Doctoral (PhD) Thesis

EARLY PHENOLOGICAL RESPONSES OF GRAPEVINE (*VITIS VINIFERA* L.) IN KUNSÁG WINE-GROWING AREA BASED ON PLANT SURVEYS, WEATHER OBSERVATIONS AND REGIONAL CLIMATE MODEL

Hlaszny Edit

Supervisors:

Dr. György Dénes Bisztray DSc
University professor

and

Dr. Márta Ladányi PhD
Associate professor

Corvinus University of Budapest
Institute of Viticulture and Oenology
Department of Viticulture
Department of Mathematics and Informatics

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Head of Ph.D. School: Prof. Dr. Magdolna Tóth
Doctor of the Hungarian Academy of Sciences
Head of Department of Fruit Sciences
CORVINUS UNIVERSITY OF BUDAPEST,
Faculty of Horticultural Sciences

Supervisors:

Dr. György Dénes Bisztray DSc
University professor
Corvinus University of Budapest
Faculty of Horticultural Sciences
Institute of Viticulture and Oenology
Department of Viticulture

and

Dr. Márta Ladányi PhD
Associate professor
Corvinus University of Budapest
Faculty of Horticultural Sciences
Department of Mathematics and Informatics

The applicant met the requirement of the PhD regulations of the Corvinus University of Budapest and the thesis is accepted for the defence process.

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Dr. Magdolna Tóth Head of Ph. D. School	Dr. György Dénes Bisztray Supervisor	Dr. Márta Ladányi Supervisor

1. Introduction

The regional effects of climate change influence the grapevine growing in the whole world. Though global warming of the past 50 years had positive effects on the quality of grapevine production and wines, we have to manage the shift of geographical borderlines of grapevine growing regions, the change of phenological schedule and the more and more frequent and severe extreme weather events as well. In many of the world's best wine regions, the average temperature of the growing increased by some 1.3 °C over the past 50 years. In the growing season in Europe, warming by 1.7 °C was measured.

RegCM 3.1 regional climate model downscaled at the Meteorology Department of ELTE, predicts more than 2.5-3 °C mean temperature increase in every season and regions in Hungary in the last third of the 21st century (Bartholy et al., 2004).

The plant phenological changes are highly correlated with the observed temperature changes:

- Climate change affects not only directly the budburst and flowering phenology of plant species but it can modify the structure and function of the whole ecosystem (Hughes 2000; Wuethrich 2000; McCarty 2001; Walther et al. 2001).
- Climate change can also induce delayed evolutionary feedback with different response time (Geber and Dawson 1993; Bradsaw and McNeilly 1991; Holfman and Parson 1997; Rodriguez and Rodriguez 1998; de Jong and Brakefield 1998).
- Climate change may directly alter the adaptability of the plants (Galen and Stanton 1991, 1993; Wookey et al. 1993), as well as it can modify their reproductive success and their interactions via impacts on flowering phenology (Hughes 2000; Beattie et al. 1973; Schemske 1977; Gross and Werner 1983; Lacey and Pace 1983; Schmitt 1983; English-Loeb and Karban 1992; Peterson 1997; Bishop and Schemske 1998).

In Hungary, the climate change induced warming can affect positively the grapevine growing in the cooler regions, but in the warmer and dryer areas, such as on the Great Plain, the risk of both production and quality deficit can increase. All these, together with the phenological changes can modify the system of grapevine growing, including plant protection, variety choice, loss prevention and growing technology, which forces the decision makers to find suitable responses at different levels. In this dissertation, we introduce the modelling of early phenological responses of grapevine (*Vitis vinifera* L.) regarding Kunság wine subregion based on long termed plant surveys, weather observations and regional climate model.

2. Objects

We aimed to examine the expected responses of some *Vitis vinifera* L. varieties to the potential climatic changes in Hungary. We tried to find an appropriate climatic indicator system by which the occurred and the potential changes can be characterized. Moreover, we investigated mathematical models that can describe the function and the potential modification of grapevine budburst and flowering schedule based on the quality and quantity of the available database. We also analysed the expected temporal shift of phenology with its potential direction and degree in the near future.

We investigated some of the most popular white and red wine varieties, an old Hungarian variety and a newly bred, promising Hungarian variety.

