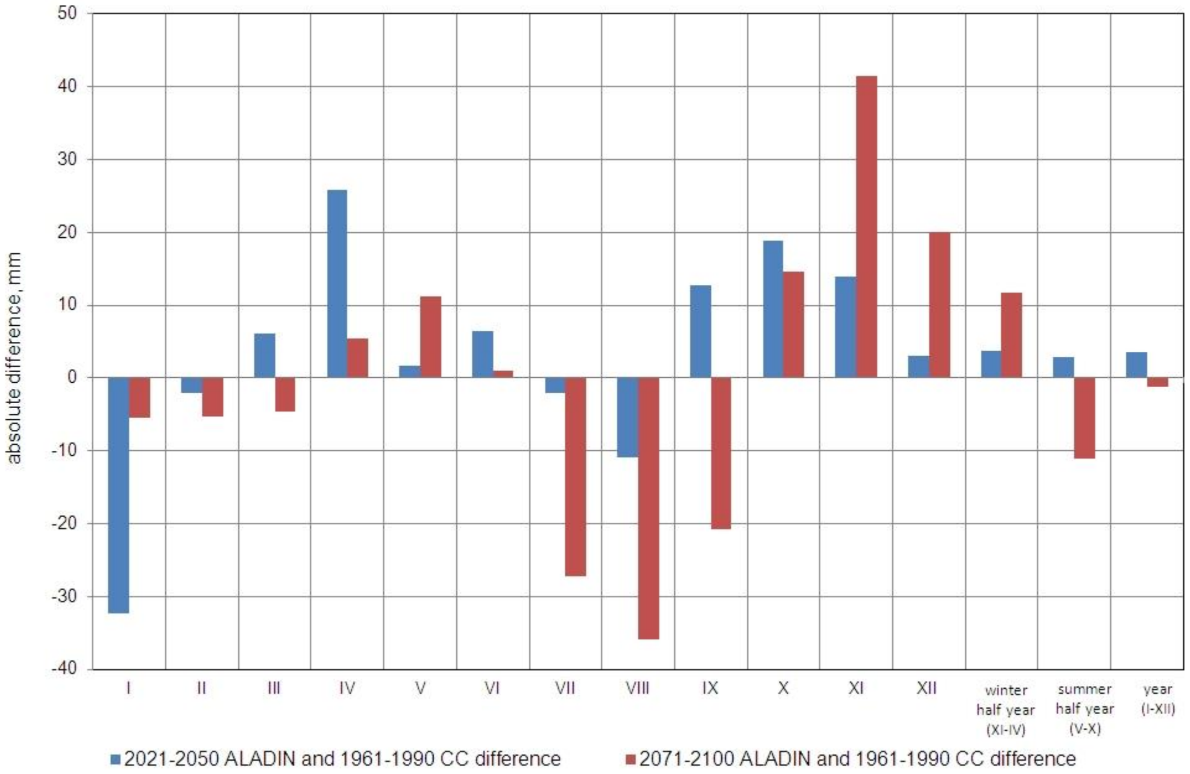

Figure 17. 30-year territorial average (mm) of the precipitation over the Balaton water surface and the absolute differences therefrom at the time of the future climate windows (2021–2050 and 2071–2100) (mm)

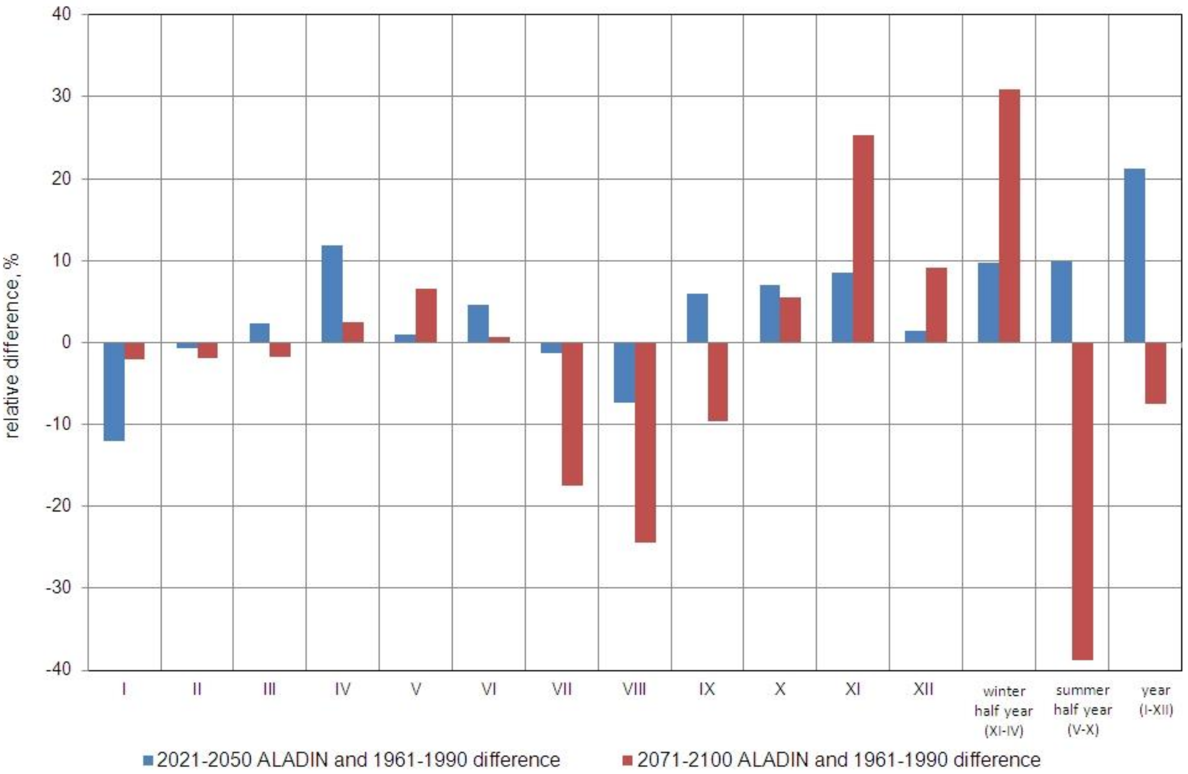

Figure 18. 30-year territorial average (mm) of the precipitation in the Balaton water surface and the relative differences therefrom at the time of the future climate windows (2021–2050 and 2071–2100) (%)

Reviewing the data concerning the time window of 2021–2050 it is found that considerable changes (exceeding ±10%) are not likely in the estimated trends of precipitation in the water surface of the Lake relative to the average values of the reference period of time over semi-annual and annual time horizons. In accordance with the relative variances applicable for the specific months, an increase above 10% is manifest in April and in the period of September to November, whereas, a decrease by 32% is recorded for January and a decrease by 11% is recorded for July. It is noted, that the reduction of length of the period under review involves the increasing uncertainty of the model results.

Reviewing the data concerning the time window of 2071–2100 it is found that considerable changes (exceeding ±10%) are not likely in the estimated trends of precipitation in the watershed of the Lake relative to the average values of the reference period of time over annual time horizons. The result concerning the decrease above 10% in summer and the increase above 10% in winter over the semi-annual time horizon related to the values of the reference period refer to the rearrangement of the annual total precipitation in time. The summer semi-annual estimated precipitation decrease is concentrated in the period of July–September, while the focus of the winter semi-annual precipitation increase is concentrated in November–December.

3.3 Calculation of territorial averages of annual mean temperature of the Balaton catchment area for the climate windows

As proposed by the experts of OMSZ – for the minimization of systematic model faults – the air temperature data concerning the periods of 2021–2050 and 2071–2100 were taken into account with the correction below:

ALADIN 2150 (corr.) = k + CC 6190, where k = ALADIN 2150 – ALADIN 6190 average
ALADIN 7100 (corr.) = k + CC 6190, where k = ALADIN 7100 – ALADIN 6190 average

The results are shown in Tables 10–12 and Figures 19–20.

Table 10. Monthly, semi-annual and annual fact (for the period of 1961–1990) and estimated (for the periods of 2021–2050 and 2071–2100) values of the 30-year territorial average of the temperature over the Balaton catchment area (°C)

Period	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Winter half year (XI–IV)	Summer half year (V–X)	Year (I–XII)
1961–1990 CC	–1.4	1.1	5.4	10.2	14.9	18.0	19.7	19.2	15.8	10.5	4.9	0.3	3.4	16.4	9.9
2021–2050 ALADIN (corr)	–0.3	2.3	6.8	11.6	16.1	19.3	21.7	21.8	17.7	12.6	6.1	2.0	4.8	18.2	11.5
2071–2100 ALADIN (corr)	1.0	3.9	8.8	12.9	17.1	20.5	24.3	24.9	20.2	13.7	6.9	2.4	5.9	20.1	13.1

Table 11. 30-year territorial average (°C) of the monthly, semi-annual and annual mean temperature of the Balaton catchment area and the absolute differences therefrom at the time of the future climate windows (2021–2050 and 2071–2100) (°C)

Period	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Winter half year (XI-IV)	Summer half year (V-X)	Year (I-XII)
1961–1990 CC	–1.4	1.1	5.4	10.2	14.9	18.0	19.7	19.2	15.8	10.5	4.9	0.3	3.4	16.4	9.9
2021–2050 ALADIN (corr)	1.1	1.2	1.4	1.4	1.2	1.2	2.0	2.6	1.9	2.0	1.2	1.6	1.4	1.8	1.6
2071–2100 ALADIN (corr)	2.4	2.9	3.4	2.6	2.3	2.4	4.7	5.7	4.3	3.2	2.0	2.0	2.6	3.8	3.2

Table 12. Statistical characteristics of the annual mean temperature of the Balaton catchment area by climate windows

Period	Min	Average	Max	Variance
1961–1990 CC	8.9	9.9	10.8	0.58
2021–2050 ALADIN (corr)	9.6	11.5	13.5	0.79
2071–2100 ALADIN (corr)	11.3	13.1	14.1	0.72

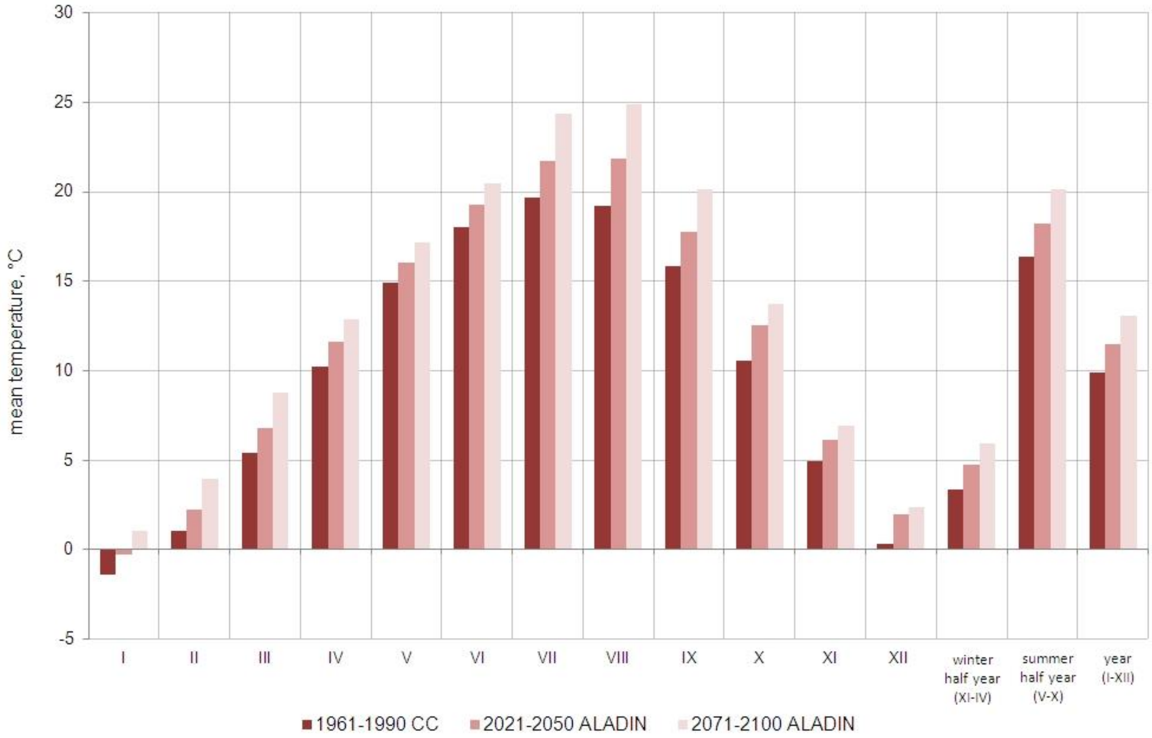

Figure 19. Monthly, semi-annual and annual fact (for the period of 1961–1990) and estimated (for the periods of 2021–2050 and 2071–2100) values of the 30-year territorial average of the temperature over the Balaton catchment area (°C)

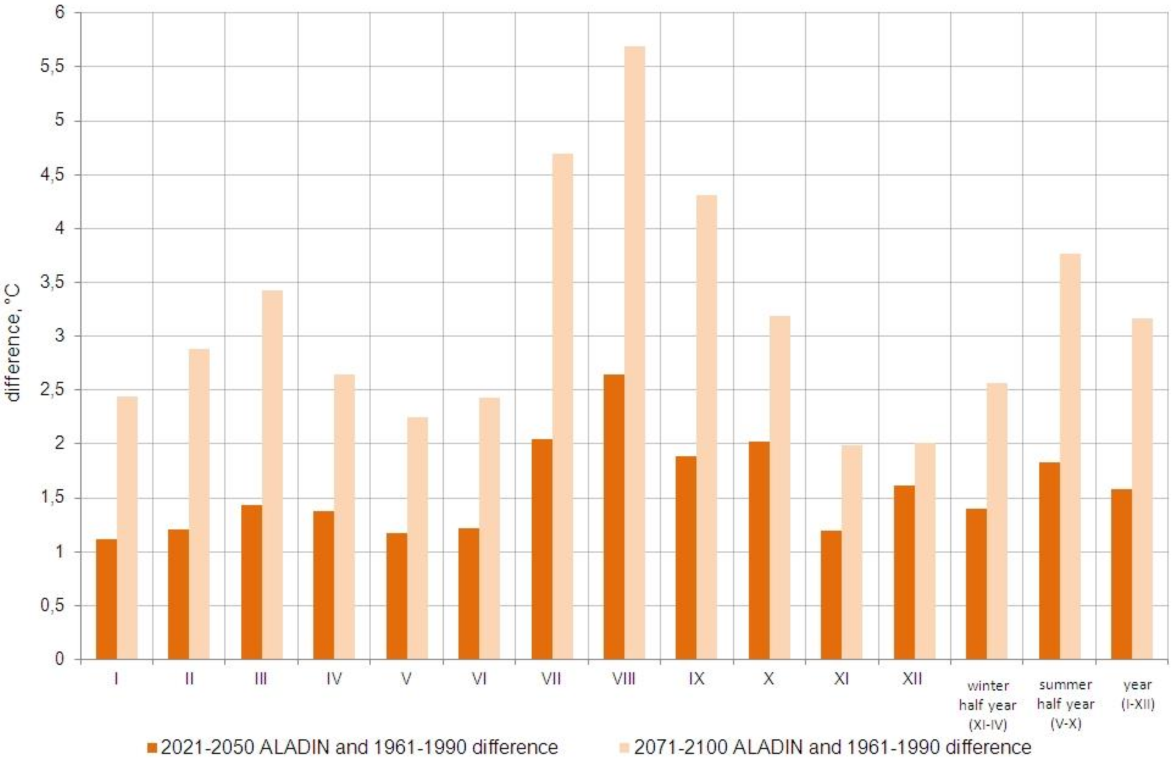

Figure 20: Absolute variances of the monthly, semi-annual and annual mean temperatures from the average of the reference period in the Balaton watershed at the time of the future climate windows (2021–2050 and 2071–2100) (°C)

Reviewing the data concerning the time window of 2021–2050, it is found that considerable change (above 1 °C) is expected in the trends of mean temperature of the Balaton watershed related to the average values of the reference period over the semi-annual and annual time horizons. Warming up by a higher rate (1.8 °C) is estimated at the summer half of the year. The most powerful temperature increase within the calendar year is focused on the period of July–October. It is noted, that the reduction of length of the period under review involves the increasing uncertainty of the model results.

