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The effects of climate change on grape production in Hungary

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Abstract—Spatial distribution of several indices characterizing wine production in Hungary are analyzed in this paper using the bias-corrected outputs of three different regional climate models: RegCM, ALADIN, and PRECIS. For this purpose, the daily minimum, maximum, and mean temperature, and daily precipitation time series were used. The indices include the active degree days, Huglin's heliothermal index, length of vegetation period according to thermal conditions, hydrothermal coefficient, and frequencies of extreme temperature events. In the study, first, the past changes of these indices are evaluated, and then, the main focus is on the projected changes until the end of the 21st century. Our results suggest that white wine grapes are very likely to lose their dominance over red wine grapes in Hungary in the next few decades. Furthermore, the ripening of late-ripening and very-late-ripening grape varieties will become more likely. Extreme high summer temperatures will become more frequent, while the risk of frost damage in the reproductive cycle is projected to decrease.

Key-words: Vitis vinifera, RegCM, ALADIN, PRECIS, regional climate change, Hungarian wine regions

1. Introduction

Wine grape production is a segment of major importance in Hungarian agriculture. The life cycle of the grape is influenced by climatic, edaphic, and biotic factors, from which climatic factors are the most dominant and dynamically changing ones (*Kozma*, 2002). As vineyards in Hungary produce grapes for 25−30 years, predicting these climatic factors for the next decades has a great importance.

In this work, we analyze the temporal trends of selected climatic factors, and use several indices to identify grape varieties in Hungary that are more suitable for the projected climatic changes. Additionally, we predict the trend of change in the probability of desease development for the next decades. Although there has been a recent work studying the future changes of ecological factors affecting Hungarian grape fields (*Szenteleki*, 2012), our work is the first climatic study of the entire Hungarian region focusing specifically on grape and wine production.

2. Studied regions and applied methods

2.1. Studied regions

The wine subregions of Hungary belong to the northern territorries of grape production. Grape production is made possible primarily by the diverse microregions of the country and their specific meso- and microclimate. Based on microclimatic similarities, the 22 Hungarian wine subregions are categorized to 7 regions (127/2009. (IX. 29.) FVM regulation, appendix 1), covering Danube (Duna), Balaton, Eger, North-Transdanubia (Észak-Dunántúl), Pannon, Sopron, and Tokaj. On these wine regions, the wine grape production is dominated by white wine grapes, however, in some regions (e.g., in Sopron region), red grape production is also important. From the grape varieties, both early-, medium-, and late-ripening ones are produced in the different regions (*Hajdú*, 2003).

2.2. Applied regional climate models

Results provided by global climate models (GCMs) cannot be applied to small regions like the Carpathian Basin and Hungary. Therefore, in our analysis we applied regional climate models (RCMs) nested in GCMs. The RCMs have finer spatial resolution than GCMs, thus they can take into account local scale landscape features and topography.

We used the outputs of the following model simulations carried out in the framework of the European ENSEMBLES project (*van der Linden* and *Mitchell*, 2009): the RegCM (*Giorgi et al.*, 1993), the ALADIN (*Déqué et al.*, 1998) regional climate models, and the PRECIS regional climate model developed by the UK Met Office Hadley Centre for Climate Prediction and Research (*Wilson et al.*, 2007) applied specifically to the Carpathian Basin (*Pieczka*, 2012). The raw RCM outputs generally overestimate the temperature in summer and the precipitation throughout the entire year (*Pongrácz et al.*, 2011; *Pieczka et al.*, 2011). Therefore, they were corrected using a percentile-based bias correction technique (*Formayer* and *Haas*, 2009) consisting of correcting the simulated daily outputs on the basis of the monthly distributions of observed meteorological data. Observations are available from the gridded E-OBS database (*Haylock et al.*, 2008). The RCM simulations use the A1B emission scenario (*Nakicenovic* and *Swart*, 2000) for the 21st century. This scenario assumes a slowly growing trend of atmospheric carbon-dioxide concentration, which is likely to exceed 700 ppm by the end of the century.

All RCMs applied a horizontal resolution of 25 kilometers. This resolution is still too coarse for detailed studies on the changing microclimatic conditions of vineyards, but it enables us to estimate some general tendencies. The simulated model datasets used in this study cover the geographic region between latitudes 44°−50° N and longitudes 14°–26° E, and contain the time interval 1951−2100 (except for the PRECIS simulation, where the time interval was 1951−2098). The applied RCM outputs include the daily minimum, maximum, and mean temperature, as well as the daily precipitation, which are used to calculate past and future time series of various indices described in Section 2.3, and derive conclusion on their effect on wine grape production in Hungary in the *middle of the 21st century* (for the period 2021−2050) and in the *end of the 21st century* (for the period 2071−2100; or between 2069−2098 for the PRECIS model due to shorter simulation time range). The years 1961−1990 is defined as the *reference period*.

2.3. The applied indices

The indices that we analyze in this paper are the following.