Based on the above, we outline our objects:

1. Based on the literature, we aimed to create a climatic indicator system with low data demand (calculated from daily temperature and precipitation data), by which the regions and vintages can be characterized well, and the changes of which can induce significant changes in viticulture. Based on the indicator system and the observations, we analyse the historical data and based on the predictions of the regional climate model RegCM 3.1 for the time intervals 2021-2050 and 2071-2100 with the reference period 1961-1990, we describe the probable changes in Kunság wine subregion.
2. To compare the calculation methods of growing season widely used in the literature and to give a proposal for a method which is suitable in case of climate change.
3. To collect phenological models used in the literature, with the aim of finding or developing one or more which is suitable and accurate to estimate the date of grapevine budburst and flowering. We introduce case studies based on the available, long termed phenological data observed in Kunság wine subregion.
4. Based on the available data, to compare the different models and varieties with the aim of finding the best model.
5. To compare the phenological models run with the output of the regional climate model RegCM 3.1 in order to describe the possible changes on Kunság wine subregion.

3. *Material and methods*

The budburst and flowering data used for modelling are from Helvécia (2000-2004) and Kecskemét (1977-2003). Both areas can be found in Duna wine region, they are parts of Kunság wine growing area. The meteorological data are from K-puszta observation station (48° 58' N, 19° 33' E, 126 m) of Hungarian Weather Service, 15 km far from Kecskemét.

We made the phenological modelling based on the data from Helvécia for 5 white wine varieties (Chardonnay, Riesling, Hárslevelű, Pinot blanc and Pinot gris) and their clones. We chose Kékfrankos, Hárslevelű, Pinot gris, Riesling and Generosa varieties from longer time series grown in Kecskemét.

With the aim of the characterization of the presently changing and in the future expected climatic conditions, we collected 36 climatic indicators (13 temperature, 16 extreme and 7 precipitation indices) which are considered as the most important factors affecting the phenology of *Vitis vinifera*, L., furthermore we calculated the values of these indices from the temperature and precipitation data measured between 1977 and 2003 in Kecskemét. We made estimations for the reference period of 1961-1990, and for the time periods of 2021-2050, 2071-2100, too. We analysed and compared the obtained results with regression analysis and ANOVA.

We introduced two different methods for the calculation of the growing season period, a traditional one and the so-called interpolation method. Their comparison was executed by Student’s t-test.

The Growing Degree Days Model (GDD) and the Unified Model (UM)

We defined a simple Growing Degree Days model. From the observed data, we accumulated the average daily temperatures above the base temperature $T_{lowerbase}$ [°C] from a starting date up to the observed budburst date for all varieties and years. The model indicates the budburst when a critical sum denoted by GDD_{u_crit} [°C] is reached. GDD_{u_crit} is defined as the average of the cumulated degree days up to the observed budburst over the examined years. The root mean square error (RMSE) was defined as the root of the average sum of the squares of the differences between the observed and estimated budburst dates measured by days. RMSE was minimized while both the base temperatures and the starting date were optimized.

We used a similar Growing Degree Days model for the estimation of full bloom time, too, but here we introduced the upper base temperature ($T_{upperbase}$ [°C] since the plant is unable to utilise the heat above a critical limit. We made predictions for the budburst dates using the regional climate model RegCM 3.1 for the time intervals 1961-1990, 2021-2050 and 2071-2100.

The longer budburst time series from Kecskemét was suitable for the comparison of two budburst date models for five grape vine varieties. Besides the GDD model we applied another model (*Unified Model – UM*) that considers the chilling effect, too.

The Unified Model is more sophisticated than the Growing Degree Days model, because this model involves the chilling effect during the endodormancy period (Chuine, 2000). Namely, in addition to breaking dormancy, chilling temperatures have an accelerating effect on bud growth. The more chilling effect indicates less degree days that are necessary to reach the budburst (Nelson and Lavender, 1979; Cannell and Smith, 1983; Murray et al., 1989; Kramer, 1994b; Chuine et al., 1999). This model begins the accumulation of chilling units from 1st September of the previous year. (The date 1st of September can be regarded as the date that is definitely before the day, when the accumulation actually starts, i.e. when the value of the accumulation function becomes greater than zero.)