Reviewing the data concerning the time window of 2071–2100, it is found that considerable change (above 2 °C) is expected in the trends of mean temperature of the Balaton watershed related to the average values of the reference period over the semi-annual and annual time horizons. Warming up by a higher rate (3.8 °C) is estimated at the summer half of the year. The most powerful temperature increase within the calendar year is focused on the period of March and July–October. It is noted, that the reduction of length of the period under review involves the increasing uncertainty of the model results.

3.4 Calculation of the periodical territorial averages of annual actual evaporation of the Balaton catchment area for the climate windows

The so-called Turc formula is used by hydrology for the calculation of the actual (territorial) evaporation of the catchment area, which yields a relatively reliable result with small data requirements. Therefore, the annual averages of the territorial evaporation were calculated with the help of this formula, using the territorial averages of the total precipitation and the annual average temperature:
The Turc formula is shown below:

$$E_{tp}^{T} = \frac{P}{\sqrt{0{,}9 + \frac{P^2}{K^2}}}$$

where $K = 300 + 25 \cdot T + 0{,}05 \cdot T^3$

P the annual amount of precipitation (mm)

T the annual mean temperature (°C)

E_{tp}^{T} actual evaporation of the bare ground (mm)

The part above the total territorial evaporation is the evaporation from the soil covering plants, the transpiration, which is taken into account in the calculations using the formula below:

$$E_{tp}^{e} = a \cdot E_{tp}^{T}$$

where E_{tp}^{T} - actual evaporation of the bare ground (mm)

E_{tp}^{e} - joint evaporation of the soil and plants (evapo-transpiration) (mm)

a - constant of plants

The value of constant of plants ‘a’ was determined by means of long-term series of measurements on the experimental catchment area, resulting in 1.13 for ‘a’ for the territory without forest (including grassland and low level plants); and 1.62 for the area covered by forest (MAJOR 1974).

In the calculation of the actual evaporation of the catchment area, we have considered the data summarized in Table 13 for forest cover and free water surface and the estimated additional evaporation data, in proportion to the area.

It is noted that the data of forest cover and free water surface area stated for 2021–2050 and 2071–2100 are the current actual values, as their future evolution is not known.

Table 13. Data of forest cover and free surface water area and estimated additional evaporation considered for the determination of the actual evaporation of the Balaton catchment area

Period	Periodical average of forest cover (%)	Periodical average area of free water surfaces (km^2)		Periodical average additional evaporation of free water surfaces (mm/year)	
		Kis-Balaton Water Protection System (KBVR)	Fishponds, minor reserviors	Kis-Balaton Water Protection System (KBVR)	fishponds, minor reservoirs
1961–1990	25	3*	32**	300	250
2021–2050	29	72	37	350	290
2071–2100	29	72	37	400	330

Note: *1961–1985: 0 km^2; 1986–1990: 18 km^2.
**** 1961–1980: 30 km^2; 1981–1990: 37 km^2.**

The evaporation values of the catchment area calculated for the annual time horizon are summarized in Table 14.

Table 14: Statistical characteristics of the annual actual evaporation of the Balaton catchment area (mm/year) by climate windows

Period	Min	Average	Max	Variance
1961–1990 CC	484	573	640	35.48
2021–2050 ALADIN (corr)	480	622	717	53.33
2071–2100 ALADIN (corr)	501	647	768	69.34

Having reviewed the data stated in Table 14, it is found that an actual increase of evaporation is estimated for the period of 2021–2050 by about 9% – in a periodical average, and by about 13% for the period of 2071–2100 – in a periodical average, compared to the average of the reference period of time.

In accordance with the points stated in sub-chapter 3.1, the estimated average annual precipitation in the watershed related to the average of the reference period forecasts a change not exceeding ±2% in the periodical average of the future climate windows. This shows that the estimated increase of the actual evaporation is not caused fundamentally by the change of precipitation volume.

The real explanation, by all certainty, should be sought in the estimated temperature rise – the remarkable warming. The ALADIN-Climate model predicts an average warming by 1.6 °C on the territory of the Balaton watershed related to the average of the reference period in 2021–2050, and an average of 3.2 °C between 2071–2100 (sub-chapter 3.3).

In the period of future climate windows, according to the estimate, with a hardly variable annual average precipitation volume the significant increase of evaporation is expected. This predicts the decrease of difference between the precipitation and the actual evaporation on the watershed area, which may result in a significant reduction of in-flow concerning the water budget of Lake Balaton.

3.5 Calculation of periodical average values of annual runoff from the catchment area of Balaton (in-flow in the water budget of Balaton) for the climate windows

Runoff from the catchment area of the Lake – as the residual member of the water balance – is interpreted as the difference of precipitation received over the catchment area and of the water amount removed from there by evaporation.

The determination and evaluation of periodical average by climate windows of the annual precipitation over the catchment was discussed in detail in sub-chapter 3.1 and of the annual evaporation from the catchment area in sub-chapter 3.4 of the study.

Table 15 shows the periodical average values of runoff interpreted as the difference of precipitation and evaporation as well as the value of runoff converted to the Balaton surface in proportion to the area and of the in-flow.

Table 15. Change of precipitation, territorial evaporation and calculated runoff in the periodical average of the climate windows on the catchment area of Balaton (mm/year)

Period	Precipitation (P)	Territorial evaporation (ET)	Calculated runoff (P-ET)	Calculated in-flow of Balaton (I)
1961–1990	689	573	116	1001
2021–2050	706	622	84	725
2071–2100	673	647	26	224

In accordance with the data stated in Table 15 – mainly as a consequence of increase of evaporation over the area – a remarkable decrease of the precipitation-evaporation can be estimated on the Balaton catchment area in the periodical average of future climate windows.

According to our calculations, within the climate windows of 30 years, the number of years, which can be characterized with negative annual precipitation / evaporation difference, provided the picture below:

- in the period of 1961–1990   1 year
- in the period of 2021–2050   6 years
- in the period of 2071–2100 13 years

In the years when the precipitation-evaporation difference is negative in the watershed area, there is still an out-flow; however, this derives overwhelmingly from the sub-surface water reserves. In the years with more precipitation, the precipitation arriving at the watershed in the beginning replenishes these missing reserves under the surface and only when it is done, the surface out-flow is expected to appear.

As the water turnover of the sub-surface water reserves, and as a result their regeneration, take place much more slowly than those of the surface water reserves, the impact of changes on the sub-surface reserves – as a protracted impact – may also cover several subsequent years.

3.6 Calculation of average values of the periodical amounts of evaporation from the water surface of Balaton to the climate windows

As a result of the professional cooperation between VITUKI and OMSZ, the evaporation of Balaton was determined in 1986 from the following empirical formula adapted from the Meyer basic formulate to Lake Balaton:

$$E_W = a \times (E-e) \times (0.59+0.013 \times v) \times n$$

where E_W – monthly evaporation of the free water surface (mm)
E – saturation vapour pressure related to the monthly mean temperature (mb)
e – monthly average value of the actual vapour pressure (mb)
v – monthly medium wind speed (m/s)
n – number of days of the month
a – empirical constant:
March a = 0.7
April a = 0.8
October a = 1.3
November a = 1.4
(in the other months a = 1)

The next 3 sub-chapters (3.6.1–3) report on the preparation of meteorological data required for the calculation of evaporation from the water surface of Balaton.

3.6.1. Calculation of territorial average values of the air temperature above the water surface of Balaton for the climate windows

As proposed by the experts of OMSZ – for the minimization of systematic model faults – the air temperature data concerning the periods of 2021–2050 and 2071–2100 were taken into account with the correction below:

ALADIN 2150 (corr.) = k + CC 6190, where k = ALADIN 2150 – ALADIN 6190 average
ALADIN 7100 (corr.) = k + CC 6190, where k = ALADIN 7100 – ALADIN 6190 average

The results are shown in Tables 16–18 and Figures 21–22.

Table 16. Monthly, semi-annual and annual fact (for the period of 1961–1990) and estimated (for the periods of 2021–2050 and 2071–2100) values of the 30-year territorial average of the annual mean temperature of the atmosphere above the water surface of Balaton (°C)

Period	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Winter half year (XI–IV)	Summer half year (V–X)	Year (I–XII)
1961–1990 CC	–1.5	1.1	5.6	10.6	15.3	18.5	20.1	19.6	16.2	10.9	5.1	0.7	3.5	16.8	10.2
2021–2050 ALADIN	–0.3	2.3	6.8	11.9	16.5	19.8	22.0	21.9	17.9	12.9	6.3	2.2	4.9	18.5	11.7
2071–2100 ALADIN	1.0	3.8	8.6	13.1	17.6	21.1	24.3	24.5	20.3	14.1	7.2	2.6	6.0	20.3	13.2

Table 17. 30-year territorial average (°C) of the monthly, semi-annual and annual mean temperature of the atmosphere above the water surface of Balaton and the absolute differences therefrom at the time of the future climate windows (2021–2050 and 2071–2100) (°C)

Period	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Winter half year (XI–IV)	Summer half year (V–X)	Year (I–XII)
1961–1990 CC	–1.5	1.1	5.6	10.6	15.3	18.5	20.1	19.6	16.2	10.9	5.1	0.7	3.5	16.8	10.2
2021–2050 ALADIN	1.2	1.2	1.2	1.3	1.2	1.3	1.9	2.3	1.8	2.0	1.2	1.6	1.3	1.7	1.5
2071–2100 ALADIN	2.5	2.7	3.0	2.5	2.3	2.6	4.3	4.9	4.1	3.2	2.1	2.0	2.5	3.6	3.0

Table 18. Statistical characteristics of annual mean temperature (°C) of the atmosphere over the water surface of Balaton by climate windows

Period	Min	Average	Max	Variance
1961–1990 CC	9.2	10.2	11.1	0.58
2021–2050 ALADIN	10.1	11.7	13.4	0.65
2071–2100 ALADIN	11.7	13.2	14.1	0.59

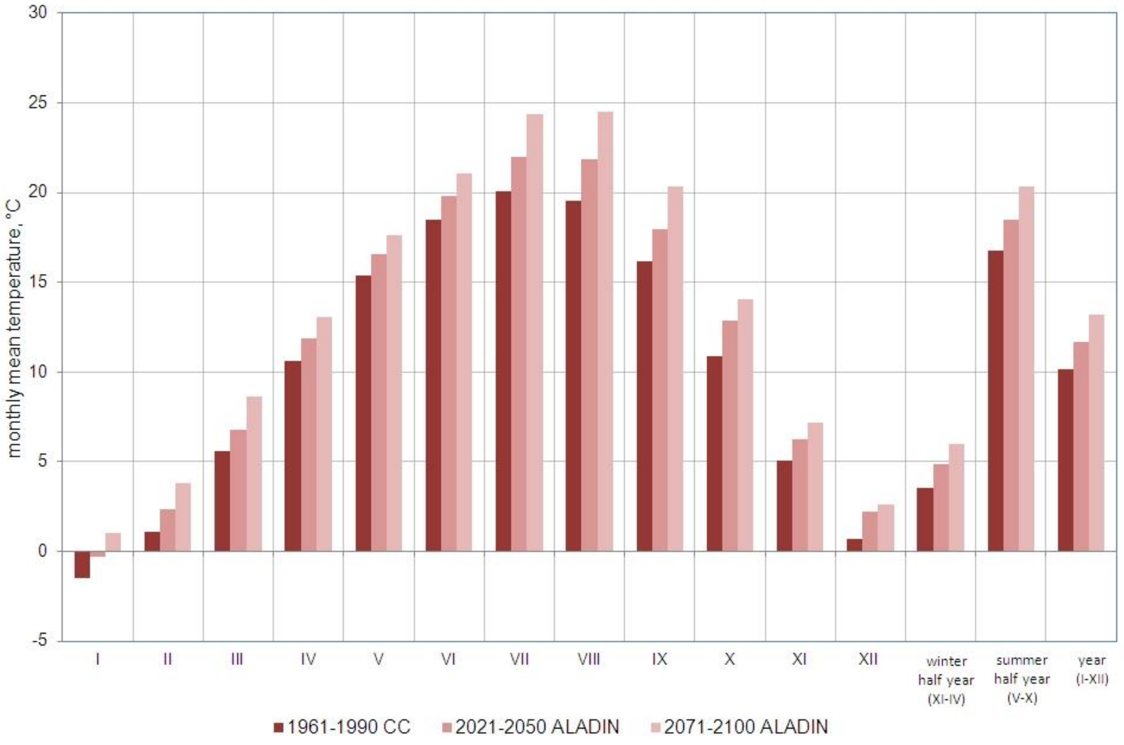

Figure 21. Monthly, semi-annual and annual fact (for the period of 1961–1990) and estimated (for the periods of 2021–2050 and 2071–2100) values of the 30-year territorial average of the annual mean temperature of the atmosphere over the Balaton (°C)

