CLIMATIC RISK FACTORS OF CENTRAL HUNGARIAN GRAPE GROWING REGIONS

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Abstract. Under global climate change we mean the observed increasing tendency of the yearly mean temperature together with the more and more frequently occurring extreme events (floods, frosts, droughts, heat waves). The border of the sites suitable for grapevine growing and the growing regions are defined mainly by climatic conditions. Quality wine production can be maintained between the isothermals of 10-16°C yearly mean temperature. Though Hungary is expected to remain amongst the regions with good quality grapevine growing conditions, according even to the most pessimistic forecasts, the expected frequency and the impact of extreme climatic events are rather serious warning signs. Continental climatic conditions in Carpathian basin can generate stress effects which can cause negative economic consequences through quality and quantity unsuitability. In this study some impactful climatic indicators are analysed which are of high importance in grapevine production. Historic data are compared with regional climate model predictions of RegCM 3.1 with A1B scenario, concerning to the Central Hungarian grape growing regions.
Keywords: *grapevine, climate change, climatic indicators, Central Hungarian region, climatic risk*

Introduction

Ecological demands of various plants are influenced different ways and in distinct extent by climate change since beneficial and unfavourable or detrimental effects of temperature, precipitation and other climatic factors are activated not generally but specifically (spatially and temporally) distributed. Yearly averages of temperatures and precipitation, therefore serve too few information for conclusions. However, learning the distributions of the climatic parameters with emphasized importance of some main time intervals of the growing season specialized for plant species is of main interest.

In this study we consider the climatic conditions of grapevine growing regions in Central Hungary according to three different time scales: 1961-1990 as reference period, 2021-2050 and 2071-2100 as prediction time intervals. Regional studies have been enabled since global climate models have been downscaled to about 10 km grid points. We applied RegCM 3.1 which was downscaled at Eötvös Loránd University, Department of Meteorology for A1B scenario (Bartholy et al., 2007, 2009, 2010; Torma et al., 2008).

The most important climatic factor in grapevine growing is temperature as higher mean temperature generally indicates higher sugar content at ripening (Zanathy, 2008).

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In low risk site selection first the yearly mean temperature is checked whether it is between 9°C and 21°C isothermals. The highest quality regions are mainly between 10°C and 16°C isothermals (Oláh, 1979). Thus regions can be suitable with latitudes between 20° and 50° north and between 20° and 40° south. Grapevine with its several varieties with wide range climatic demands can be regarded as well adaptable plant; nevertheless, special varieties need special treatment (Varga et al., 2007).

Historical wine regions in Hungary, however, have their well defined and widely requested character based on their typical varieties grown there. Cool climate regions with short growing season are famous for their early ripening, fragrant, aromatic varieties while warmer regions with plenty of sunny hours benefit from their varieties with longer growing season demand. With only 1°C mean temperature increase of cool climate regions classified by Huglin Index (Huglin, 1978) the change can be quite favourable as the variety assortment can be widen with bringing nice varieties from southern regions into production. 2°C or higher mean temperature increase, however, can endanger the suitability of the region for fragrant varieties such as Pinot gris or Traminer (Jones, 2006) as the typical taste and flavour can disappear from the wine. Huglin Index calculations throughout European wine regions all agree in an expected shift towards a warmer or hotter class (Schultz, 2000; Battaglini, 2003). Phenological phases are expected to occur earlier and the time intervals between the phenological phases are becoming shorter (Wolfe et al., 2005; Jones and Davis, 2000; Jones, 2006).

Accordingly, veraison and maturation can be connected to higher temperature conditions which can cause a definite change in wine character when the sugar content of the berries at maturation together with the alcohol content of wine increase (Bindi et al., 2001; Duchêne and Schneider, 2005) and acid content decrease with a higher pH value (Jones and Davis, 2000; Stock et al., 2003). Quality changes are expected to be associated with a moderate impact of vintage. However, the increasing frequencies and seriousness of pest and disease events (DeLucia et al., 2008), the higher UV-radiation (Schultz, 2000), the site and soil dependent nutrient stress as well as water stress can endanger the security of production. Meanwhile, a low level water stress can be advantageous to the quality; water supply and irrigation potential are of great importance (Bravdo and Hepner, 1987; Carbonneau, 1998).

Materials and methods

Risk assessment was made for each of the 17 subregions of Central Hungary. To this the predictions of regional climate model RegCM 3.1 were used with 10 km resolution. As there were more grid points than subregion, the most representative 17 grid points were chosen that are situated the closest to the subregion centres. Calculations were made for three time scales: 1961-1990 as reference period, 2021-2050 and 2071-2100 as prediction time intervals. The time intervals cover 30 years, therefore the modelled data can represent the distribution of the climatic parameters.

Though Central Hungary is not belonging to the most prominent grape growing regions and no wine producing region is involved entirely in it, it lies on three wine regions (Kunsági, Etyek-Budai, Mátrai). Thousands of hectares of Kunsági wine region together with the one third part of Etyek-Budai region and some wine communities of Mátrai wine region are situated in Central Hungary (*Fig. 1*). This study is a part of an extensive object to measure the regional and plant specific climate potential of Hungary in order to learn the present state and the future possibilities of adaptation strategies.