We distinguish chilling effects (*CH*) and forcing effects (*F*) and define them dimensionless:

$$CH_j = \sum_{1.Sept.}^{t_j} \frac{1}{1+\exp\left(a\left(T_{aver\_i,j}-T_{base,CH}\right)^2 + b\left(T_{aver\_i,j}-T_{base,CH}\right)\right)}$$

$$F_j = \sum_{t_j}^{budbreak} \frac{1}{1+\exp\left(c\left(T_{aver\_i,j}-T_{base,F}\right)\right)}$$

where *a, b, c* are empirical parameters, $T_{aver\_i,j}$ denotes the daily average temperature in a year *j* and on a day *i*, $T_{base,CH}$ and $T_{base,F}$ are base temperature parameters regarding the chilling and forcing effects, respectively, t_j is the point of time when the required chilling effect (CH_{crit}) is fulfilled in a year *j*. At this point the model indicates the end of the endodormancy and the heat accumulation of F_j sets off. Budburst date is highlighted by the model when the required effective heat sum GDD_{u_crit} is reached.

We formulate the function of chilling effect f_{CH} and forcing effect $f_F(x)$ as:

$$f_{CH}(x) = \frac{1}{1+\exp\left(a\left(x-T_{bázis,HiH}\right)^2 + b\left(x-T_{bázis,HiH}\right)\right)}, \text{ and } f_F(x) = \frac{1}{1+\exp\left(c\left(x-T_{bázis,HöH}\right)\right)}$$

(*x* denotes the daily average temperature).

The range of the chilling and forcing functions is the interval]0,1[. The shape of the chilling effect function (f_{CH}) is a curve with a peak at the point where the chilling effect is optimal; its maximum value is $x = \frac{-b}{2a} + T_{base,CH}$ in Celsius degree and limits of zero as tending to positive or negative infinity.

The forcing function f_F has a sigmoid type curve, monotonous increasing, limits of one tending to positive infinity and limits of zero tending to negative infinity, it has an inflexible point at point $x = T_{base,F}$ (Fig. 1).

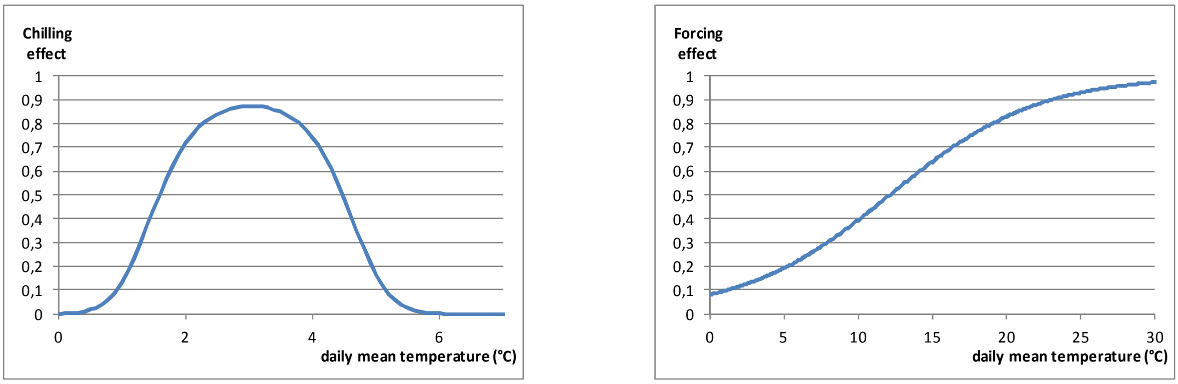

Figure 1. *A Chilling and forcing effect characteristic curves*

In *Figure 2* we can see the chilling and forcing effect accumulation process in a randomly chosen year. The horizontal lines are for the chilling and forcing accumulation criteria CH_{crit} and GDD_{u_crit}, respectively. The vertical lines are for the model predicted date of dormancy break and date of budburst, respectively.