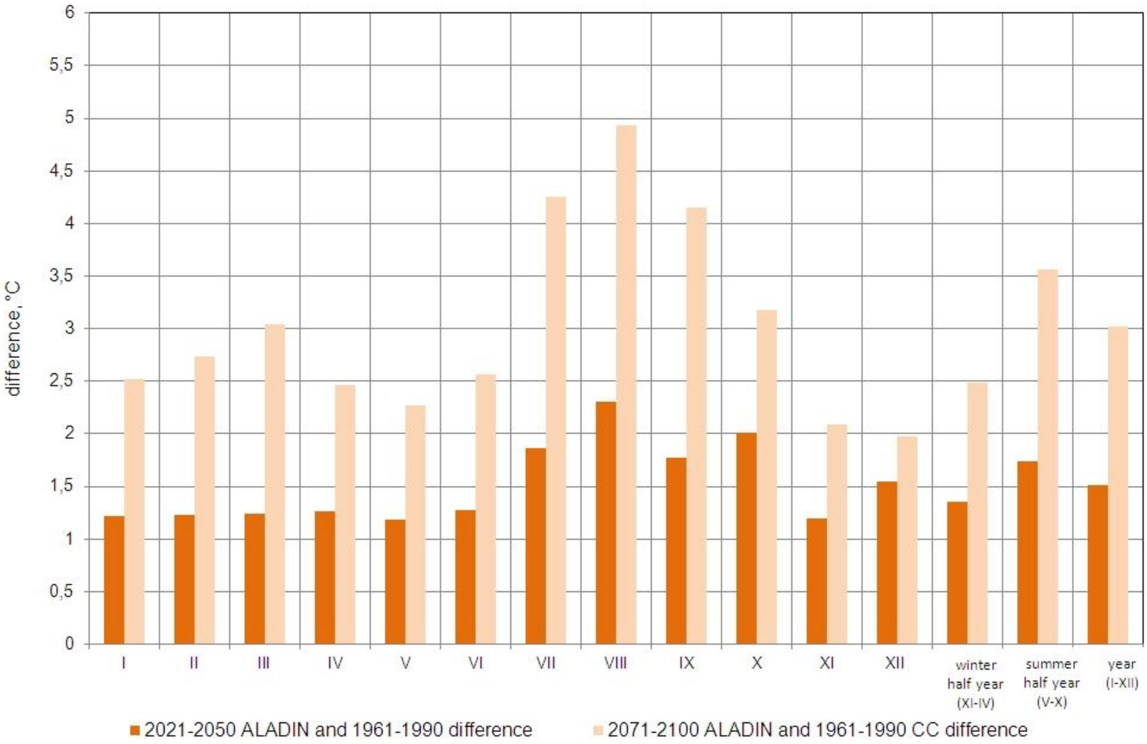

Figure 22. Absolute variances of the monthly, semi-annual and annual mean temperatures from the average of the reference period in the atmosphere over Balaton at the time of the future climate windows (2021–2050 and 2071–2100) (°C)

Reviewing the data concerning the time window of 2021–2050, it is found that considerable change (above 1 °C) is expected in the trends of mean temperature of the atmosphere over Balaton related to the average values of the reference period over the semi-annual and annual time horizons. Warming up by a higher rate (1.7 °C) is estimated at the summer half of the year. The most powerful temperature increase within the calendar year is focused on the period of July–October. It is noted, that the reduction of length of the period under review involves the increasing uncertainty of the model results.

Reviewing the data concerning the time window of 2071–2100, it is found that considerable change (above 2 °C) is expected in the trends of mean temperature of the Balaton watershed related to the average values of the reference period over the semi-annual and annual time horizons. Warming up by a higher rate (3.6 °C) is estimated at the summer half of the year. The most powerful temperature increase within the calendar year is focused on the period of March and July–October. It is noted, that the reduction of length of the period under review involves the increasing uncertainty of the model results.

3.6.2. Calculation of regional average values of relative humidity above the water surface of Balaton for the climate windows

As proposed by the experts of OMSZ – for the minimization of systematic model faults – the relative humidity data concerning the periods of 2021–2050 and 2071–2100 were taken into account with the correction below:

ALADIN 2150 (corr.) = k + CC 6190, where k = ALADIN 2150 – ALADIN 6190 average
ALADIN 7100 (corr.) = k + CC 6190, where k = ALADIN 7100 – ALADIN 6190 average

The results are shown in tables 19–22 and figures 23–25.

Table 19. Periodical average vales of relative humidity content of the atmosphere over Balaton by climate windows (%)

Period	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Winter half year (XI–IV)	Summer half year (V–X)	Year (I–XII)
1961–1990 CC	86.0	79.8	73.7	68.5	70.9	71.6	70.1	73.0	77.2	80.1	83.5	85.1	79.4	73.8	76.6
2021–2050 ALADIN	85.6	79.3	75.1	69.2	70.9	71.0	68.6	70.6	74.4	80.6	83.4	85.7	79.7	72.7	76.2
2071–2100 ALADIN	85.7	79.7	74.6	68.6	69.1	69.5	64.4	65.6	69.8	79.5	82.5	85.2	79.5	69.7	74.5

Table 20. Absolute variances of the values of relative humidity content of the atmosphere above Lake Balaton calculated for future climate windows from the values of the reference period (%)

Period	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Winter half year (XI–IV)	Summer half year (V–X)	Year (I–XII)
1961–1990 CC	86.0	79.8	73.7	68.5	70.9	71.6	70.1	73.0	77.2	80.1	83.5	85.1	79.4	73.8	76.6
2021–2050 ALADIN	–0.4	–0.5	1.4	0.7	0.0	–0.7	–1.5	–2.3	–2.8	0.5	–0.2	0.6	0.2	–1.1	–0.4
2071–2100 ALADIN	–0.3	0.0	0.9	0.1	–1.8	–2.1	–5.7	–7.4	–7.3	–0.6	–1.0	0.1	0.0	–4.2	–2.1

Table 21. Relative variances of the values of relative humidity content of the atmosphere above Lake Balaton calculated for future climate windows from the values of the reference period (%)

Period	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Winter half year (XI–IV)	Summer half year (V–X)	Year (I–XII)
1961–1990 CC	86.0	79.8	73.7	68.5	70.9	71.6	70.1	73.0	77.2	80.1	83.5	85.1	79.4	73.8	76.6
2021–2050 ALADIN	–0.5	–0.6	1.8	1.0	–0.1	–0.9	–2.1	–3.2	–3.6	0.6	–0.2	0.7	0.3	–1.5	–0.6
2071–2100 ALADIN	–0.4	0.0	1.2	0.2	–2.5	–3.0	–8.1	–10.1	–9.5	–0.7	–1.2	0.1	0.0	–5.6	–2.8

Table 22. Statistical characteristics of the relative humidity (%) of the atmosphere above the Balaton water surface, by climate windows

Period	Min	Average	Max	Variance
1961–1990 CC	73.7	76.6	79.5	1.4
2021–2050 ALADIN	70.1	76.2	81.4	2.5
2071–2100 ALADIN	69.2	74.5	80.0	2.8

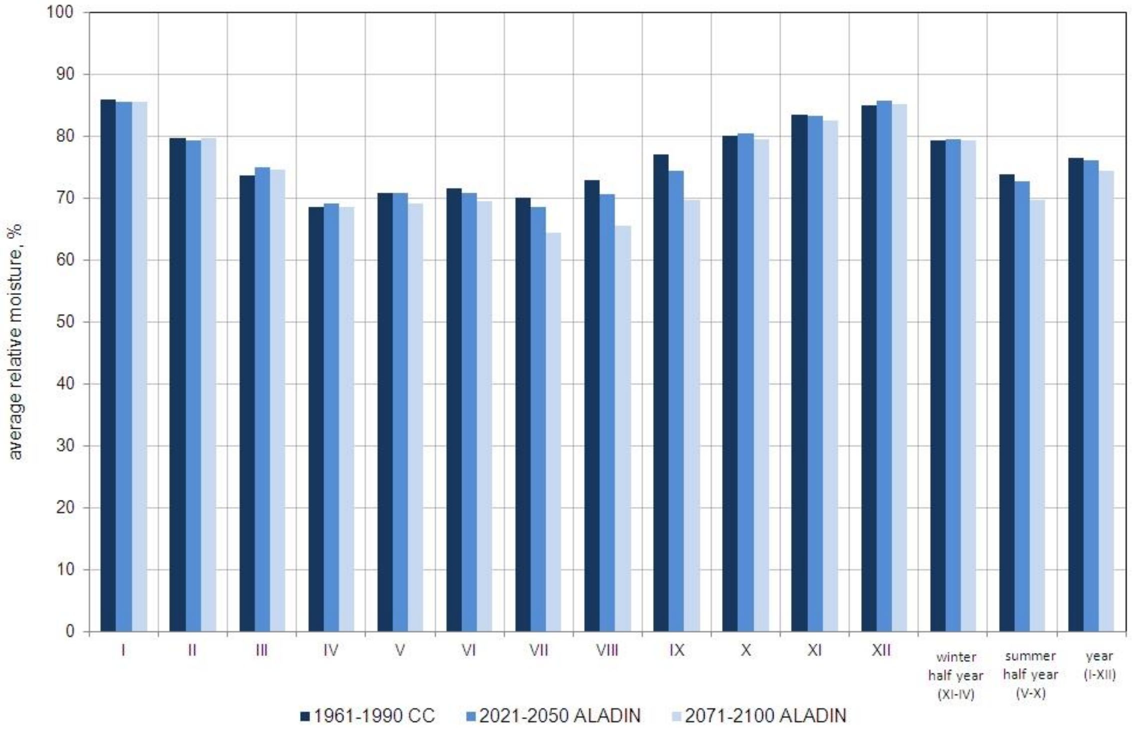

Figure 23. Monthly, semi-annual and annual fact (for the period of 1961–1990) and estimated (for the periods of 2021–2050 and 2071–2100) values of the 30-year average of the relative humidity of the atmosphere above Balaton (%)

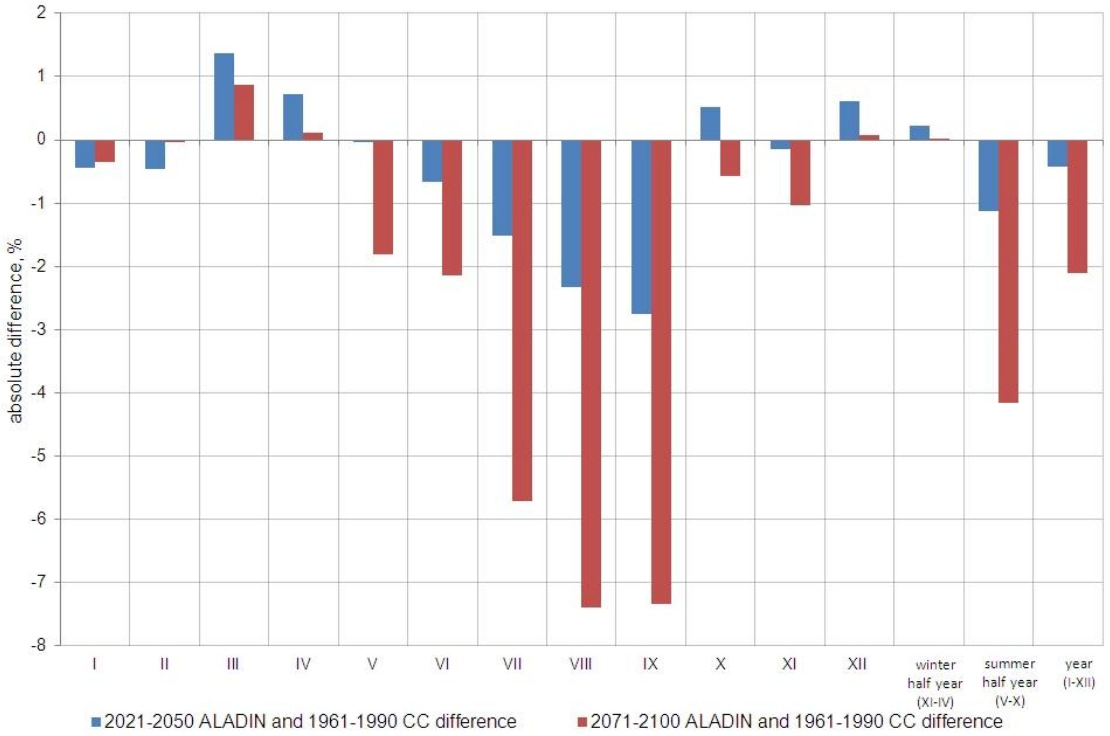

Figure 24. Absolute variances of the monthly, semi-annual and annual relative humidity of the atmosphere above Balaton at the time of the future climate windows (2021–2050 and 2071–2100) (%)

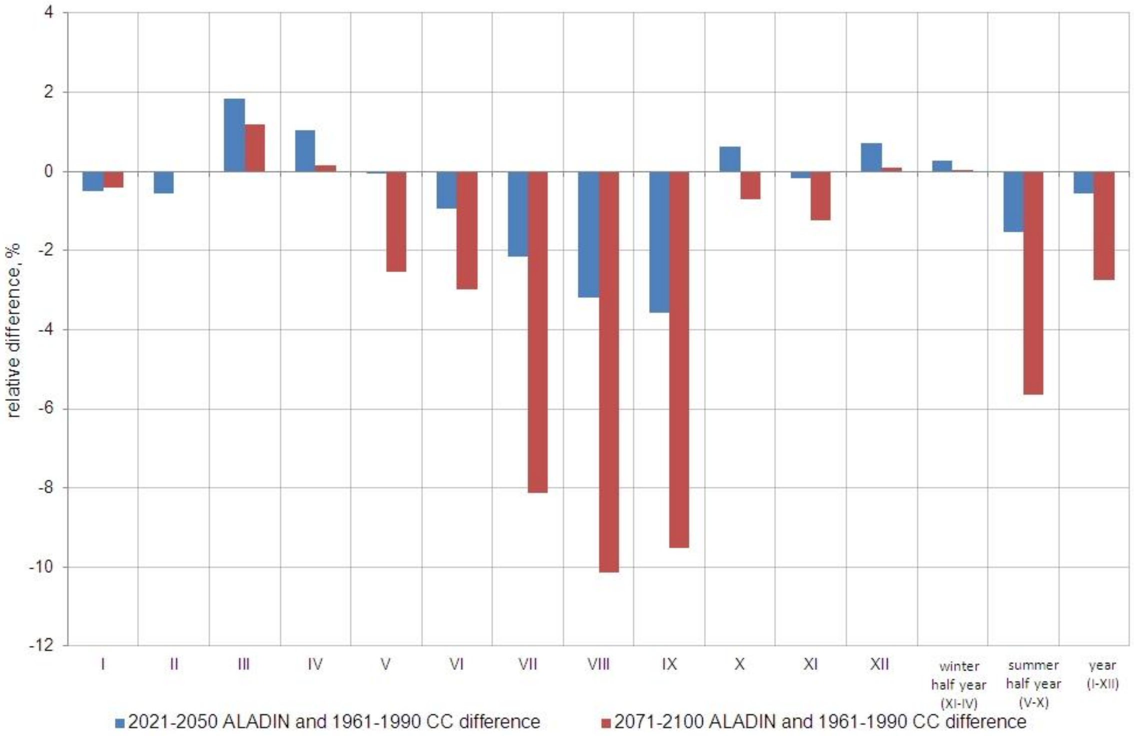

Figure 25. Relative variances of the monthly, semi-annual and annual relative humidity from the average of the reference period in the Balaton of the atmosphere above Balaton at the time of the future climate windows (2021–2050 and 2071–2100) (°C)

Reviewing the data concerning the time window of 2021–2050, it is found that considerable changes (exceeding 5%) are probable in the semi-annual and annual time horizons in the relative humidity trends of the atmosphere above Balaton compared to the average values of the reference period. A more substantial change (decrease) of relative humidity is manifest in the period of July–August (Table 21, Figure 25). It is noted, that the reduction of length of the period under review involves the increasing uncertainty of the model results.