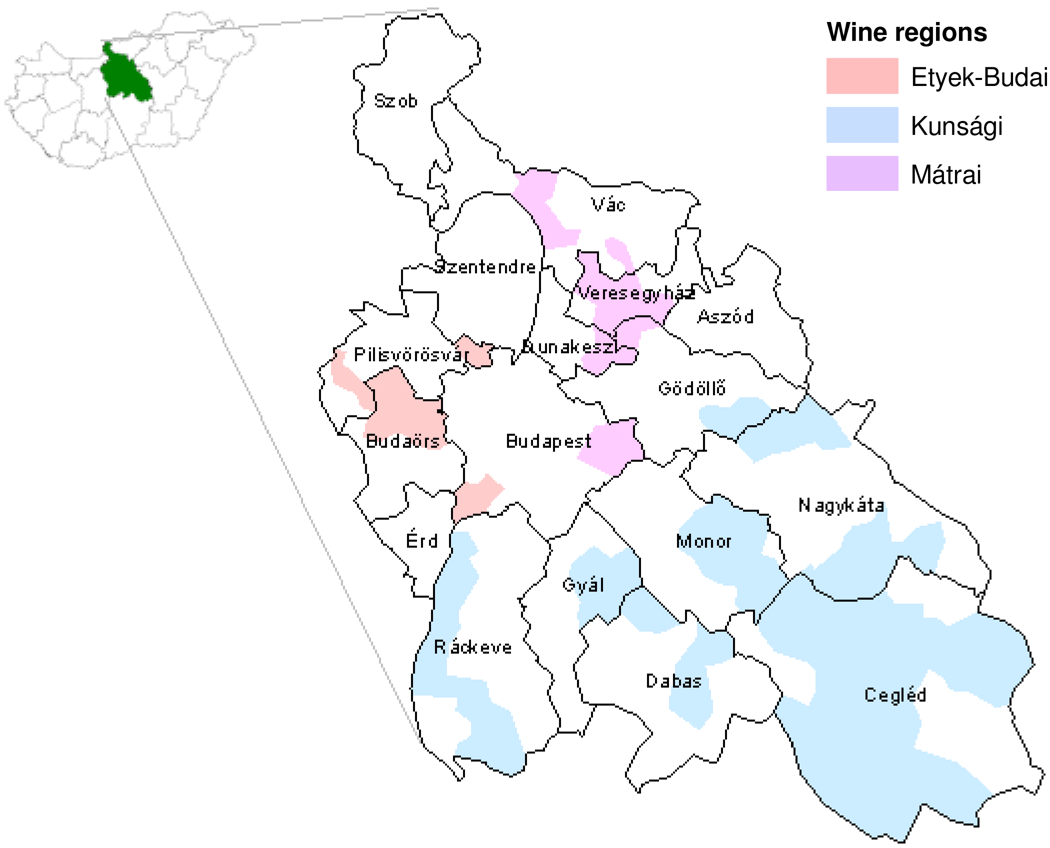

Figure 1. *Central Hungary (with 17 subregions) and the wine regions*

The most important climatic factors of grape growing are temperature and precipitation (Dunkel et al., 1981). The distributions of these two factors are the most important determinants of vintage. From these main factors the following indicators were focused:

- effective degree days above 10°C (EDD, °C)
- Huglin Index (HI, °C)
- the number of days with maximal daily temperature above 30°C (C30, days)
- the number of days with maximal daily temperature above 35°C (C35, days)
- the number of frosty days (below -1°C) after the 1st of April (F-1, days)
- the number of days with minimal daily temperature below -15°C (days)
- the number of days with minimal daily temperature below -18°C (days)
- the first, second and third maximal lengths of consecutive days with precipitation less than 1 mm (D1, D2, D3, days)
- the maximal length of consecutive days with precipitation more than 5 mm (days)
- yearly precipitation sum (mm)
- precipitation sum of the growing season (1st of April – 30th of September) (mm)

With a software developed specially for our aims all the 13 indicators above were calculated for each year of the three time series with 30 years and each of the 17 subregion grid points.

The data from three wine regions (Cegléd of Kunsági wine region, Budaörs from Etyek-Budai wine region and Veresegyház of Mátrai wine region) were analysed and compared. Moreover, we checked a subregion named Szob which is not belonging to any wine region yet whether it is expected to become to be suitable for grape growing.

Effective degree days and Huglin Index

The effective degree days (EDD, °C) are calculated as the cumulated sum of daily mean temperatures above the base temperature (10°C) between the 1st of April and 30th of September (Oláh, 1979). Grape varieties can be grouped according to their effective degree days demands up to full ripening.

The groups of grape varieties according to their effective degree days demand up to full ripening are displayed in *Table 1*.

Table 1. *Groups of grape varieties according to their effective degree days demand up to full ripening (Botos and Hajdú, 2004)*

Effective degree days	Ripening categories
690–850°C	very early ripening varieties
850–1150°C	early ripening varieties
1150–1350°C	medium ripening varieties
1350–1600°C	late ripening varieties
above 1600°C	very late ripening varieties

We also calculated the widely applied Huglin Index (HI, °C) which takes the maximal daily temperatures into consideration as well:

$$HI = k * \frac{\sum_{1.Apr.}^{30.Sept.} \max\left((T_{mean} - 10);0\right) + \sum_{1.Apr.}^{30.Sept.} \max\left((T_{\max} - 10);0\right)}{2}$$

where T_{mean} and $T_{\max}$ are the daily mean and maximal temperatures and k is a latitude coefficient that takes into account increasing day lengths from 35° to 50°, starting with 1.00 at 35°, ending with 1.06 at 50° and is based upon day lengths using Julian day and latitude as inputs. In case of Hungary k=1.05 was applied.

According to the values of Huglin Index the following site type classes are defined (Tonietto and Carbonneau, 2004, *Table 2*).

Table 2. *Groups of site types according to their Huglin Index*

Huglin Index (°C)	Class name
HI ≤ 1500	very cool
1500 < HI ≤ 1800	cool
1800 < HI ≤ 2100	temperate
2100 < HI ≤ 2400	warm temperate
2400 < HI ≤ 3000	warm to very warm
3000 < HI	hot

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Results

Cegléd subregion

The effective degree days and Huglin Index values of Cegléd subregion are presented in *Table 3*.

Table 3. *Effective degree days and Huglin Indices in Cegléd subregion*

	Time interval		
	1961-1990	**2021-2050**	**2071-2100**
EDD (°C)	1240	1433	1898
Huglin Index (°C)	1760	1960	2427

In Cegléd while the medium ripening varieties were expected to ripen appropriately in the reference time interval (1961-1990), the heat demands of the late ripening varieties can be filled in the middle of the 21st century and even the effective degree days suitable for the very late ripening varieties can be reached at the end of the century.

According to the Huglin Index values Cegléd subregion was belonging to the cool class in the last century and up to the middle of the 21st century it is expected to belong to the temperate class tending to the warm temperate one at the end of the century.

The increase of the effective degree days and Huglin Index values is moderate in medium term and more intensive in the long run.

Though Huglin Index is used quite widely, in case of extreme heat events it does not express the negative effects. Above 30°C respiration increases rapidly resulting in a rapid decrease in net photosynthesis, net assimilation is impeded. Above 35°C extra energy is used to maintain the life processes. Moreover, extreme high temperature events mainly associated with lack of precipitation and high level of solar radiation with high risk of sunburn.

