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Performance of several models for predicting budburst date of grapevine (*Vitis vinifera* L.)

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Abstract The budburst stage is a key phenological stage for grapevine (*Vitis vinifera* L.), with large site and cultivar variability. The objective of the present work was to provide a reliable agro-meteorological model for simulating grapevine budburst occurrence all over France. The study was conducted using data from ten cultivars of grapevine (Cabernet Sauvignon, Chasselas, Chardonnay, Grenache, Merlot, Pinot Noir, Riesling, Sauvignon, Syrah, Ugni Blanc) and five locations (Bordeaux, Colmar, Angers, Montpellier, Epernay). First, we tested two commonly used models that do not take into account dormancy: growing degree days with a base temperature of 10°C (GDD_{10}), and Riou's model (RIOU). The errors of predictions of these models ranged between 9 and 21 days. Second, a new model (BRIN) was studied relying on well-known formalisms for orchard trees and taking into account the dormancy period. The BRIN model showed better performance in predicting budburst date than previous grapevine models. Analysis of the components of BRIN formalisms (calculation of dormancy, use of hourly temperatures, base temperature) explained the better performances obtained with the BRIN model. Base temperature was the main driver, while dormancy period was not significant in simulating budburst date. For each cultivar, we provide the parameter estimates that showed the best performance for both the BRIN model and the GDD model with a base temperature of 5°C.

Keywords *Vitis vinifera* L. · Budburst · Dormancy · Temperature response · Base temperature

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Introduction

Budburst in the grapevine (*Vitis vinifera* L.) defines the beginning of the growth cycle. Any delay in this stage impacts the whole cycle. Therefore, calculating budburst date is a major challenge for managing vineyards. Hence, budburst is critical in the choice of cultivar, which is partly characterised by its precocity, and in vineyard establishment. This, for example, is the case of northerly vineyards liable to spring frosts (Moncur et al. 1989). In a situation of climate change, calculation of the date of budburst of the grapevine has real predictive value as an indicator of earliness, and thus of the adaptability of cultivars (McIntyre et al. 1982; Schultz 2000; Jones et al. 2005; García de Cortázar-Atauri 2006; Webb et al. 2007). Budburst is also the initial stage of growth of the plant in agronomic models, whether they be specific to grapevine (Gutierrez et al. 1985; Williams et al. 1985a, b; Wermelinger et al. 1991; Bindi et al. 1997a, b) or more generic (Brisson et al. 2003, García de Cortázar-Atauri 2006). However, spatial and temporal robustness is needed to give more certainty to extrapolations of global change scenarios (Chuine 2000).

Several scales of phenological observation for the grapevine are available (Jones 2003), but the most frequently used are Baggiolini (1952), and Eichhorn and Lorenz (1977) modified by Coombe (1995) (Table 1). Galet (1976) defined budburst as the stage corresponding to 50% of the buds of a given grapevine having burst. He also explained the

Table 1 Vineyard budburst stages defined by the most commonly used phenological scales

Phenological scale	Stages
Baggiolini (1952)	B. Budswell or Woolly bud
	C. Green Tip
Eichhorn and Lorenz (1977) modified by Coombe (1995)	2. Budswell
	3. Wool stage, brown wool stage clearly visible
	4. Green tip, first leaf tissue visible (Budburst or Bud Break)
	5. Bud breaking, first green of shoot visible

difficulties in agreeing on a common stage, which can lead to observational errors in the range of several days.

Phenological models assume that budburst is regulated by temperature and is induced by a period with chilling temperatures (dormancy) followed by a period with forcing temperatures (post-dormancy) (for a review see Chuine et al. 2003). Dormancy corresponds to an inactivity of the meristems placed in conditions in which they would normally be active apart from any correlative inhibition in a favourable environment; it is a period of reduced growth independently of the ecological conditions (Lang et al. 1987). Sarvas (1974) separates dormancy in two periods: the "rest" period is defined as the period when buds are dormant due to physiological conditions (endodormancy), and the "quiescence" period is when buds remain dormant due to unfavourable environmental conditions (ecodormancy). However, "operational" models do not consider the rest period to simulate budburst of flowering (Cesaraccio et al. 2004).