Reviewing the data concerning the time window of 2071–2100, it is found that considerable changes (exceeding 5%) are probable in the semi-annual and annual time horizons in the relative humidity trends of the atmosphere over Balaton in the summer half of the year compared to the average values of the reference period. A more substantial change (decrease) of relative humidity is manifest in the period of July–September (Table 21, Figure 25). It is noted, that the reduction of length of the period under review involves the increasing uncertainty of the model results.

3.6.3. Calculation of the territorial average values of wind speed above the water surface of Balaton for the climate windows

As proposed by the experts of OMSZ – for the minimization of systematic model faults – the wind speed data concerning the periods of 2021–2050 and 2071–2100 were taken into account with the correction below:

ALADIN 2150 (corr.) = (CC 6190)×k, where k = (ALADIN 2150)/(ALADIN 6190 average)

ALADIN 7100 (corr.) = (CC 6190)×k, where k = (ALADIN 7100)/(ALADIN 6190 average)

The results are shown in Tables 23–26 and Figures 26–28.

Table 23. Absolute variance of the values of average wind speed of the atmosphere above Balaton calculated for future climate windows from the values of the reference period (m/s)

Period	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Winter half year (XI–IV)	Summer half year (V–X)	Year (I–XII)
1961–1990 CC	3.0	3.2	3.4	3.7	3.4	3.2	2.6	2.4	2.8	2.4	2.9	3.1	3.2	2.8	3.0
2021–2050 ALADIN	2.8	3.1	3.3	3.8	3.0	3.3	2.7	2.5	2.8	2.5	2.9	3.1	3.2	2.8	3.0
2071–2100 ALADIN	2.7	3.1	3.1	3.6	3.5	3.6	2.6	2.4	2.6	2.2	3.0	3.1	3.1	2.8	3.0

Table 24. Absolute variances of the values of average wind speed content of the atmosphere above Lake Balaton calculated for future climate windows from the values of the reference period (m/s)

Period	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Winter half year (XI–IV)	Summer half year (V–X)	Year (I–XII)
1961–1990 CC	3.0	3.2	3.4	3.7	3.4	3.2	2.6	2.4	2.8	2.4	2.9	3.1	3.2	2.8	3.0
2021–2050 ALADIN	–0.2	–0.1	–0.1	0.1	–0.3	0.2	0.1	0.1	0.1	0.0	0.0	0.0	–0.1	0.0	0.0
2071–2100 ALADIN	–0.3	–0.1	–0.3	–0.1	0.1	0.4	0.0	0.0	–0.1	–0.2	0.1	0.0	–0.1	0.0	0.0

Table 25. Relative variances of the values of average wind speed content of the atmosphere above Lake Balaton calculated for future climate windows from the values of the reference period (%)

Period	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Winter half year (XI–IV)	Summer half year (V–X)	Year (I–XII)
1961–1990 CC	3.0	3.2	3.4	3.7	3.4	3.2	2.6	2.4	2.8	2.4	2.9	3.1	3.2	2.8	3.0
2021–2050 ALADIN	–6.6	–3.4	–4.3	1.9	–9.8	5.3	3.2	3.6	3.3	1.5	0.3	0.9	–2.0	0.8	–0.6
2071–2100 ALADIN	–8.5	–4.5	–9.3	–2.5	3.5	12.2	0.4	0.2	–5.2	–7.7	3.2	–0.1	–4.0	1.1	–1.5

Table 26. Statistical characteristics of the average values of wind speed above Balaton water surface (m/s) by climate windows

Period	Min	Average	Max	Variance
1961–1990 CC	2.7	3.0	3.7	0.2
2021–2050 ALADIN	2.7	3.0	3.4	0.2
2071–2100 ALADIN	2.6	3.0	3.4	0.2

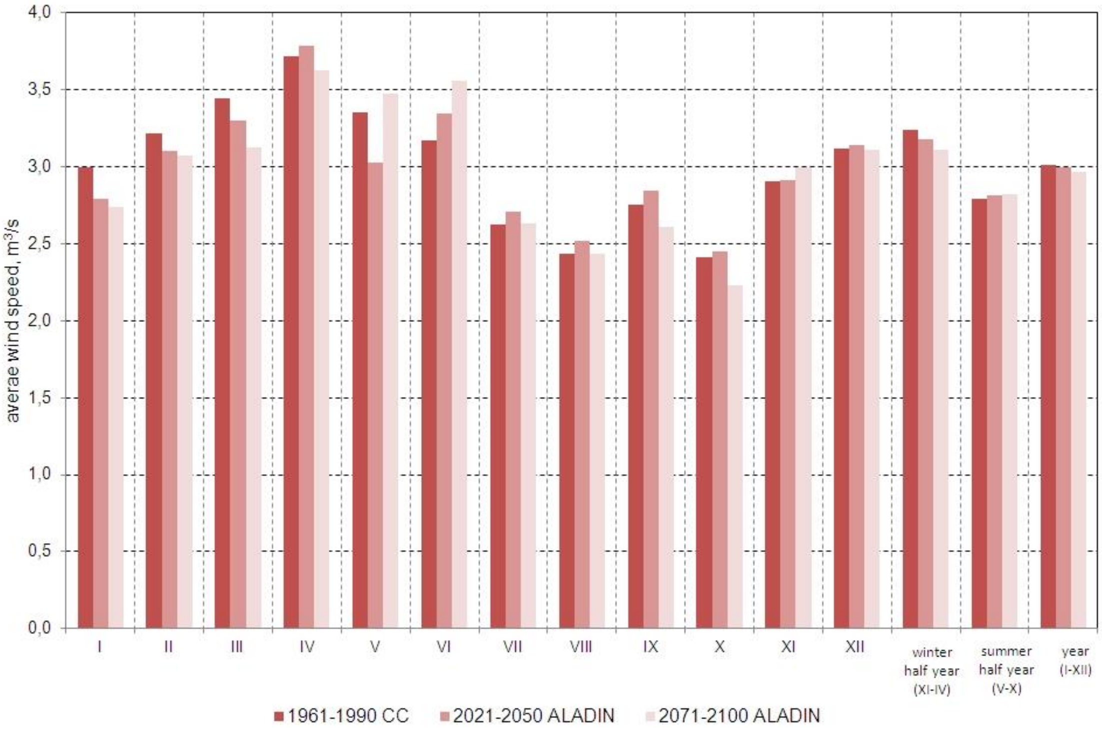

Figure 26. Monthly, semi-annual and annual fact (for the period of 1961–1990) and estimated (for the periods of 2021–2050 and 2071–2100) values of wind speed above the water surface of Balaton (m/s)

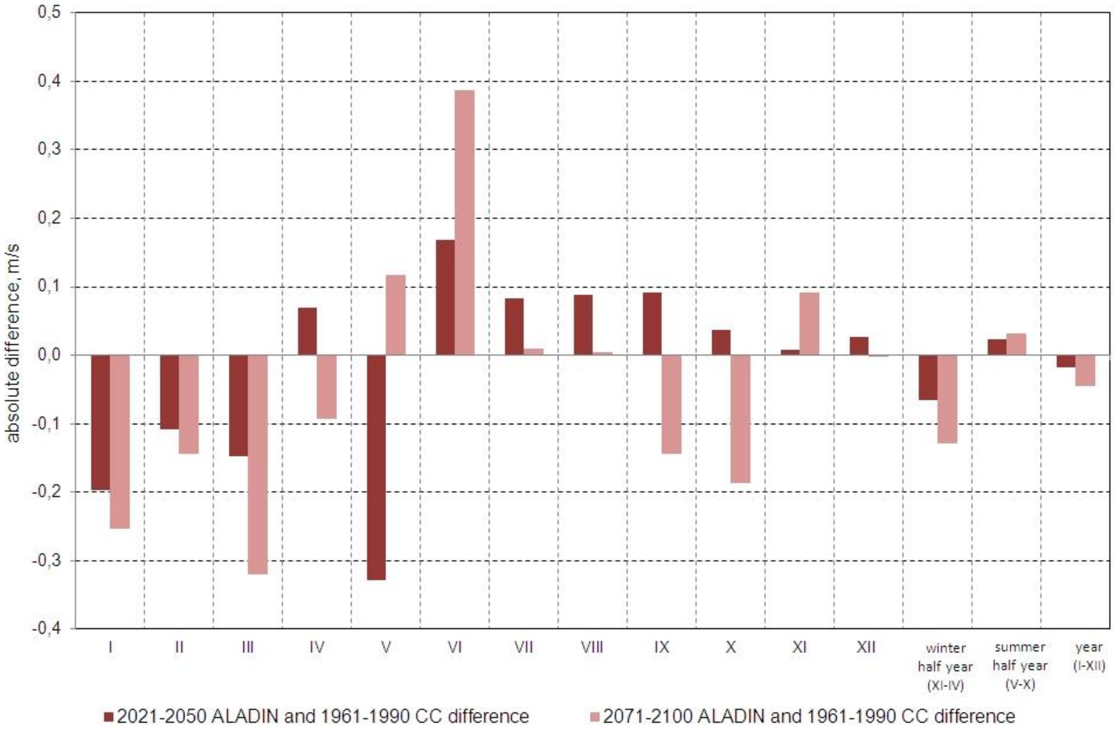

Figure 27. Absolute variances of the monthly, semi-annual and annual average wind speed from the average of the reference period in the atmosphere above Balaton at the time of the future climate windows (2021–2050 and 2071–2100) (m/s)

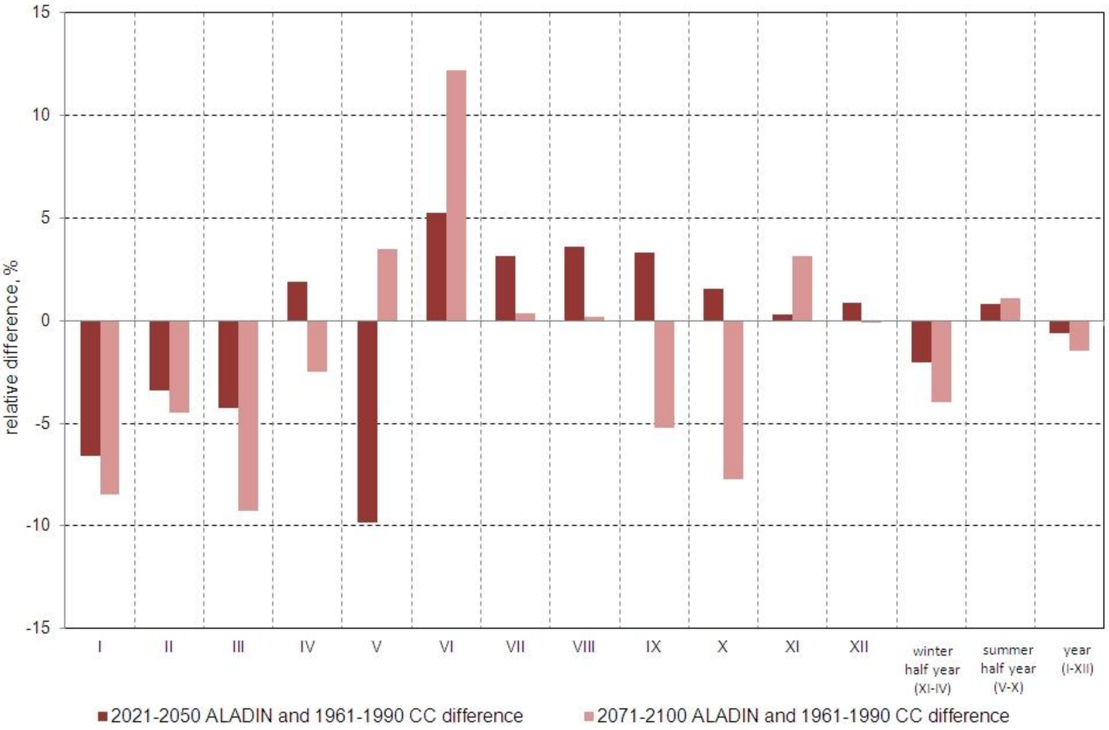

Figure 28. Relative variances of the monthly, semi-annual and annual average wind speed from the average of the reference period in the atmosphere above Balaton at the time of the future climate windows (2021–2050 and 2071–2100) (%)

Reviewing the data concerning the time window of 2021–2050, it is found that considerable changes (exceeding 5%) are not probable in the semi-annual and annual time horizons in the average wind speed trends of the atmosphere above Balaton compared to the average values of the reference period. At the monthly level, a difference above 5% was manifest in January, May and June (Table 25, Figure 28). It is noted, that the reduction of length of the period under review involves the increasing uncertainty of the model results.

Reviewing the data concerning the time window of 2071–2100, it is found that considerable changes (exceeding 5%) are not probable in the semi-annual and annual time horizons in the average wind speed trends of the atmosphere above Balaton compared to the average values of the reference period. At the monthly level, a difference above 5% was manifest in January, March, June, September and October (Table 25, Figure 28). It is noted, that the reduction of length of the period under review involves the increasing uncertainty of the model results.

3.6.4. Calculation of evaporation of Balaton for the climate windows

After the data preparation described in detail in sub-chapters 3.6.1–3., by means of the evaporation calculation formula presented in the beginning of sub-chapter 3.6., the evaporation of Balaton was calculated for the periods of the climate windows. For the comprehensive use of the formula, the member of the difference ‘e’ (actual vapour pressure) of the saturation shortage – difference of saturation and actual vapour pressure (E–e) – was determined by means of using the Sprung-formula, as the product of the saturation vapour pressure and the relative humidity.

The results are shown in Tables 27–30 and Figures 29–31.