The frequencies of extreme temperature events in Cegléd subregion are presented in *Table 4*. According to the regional climate model RegCM 3.1 the expected number of extreme warm days with maximum daily temperature above 30°C seem to increase moderately up to the middle of the 21st century, however, it is estimated to double up to the end of the century, compared to its value of the reference period 1961-1990, from a yearly mean of about 18 to about 35 days.

Table 4. *Frequencies of extreme temperature events in Cegléd subregion (days / 30 years)*

	Time interval		
	1961-1990	**2021-2050**	**2071-2100**
Daily max. temperature above 30°C	544	597	1046
Daily max. temperature above 35°C	73	172	557
Daily min. temperature below -1°C (after 1st of April)	49	18	8
Daily min. temperature below -15°C	11	1	0
Daily min. temperature below -18°C	3	0	0

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The expected number of extreme hot days with maximum daily temperature above 35°C is estimated to increase more drastically, from the yearly mean of about 2 days to almost 6 days at medium term and above 18 days at long term (*Table 4*).

These trends are risk factors of unfavourable sugar-acid ratio of some white varieties as well as harvest management and vinification (Hajdú, 2005; Horváth, 2008). Thus agricultural and phytotechnical practices should newly be adjusted to varieties and changed climate in order to minimize the risk of quality degradation.

Extreme cold events are also very harmful (Dunkel and Kozma, 1981). Minimum temperature below -15°C can cause significant damage of several varieties; frost injury is surely serious if temperature is below -18°C. Late spring frost events below -1°C can bring a meaningful yield loss.

Nevertheless, the risk of extreme cold events is expected to decrease. The yearly mean numbers of spring (1.6 days which means about 2 days in three years) and winter frost events (0.36 below -15°C – about once in three years; or 0.1 below -18°C – about once in ten years) are expected to decrease remarkably even in medium term and the frost risk becomes very low up to the end of the century with an only spring frost event expected in three years.

Let us consider the precipitation indices in Cegléd subregion presented in *Table 5*. The yearly mean precipitation sum is a relevant parameter of a site. Having a deep growing root system grapevine can tolerate moderate water stress relatively well with a yearly precipitation sum demand of 500-600 mm. From this amount it is necessary to have at least 260-320 mm precipitation sum in the growing season to ensure the appropriate shoot and berry development. Precipitation risk factors are long term rainfall events and drought events.

Yearly and vegetation period precipitation sum demand of grapevine is satisfied in all the three time intervals (1961-1990, 2021-2050, 2071-2100), according to the regional climate model RegCM 3.1. The distribution of the precipitation in vegetation period, however, is expected to change disadvantageously.

Table 5. *Averages of precipitation indices in Cegléd subregion*

	Time interval		
	1961-1990	**2021-2050**	**2071-2100**
Yearly precipitation sum (mm)	645	605	639
Precipitation sum 1st of Apr – 30th of Sept (mm)	301	306	291
The max. length of consecutive days with precipitation less than 1 mm (days)	22.1	25.6	28.0
The 2nd max. length of consecutive days with precipitation less than 1 mm (days)	16.2	17.8	18.6
The 3rd max. length of consecutive days with precipitation less than 1 mm (days)	12.3	14.0	12.7

In *Table 5* we display the lengths of the three longest dry periods as a 30-year mean. The length of the longest dry period with consecutive days of daily precipitation less than 1 mm increases significantly both at medium and long term level reaching its value of 28 days up to the end of the 21st century. The lengths of the second and third longest periods are also estimated to increase. Considering the significant increase of the expected daily average and maximum temperatures, the negative impacts of these phenomena can only be mitigated if the variety structure, the training system as well as the agricultural and phytotechnical practices are adequately modified.

According to the regional climate model RegCM 3.1 the three longest wet periods with consecutive days of precipitation above 5 mm do not indicate significant change in the future. The longest period has its yearly mean of 3.2 days with respect to the reference period 1961-1990.

Veresegyház subregion

Veresegyház subregion is situated in the west hilly border of Mátra wine region, north to Cegléd subregion (Gödöllő hills).

The effective degree days and Huglin Index values of Veresegyház subregion are presented in *Table 6*.

Table 6. *Effective degree days and Huglin Indices in Veresegyház subregion*

	Time interval		
	1961-1990	**2021-2050**	**2071-2100**
EDD (°C)	1050	1216	1649
Huglin Index (°C)	1549	1721	2182

In Veresegyház mainly the early ripening varieties were expected to ripen appropriately in the reference time interval (1961-1990), the heat demands of the medium ripening varieties can be filled in the middle of the 21st century and the effective degree days demand of the late and very late ripening varieties can be reached at the end of the century.

According to the Huglin Index values Veresegyház subregion was belonging to the cool class in the last century and up to the middle of the 21st century it is expected to remain in the same class tending to be warmer and warmer and it probably reaches the warm temperate class at the end of the century.

Similarly to Cegléd subregion the increase of the effective degree days and Huglin Index values is moderate in medium term and more intensive in the long run.

The frequencies of extreme temperature events in Veresegyház subregion are presented in *Table 7*. The numbers of extreme warm days with maximum daily temperature above 30°C as well as of the extreme hot days with maximum daily temperature above 35°C are lower than they were detected in Cegléd subregion.

Table 7. *Frequencies of extreme temperature events in Veresegyház subregion (days / 30 years)*

	Time interval		
	1961-1990	**2021-2050**	**2071-2100**
Daily max. temperature above 30°C	371	414	899
Daily max. temperature above 35°C	22	64	316
Daily min. temperature below -1°C (after 1st of April)	60	27	10
Daily min. temperature below -15°C	22	2	0
Daily min. temperature below -18°C	4	0	0

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However, the expected number of extreme warm days is estimated to increase up to the end of the 21st century from yearly mean of about 12 days to about 30 days, compared to its value of the reference period 1961-1990. The expected number of extreme hot days is estimated to increase again more drastically, from the yearly mean of less than 1 day to about 2 days at medium term and above 10 days at long term (*Table 7*).

The risk of extreme cold events is expected to decrease in Veresegyház subregion, too. The yearly mean numbers of spring (2 days) and winter frost events (0.7 days below -15°C – about twice in three years; or 0.13 below -18°C – about once in eight years) are expected to decrease remarkably even in medium term and the frost risk becomes very low up to the end of the century with an only spring frost event expected in three years which declares a very similar distribution of frost events to the one we learned in Cegléd subregion.