Active degree days (ADD). This can be easily calculated from the daily mean temperatures and can be used to determine the grape varieties that the given region is suitable for (see *Table 1*). The calculation is carried out by summing the residual above 10 °C of the daily mean temperatures throughout the growing season (*Davitaja*, 1959; *Kozma*, 2002). Note, that in all our calculations we defined the growing season as the period of a year when the daily mean temperature is above 10 °C for at least three consecutive days (*Kozma*, 2002). This practically corresponds to the time beginning with budburst and ending with leaf-fall, and thus, covers a longer interval of the year than the one discussed in *Table 1*.

Table 1. Grouping of grape varieties based on the active degree days (*Davitaja*, 1959; *Kozma*, 2002)

Ripening categories	**Active degree days**	**Number of days**
	(from budburst to full ripening of berries)	
very-early-ripening varieties	690–850 °C	110–120 days
early-ripening varieties	850–1150 °C	120–130 days
medium-ripening varieties	1150–1350 °C	130–145 days
late- & very-late-ripening varieties	>1350 °C	>145 days

Huglin's heliothermal index (HI) (*Huglin,* 1978). This gives a measure on the suitability of a region for different grape varieties based on the daily mean and maximum temperatures of the region, and on a factor denoted as *d*, which depends on the geographic latitude of the region (and thus the average length of the days during the growing season). Huglin's heliothermal index can be written as:

$$HI = d\sum\frac{\left[\left(T-10°\mathrm{C}\right)+\left(T_x-10°\mathrm{C}\right)\right]}{2}, \qquad (1)$$

where d is the latitude coefficient increasing monotonically from d_{40}=1.02 at latitude 40° N to d_{50}=1.06 at latitude 50° N; T is the daily mean temperature, and T_x is the daily maximum temperature, both given in °C. In Eq. (1), each term of the sum corresponds to one day in the growing season, and thus, the sum goes through all the days of the growing season. The optimal values of *HI* for selected grape varieties are shown in *Table 2*.

Table 2. The optimal values for Huglin's heliothermal index (HI) for selected white (normal fonts) and red (italic fonts) wine grape varieties. (*Huglin*, 1978; *Kozma*, 2002)

Huglin's Heliotermal Index (HI; in °C)	Grape varieties
2300	*Aramon*
2200	*Carignan, Zinfandel*
2100	*Cinsaut, Grenache, Syrah, Sangiovese*
2000	Ugni blanc
1900	Chenin blanc, Welschriesling, *Merlot, Cabernet Sauvignon*
1800	*Cabernet franc, Blaufränkisch*
1700	Chardonnay, Rhine Riesling, Silvaner, Sauvignon blanc, *Pinot noir*
1600	Pinot blanc, Gewürztraminer, *Gamay*
1500	Müller-Thurgau
1400	Irsai Olivér

Occurrences of extreme temperature episodes. Thermal susceptibility of wine grapes depends on many biotic and climatic factors, and it is variety and site specific according to different levels of risk severity at different extreme temperature values. Therefore, several thermal indices can be defined. To give examples, we used the following measures in studying the occurrences of extreme temperatures (*Dunkel* and *Kozma,* 1981; *Kozma*, 2002):

◇ daily minimum temperature is below −17 °C in the reproductive cycle,

◇ daily minimum temperature is below −21 °C in the reproductive cycle,

◇ daily maximum temperature is above 35 °C in the vegetative cycle.

Hydrothermal coefficient (HTC). We can characterize the combined effect of precipitation and temperature on grapes using the hydrothermal coefficient (*HTC*). This characteristic number, which measures the water supply of a vegetation, is calculated as:

$$HTC = 10P / T_0, \qquad (2)$$

where P is the precipitation during the growing season in mm and T_0 is the effective degree days in °C (which is the sum of daily mean temperatures for days of the growing season when this temperature is above 10 °C). In areas, where the *HTC* is below 0.5 mm/°C, grape production is only possible if the humidity is high or if irrigation is applied. The maximum value of the *HTC* is in the range of 1.5−2.5 mm/°C, while its optimal value is around 1.0 mm/°C (*Szeljanyinov*, 1928; *Kozma*, 2002).

3. Results and discussion

According to the RCM simulations, the ADD values were in the range of 1200−1400 °C* in the Hungarian wine regions during the 1961–1990 reference period (*Fig. 1*). These results suggest that climatic conditions were in favor of early- and medium-ripening grape varieties at the end of the 20th century. However, there are certain regions where late-ripening varieties are also produced (*Hajdú*, 2003). The reason for this controversy is that RCMs do not take into account the extra heat the grapes are subjected to when they are grown on hill- and mountainsides and are being exposed to sunlight at lower incoming angles. Thus, maps of heat distribution are biased to lower-than-actual heat supply conditions at hilly terrains (such as the Sopron regions), and consequently, they falsely suggest that these regions are only suitable for low heat demanding grape varieties. As it can be seen in *Fig. 2*, based on *HI*, we could think that heat conditions in Sopron wine regions can only support less heat demanding varieties, and only the Danube regions are optimal for more heat demanding ones. In practice, the Sopron regions are known to be optimal for more heat demanding varieties, which can be explained by taking into account the extra heat the regions are obtaining from sunlight arriving at lower incoming angles.