Table 27. Average values of evaporation of Balaton calculated for the monthly, semi-annual and annual periods of the climate windows (lake mm)

Period	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Winter half year (XI–IV)	Summer half year (V–X)	Year (I–XII)
1961–1990 CC	15	24	34	62	100	115	137	119	79	65	39	19	191	615	807
2021–2050 ALADIN	17	27	35	67	108	129	163	149	99	72	41	20	207	720	926
2071–2100 ALADIN	18	29	39	72	123	147	214	206	135	83	47	22	226	909	1137

Table 28. Absolute variance of the values of the evaporation of Balaton calculated for the future climate windows from the reference period values (lake mm)

Period	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Winter half year (XI–IV)	Summer half year (V–X)	Year (I–XII)
1961–1990 CC	15	24	34	62	100	115	137	119	79	65	39	19	191	615	807
2021–2050 ALADIN	2	2	1	5	8	15	26	30	20	6	3	2	16	105	926
2071–2100 ALADIN	4	5	5	10	23	32	78	87	56	18	8	3	35	295	1137

Table 29. Relative variance of the values of the evaporation of Balaton calculated for the future climate windows from the reference period values (%)

Period	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Winter half year (XI–IV)	Summer half year (V–X)	Year (I–XII)
1961–1990 CC	15	24	34	62	100	115	137	119	79	65	39	19	191	615	807
2021–2050 ALADIN	15	10	4	8	8	13	19	25	25	10	7	8	8	17	15
2071–2100 ALADIN	24	19	16	17	24	28	57	73	71	27	22	16	18	48	41

Table 30. Statistical characteristics of the evaporation of Balaton by climate windows (lake mm)

Period	Min	Average	Max	Variance
1961–1990 CC	702	807	938	66.3
2021–2050 ALADIN	658	926	1364	151.4
2071–2100 ALADIN	740	1137	1472	179.1

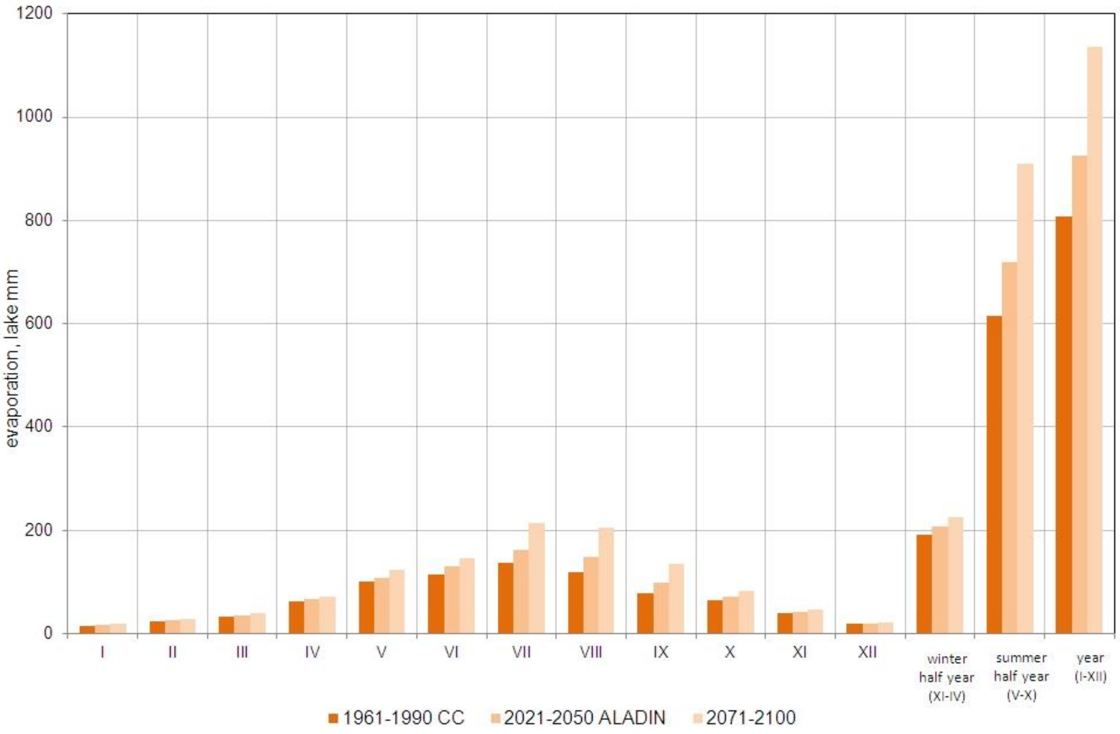

Figure 29. Average values of evaporation of Balaton calculated for the monthly, semi-annual and annual periods of the climate windows (lake mm)

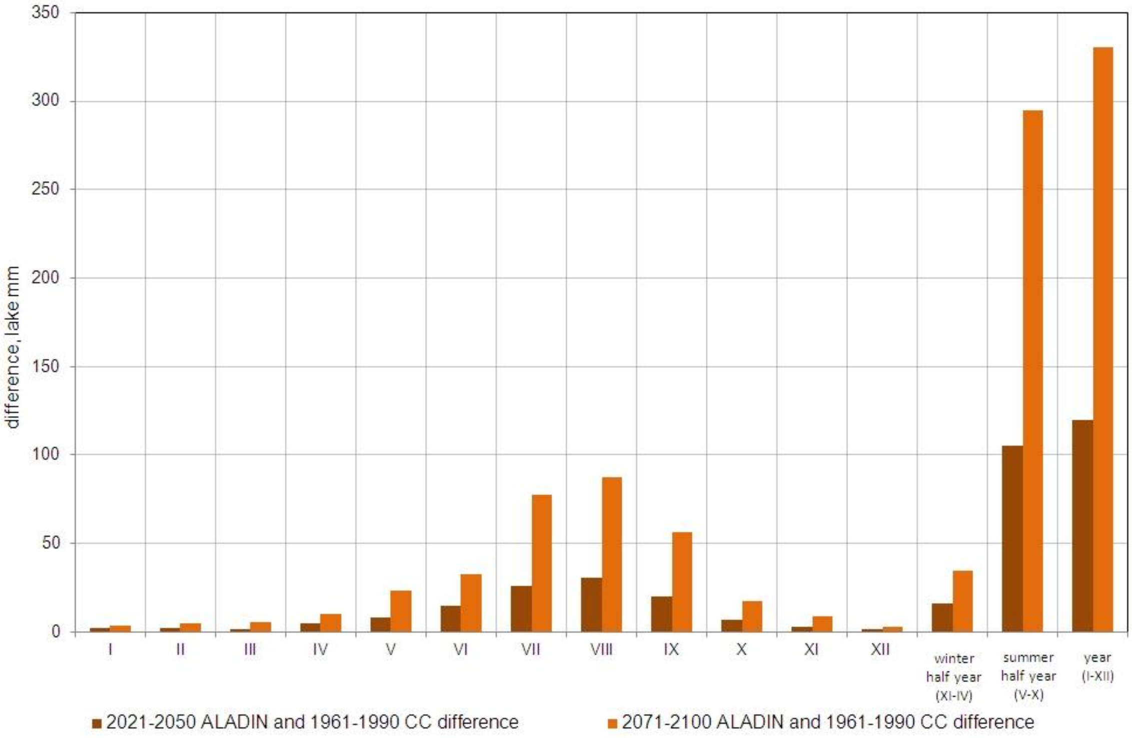

Figure 30. Absolute variance of the values of the evaporation of Balaton calculated for the future climate windows from the reference period values (lake mm)

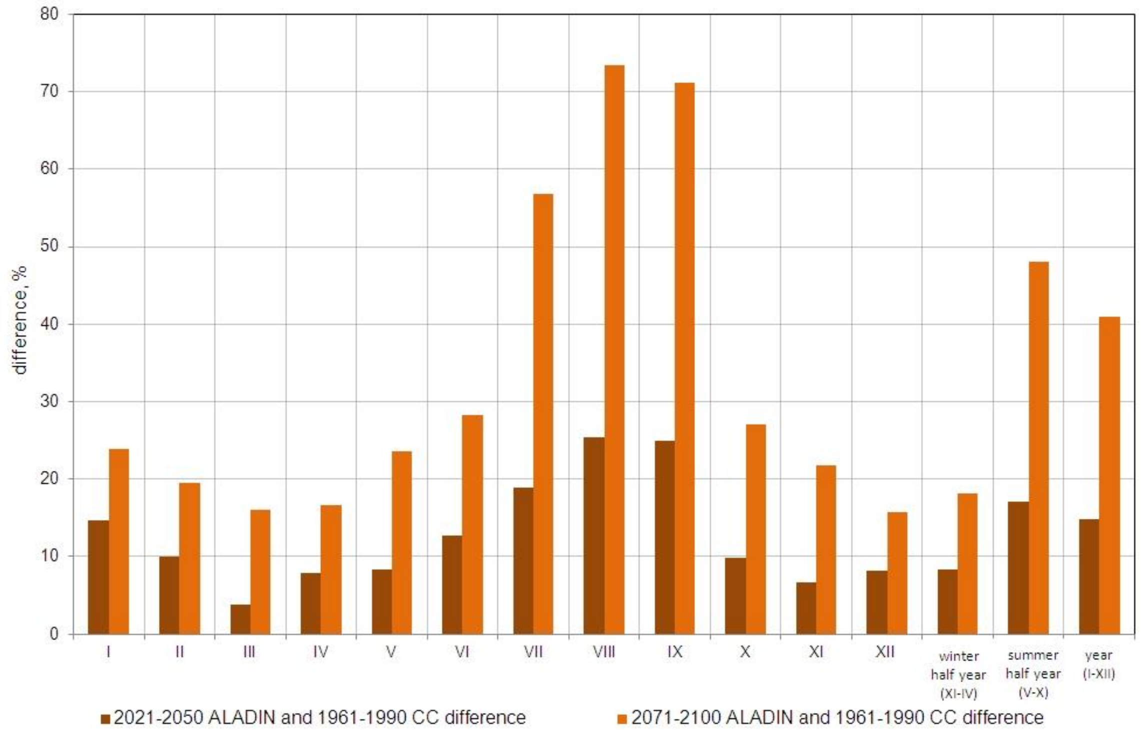

Figure 31. Relative variance of the values of the evaporation of Balaton calculated for the future climate windows from the reference period values (%)

Reviewing the data concerning the time window of 2021–2050, it is found that considerable changes (exceeding 10%) are probable in the semi-annual and annual time horizons in the evaporation trends of Lake Balaton compared to the average values of the reference period. At the monthly level, a difference above 15% can be observed in July–September (Table 29, Figure 31). It is noted, that the reduction of length of the period under review involves the increasing uncertainty of the model results.

Reviewing the data concerning the time window of 2071–2100, it is found that a remarkable change (an increase exceeding 40%!) is probable on the summer semi-annual and annual time horizons in the evaporation trends of Lake Balaton compared to the average values of the reference period. On a monthly level, the biggest differences related to the reference period (57–73%!) were manifest in July–September (Table 29, Figure 31). It is noted, that the reduction of length of the period under review involves the increasing uncertainty of the model results.

The estimated large-scale increase of evaporation of Lake Balaton in actual fact can be explained by the higher value of saturation vapour pressure (E) belongs to the higher air temperature with warming, at the same time, the climate model predicts a diminishing relative humidity concerning both future climate windows (and within that, for the half-year summer period). Jointly, this means that the material increase of saturation shortage of the air – the difference between the saturation and actual vapour pressure (E-e) – is expected. The saturation deficit is included in the empirical formula applied for the calculation of Balaton’s evaporation; it is particularly sensitive to that parameter.

3.7 *Calculation of annual natural water reserve change of Lake Balaton for the climate windows*

The water budget of Balaton is defined as the algebraic total of the natural change of water reserves and of those factors of water budget, whose evolution in space and over time is determined by the natural factors only. These are: precipitation falling on the surface of the Lake, runoff into the Lake and evaporation from the surface of the Lake.

In sub-chapters 3.6.1–4, the meteorological and hydrological factors were determined and evaluated for the reference period of 1961–1990 and for the two future climate windows (2021–2050 and 2071–2100), which are necessary for the future estimates of natural water reserve change of Balaton.

The results of the calculations carried out are shown in Table 31.

Table 31. Estimated annual average values of water budget factors determined by the natural factors of the Lake Balaton and of the derived natural water reserves (lake mm/year)

Period	Precipitation	Inflow	Evaporation	Natural water reserve change
1961–1990 CC	609	1001	807	803
2021–2050 ALADIN	631	725	926	430
2071–2100 ALADIN	602	224	1137	–311

Note: 1 lake mm is equivalent about 600,000 m^3 water.

In our calculations, the number of years which can be characterized by annual natural water reserve change with a negative sign within the 30-year climate windows resulted in the picture below:

- in the period of 1961–1990 7 years
- in the period of 2021–2050 9 years
- in the period of 2071–2100 19 years

In accordance with the estimates of ALADIN-Climate model for future climate windows significant climate change may occur on the watershed of Lake Balaton in the periods of 2021–2050 and 2071–2100 in comparison with the climate data measured in the reference period (1961–1990). The most remarkable and robust change is manifest in the estimated rise of the temperature. The rise of the temperature supplies more additional energy for evaporation, as a result of which increased evaporation is expected both on the watershed and the free water surface. The territorial evaporation on the watershed (the joint process of evaporation and transpiration) is expected to increase even if the water reserve available for evaporation is typically limited. The water budget pattern of the watershed changes due to the increasing territorial evaporation, which results in a significant decline of runoff as a consequence of increased evaporation.

The decrease of runoff leads to a deficit on the in-flow side of water budget of Balaton and enhances the deficit nature of the water budget.

The increase of evaporation is even more remarkably present on the free water surface of unlimited water supply. The weight of the out-flow side of the balance of water budget increases, the evolution of the water budget is determined by the out-flow side.

Altogether, the decline of the in-flow side and the increase of the down flow side can be predicted for the water budget of Balaton. This double effect will fundamentally change the hydrology of the Lake compared to the average conditions of the reference period – particularly in the second future climate window (2071–2100). The water exchange activity of the Lake will substantially deteriorate, here will be more frequent and longer periods without down flow and what is more, by the last decades of the 21st century, Lake Balaton may become practically a lake without down flow.

It is also important to heed the fact that because of the permanent deficit in the water budget, the Lake gradually shifts towards a new hydrological equilibrium. In addition to the decrease of water level, this also means a reduction of the surface area. As a result of this change, the extreme values of the water balance elements may become more moderated, however, the sustainable satisfaction of the demands concerning the use of the Lake will no longer be possible with the contents and in the form known today.

One of the obvious questions related to the future of natural water reserve change is the time estimated in the process of change of occurrence of the change of sign, i.e. the moment from which it is expected that the natural input (precipitation + runoff) goes below the natural output (evaporation) in the water turnover of the Lake. We have repeatedly had consultations about this question with the meteorologist experts participating in the production of the study.

The contents of consultations can be summarized as follows.

In theory, it would be possible to conduct a study in which meteorological and based on them, hydrological calculations would be made not only for the periods of 2021–2050 and 2071–2100, but also with the rolling forward of the 30-year period every year or every 5 years until 2100. This would also manifest a kind of distribution over time, however, subject to the condition of availability of the meteorological data for the total period of time – without interruptions.

When elaborating this study, MFGI had meteorological data only for the periods of the climate windows considered (they have been used for producing the study).

OMSZ has data for the periods between the climate windows, which can be made available against a fee for further studies and analyses.

Estimating the expected change of climate – and within that the estimated changes of values of the specific climate elements – are burdened by faults and uncertainties which inevitably enhance the uncertainty of hydrological calculation results – in addition to the faults, uncertainties and generalization existing in the methodology of hydrology calculations.

In this study, we discuss those factors of the Balaton’s water budget, the change of which in time is essentially determined by the natural factors. In the trends of the total water turnover – which ultimately in aggregation leads to the change of water level – the anthropogenic effect may not be ignored, in addition to the role of natural factors.