The precipitation indices in Veresegyház subregion are presented in *Table 8*. The precipitation sum demand of grapevine is profusely satisfied in all the three time intervals (1961-1990, 2021-2050, 2071-2100) regarding for both the yearly and the vegetation period, according to the regional climate model RegCM 3.1. The distribution of the precipitation in vegetation period is optimal and it also remains as optimal.

In *Table 8* we display the lengths of the three longest dry periods as a 30-year mean. The length of the longest dry period with consecutive days of daily precipitation less than 1 mm increases insignificantly. The lengths of the second and third longest dry periods are also estimated to increase very slightly. The longest wet periods with consecutive days of precipitation above 5 mm indicates an increase of 20 % up to the end of the 21st century compared to its yearly mean value (3.2 days) of the reference period 1961-90. The increase of the lengths of second and third longest wet periods is insignificant.

Table 8. *Averages of precipitation indices in Veresegyház subregion*

	Time interval		
	1961-1990	**2021-2050**	**2071-2100**
Yearly precipitation sum (mm)	743	696	730
Precipitation sum 1st of Apr – 30th of Sept (mm)	335	342	310
The max. length of consecutive days with precipitation less than 1 mm (days)	22.0	24.2	24.9
The 2nd max. length of consecutive days with precipitation less than 1 mm (days)	14.8	16.1	16.9
The 3rd maxi. length of consecutive days with precipitation less than 1 mm (days)	11.6	12.2	12.9

Budaörs subregion

Some parts of the Etyek-Budai wine region are situated in Central Hungary. The climatic conditions of Budaörs subregion are very similar to the ones of Veresegyház subregion with a slightly less mean temperature and precipitation sum values. Further survey should examine how the change of ecological conditions of the region with a long history of sparkling wine production affects the decrease of the acidity of the yield. What is the future of production of base wine? Should we introduce new technology such as verjus addition in order to preserve the original character of Törley sparkling wine?

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Szob subregion

Since Hungarian wine regions have their particular character of soil, relief and historical traditions, the climatic shift to north does not have its direct consequence of change of wine region locations at all. Nevertheless, from time to time it is reasonable to check the changed climatic conditions of some new regions as well to find out whether some new regions are developed with suitable climatic conditions for grape growing. The increase of the mean temperature at a rate of 1°C can cause a geographical shift of the border of the suitable wine regions with 180 km to north (Moisselin et al, 2002).

Szob subregion is situated in the north part of Central Hungary. At present it does not belong to any wine region. In what follows we check the future climatic conditions of Szob subregion whether it is expected to become suitable land for grape growing.

The effective degree days and Huglin Index values of Szob subregion are presented in *Table 9*.

Table 9. *Effective degree days and Huglin Indices in Szob subregion*

	Time interval		
	1961-1990	**2021-2050**	**2071-2100**
EDD (°C)	881	1017	1422
Huglin Index (°C)	1318	1463	1917

According to the classification of effective degree days (*Table 1*) in Szob only the early ripening varieties were expected to ripen appropriately in the reference time interval (1961-1990), the heat demands of again only the early ripening varieties can be filled in the middle of the 21st century and the effective degree days suitable for the late ripening varieties can be reached at the end of the century (*Table 9*).

According to the Huglin Index values Szob subregion was belonging to the very cool class in the last century and up to the middle of the 21st century it is expected to remain in the same class tending to be warmer and warmer and it probably reaches the temperate class at the end of the century.

The frequencies of extreme temperature events in Szob subregion are presented in *Table 10*.

Table 10. *Frequencies of extreme temperature events in Szob subregion (days / 30 years)*

	Time interval		
	1961-1990	**2021-2050**	**2071-2100**
Daily max. temperature above 30°C	203	244	700
Daily max. temperature above 35°C	9	26	166
Daily min. temperature below -1°C (after 1st of April)	101	38	17
Daily min. temperature below -15°C	30	3	0
Daily min. temperature below -18°C	8	0	0

The numbers of extreme warm days with maximum daily temperature above 30°C as well as of the extreme hot days with maximum daily temperature above 35°C are lower than they were detected in Cegléd and in Veresegyház subregions. However, the

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expected number of extreme warm days is estimated to increase up to the end of the 21st century from yearly mean of about 7 days to about 23 days, compared to its value of the reference period 1961-1990.

The expected number of extreme hot days is estimated to increase again more drastically, from the yearly mean of about 0.3 day to about 1 day at medium term and above 5 days at long term (*Table 10*).

The risk of extreme cold events is expected to decrease in Szob subregion, too. The yearly mean numbers of spring (3 days) and winter frost events (1 below -15°C; or 0.27 below -18°C – about once in four years) are expected to decrease remarkably even in medium term; the frost risk becomes very low up to the end of the century with an only spring frost event expected in two years which declares a very similar distribution of frost events of Cegléd and Veresegyház subregions.

Table 11. *Averages of precipitation indices in Szob subregion*

	Time interval		
	1961-1990	**2021-2050**	**2071-2100**
Yearly precipitation sum (mm)	873	828	858
Precipitation sum 1st of Apr– 30th of Sept (mm)	418	420	373
The max. length of consecutive days with precipitation less than 1 mm (days)	19.1	19.8	20.4
The 2nd max. length of consecutive days with precipitation less than 1 mm (days)	13.2	14.6	15.3
The 3rd max. length of consecutive days with precipitation less than 1 mm (days)	10.6	10.7	11.5

The precipitation indices in Szob subregion are presented in *Table 11*. The precipitation sum demand of grapevine is exceeded in all the three time intervals (1961-1990, 2021-2050, 2071-2100) regarding for both the yearly and the vegetation period, according to the regional climate model RegCM 3.1. The amount of precipitation in vegetation period is expected to decrease slightly up to the end of the 21st century but still remains too much.

In *Table 11* we display the lengths of the three longest dry periods as a 30-year mean. The length of the longest dry period with consecutive days of daily precipitation less than 1 mm increases insignificantly. The lengths of the second and third longest dry periods are also estimated to increase very slightly. All the estimated lengths of dry periods are shorter in Szob subregion than in Cegléd or Veresegyház subregions.

According to the regional climate model RegCM 3.1 the longest wet periods with consecutive days of precipitation above 5 mm are the longest in Szob subregion, compared to Cegléd and Veresegyház subregions.