* These values are only averages, i.e., in some years the *ADD* can be lower or higher. Negative deviations from these averages can lead to an insufficient amount of heat for the ripening of grape varieties that require a longer growing season.

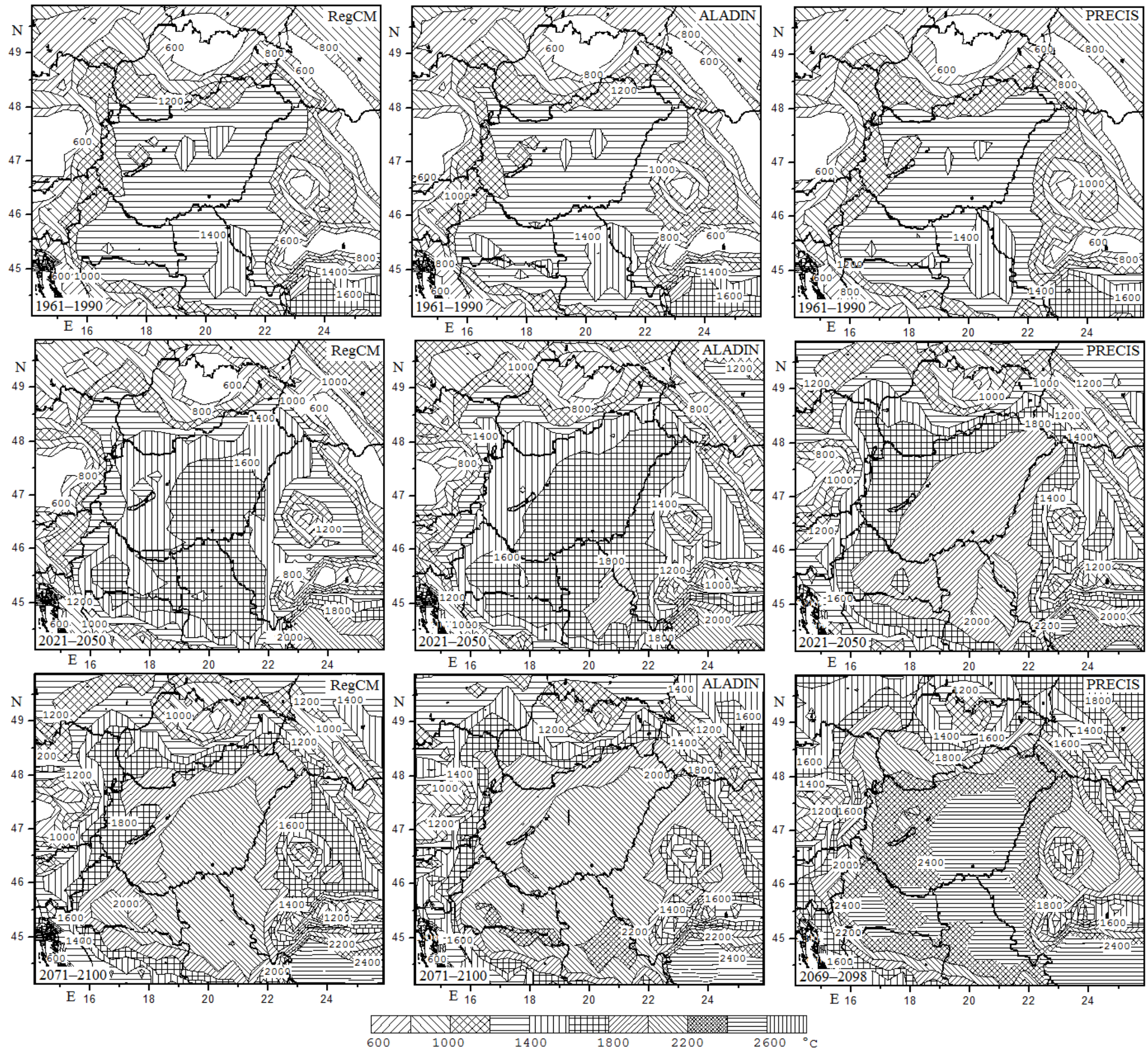

Fig. 1. The values of active degree days (*ADD*) in the Carpathian Basin. The upper row corresponds to the reference period, while the middle and lower rows correspond to the predicted middle and end of the 21st century, respectively. The three columns show our results using the RegCM (left), ALADIN (middle), and PRECIS (right) regional climate models' outputs.