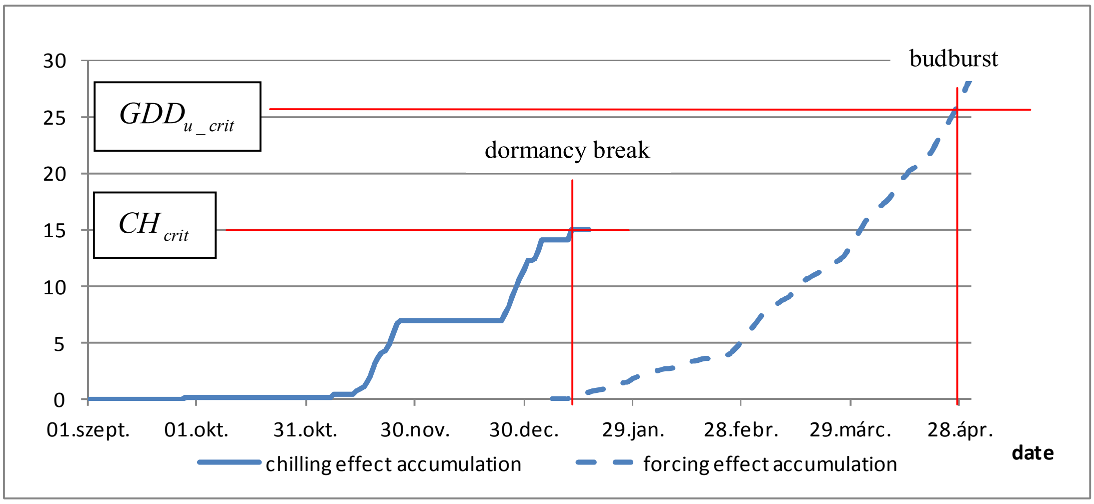

Figure 2. *Chilling and forcing effect accumulation during the dormancy and after the dormancy break in an arbitrary chosen year. At the point of time when the required chilling effect is fulfilled, the model indicates the end of the endodormancy and heat accumulation sets off. Budburst date is highlighted by the model when the required effective heat sum is reached.*

The available dataset was split into two parts: data of 10 years were used for calibration while the remaining ones for validation. We minimized the root mean square error (RMSE) with an innovative genetic algorithm (GA technology) by optimization of seven parameters (a, b, c, $T_{base,CH}$, $T_{base,\ F}$, CH_{crit} *and* GDD_{u_crit}) together. The advantage of this method that it does not get stuck at local solutions, but instead, looks at the entire range of possible solutions. It enables us to find the global optimal solution instead of a local extreme value (Weise, 2009). After the calibration and validation the model was run with the output of the regional climate model RegCM 3.1 so that we get estimations of the expected budburst date for three time intervals: 1961-1990 as reference period, together with 2021-2050 and 2071-2100.
We compared the results with one way ANOVA.

4. *Results and discussion*

4.1 Indicator analysis

Significant growth of almost all temperature and extreme indicators can be detected between 1977 and 2003 (Table 1.). Precipitation indicators, however, have not changed significantly (Table 2.). We also estimated the future changes with the help of regional climate model RegCM 3.1: we got significant higher average temperature indicator values, though the minimum temperature average values are expected to decrease till the end of the 21st century.

Table 1 Temperature and extreme indicators observed at K-puszta between 1977 and 2003, in the reference period of regional climate model RegCM 3.1 (1961-1990) as well as in time intervals 2021-2050 and 2071-2100

Temperature and extreme indicators	1977-2003	1977-2003	1961-1990	2021-2050	2071-2100
	slope	average	average	average	average
Huglin-index (HI) [°C]	0.73***	2193 a	1815 b	2012 c	2462 d
Winkler-index (WI) [°C]	0.76***	1709 a	1255 b	1439 c	1879 d
Biologically Effective Day Degrees (BEDD) [°C]	0.68***	1333 c	1073 a	1203 b	1394 c
Mean July Temperature (MJuT) [°C]	0.52***	23 b	20 a	21 a	24 c
Mean January Temperature (MJaT) [°C]	0.26ns	-1 a	1.5 b	3 b	4 c
Growing Season Average Temperature (GSAT)[°C]	0.73***	18 c	15 a	16 b	19 d
Growing Season Average Maximum Temperature (GSATX) [°C]	0.69***	23 b	21 a	22 ab	25 c
Growing Season Average Minimum Temperature (GSATN)[°C]	0.32ns	11 a	11 a	12 b	13 c
Harvest Maximum Temperature (HMX), [°C]	0.62***	26 b	24 a	25 ab	28 c
Winter Minimum Temperature (WMN), [°C]	0.10ns	-17 a	-11 b	-8 c	-5 d
Ripening Average Temperature (RAT) [°C]	0.62***	17 b	15 a	16 a	18 b
Cool Night Index (CNI) [°C]	0.06ns	10 a	11 b	11 a	14 b
Continentality (CO) [°C]	0.11ns	24 b	19 a	18 a	20 a
Number of Extremely Hot Days (NEHD) [day]	0.50**	4 a	3 a	7 a	19 b
Number of Hot Days (NHD) [day]	0.72***	29 a	21 a	27 a	53 b
Number of Summer Days (NSD) [day]	0.65***	85 b	59 a	72 b	102 d
Number of Frost Days (NFD) [day]	0.30ns	62 d	47 c	34 b	22 a
Number of Icy Days (NID) [day]	0.05ns	8 c	3 b	1 ab	0 a
Vitis Frost Risk Days (F8D) [day]	-0.05ns	12c	4b	2ab	0a
Vitis Serious Frost Risk Days (FS15D) [day]	-0.09ns	2b	0ab	0a	0a
Number of Spring Frost Days (NSFD) [day]	0.41*	15 b	13 b	8 a	5 a
Number of Fall Frost Days (NFFD) [day]	0.05ns	15 c	9 b	6 b	2 a
Spring Frost Days of Gladstones (SFIGlad) [ºC]	0.69***	13 b	11 a	12 ab	11 a
Spring Frost Days of Wolf-Boyer (SFIWB) [ºC]	0.53**	5.82 c	4.59 a	5.11 b	4.81 ab
Diurnal Range (DR) [°C]	0.58**	25 a	25 a	26 ab	27 b
Mean April Daily Range (MADR) [°C]	0.53**	12 c	9 a	10 b	10 ab
Mean Harvest Daily Range (MHDR) [°C]	0.24ns	12 c	10 a	10 ab	11 b
Sum of Daily Temperature Excursion (ET) [°C]	0.48*	1919 c	1602 a	1642 a	1738 b
Riberau-Gayon-Peynaud Index (RGP) [ºC]	0.58ns	2032 c	1549 a	1791 b	2287 d