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Comparison of the subregions

The comparison of the subregions can be made considering the *Figures 2* and *3* with the effective degree days (°C) and Huglin Indices (°C) of all the three time periods (1961-1990, 2021-2050 and 2071-2100).

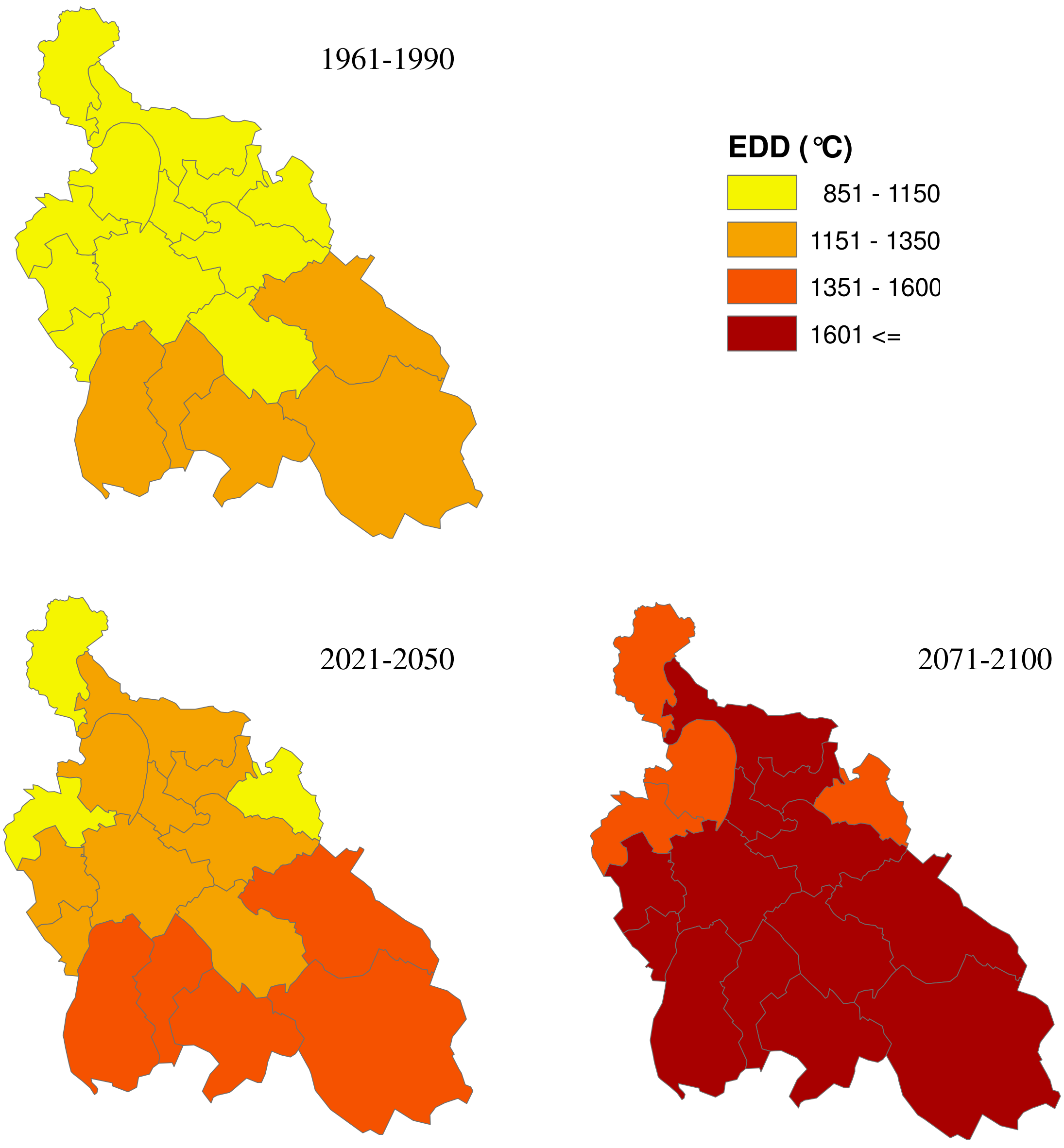

Figure 2. *Effective degree days(°C) of Central Hungarian subregions estimated by the regional climate model RegCM 3.1 for the time intervals*

According to the map of effective degree days (°C) as well as the one of Huglin Indices (°C) displayed in *Figures 2 and 3* there can be detected a significant increase in all the subregions of Central Hungary, especially in the long run up to the end of the 21st century. The region, however, preserves its character with differences between the subregions: Cegléd subregion remains the warmest one, Szob keeps being cooler with no reason to introduce it as a new grape growing region.