The length of the growing season allowed by the thermal conditions in Hungary is between 160−190 days within the reference period of the RCM simulations. This is about 1 month longer than that is necessary for early- and medium-ripening varieties (see *Table 1* and *Fig. 3*). Thus, we can conclude that the projected thermal conditions by the end of the 21st century are optimal for late-ripening and very-late-ripening grape varieties.

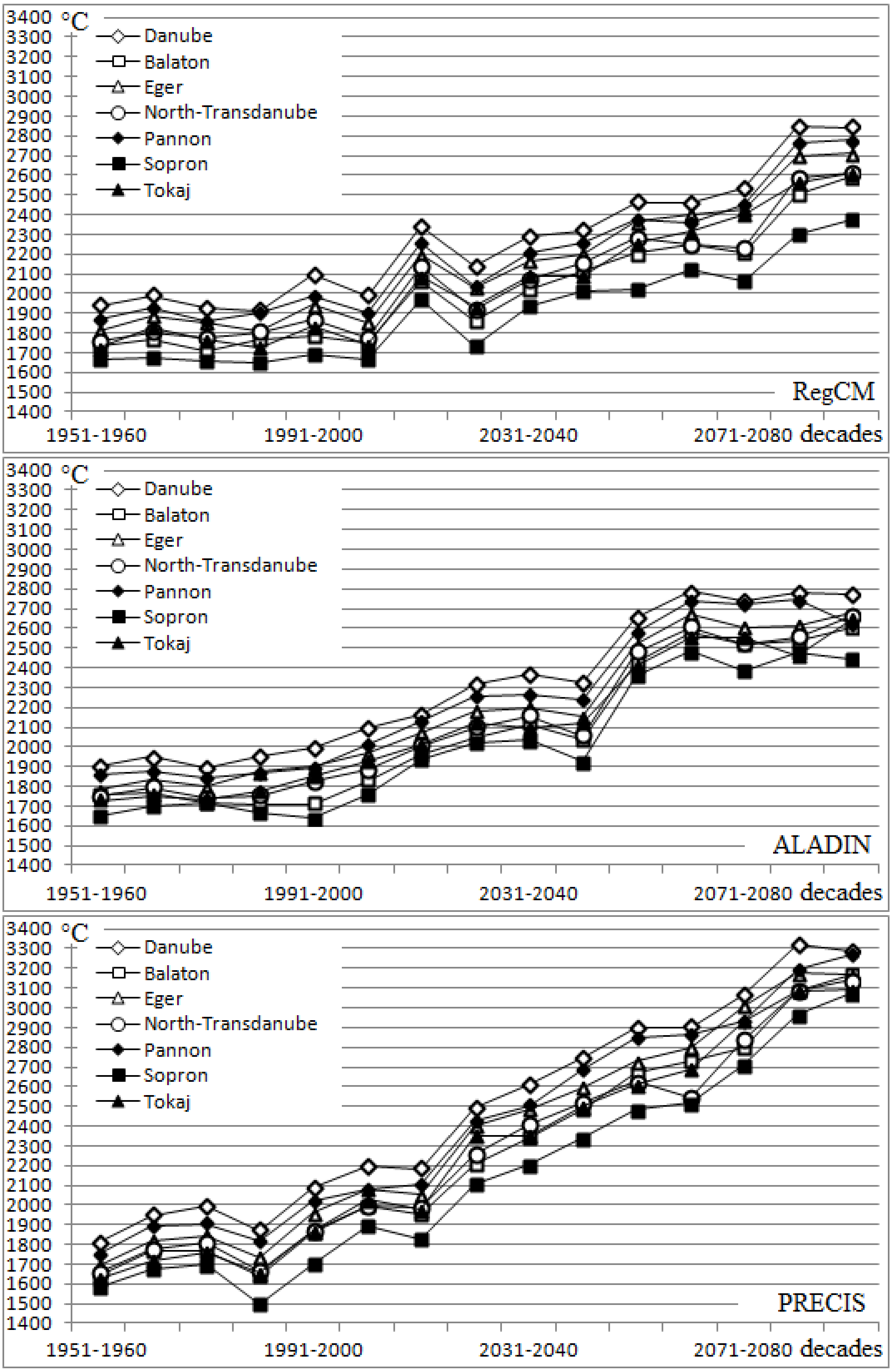

Fig. 2. The temporal evolution of Huglin's heliothermal index (*HI*) in the Carpathian Basin based on the RegCM (upper), ALADIN (middle), and PRECIS (lower) regional climate models' outputs.