Of these impacts, the most important ones are as follows.

Balaton is a lake regulated from the bottom, which means that its down flow is regulated through the canal Sió. The principles and practice of water level regulation are adjusted to the water level variability of the Lake and its future changes are not known. These days efforts are made to raise the level of low water periods arising as a result of negative water budget extremes by increasing storage in the basin (elevating the upper limit of the water level regulating range by 5–10 cm). This is a good solution; however, it is a question whether this solution would prove adequate over a period of several decades to satisfy the demands of the sustainable lake use. Based upon the results of this study, the answer to this question is a clear no.

The cases of water use existing on the watershed and with direct impact on the Lake (water off takes, water inlets in the water system) also have an effect on the water turnover. We must also heed the area use of the watershed, its natural and human-induced changes (afforestation, change of farming sectors and methods, regulation of run-off, change of expansion of free water surfaces, etc.).

It is practically impossible to estimate the long-term change (for the next 6–8 decades) of the anthropogenic factors listed. This fact burdens the results of the 'water management sector' with additional uncertainties and, at the same time, it warrants great caution and highlighting the uncertainties concerning their use.

4 SUMMARY EVALUATION OF CHANGES IN THE WATER TURNOVER OF BALATON COMPARED TO THE REFERENCE PERIOD (1961–1990) IN THE TWO CLIMATE WINDOWS OF THE 21ST CENTURY (2021–2050 AND 2071–2100) AND THEIR COMPARISON WITH THE RESULTS OF AN EARLIER STUDY MADE WITH A SIMILAR PURPOSE

The large lakes in Hungary (Balaton, Lake Velence, Lake Fertő, Lake Tisza) are, without exception, typical shallow lakes with average depth remaining below 5 m. An important feature of the shallow lakes in the moderate climate zone is the high quantitative and qualitative sensitivity to the changes of environmental factors (including climate factors) in space and time.

Quantitative sensitivity is manifest in the water balance (typical water turnover) of the lake, consequently in its change of its water level, water reserve and water surface.

This study includes the estimated trends in the water balance relations of Lake Balaton – the natural factors defining water turnover (the natural water reserve change interpreted as the algebraic total of precipitation, in-flow and evaporation), the results of the hydrological calculations completed based on the ALADIN-Climate model results of the Hungarian Meteorological Service covering the reference period of 1961–1990 and the 30 years' time periods of 2021–2050 and 2071–2100, respectively. The natural water reserve change and the estimated changes of the water budget factors determining its trends compared with the average of the reference period are summarized below.

Reviewing the data concerning the time period of 2021–2050 it is found that considerable changes (exceeding ±10%) are not likely in the estimated trends of **precipitation in the water surface of the Lake** relative to the average values of the reference period of time over semi-annual and annual time horizons. In accordance with the relative variances applicable for the specific months, an increase above 10% is manifest in April and in the period of September to November, whereas, a decrease by 32% is recorded for January and a decrease by 11% is recorded for July.

Reviewing the data concerning the time period of 2071–2100 it is found that considerable changes (exceeding ±10%) are not likely in the estimated trends of precipitation in the watershed of the Lake relative to the average values of the reference period of time over annual time horizons. The results concerning the decrease above 10% in summer and the increase above 10% in winter over the semi-annual time horizon related to the values of the reference period refer to the rearrangement of the annual total precipitation in time. The summer semi-annual estimated precipitation decrease is concentrated in the period of July–September, while the focus of the winter semi-annual precipitation increase is concentrated in November–December.

As a consequence of increase of evaporation over the area a remarkable decrease of the difference of precipitation-evaporation can be estimated on the Balaton catchment area in the periodical average of future climate windows (**runoff**, in the Balaton's water budget, the in-flow).

According to our calculations, within the climate windows of 30 years, the number of years, which can be characterized with negative annual precipitation / evaporation difference, provided the picture below:

- in the period of 1961–1990 1 year
- in the period of 2021–2050 6 years
- in the period of 2071–2100 13 years

In the years when the precipitation-evaporation difference is negative in the watershed area, there is still an out-flow; however, this derives overwhelmingly from the sub-surface water reserves. In the years with more precipitation, the precipitation arriving at the watershed in the beginning replenishes these missing reserves under the surface and only when it is done, the surface out-flow is expected to appear. As the water turnover of the sub-surface water reserves, and as a result their regeneration, take place much more slowly than those of the surface water reserves, the impact of changes on the sub-surface reserves – as a protracted impact – may also cover several subsequent years.

Reviewing the data concerning the time period of 2021–2050, it is found that considerable changes (exceeding 10%) are probable in the semi-annual and annual time horizons in the **evaporation** trends of Lake Balaton compared to the average values of the reference period. At the monthly level, a difference above 15% can be observed in July–September.

Reviewing the data concerning the time period of 2071–2100, it is found that a remarkable change (exceeding 40%!) is probable on the summer semi-annual and annual time horizons in the evaporation trends of Lake Balaton compared to the average values of the reference period. On a monthly level, the biggest differences related to the reference period (57–73%!) were manifest in July–September. It is noted, that the reduction of length of the period under review involves the increasing uncertainty of the model results.

The estimated large-scale increase of evaporation of Lake Balaton in actual fact can be explained by the higher value of saturation vapour pressure (E) belonging to the higher air temperature with warming, at the same time, the climate model predicts a diminishing relative humidity concerning both future climate windows (and within that, for the half-year summer period). Jointly, this means that the material increase of saturation shortage of the air – the difference between the saturation and actual vapour pressure (E-e) – is expected. The saturation deficit is included in the empirical formula applied for the calculation of Balaton's evaporation; it is particularly sensitive to that parameter.

In our calculations, analyzing the estimated trends **of natural water reserve change,** the number of years which can be characterized by annual natural water reserve change having a negative sign, within the 30-year climate windows, resulted in the picture below:

- in the period of 1961–1990 7 years
- in the period of 2021–2050 9 years
- in the period of 2071–2100 19 years

In accordance with the estimates of ALADIN-Climate model for future climate windows significant climate change may occur on the watershed of Lake Balaton in the periods of 2021–2050 and 2071–2100 in comparison with the climate data measured in the reference period (1961–1990).

The most remarkable and robust change is manifest in the estimated rise of the temperature. The rise of the temperature supplies additional energy for evaporation, as a result of which increased evaporation takes place both on the watershed and the free water surface. The territorial evaporation on the watershed (the joint process of evaporation and transpiration) is expected to increase even if the water reserve available for evaporation is limited. The water budget pattern of the watershed changes due to the increasing territorial evaporation, which results in a significant decline of runoff as a consequence of increased evaporation.

The decrease of runoff leads to a deficit on the in-flow side of water budget of Balaton and enhances the deficit nature of the water budget.

The increase of evaporation is even more remarkably present on the free water surface of unlimited water supply. The weight of the out-flow side of the balance of water budget increases, the evolution of the water budget is determined by the out-flow side.

Altogether, the decline of the in-flow side and the increase of the down flow side can be predicted for the water budget of Balaton. This double effect will fundamentally change the hydrology of the Lake compared to the average conditions of the reference period – particularly in the second future climate window (2071–2100). The water exchange activity of the Lake will substantially deteriorate, here will be more frequent and longer periods without down flow, what is more, by the last decades of the 21st century, Lake Balaton may become practically a lake without down flow.

It is also important to heed the fact that because of the permanent deficit in the water budget, the water turnover of the Lake gradually shifts towards one new hydrological equilibrium. As a result of the decrease of water level and water surface expected to take place, the extreme values of the water balance elements may become more moderated, however, the sustainable satisfaction of the diverse demands concerning the use of the Lake will no longer be possible with the contents and in the form known today.

Several experts have also performed the analysis and estimation of the water budget of Balaton earlier – covering the period of climate windows in the 21st century. The aggregated summary of the research results are included in sub-chapter 2.2 of this study.

The assessments based upon various climate scenarios and made with different methods also offer a possibility for one kind of assessment comparison. The impact assessments agree that the water balance of the Lake will deteriorate due to global warming (the deficit character will intensify), and according to most of the impact assessments, the annual natural water reserve change will decrease. However, there are significant differences in the rate of deterioration; what is more, there are studies which even expect an improvement of the water balance in the coming decades. It is to be noted, that the rate of deterioration is closely related to the increase of aridity of the climate, which may be triggered by the declining precipitation, the increase of temperature and the joint occurrence of the two.

The results of the EULAKES project of 2012 can be considered to be the closest to the test results published in this study.

5 PROPOSAL FOR THE USE OF THE STUDY

5.1 Proposal for the possibility of using the data which describe the expected changes in waterflow scheme

The climate change can be analyzed by means of climate models. In this study, we have used the results of the ALADIN-Climate model used at the Hungarian Meteorological Service, highlighting the possibilities and limits.

The 'long-term predictability' in the classic meaning cannot be implemented with the climate models. The global connected models can describe processes and interactions having slow enforcing impact on the circulation and the climate of the entire Earth, therefore, the asymptotic characteristics of the behavior of the climate system can be determined with their help. The results of the climate models on a climate time scale, therefore, must be considered as a statistical multitude, where no prognostic significance is attached to the specific moment in time to which the given forecast applies and the reliability of the models is classified in accordance with the accuracy with which they can reflect the statistical characteristics of a selected period.

As of necessity, the regional (and global) model results are burdened by smaller or larger errors, which must be taken into account while evaluating the projections for the future. This can be done by determining change values: the model results for the future are not interpreted in themselves, but related to the own reference period of the models, therefore, the systematic model faults concerning the future and the past partly eliminate each other by generating the difference; and the change values are added to the values calculated on the basis of measurements for the reference period (in case of a relative change, the values of measurement and change are multiplied).

Just like the past model results, the same way the data for the future cannot be interpreted as 'predicted time series of climate change', but only as one possible realization of the meteorological variables. Within the periods of 30 years, the annual data constitute such statistical populations, which can be interchanged in time. This means that an arbitrary annual data line can be related to any year of the period.

It is impossible to match a trend to a data line within the period, and the data applicable for the specific year cannot be considered as a long-term weather forecast. The attention must also be directed to the point that the climate system is a system of non-linear evolution; therefore, it is impossible to draw conclusions from the trends of a specific period for the characteristics of another period.

From all these points it is possible to conclude that the analysis of changes in time within the individual climate window periods is not relevant. Factually – by meteorological and hydrological elements as well as by time horizons – the comparison of average values calculated for the specific climate windows and their evaluation may provide a picture about primarily the direction and – with a much more careful evaluation – the rate of the expected changes.

5.2 Proposal to define the expected target audience, method, conditions and limits of use of the information to be offered to lay and professional visitors

In view of the outstanding significance of Lake Balaton in the fields of tourism, recreation and many others related to different sectors of national economy, as well as the water budget extremes experienced in the past one and a half decades occurring more frequently and for longer periods of time than before, a target audience is expected in great numbers, which is very diverse with respect to their prior education and openness.

From professional aspects, primarily the most likely areas showing interest in the theme and the results of the study are hydrology, environmental protection and nature conservation, water quality and ecology.

It is suggested to include the description of methodology of the work completed and the scope of data used in the scope of information to be provided for a professional target audience. Emphasis should be put on presenting, characterizing and assessing the relative differences among the meteorological and hydrological parameters defined for the climate window periods when introducing the results. It is important to highlight the effect of methodological deficiencies and the uncertainties also originating from them, the human activity concerning the water turnover of the Lake, which cannot be estimated over the long-term, and the uncertainty originating from all these, and – from case to case – the impacts mutually reinforcing each other.

Presentation of the results of the study for articles to be published in professional journals (e.g. Hidrológiai Közlöny, Időjárás, etc.) and for the professional organizations (e.g. Hungarian Hydrology Society, Hungarian Meteorology Society, Balaton Development Council, institutes of higher education and research entities addressing the theme) organizing national (national migratory conferences of the associations) and regional professional events (in the framework of presentations to be delivered in sessions).

It is important that the presentation of the results – both verbally and in writing – should take place with the involvement of the meteorologist and hydrologist professionals who were participating in drawing up the study. Collection and evaluation of questions, observations and comments from the audience in the professional events are highly significant part of the ‘follow-up’ to the work, as these reflections may provide the basis for planning the continuation of the work – if a possibility arises – and for defining the objectives.

The lay target audience may be very diverse. They may include the representatives of local governments around Lake Balaton, the various NGOs and interested individuals.

In the course of providing information for this target audience, it is preferable to focus on the results defined in the study, within that, primarily on the differences of meteorological and hydrological average values concerning the climate windows and the direction of changes. It is very important to emphasize the uncertainties composed of several reasons and sources. The detailed methodological presentation and analysis of the calculations conducted are not relevant for this target audience.

5.3 Submission of proposal for solving the problems originating from the eventual data shortage and the possibilities of methodological development

Assessing the results of this study, it can be stated that no well-grounded statements can be made concerning the uncertainty of the results from the analysis of the results of a single model simulation, in this particular case from the ALADIN-Climate model simulation. There is no guarantee that the models well describing the past may give successful climate estimates for the future, therefore, the faults calculated in the validation and the changes estimated for the future cannot be 'blended'.

Uncertainties can only be described correctly by means of several model experiments. The application of two models already provides a good starting base for the fundamental quantification of uncertainties. Therefore, for the interpretation of future changes, it is necessary by all means to analyze the results of a suitably selected model experiment.

In the course of calculations conducted in the framework of the study and the assessment of their results a finding of outstanding importance was that the number and duration of the deficit periods are expected to increase in the water budget of Balaton. It was self-evident question which presented itself as to from what time should the state be expected by which the natural water input of the Lake (precipitation + in-flow) typically and permanently remains below the natural water loss of the Lake (evaporation).

In theory, it would be possible to conduct a study in which meteorological and based on them, hydrological calculations would be made not only for the periods of 2021–2050 and 2071–2100, but also with the rolling forward of the 30-year period every year or every 5 years until 2100. This would also manifest a kind of distribution over time, however, subject to the condition of availability of the meteorological data for the total period of time without interruptions.

When elaborating this study, the MFGI had meteorological data only for the periods of the climate windows considered (they have been used for producing the study).

OMSZ has data for the periods between the climate windows, which can be made available against a fee for further studies and analyses.

LIST OF FIGURES

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ANNEX

Results of ALADIN-Climate model simulations

Compiled by:

Gabriella Szépszó, Anett Csorvási
Hungarian Meteorological Service

Results of ALADIN-Climate model simulations

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Hungarian Meteorological Service

The analysis of the climate change is possible with the help of the climate models and four regional climate models are used in Hungary for mapping the changes expected in our region in the 21st century. Of these models, at this time, we present the results of ALADIN-Climate employed in the National Meteorological Service (**Table 1**). Using the model, a model simulation of 10 km grid was made for an area covering the Carpathian basin (CSIMA and HORÁNYI, 2008). The description of the processes outside the range (i.e. the lateral boundary conditions) were provided by the data of the global climate model ARPEGE-Climate. In the course of simulations, a medium scenario, A1B SRES (Special Report on Emissions Scenarios; NAKICENOVIC et al., 2000) was used as emission scenario for considering the impact of future anthropogenic activities. In the following, first the validation of model results concerning temperature and precipitation by measurements is presented for the period of 1961–1990 and then a review of the changes expected in 2021–2050 and 2071–2100 is given, using the period of 1961–1990 as reference.