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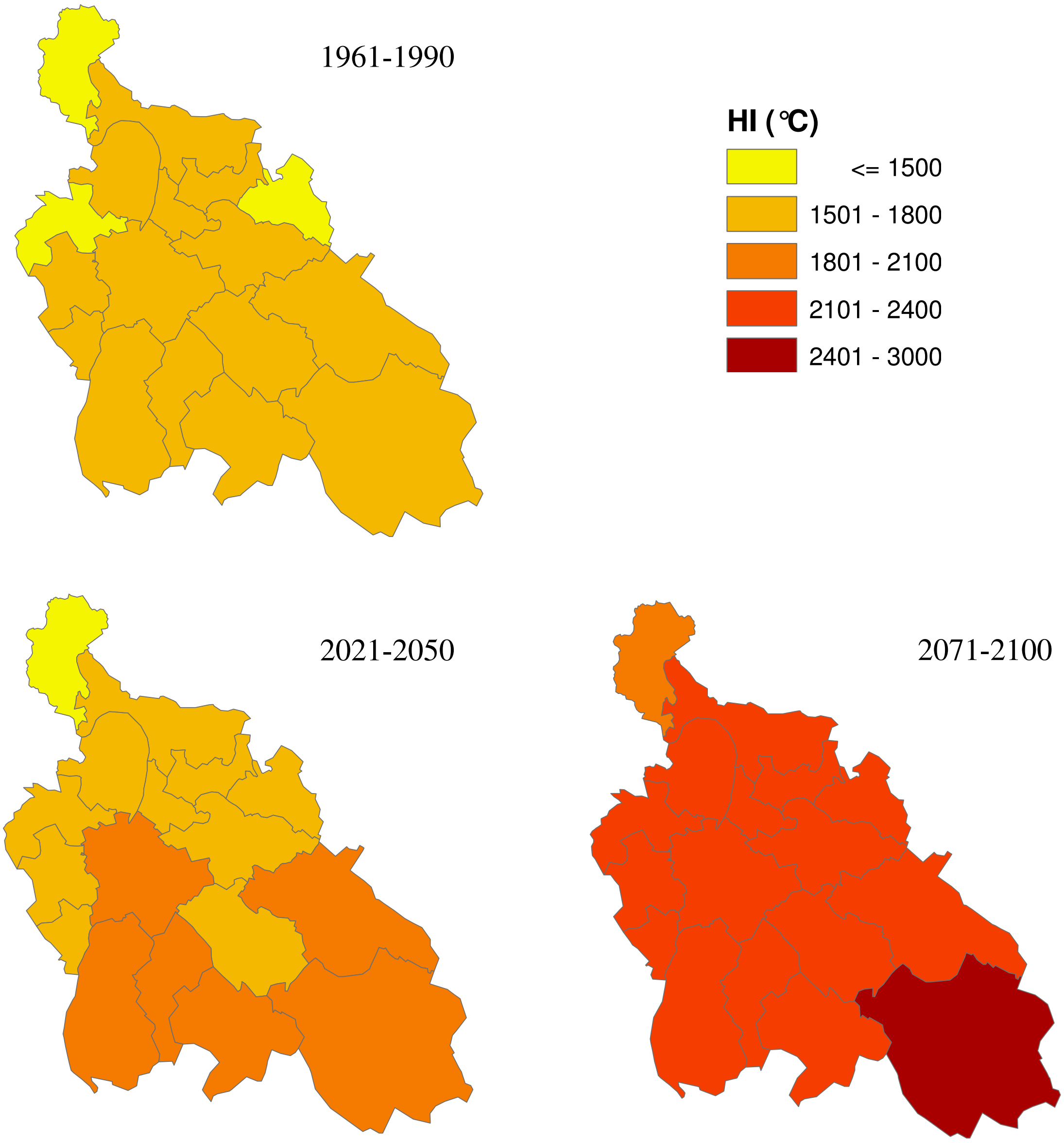

Figure 3. *Huglin Indices(°C) of Central Hungarian subregions estimated by the regional climate model RegCM 3.1 for the time intervals*

The numbers of extreme warm and extreme hot days with maximum daily temperature above 30°C and 35°C, respectively, estimated by the regional climate model RegCM 3.1 for the time intervals (1961-1990, 2021-2050, 2071-2100) and for Central Hungarian subregions can be seen in *Figures 4 and 5*. The increasing trends we can observe on the figures are more significant in long term time scale.

We can state that the expected numbers of spring and winter frost events seem to decrease intensively. The frequency of spring frost events is estimated as about one in three years while the frequency of winter frost events becomes very low.

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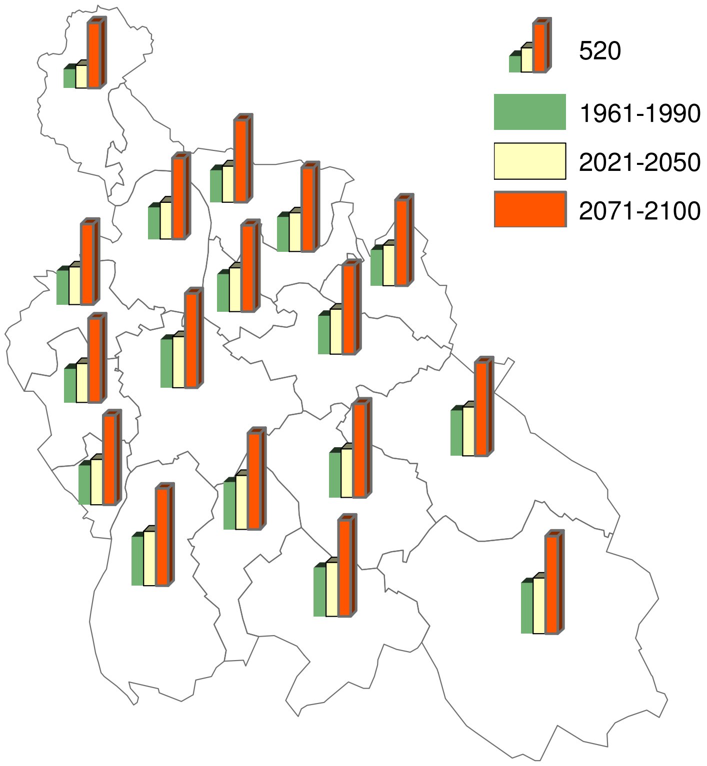

Figure 4. *The numbers of extreme warm days with maximum daily temperature above 30°C (the value refers to the highest column in the chart symbol)*

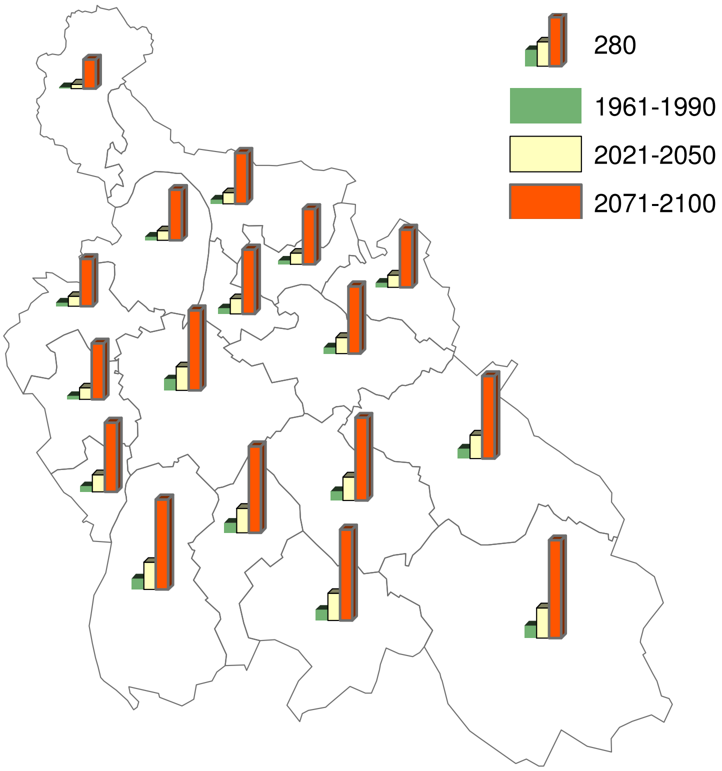

Figure 5. *The numbers of extreme hot days with maximum daily temperature above 35°C (the value refers to the highest column in the chart symbol)*

General characterization of Central Hungary region

Now we consider the climatic indices calculated for the whole Central Hungary region with its all the 17 subregions.