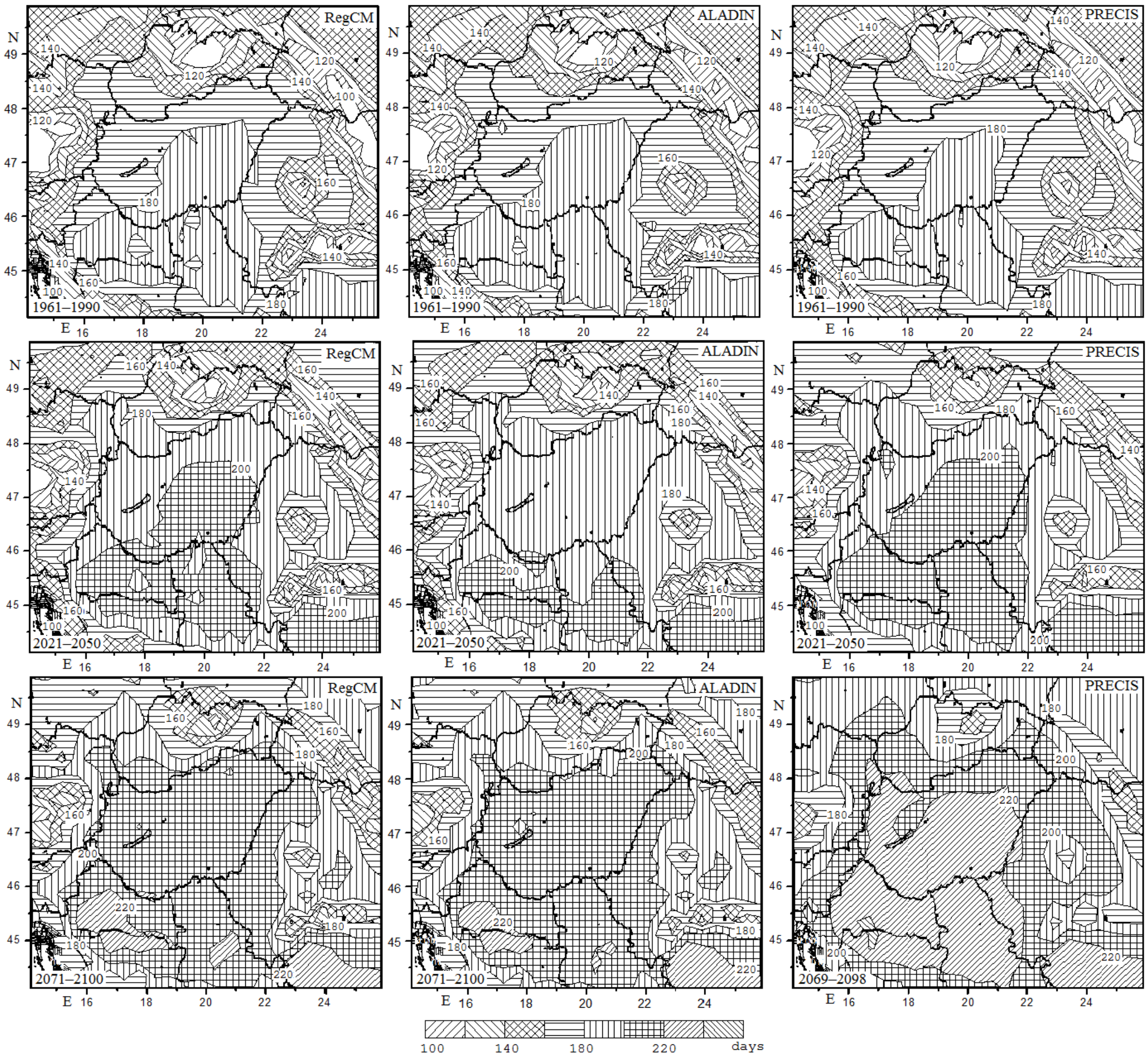

Fig. 3. The length of the growing season in days allowed by thermal conditions. The upper row corresponds to the reference period, while the middle and lower rows correspond to the predicted middle and end of the 21st century, respectively. The three columns show our results using the RegCM (left), ALADIN (middle), and PRECIS (right) regional climate models' outputs.

Results obtained from the ALADIN and RegCM data show a correlation with each other in the middle of the 21st century. Based on these, the *ADD* will increase up to 1400−1700 °C in this period. The value of *HI* is projected to increase to 1800 °C, however, in the Danube region values above 2300 °C will also be possible. The values of *HI* increase with an increased rate from the 1980s in every wine region, as shown in *Fig. 2*.

The PRECIS model simulation suggests a much more significant rise in the index values. The *ADD* can increase up to 1600−2000 °C in the middle of the 21st century. *HI* will reach 2300 °C in the whole country. In *Fig. 2*, curves corresponding to the PRECIS model increase with the highest rate, which shows that this model predicts the greatest change in the local climate by the middle of the 21st century.

All three models predict longer growing season in the immediate future (see *Fig. 3*) compared to the reference period. By the middle of the 21st century, the vegetation cycle length allowed by thermal conditions can be as long as 180−210 days, however, the change will be slightly smaller (180−200 days) according to the ALADIN model.

Similar tendencies are expected to occur in the end of the 21st century. Based on the ALADIN and RegCM models, the *ADD* can be as high as 1700−2200 °C. Similar to the results for the end of the 21st century, PRECIS predicts a more remarkable change: according to this model, *ADD* can be between 2000−2500 °C. In this period, all three models predict *HI* to be above 2300 °C throughout the whole country.