*$p<0.05$; **$p<0.01$; $p<0.001$ ns: not significant

The average annual precipitation, the winter precipitation and the number of growing season rainy days are expected to increase, compared to the observed time interval, however, the summer rainfall is expected to decrease (Table 2.).

Table 2 Precipitation indicators observed at K-puszta between 1977 and 2003, in the reference period of regional climate model RegCM 3.1 (1961-1990) as well as in time intervals 2021-2050 and 2071-2100

Precipitation indicators	1977-2003	1977-2003	1961-1990	2021-2050	2071-2100
	slope	average	average	average	average
Annual Rainfall. (AR) [mm]	0.22ns	474 a	628 b	583 b	614 b
Summer Rainfall. (SR) [mm]	0.13ns	108 c	96 ab	92 ab	73 a
Winter Precipitation. (WR) [mm]	0.01ns	160 a	275 b	236 b	270 b
Growing Season Precipitation. (GSR) [mm]	0.28ns	317 a	346 a	344 a	339 a
Bloom Period Precipitation. (BPR) [mm]	0.04ns	61 a	48 a	55 a	46 a
Ripening Period Precipitation. (RPR) [mm]	0.30ns	79 a	94 a	107 a	106 a
Number of Growing Season Rain Days. (GSRD) [nap]	0.14ns	60 a	92 d	84 c	75 b

*p<0.05; **p<0.01; p<0.001 ns: not significant

4.2 Critical comparison of growing season calculation methods

Comparing the traditional and the interpolation growing season calculation methods with Student's t-test we have verified significant differences. The interpolation method results earlier growing season start, systematically. Nevertheless, similar systematic difference cannot be detected, concerning the end of growing season calculation. The interpolation method is proved to be more precise than the traditional method, however, this method is preferably suggested for terroir comparisons, only, emphasized the advantage of this method, namely, that it is simple and widely applicable. Nevertheless, because of the increasing frequent extreme weather events caused by climate change, besides the interpolation method, the growing season calculation method based on phenological models becomes more and more reasonable.

4.3 Growing Degree Days Model (GDD)

Using the budburst data observed in Helvécia (2000-2004), we estimated the budburst dates of different varieties and their clones with the simple Growing Degree Days model. Minimizing the error of estimation, we optimized the lower base temperature and the starting day of heat sum accumulation. According to our calculations based on phenological data from Helvécia, the optimal lower base temperature was 6 °C, the optimal starting date was the 41st Julian day of the year which means that the statistically calculated date of the end of the endodormancy is the 10th of February. The average error of the absolute differences between the observed and predicted dates was 2.07 days, the maximal error was 5 days.

We used the simple Growing Degree Days model started from budburst and completed with upper base temperature for the estimation of full bloom data. Thus we determined the optimal lower base temperature at 11 °C and the upper base temperature at 26 °C. Analysing the differences between the observed and estimated dates, we can state that the full bloom dates of the varieties Chardonnay and Pinot gris were the most difficult to predict. The absolute error of the most varieties moves around the average (2.12 days), which indicates the high stability of the model. The minimal error of the model was obtained in the case of Chardonnay 96 and Riesling 378 clones (1.2 days on average). The average absolute error was 1.81 days and the maximal error was 6 days.