Table 1. Characteristics of simulation made with the regional climate model ALADIN-Climate

Regional climate model	**ALADIN-Climate**
Model version	4.5
Horizontal resolution	10 km
Lateral boundary conditions	ARPEGE-Climat
Emission scenario	SRES A1B

Validation

Essentially, two kinds of model running can be performed for past periods of time. In one of the cases the driving initial and boundary conditions for the regional model are provided by some re-analysis database, while in the other type of experiment, the attached atmosphere-ocean general circulation models provide the driving fields. The model runs made with the use of re-analysis fields show the extent to which the regional climate model can precisely estimate the current climate of the region, while the simulations executed with the results of global climate model experiments highlight the joint faults of the global and regional models. Initial data are provided by the regional climate model results from this latter type of experiment for the impact assessments to be carried out in the framework of the National Adaptation Geo-information System, therefore, the analysis of these data is presented.

The basic difference between the weather forecasts and climate simulations is that while in the first case, we demand the model to reflect the material weather events as precisely as possible both in space and time, this is not a realistic expectation in the case of climate models. The forecasting task concerning a range with limits is converted into a limit value problem on the climate scale and because the boundary conditions for the regional model are provided by the forecasts of global models throughout the entire time horizon, a perfect global simulation would be required for the perfect regional results. **Therefore, the 'long-term predictability' in the classic meaning cannot be implemented with the climate models (Szépszó 2014).** The global connected models can describe processes and interactions having slow enforcing impact on the circulation and the climate of the entire Earth, therefore, **the asymptotic characteristics of the behavior of the climate system can be determined** with their help. **The results of the climate models on a climate time scale, therefore, must be considered as a statistical multitude, where no prognostic significance is attached to the specific moment in time to which the given forecast applies and the reliability of the models is classified in accordance with the accuracy with which they can reflect the statistical characteristics of a selected period (Szépszó 2014).** In line with the recommendation of the Meteorological World Organization, the results of the models are analyzed in general for 30-year periods and the annual or seasonal expected value, variance, density function and other statistical characteristics calculated for these periods are investigated in case of the climate simulations. In the interest of a technically simpler comparison, in general such measuring databases are used for validation, which are generated through interpolation procedures by means of using the surface station data series.

In the course of the current validation the extent of the error is analyzed, by which the climate model can estimate Hungary's climate properties concerning temperature and precipitation in the reference period of 1961–1990. In the course of current validation, the size of the assessment of other variables (e.g. wind speed, relative humidity) is not included. In the course of validation, the model data were compared with the grid observation database of 20 km resolution CRU (Climatic Research Unit; Mitchell et al. 2004). **Table 2** summarizes the values of average annual and seasonal temperature error generated by considering the grid points over the territory of Hungary. In addition to defining the average error, significance test was used to quantify the average error value obtained at the grid points as contrasted with the variance of seasonal and annual error values of the reference period. **Figure 1** shows the spatial distribution of annual and seasonal average temperature and precipitation amount errors of the model simulations. Dots indicate in the maps the grid points where the error is significant, moreover, the values stated above the maps show the significant errors over a specific proportion of Hungary's territory. **Figure 2** shows the annual process of national monthly average temperature and precipitation amount values calculated for the grid points in Hungary, based upon the model simulation under review and the data measured.

In case of the annual average temperature related to the period of 1961–1990, ALADIN slightly under-estimates the references values (**Table 2**). The negative variances taken from the observations are typical in the northern, north-eastern and south-western parts of the country and are significant as well (**Figure 1**), while in the Balaton region, some over-estimation can be seen. In the transitory seasons, significant under-estimation in excess of

2 °C is typical (particularly in the northern regions at higher elevations), the rate of which comes to 4 °C in April and October (**Figure 2**). In summer and winter, the error is smaller and has an opposite sign on the average for the country. The average over-estimation is as low as 0.1 °C in winter, and this is not significant either on a great part of the country. However, in the Balaton region, the over-estimation of temperature is exceedingly high, which originates from the simplified description of the Lake's micro-climate (e.g. ALADIN considers the typical value of the Adriatic Sea applicable for the water temperature of Balaton). The analysis of the annual process of temperature refers to the point that in the ALADIN results, the warming up in the spring takes place much more slowly and the cooling down in the autumn takes place much more quickly than in reality.

Table 2. The average annual and seasonal temperature and precipitation (°C and mm/month) variances between the results of ALADIN-Climate regional climate model and the values of the CRU grid observation database for 1961–1990

	Annual	Spring	Summer	Autumn	Winter
Temperature	–0.8	–2.0	1.1	–2.7	0.1
Precipitation	9	32	15	–10	1

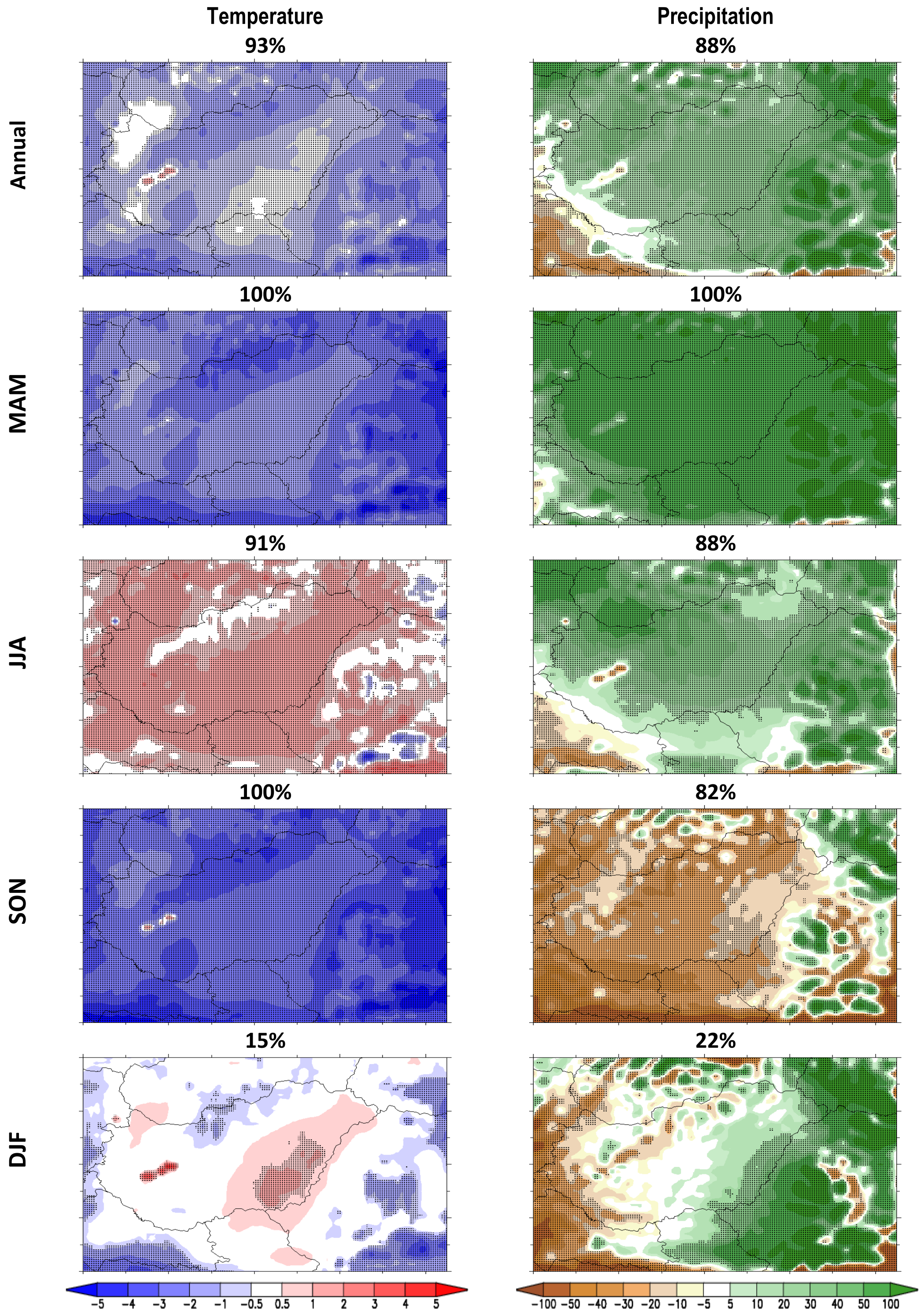

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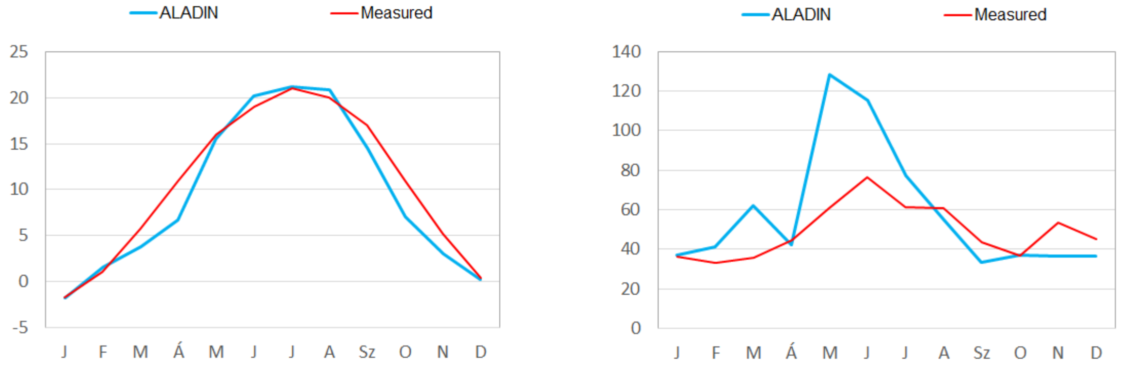
Figure 1. The average annual and seasonal temperature and precipitation (°C and %) variances between the results of ALADIN-Climate regional climate model and the values of the CRU grid observation database for 1961–1990. The percentage values stated above the maps show the proportion of those grids in Hungary, where the error is significant at a confidence level of 0.05

Reviewing the annual trends of average monthly simulated precipitation amounts in 1961–1990, it can be stated that ALADIN, in most of the cases yields greater precipitation amounts than the observations (**Figure 2**). The model well-matches the seasonal trends observed, however, the over-estimation of the amounts in May-July is significant. The over-estimation in spring and summer is manifest not only on the national average, however, on the total territory of the country (deducting the grids of Balaton) and is also significant to a great deal (**Figure 1**). Under-estimation can be observed in the autumn, the rate of which does not exceed 30 %. The map of winter average precipitation amounts shows significant under-estimation and over-estimation in about 11 % of the grids within the country - the former in the west, the latter in the eastern regions – resulting in a slight positive error on a national average (**Table 2**).



Monthly average temperature (°C)

Amount of precipitation (mm)

Figure 2. Values of monthly average temperature (°C) and amount of precipitation based upon the results of ALADIN-Climate regional climate model and the observation database of CRU grids for 1961–1990

The results of the climate models for the future can be interpreted knowing the extent to which the models can reproduce the values characterizing the past climate. It is to be noted that while validation is an important and inevitable step of climate modelling, at the same time, there is no guarantee that the models precisely describing the past will also yield successful climate estimates in a similar manner for the future.

Projections

As of necessity, the regional (and global) model results are burdened by a smaller or larger fault which must be taken into account while evaluating the projections for the future. This can be done **by giving change values: the model results for the future are not interpreted in themselves, but related to the own reference period of the models, therefore, the systematic model faults concerning the future and the past partly eliminate each other by generating the difference; and the change values are added to the values calculated on the basis of measurements for the reference period** (in case of a relative change, the values of measurement and change are multiplied). At this time, in the course of the so-called *delta method* (HAWKINS et al., 2013) is used, in the course of which it is assumed that the errors do not significantly change in the course of integration on the average of several decades (this is not the case by all means). Many authors use various correction processes to 'eliminate' the model errors (e.g. PIECZKA 2012; KIS 2013), based upon the simpler dedication of the systematic error or matching the density function produced by the model results to the measuring data series. The correction procedure determines the correction to be used also for the future data series by means of past observation information, therefore, it cannot consider if for instance, the shape of the density function changes both in the model and in the reality as a consequence of climate change, together with the characteristics of the model faults (SZÉPSZÓ 2014).

Just like the past model results, the same way **the data for the future cannot be interpreted as 'predicted time series of climate change', only as one possible realization of the meteorological variables. Within the periods of 30 years, the annual data constitute such statistical populations, which can be interchanged in time.** This means, that an arbitrary annual data series can be set against any year of the period. [Naturally, within a given year, it cannot be done (that is, the January data cannot be exchanged with the September data for example), because through the dynamic processes, they must reflect the climatology of the region.] Therefore, the data series applicable to the specific period of time can be analyzed by means of expected values, variances, distribution functions, etc., just like the model results applicable to the past. **It is impossible to match a trend to a data line within the period, and the data applicable for the specific year cannot be considered as a long-term weather forecast.** The attention must also be directed to the point that **the climate system is a system of non-linear development, therefore, it is impossible to draw conclusions from the tends of a specific period for the characteristics of another period.** For example, the tendencies observed on the basis of measurements cannot be extrapolated to the future and the same way, no similar statistical match can be performed for the decades between two future periods; the relations of these periods must be explored through dynamic model simulations. Therefore, in this study, the changes indicated by the ALADIN model are published by applying the delta-method, in the form of 30-year averages, using a significance test to isolate the change 'signal' from the natural variability of the climate in the projection results.

The ALADIN regional climate model assumes the atmospheric carbon-dioxide concentration trends of average rate and describes the modification of climate in the Carpathian basin in the 21st century. Based upon the model results, the increase of average temperature is continued in the 21st century in the Carpathian basin, as it is shown in **Table 3** and the results of **Figures 3-4**. These changes are statistically significant in case of every period; therefore, they are not indicated separately on the temperature maps.