The vegetation cycle length allowed by thermal conditions can be even longer in the far future (see *Fig. 3*). Its duration can reach 200−220 days, or 210−230 days according to the PRECIS model.

All these suggest that certain regions will allow the ripening of late-ripening grape varieties by the middle of the 21st century. As the increased heat allows the development of color- and aroma essences, growing a higher ratio of red wine grapes will be feasible in several wine regions. According to results corresponding to the end of the 21st century, the thermal conditions of the Hungarian wine regions will allow the growing of Mediterranean red wine grapes.

In addition to the average conditions, the occurrences of extreme temperatures in the reproductive and vegetation cycles also have important roles. Since PRECIS simulation does not include any occurrence of daily minimum temperature below −17 °C, we only analyze the extremes based on the other two RCMs simulations.

The regional distribution of the number of days with minimum temperatures below −17 °C (as obtained from the RegCM and ALADIN simulations) is in a good agreement with the results presented in *Dunkel* and *Kozma* (1981) (see *Fig. 4*). However, note, that the time interval investigated in *Dunkel* and *Kozma* (1981) is slightly different from our reference period.

We found that less frost-tolerant grape varieties suffered frost damage in every 2−3 years within the reference period (see *Table 3*). This occurrence is projected to decrease by the middle of the 21st century to only one major frost damage in the winter season in every 4−10 years. The risk of frost damage will almost disappear in the end of the 21st century.

The RCM simulations underestimate the number of days with a minimum temperature below −21 °C compared to the findings of *Dunkel* and *Kozma* (1981). This difference can be related to the slightly different periods applied. Independently from this fact, the occurrence of extreme cold temperatures will decrease in the middle of the 21st century, and almost completely disappear in the end of the 21st century.

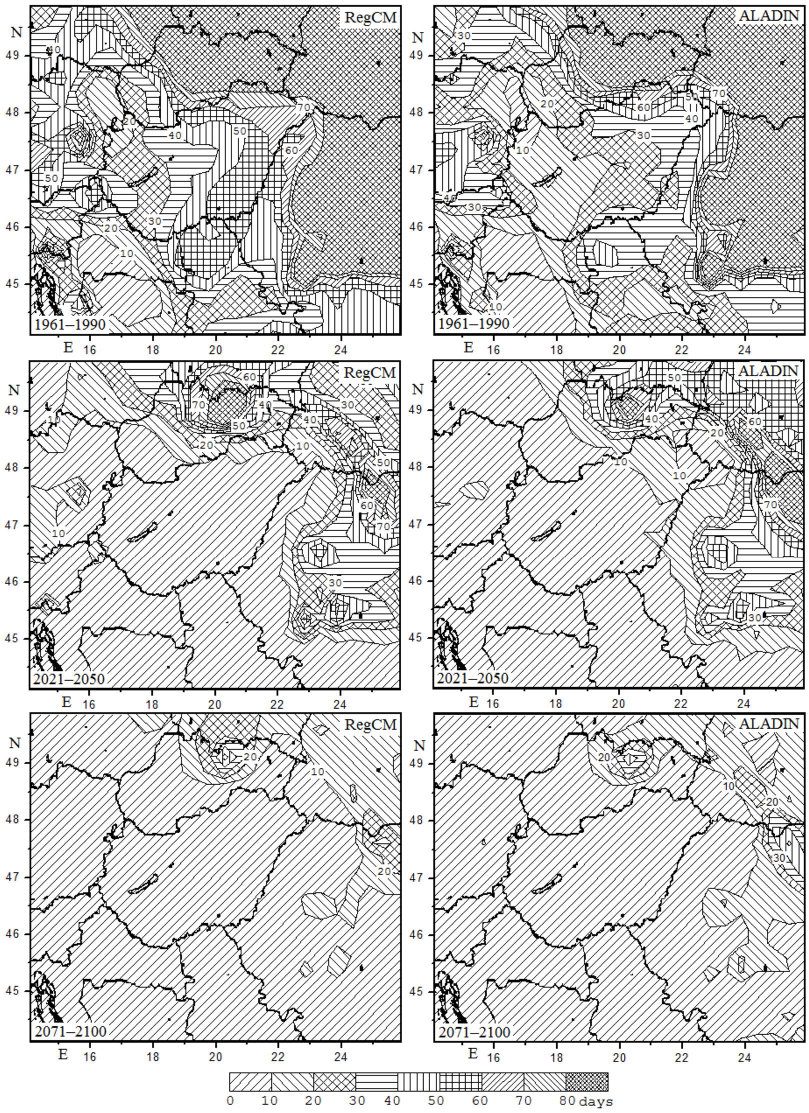

Fig. 4. The number of days in the reproductive cycle with minimum temperature below –17 °C. The two columns correspond to the RegCM (left) and ALADIN (right) simulations' results. The rows of the figure show the model results for the reference period (upper), and the predictions for the middle (middle) and the end (lower) of the 21st century.