The model was run with the output of the regional climate model RegCM 3.1, too, in order to outline the expected phenological schedule in the near future (2021-2050). In Helvécia, the model estimated the beginning of budburst five days earlier, the beginning of full bloom five days later on average, in the examined time interval. Our results correspond to the results due to Dunne et al., (2003), Arft et al., (1999) and Price and Waser, (1998), who documented in many cases the acceleration of growing and flowering of plants in the same phases, especially in the case of early spring flowering varieties. In the case of varieties bursting later in spring, they have reported that these plants either do not react on warming at all (Dunne et al., 2003), or – even having earlier budburst – they have their flowering late, especially if the temperature rises above their physiological tolerance (Sherry, et al., 2007).

4.4 The Unified model (UM)

Based on the phenology data measured in Kecskemét-Katonatelep between 1977 and 2003, we developed a model that takes the information of the chilling effect into account (Chuine, 2000) and we compared it with the simple Growing Degree Days model run with the same data series. The optimized parameters of the models can be found in *Table 3*.

We judged the UM as a better tool for the estimation of budburst, as the RMSEs, the mean and the absolute error values are considerably smaller in case of this model (*Table 4*). The explained variances (R^2) are significant for both models ($p<0.05$), the ones of Unified Models are mostly significantly not lower (Table 5).

Table 3 The optimized parameters of Growing Degree Days Model and the Unified Model for the data series measured for five varieties in Kecskemét and (1977-2003)

Variety	Growing Degree Days Model		Unified Model			
			Chilling effect		Forcing effect	
Kékfrankos	starting Julian day	47	a	1,00	c	-0.20
	$T_{lowerbase}$ (°C)	4.54	b	2,65		
	$T_{upperbase}$ (°C)	18.4	$T_{base,CH}$ (°C)	4,58	$\mathrm{T}_{\mathrm{base,F}}$ (°C)	12.11
	GDD_{u_crit} (°C)	260	CH_{crit}	14	GDD_{u_crit}	25
Hárslevelű	starting Julian day	41	a	1,00	c	-0.26
	$T_{lowerbase}$ (°C)	4.54	b	2,65		
	$T_{upperbase}$ (°C)	19.17	$T_{base,CH}$ (°C)	4,48	$\mathrm{T}_{\mathrm{base,F}}$ (°C)	12.50
	GDD_{u_crit} (°C)	299	CH_{crit}	8,82	GDD_{u_crit}	24.66
Pinot gris	starting Julian day	47	a	0,92	c	-0.20
	$T_{lowerbase}$ (°C)	4.54	b	2,65		
	$T_{upperbase}$ (°C)	18.4	$T_{base,CH}$ (°C)	4,48	$\mathrm{T}_{\mathrm{base,F}}$ (°C)	12.15
	GDD_{u_krit} (°C)	260	CH_{crit}	14,5	GDD_{u_crit}	25.25
Riesling	starting Julian day	41	a	1,00	c	-0.26
	$T_{lowerbase}$ (°C)	4.54	b	2,65		
	$T_{upperbase}$ (°C)	18.3	$T_{base,CH}$ (°C)	4,10	$\mathrm{T}_{\mathrm{base,F}}$ (°C)	12.50
	GDD_{u_crit} (°C)	291	CH_{crit}	8,81	GDD_{u_crit}	24.67
Generosa	starting Julian day	41	a	0,85	c	-0.20
	$T_{lowerbase}$ (°C)	4.40	b	2,65		
	$T_{upperbase}$ (°C)	19.18	$T_{base,CH}$ (°C)	4,00	$\mathrm{T}_{\mathrm{base,F}}$ (°C)	12.39
	GDD_{u_crit} (°C)	306.51	CH_{crit}	8,82	GDD_{u_crit}	24.67

Table 4. Root mean square errors (RMSE [days]) and mean absolute errors ([days]) of the Growing Degree Days Model (DDM) and Unified Model (UM) for the calibrated and validated data set measured for five varieties in Kecskemét and (1977-2003)