Table 3. Variability of annual and seasonal average temperature in Hungary (°C) for 2021–2050 and 2071–2100 compared to the reference period of 1961–1990 based upon the results of the ALADIN-Climate regional climate model

	Annual	Spring	Summer	Autumn	Winter
2021–2050	1.1	1.6	0.7	0.8	1.1
2071–2100	3.1	2.8	3.5	3.0	2.5

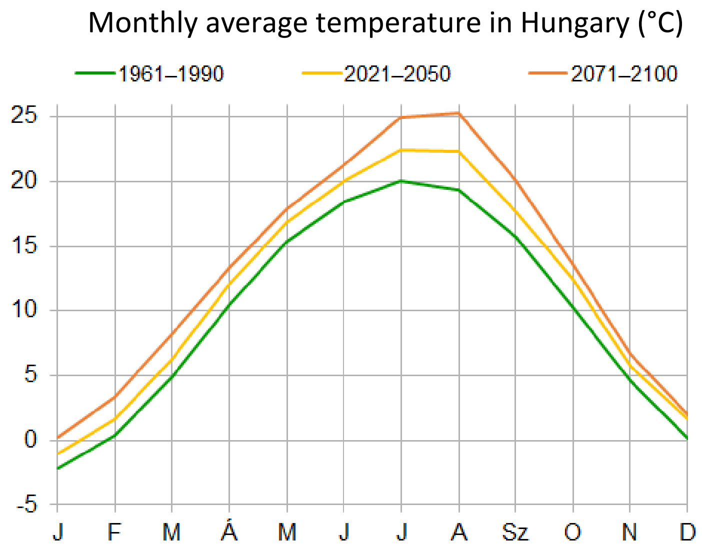
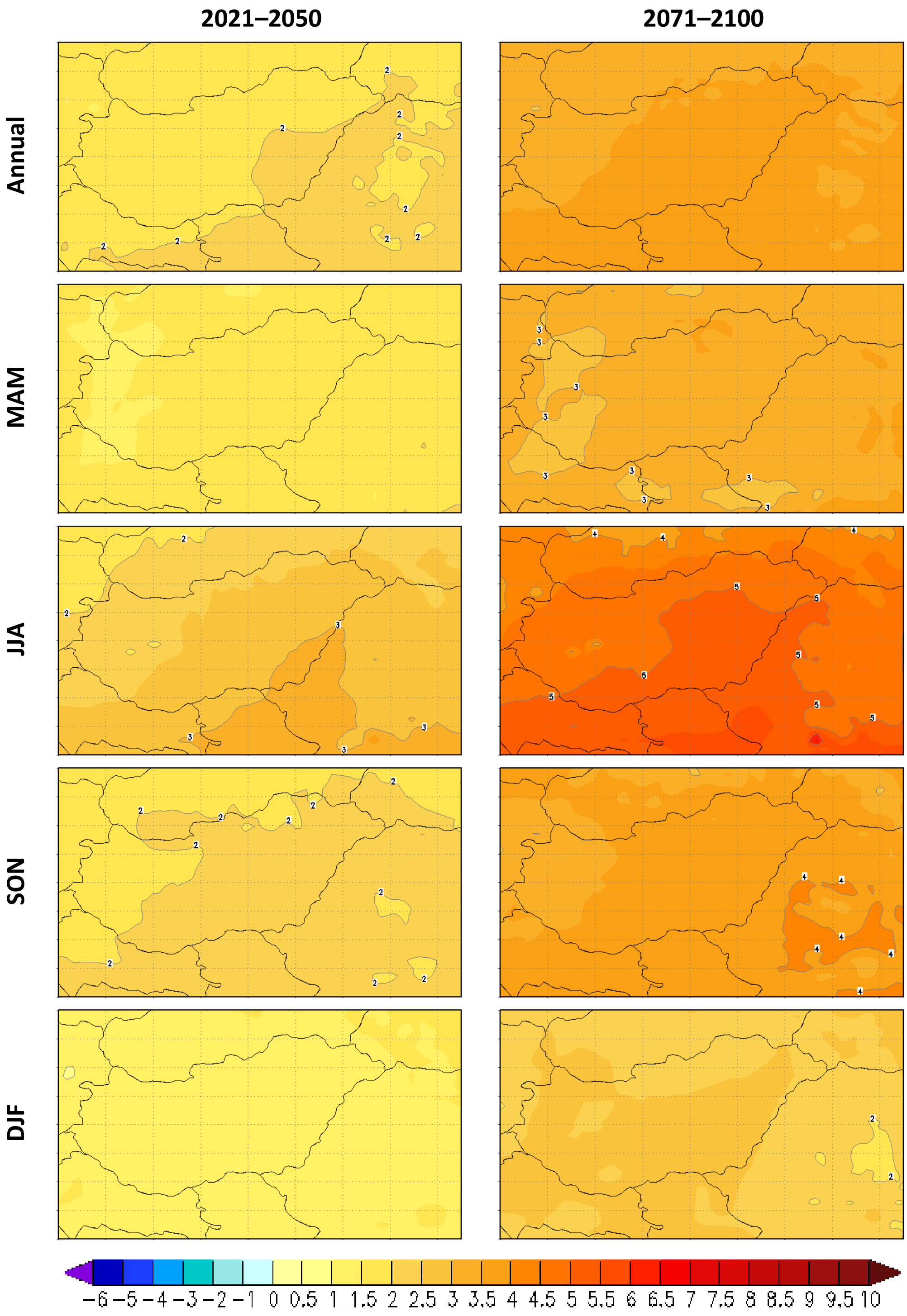


Figure 3. Monthly average temperature in Hungary (°C) based upon the measurements in 1961–1990, and for 2021–2050 and 2071–2100 and under the combination of the results of the ALADIN-Climate regional climate model with measuring data.

The increase of temperature on an annual average **(Figure 4)** for 2021–2050 will be approximately 1–2 °C and by 2071–2100, the rate of warming up will exceed 3 °C everywhere in our country but it will be smaller than 5 °C. That is, the temperature increase - with a slightly accelerating rate - can be considered continuous throughout the 21st century. The greatest increase in the tends of average temperature is expected in the summer in both future periods, this can even be as high as 6 °C in August by the end of the century, as it is shown in **Figure 4**. By the middle of the century, changes exceeding 1 °C but not greater than 2 °C are expected almost everywhere in the country in the spring and winter, while slightly greater changes are expected in the autumn, and by the end of the century warming up between 3 and 4 °C is probable over the total area of our country in all the three seasons. Considering the distribution of changes within the country, temperature increase of greater extent is expected in the eastern and southern parts of the country.



The Project is supported by a grant from Iceland, Liechtenstein and Norway.

Figure 4: Change of the annual and seasonal average temperature (°C) for 2021–2050 and 2071–2100, related to the reference period of 1961–1990 based upon the results of the ALADIN-Climate regional climate model

The change of amount of precipitation expected in Hungary is much more difficult to analyse and interpret than the temperature changes. The underlying reason is that precipitation is an element which is very variable both in space and time, which is difficult not only to predict, but the highlighting of its trends and changes is possible over a long period of time only. Therefore, the changes indicated by the models are frequently not significant either, therefore, due care must be exercised when interpreting them.

Table 4. Variability of average annual and seasonal precipitation amount in Hungary (%) for 2021–2050 and 2071–2100, compared to the reference period of 1961–1990 based upon the results of the ALADIN-Climate regional climate model

	Annual	Spring	Summer	Autumn	Winter
2021–2050	–7	–10	-5	3.8	–10
2071–2100	–5	–5	–20	4.6	–3.1

If we look at the relative change of the annual amount of precipitation (**Table 4**), it is seen that there is a slight decrease expected in both periods on the national average (below 10 %). The change, however, will not be uniform in terms of area over the coming decades: increase is expected on the western half of the country and decrease on the eastern areas (**Figure 6**). The within the year distribution of the annual amount of precipitation is modified in contrast with the reference period (**Figure 5**). Currently, summer is our season with most of the precipitation, and in the future, the summer precipitation will decline, while some increase is expected in the somewhat dryer period of October-December. In the period of 2021–2050, summers may still see areas in the country, where more precipitation would fall on the average than in the past. However, by the end of the century, the summer decline of precipitation will already spread to the entire territory of the country and it will be significant on a large part of the area (–20 % on a national average). Altogether, more precipitation is expected than at present in the autumn and spring (with the eastern regions of the country being the exceptions), and decrease is expected in the winter, similarly to summer.

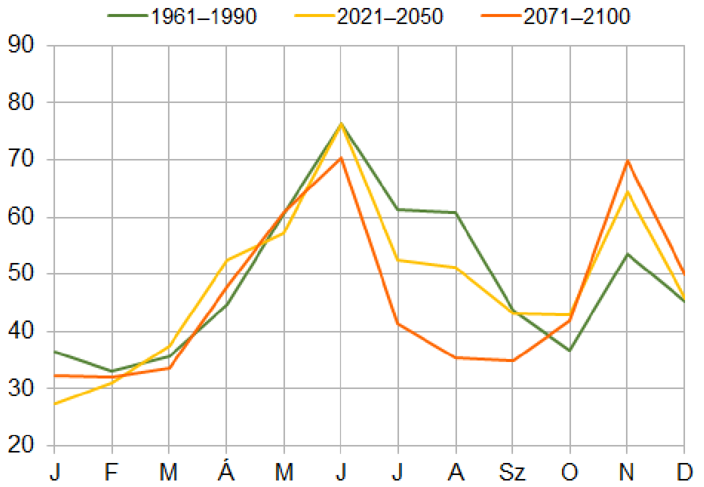


Figure 5. Monthly average precipitation amount in Hungary (mm) based upon the measurements in 1961–1990, and for 2021–2050 and 2071–2100 and under the combination of the results of the ALADIN-Climate regional climate model with measuring data

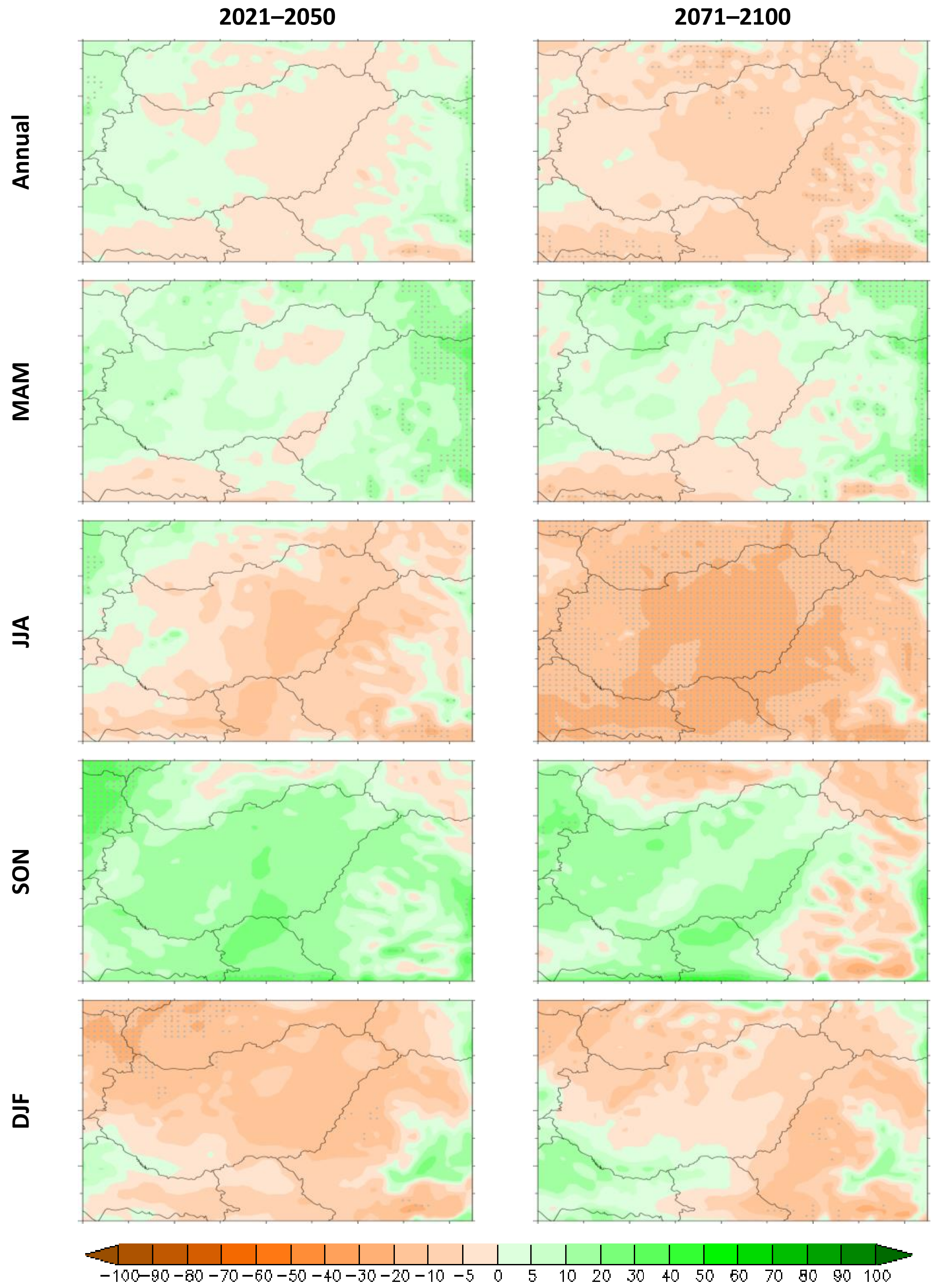


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Figure 6. Variability of average annual and seasonal precipitation amount (%) for 2021–2050 and 2071–2100, compared to the reference period of 1961–1990 based upon the results of the ALADIN-Climate regional climate model. Dots indicate in the maps the grid points where the change is significant

Outlook

The meteorological forecasts embody a multitude of uncertainties, which on the one hand originate from the chaotic characteristics of the processes intended to be described and, on the other hand, from the character of approximation of the models used for their simulation (definition of the initial and boundary conditions, the applied numerical and physical parametric methods and the impact of the anthropogenic activities). The interpretation of the projections can be regarded correct if they include information also about the probability of their realization. One instrument for this is the so-called *ensemble technique*, when several simulations with different settings are performed and their results are jointly evaluated. The setting of the individual experiments are selected so in general, that each of them provides an equally probable description of the climate system and the ensemble created thereby gives the possibility of communicating the results in a probability form. The user in such a case received not a single, so-called *categorical forecast* but an information of probability character, having this benefit a much more justified decision can be made than under a single forecast (SZÉPSZÓ 2014).

It is the objective of the tests which determines the settings which would be changed during the model experiments to be carried out. It is because the types of uncertainties presented contribute to the total uncertainty characterizing the simulations differ in the function of the time horizon and the geographic range as well as with respect to the different meteorological variables (HAWKINS and SUTTON 2009, 2011). In case of the climate projections, in most of the cases, the ensemble systems are consolidated from such simulations which were performed using different climate models, employing several emission scenarios for describing the future anthropogenic activities.

No justified statements can be made concerning the uncertainty of results by analyzing the results of a single model simulation – ALADIN-Climate in this case. As noted earlier, there is no guarantee that the models well describing the past may give successful climate estimates for the future, therefore, **the faults calculated in the validation and the changes estimated for the future cannot be 'blended'. Uncertainties can only be described correctly by means of several model experiments.** The application of two models already provides a good starting base for the fundamental quantification of uncertainties. Therefore, for the interpretation of future changes, it is necessary by all means to analyze the results of a suitably selected model experiment.

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