The plants can be damaged due to extreme hot days in the growing season, too. In the reference period, the occurrence of days with maximum temperature above 35 °C was one per 2−10 years according to the RCM results (see *Fig. 5*). The most of such years are simulated by the RegCM model, and the least by the ALADIN model. On yearly average, about 1−4 days occurred when the maximum temperature exceeded 35 °C.

Table 3. The number of years having at least one day in the reproductive cycle with minimum temperature below –17 °C. The numbers are given for the different Hungarian wine regions, and using the RegCM (Re) and ALADIN (AL) simulations outputs.

	Danube		**Balaton**		**Eger**		**North-Transdanubia**		**Pannon**		**Sopron**		**Tokaj**	
	Re	AL	Re	AL	Re	AL	Re	AL	Re	AL	Re	AL	Re	AL
Reference period	19	17	14	15	21	19	16	16	15	12	11	10	21	18
Middle of the 21st cenrury	5	8	6	2	8	8	5	3	5	2	2	1	7	7
End of the 21st century	1	2	2	3	2	4	2	1	1	1	0	2	1	2

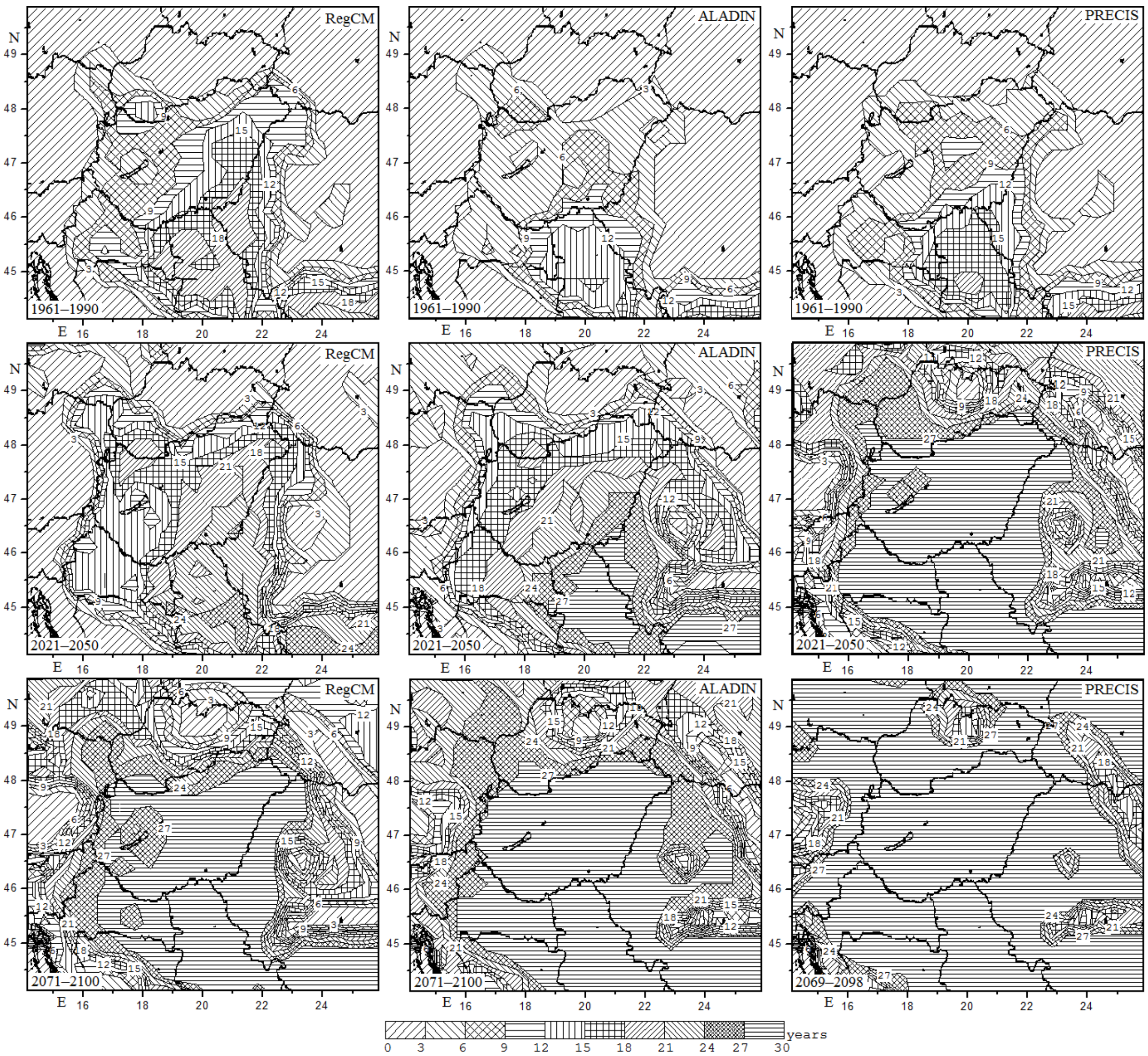

Fig. 5. The number of days in the vegetation cycle with maximum temperature above 35 °C. The two columns correspond to the RegCM (left), ALADIN (middle), and PRECIS (right) simulations' results. The rows of the figure show the model results for the reference period (upper), and the predictions for the middle (middle) and the end (lower) of the 21st century.