	Error (RMSE [day])				Average absolute error [day]			
	calibrated		validated		calibrated		validated	
	DDM	UM	DDM	UM	DDM	UM	DDM	UM
Kékfrankos	3.74	2.40	5.53	4.96	2.89	2.00	3.89	3.83
Hárslevelű	3.13	4.56	5.65	5.56	2.67	4.00	3.83	4.00
Pinot gris	3.92	3.91	4.97	4.81	3.00	3.30	3.70	4.10
Riesling	4.43	3.82	3.87	3.97	2.60	3.20	2.32	3.26
Generosa	3.23	4.50	5.53	5.18	2.44	3.78	4.32	4.47

Table 5 The calibrated and validated values of maximum absolute errors ([days]) and the explained variance (R^2) for the data series measured for five varieties in Kecskemét and (1977-2003)

	Maximum absolute error [day]				R^2			
	calibrated		validated		calibrated		validated	
	DDM	UM	DDM	UM	DDM	UM	DDM	UM
Kékfrankos	8	4	13	10	0.86***	0.94***	0.64***	0.74***
Hárslevelű	7	8	12	9	0.89***	0.75*	0.53*	0.61**
Pinot gris	8	7	15	9	0.85**	0.88***	0.71***	0.69***
Riesling	10	7	10	7	0.68*	0.87**	0.78***	0.75***
Generosa	6	7	11	8	0.92***	0.79**	0.64**	0.67**

*** $p<0.001$ **$p<0.01$ * $p<0.05$ +$p<0.1$

Table 6 The averages of budburst dates and results of ANOVA comparisons of the five varieties obtained by the GDD and Unified models based on the observed data with the significance of paired Student's t-test

Variety	Average [Julian day] Growing Degree days model		Average [Julian day] Unified model	
Kékfrankos	1977-2003 p = 0.45	116.70 b	1977-2003 p = 0.83	117.41 b
	1961-1990	123.10 c	1961-1990	113.33 b
	2021-2050	111.00 ab	2021-2050	104.90 a
	2071-2100	105.53 a	2071-2100	102.90 a
Pinot gris	1977-2003 p = 0.15	116.37 b	1977-2003 p = 0.29	116.33 b
	1961-1990	123.1 c	1961-1990	113.33 b
	2021-2050	111.0 ab	2021-2050	104.90 a
	2071-2100	105.5 a	2071-2100	102.90 a
Hárslevelű	1977-2003 p = 0.92	119.15 b	1977-2003 p = 0.97	119.07 b
	1961-1990	126.90 c	1961-1990	121.60 b
	2021-2050	114.33 ab	2021-2050	109.83 a
	2071-2100	108.53 a	2071-2100	103.47 a
Riesling	1977-2003 p = 0.78	118.44 b	1977-2003 p = 0.40	119.26 b
	1961-1990	126.13 c	1961-1990	122.53 b
	2021-2050	113.77 ab	2021-2050	110.33 a
	2071-2100	107.97 a	2071-2100	105.37 a
Generosa	1977-2003 p = 0.60	119.26 b	1977-2003 p = 0.97	117.89 b
	1961-1990	126.90 c	1961-1990	121.10 b
	2021-2050	114.50 ab	2021-2050	108.83 a
	2071-2100	108.77 a	2071-2100	104.62 a

The simple GDD model estimates the beginning of budburst of the five varieties about 10-11 days earlier at the and of the century, compared to the observed time period. The UM model predicts earlier budburst starts for all the five varieties in the last 30 years of the 21st century, compared to the observed time period: the average shift is 14.5 days for Kékfrankos variety, 13.5 days for Pinot gris, 15.5 days for Hárslevelű, 17 days for Riesling and 13 days for Generosa (*Table 6*).

Comparing the relative frequency histograms of the estimated budburst dates, based on the observed, together with the regional climate model RegCM3.1 data series with three time intervals, we can see that the standard deviation of budburst dates increases. It indicates that it is expected a significantly greater fluctuation between the years. The probability of very early and very late budburst dates are due to increase. The reason of early budburst can be the short, but still appropriate cold winter temperature, while the late budburst can be the result of a very mild winter when, for grapevine, the necessary chilling units for the endodormancy break accumulates only very slowly.

According to the Unified Model, the average budburst date of the five varieties is the 118th. Julian day both in the observed (1977-2003) and in the reference period (1961-1990) which means that there is no significant difference. The average budburst dates of time intervals 2021-2050 and 2071-2100 (108th and 104th Julian day) do not differ significantly from each other, either, however, they both differ significantly from both the dates of the observed time period and the reference period ($p<0.001$).