The effective degree days and Huglin Index values of Central Hungary region are presented in *Table 12*.

Table 12. *Effective degree days and Huglin Indices in Central Hungary*

	Time interval		
	1961-1990	2021-2050	2071-2100
EDD (°C)	1091	1265	1705
Huglin Index (°C)	1593	1776	2236

In Central Hungary mainly the early ripening varieties were expected to ripen appropriately in the reference time interval (1961-1990), the heat demands of the medium ripening varieties can be filled in the middle of the 21st century and the effective degree days demand of the late and very late ripening varieties can be reached at the end of the century.

According to the Huglin Index values Central Hungary region was belonging to the cool class in the last century and up to the middle of the 21st century it is expected to remain in the same class tending to be warmer and warmer and it reaches the warm temperate class at the end of the century.

The frequencies of extreme temperature events in Central Hungary region are presented in *Table 13*. The numbers of extreme warm days with maximum daily temperature above 30°C as well as of the extreme hot days with maximum daily temperature above 35°C are all estimated to increase intensively up to the end of the 21st century.

The expected number of extreme warm days grows from about 14 days to about 31 days in the long run, compared to its value of the reference period 1961-1990.

The expected number of extreme hot days is estimated to increase more drastically, from the yearly mean of about 1 day to about 2 days at medium term and to about 13 days at long term (*Table 13*).

Table 13. *Frequencies of extreme temperature events in Central Hungary (days / 30 years)*

	Time interval		
	1961-1990	**2021-2050**	**2071-2100**
Daily max. temperature above 30°C	420	473	939
Daily max. temperature above 35°C	40	100	388
Daily min. temperature below -1°C(after 1st of April)	61	24	9
Daily min. temperature below -15°C	17	1	0
Daily min. temperature below -18°C	3	0	0

The risk of extreme cold events is expected to decrease in Central Hungary region. The yearly mean numbers of spring (2 days) and winter frost events (0.6 below -15°C – about once in two years; or 0.1 below -18°C – about once in ten years) are expected to

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decrease remarkably even in medium term; the frost risk becomes very low up to the end of the century with an only spring frost event expected in three years.

The precipitation indices in Central Hungary region are presented in *Table 14*. The precipitation sum demand of grapevine is satisfied in all the three time intervals (1961-1990, 2021-2050, 2071-2100) regarding for both the yearly and the vegetation period, according to the regional climate model RegCM 3.1. The amount of the yearly precipitation sum is expected to decrease slightly up to the middle of the 21st century and to increase thereafter. In the growing season there is only a decreasing trend detected up to a rate of about 10 % in a century.

Table 14. *Averages of precipitation indices in Central Hungary*

	Time interval		
	1961-1990	**2021-2050**	**2071-2100**
Yearly precipitation sum (mm)	714	656	693
Precipitation sum 1st of Apr– 30th of Sept (mm)	327	324	298
The max. length of consecutive days with precipitation less than 1 mm (days)	22.4	24.5	26.7
The 2nd max. length of consecutive days with precipitation less than 1 mm (days)	15.6	16.7	17.6
The 3rd max. length of consecutive days with precipitation less than 1 mm (days)	12.1	13.0	13.5

In *Table 14* we display the lengths of the three longest dry periods as a 30-year mean. The length of the longest dry period with consecutive days of daily precipitation less than 1 mm increases from 22.4 to 26.7 in the long run, compared to the reference period 1961-1990. The lengths of the second and third longest dry periods are also estimated to increase.

According to the regional climate model RegCM 3.1 the length of the longest wet periods (3.2-3.4 days) with consecutive days of precipitation above 5 mm does not generate notable risk with an expected stagnancy in the future.

The comparative diagrams of the relative change of risk factors in Central Hungary expressed by the climatic indicators referring to medium term (2021-2050) and long term (2071-2100) can be seen in *Figures 6 and 7*. From the factors involving risk or benefit with changing values we highlight the most important ones which have decisive impact on the crop quality. In the figures we use the following abbreviations:

- D1, D2, D3, days: the first, second and third maximal lengths of consecutive days with precipitation less than 1 mm;
- F-1, days: the number of frosty days (below -1°C) after the 1st of April;
- C35, days: the number of days with maximal daily temperature above 35°C;
- C30, days: the number of days with maximal daily temperature above 30°C;
- HI, °C: Huglin Index;
- EDD, °C: effective degree days

The lengths of the dry periods (D1, D2, D3) do not increase drastically, however, considering their approximate values in the reference period (above 20 days for D1, above 15 days for D2 and above 12 days for D3), a still existing risk of water stress is warned with a motivation for making efforts toward risk mitigation practices.

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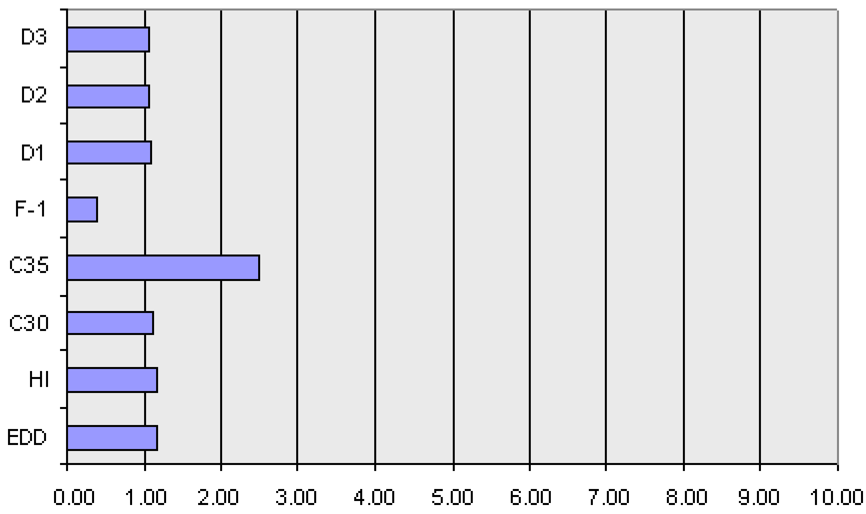