There will be a drastic rise in the number of years with extreme high temperature both in the middle and the end of the 21st century. All three models predict such days to occur in every two years in the middle of the 21st century, and in every year in the end of this century. In years, when there is at least one day with a maximum temperature above 35 °C, there will be a rise in the number of such days both in the middle and the end of the 21st century. The highest occurrence of such days is projected in Duna region. According to the RegCM predictions, there will be 2−4 days yearly with extreme hot temperatures in the middle of the 21st century, and can be as many as 5−13 such days per year in the end of this century. The rise in the number of extreme hot days is even greater when using the ALADIN and PRECIS simulations' outputs. Based on these models, we can expect 8−16 extreme hot days per year in the middle of the 21st century and 27−40 such days per year in the the end of this century.

Our results based on the three RCMs' simulations show (see *Table 4*) that the *HTC* will not reach the critical threshold value of 0.5 mm/°C neither in the immediate, nor in the far future. This means that the climatic conditions will be suitable for wine production in the Hungarian wine regions. It depends on the deviation of the *HTC* from 1 mm/°C whether these conditions move closer to or away from the optimum in particular regions.

Table 4. The values of the hydrothermal coefficient (*HTC*, in mm/°C) in the different Hungarian wine regions based on RegCM (Re), ALADIN (AL), and PRECIS (PR) model predictions.

	Danube			**Balaton**			**Eger**			**North-Transdanubia**		
	Re	AL	PR	Re	AL	PR	Re	AL	PR	Re	AL	PR
Reference period	0.90	0.92	0.89	1.12	1.21	1.15	1.05	1.07	1.03	0.99	1.03	1.00
Middle of the 21st cenrury	0.90	0.83	0.71	1.18	1.14	0.95	1.02	0.95	0.72	1.01	0.98	0.78
End of the 21st century	0.75	0.71	0.59	1.01	0.88	0.75	0.85	0.78	0.60	0.87	0.78	0.67

	Pannon			**Sopron**			**Tokaj**		
	Re	AL	PR	Re	AL	PR	Re	AL	PR
Reference period	0.92	0.98	0.94	1.24	1.32	1.32	1.15	1.19	1.14
Middle of the 21st cenrury	0.96	0.89	0.79	1.28	1.29	1.04	1.13	1.02	0.79
End of the 21st century	0.82	0.75	0.68	1.14	1.00	0.82	0.93	0.81	0.63

In the reference period, all three models showed excess heat in Danube and Pannon regions, and excess precipitation in Balaton, Eger, Sopron, and Tokaj regions. All three models resulted in North-Transdanubia region being climatic optimal.

The changes in the middle of the 21st century are not unambiguous. RegCM simulation does not show any change for Danube region, while for Balaton and Pannon regions it predicts an increase in excess precipitation. The climatic conditions are projected to become more suitable for grape production in Eger, Pannon, and Tokaj regions. ALADIN simulation predicts a decrease in excess precipitation or an increase in excess heat for all regions. This could lead to more favorable conditions in Balaton, Eger, Sopron, and Tokaj. Similarly to ALADIN, PRECIS simulation shows either a decrease in excess precipitation or an increase in excess heat for all wine regions, which results in an improvement in Balaton and Sopron regions.

All three models project similar conditions for the end of the 21st century, which means that we expect a decrease in excess precipitation or an increase in excess heat in all regions compared to the reference period. According to all three models, this again means better conditions for Sopron region and worse for Danube, Eger, North-Transdanubia, and Pannon regions compared to the conditions in the reference period. This change lead to more favorable conditions in Balaton (according to RegCM and ALADIN) and Tokaj (according to RegCM) regions.

4. Conclusions

Our investigations showed that in terms of modeled heat conditions, the 21st century will favor red wine grape and late-ripening varieties. We can derive this conclusion from the estimated increasing tendency of active degree days and of Huglin's heliothermal index. At the same time, we expect longer growing season allowed by the climatic conditions.

Frost-damages in the dormancy periods would become more rare due to the warming climate. However, the number of days with maximum temperature above 35 °C may increase, which could lead to serious heat damages. There should be more care spent on preventing and mitigating damages due to increased heat stress using adequate horticultural practices.

We expect a decrease in the hydrothermal coefficient in all regions by the end of the 21st century, which can lead to non-optimal climatic conditions, because heat as its denominator will likely be dominant.

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