Besides the shift of budburst dates to earlier points of time, the range of budburst dates is also expected to widen which corresponds to the results of Khanduri et al. (2008). This means that, as a consequence of the expected extreme weather events, we should reckon with the occurrence of both extremely early and extremely late budburst dates.

Apart from the temperature-controlled effects discussed in this study, many other special weather and climate factors (e.g. solar radiation, heat accumulation, temperature extremes, precipitation, wind, extreme weather events such as hail, frost, storm, drought, flood, etc.) influence the development of grapevine and thus the quality of the end product, i.e. wine. However, the length of the vegetation period together with temperature are such critical factors that determine dominatively the process of grapevine ripening, the formation of sugar, acid and pigment content, and, consequently, the quality and character of wine.

According to the prognoses, future climate warming has probably several advantageous and disadvantageous effects at continental and regional levels, too (Jones, 2007). On the one hand, new regions will appear as to be appropriate for vine growing, and the other hand, meantime the changes force the growers and oenologists to face serious challenges. The degree and character of climate change will induce numerous different changes in oenology sector, including further changes in phenology schedule of *Vitis vinifera*, in composition of grapevine and wine which can cause unbalanced production in certain years and can endanger the regular harmonic flavours. The risk of the change of region-specific composition of the cultivated varieties motivates the growers to re-evaluate the grapevine growing regions and to decide deliberately about the necessary modifications.

4.5 New scientific results

1. As a results of the analysis of 36 climate indicators calculated from the daily temperature and precipitation data measured between 1977 and 2003 in Kecskemét, it was shown that during the 27 years significant increase of the following indicators can be detected: Huglin and Winkler indices, July Mean Temperature, Growing Season Average and Maximum Temperature, Ripening Average Temperature, Harvest Maximum Temperature, the Number of Hot and Summer Days and Gladstones's Spring Frost Days. According to the estimations of the regional climate model RegCM 3.1 for the reference period 1961-1990 and for the future time intervals 2021-2050 and 2071-2100, the values of some of the indicators are expected to increase even further after 2021. Meanwhile the yearly amount of precipitation is not expected to change significantly, summer and vegetation period precipitation are expected to decrease and winter precipitation is expected to increase after 2050 in Kecskemét.
2. Compared the vegetation period calculation methods generally used in the literature, it was shown that the one based on phenological models becomes more and more reasonable since the increasing frequent extreme weather events caused by climate change make the traditional methods inaccurate.
3. With a simple Growing Degree Days model the budburst start observation data of 6 *Vitis vinifera* varieties and their clones measured during five years in Helvécia were appriximated. Instead of following the routine usually published in the literature, beyond the base temperature, we optimized the starting date of heat sum accumulation as well. For the calibration results obtained for Helvécia vineyard observations we got 6 °C as the base temperature and the 10th February as the optimal starting day of the heat accumulation for the budburst date estimation. For the estimation of full bloom start, both lower and upper base temperature were fitted in the model and the optimal values were obtained as 11 °C and 26 °C.
4. Based on the phenology data measured in Kecskemét-Katonatelep between 1977 and 2003, besides the simple Growing Degree Days model, we developed a model that takes the information of the chilling effect into account and we compared it with the simple Growing Degree Days model run with the same data series. The optimal parameters of the simple Growing Degree Days model were calibrated for this data set, too. We judged the UM as a better tool for the estimation of budburst of each axamined variety, as the RMSEs, the mean and the absolute error values are considerably smaller in case of this model. The explained variances (R2) are significant for both models, the ones of Unified Models are mostly significantly higher or not significantly lower.
5. Besides validation, the relevancy and accuracy of the data measured in Kecskemét made the calibration possible, so we could run the models also with the outputs of the regional climate model RegCM 3.1 with reference period 1961-1990 and prediction time intervals 2021-2050 and 2071-2100. Based on the results, we can state that after 2020 the budburst of each variety is expected to be shifted to earlier dates in Kecskemét, moreover, after 2070, even the range of budburst dates is expected to broaden. The simple GDD model estimates the beginning of budburst of the five varieties about 10-11 days earlier at the and of the century, compared to the observed time period. The UM model predicts earlier budburst starts for all the five varieties in the last 30 years of the 21st century, compared to the observed time period: the average shift is 14.5 days for Kékfrankos variety, 13.5 days for Pinot gris, 15.5 days for Hárslevelű, 17 days for Riesling and 13 days for Generosa.

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