Figure 6. *The change of risk in Central Hungary expressed by the climatic indicators and calculated by the regional climate model RegCM 3.1 for the time interval 2021-2050 related to 1961-1990 (D1, D2, D3, days: the first, second and third maximal lengths of consecutive days with precipitation less than 1 mm; F-1, days: the number of frosty days (below -1°C) after the 1st of April; C35, days: the number of days with maximal daily temperature above 35°C; C30, days: the number of days with maximal daily temperature above 30°C; HI, °C: Huglin Index; EDD, °C: effective degree days)*

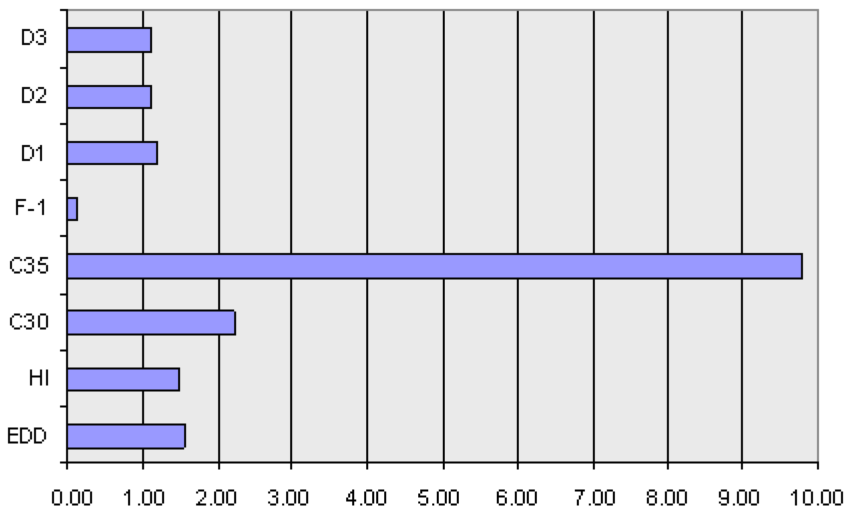

Figure 7. *The change of risk in Central Hungary expressed by the climatic indicators and calculated by the regional climate model RegCM 3.1 for the time interval 2071-2100 relative to 2021-2050 (D1, D2, D3, days: the first, second and third maximal lengths of consecutive days with precipitation less than 1 mm; F-1, days: the number of frosty days (below -1°C) after the 1st of April; C35, days: the number of days with maximal daily temperature above 35°C; C30, days: the number of days with maximal daily temperature above 30°C; HI, °C: Huglin Index; EDD, °C: effective degree days)*

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The number of hot days (C35) doubles in the middle term and increases almost to its tenfold value in long term. The number of warm days (C30) increases significantly and doubles in the second half of the 21st century, only.

The spring frost risk (F-1) decreases throughout the whole century.

The increasing tendency of Huglin Index values (HI) together with the one of the effective degree days (EDD) can affect fairly beneficial.

Conclusions

Considering the climatic indicators of Central Hungarian grape growing region we can state that in middle or even in long term with the increasing values of the temperature indices (effective degree days, Huglin Index) besides early and medium ripening varieties some late varieties can be introduced in the production in the subregions changing their cool climate class into temperate one. With warming the probabilities of spring and winter frost events are decreasing and therefore some frost sensitive table grape varieties can gain their higher security of crop production.

Nevertheless we stress the point that low probability events with high damage can still be very harmful. Low probability-high impact events are very complex to handle as their distributions are very difficult to estimate and even 10 km resolution regional climate model outputs have still too high error term to solve this problem appropriately.

The significantly decreased probability of frost events does not give enough reason to give up the research, breeding or application of frost resistant varieties especially in plain region viticulture regions with lower altitude or sites with cool collecting structure of terrain. Still at present we regularly observe quite serious frost events. For example, one of the typical frost affected areas of Kunsági wine region, *Gál Vineyard and Winecellar* sustained winter frost damage in the last two years. On the 21st of December, 2009 temperature dropped to -19.6°C and on the 19th of December, 20010 to -15.8°C which caused 60% and 30% bud frost in case of the Kékfrankos variety that is moderately sensitive to winter frost (Gál et al., 2011; Zanathy et al., 2011). Meanwhile, in case of more sensitive varieties even 80% of buds were frost dead in 2009 (Sz-Nagy, personal communication).

According to our results the significant increase of the number of warm and hot days involves both quantity (biomass increase) and quality risk of production (change of balance of sugars and acids). The structure of plantation, the system of cultural practices, especially the canopy manipulation and soil management practices have probably be modified and adjusted to the changed conditions in order to prevent the damages or mitigate the risk of loss. Moreover, we have to prepare for the possible modification of the characteristics of wines and the feature of some regions. The deviation between the results of the different years can moderate as the climate factors affect together with their interaction with the shifted phenological stages. The realized change of the character of a region is very difficult to prognosticate. Not only the change of the climate with its direct impact but also the effect of the modified edaphic factors, the plantation structure and the applied cultivation and practices with their interactions should be taken into consideration.

The water supply even with its possible decrease remains in the optimal range, considering the yearly precipitation sum, the risk of serious water stress is not high. The precipitation sum in the vegetation period tends to be near optimal. Moderate water stress, however can be caused by the longer and longer dry periods growing up to 27 days by the end of the 21st century. As a consequence of the increased aridity, we also have to prepare for unbalanced growing process.

To sum it up we can state that regional climate model RegCM3.1 forecasts a warmer and dryer future in Central Hungary with respect to the long term mean distribution parameters which does not endanger the growing demands of grapevine producers. However, the increasing frequencies and seriousness of extreme events, especially warm and hot days as well as long dry periods bring us new risk factors to face which motivates us to find out new strategies such as modified or new plantation systems, vineyard establishment practices or viticultural management techniques. Since grapevine is planted for a long time (30-40 years), new plantations should be introduced considering the expected changes in the future.

Both regional and subregional surveys are necessary to learn the present and the expected future situation of a region with the possible changes of its border. Responsible decisions on the modification of grape growing regions can be made according to the evaluations of the continuous monitoring and survey.

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