For grapevine, most research studies on grapevine dormancy were conducted some considerable time ago under controlled conditions (Alleweldt 1963; Pouget 1963; Nigond 1967). Such studies highlighted three characteristic periods in the conditions of temperate and Mediterranean climates: (1) a pre-dormancy period that takes place in summer when plants acquire their dormancy capacity; (2) breaking of dormancy, which occurs during winter (Alleweldt 1963; Pouget 1963; Nigond 1967); and (3) the post-dormancy period, during which buds do not yet develop because of unfavourable weather conditions. Although it is possible to identify these three phases in controlled conditions (Pouget 1963; Bidabe 1965a, b; Nigond 1967; Richardson et al. 1974; Gilreath and Buchanan 1981; Shaultout and Unrath 1983; Bernstein 1984), no simple non-destructive field method is currently available. For grapevine, Pouget (1972) and Bernstein (1984) showed the importance of exposure of the buds to temperatures below 10°C during a certain period and its effect on the rate of dormancy breaking and budburst. This response to temperature for orchard trees is known as "Cold Actions" (Bidabe 1965a, b) or "Chilling requirements" (Richardson et al. 1974; Chuine 2000; De Melo-Abreu et al. 2004; Cesaraccio et al. 2004; Crepinsek et al. 2006; Rea and Eccel 2006).

Several authors have developed models for predicting budburst date of grapevine. McIntyre et al. (1982) classified 114 cultivars simply using the mean number of days between 1 January and budburst date. Most other models use air temperature as an input variable. The response function to temperature is either linear (Williams et al. 1985a, b; Moncur et al. 1989; Wermelinger et al. 1991; Oliveira 1998) or logarithmic (Pouget 1968, 1988; Riou 1994). Daily or hourly responses (also called forcing units) are accumulated from a starting date and up to a critical threshold. These formalisms are often used in predictive studies (Gutierrez et al. 1985; Williams et al. 1985a, b; Moncur et al. 1989; Riou 1994; Bindi et al. 1997a, b; Oliveira 1998; Brisson et al. 2003). However, these models often need to be adapted to local conditions (Pouget 1988). Depending on the authors, accumulation of forcing units begins on 1 January (Gutierrez et al. 1985; Moncur et al. 1989; Wermelinger et al. 1991; Riou 1994; Bindi et al. 1997a, b; Oliveira 1998) or later (Williams et al. 1985a, b), implicitly assuming that dormancy was already broken and that the preceding pre-dormancy period was completed.

Other models accounting for dormancy have been developed for predicting budburst and flowering dates of orchard and forest species (Bidabe 1965a, b; Richardson et al., 1974, 1975; Chuine 2000). However, these models require more parameters than those mentioned earlier. Finally, it has been shown that soil texture and soil temperature may also have an impact on grapevine phenology (Jones 2003).

The aim of this work is to propose a model able to predict accurately budburst stage of grapevine anywhere in France. It should thus be spatially and temporally robust and should apply over a range of cultivars of French vineyards. To achieve this goal, we first tested the models described in the literature, and second developed a new model taking account of dormancy. This work is based on phenological data collected in France.

Materials and methods

The database

We used the phenological database PHENOCLIM produced by the French National Agronomic Research Institute (INRA) (Chuine and Seguin 2008), which brings together series of observations for orchard trees and grapevines and associates them with temperature records from the appropriate weather stations. We used grapevine budburst dates over the period 1970 to 2002 (Table 2), collected in five regions (Anjou, Champagne, Languedoc, Bordeaux, Alsace), managed mostly by INRA, and one by the Comité Interprofessionnel des Vins de Champagne (CIVC). These observations were obtained by individuals at research stations trained to observe the different phenological stages (budburst, flowering, veraison). The PHENOCLIM database retrieves data from old and current experiments carried out in the research stations. This regional diversity allows us to cover the climatic variability of French vineyards. More precisely, the observatories are located at Angers (47° 7′N, 0° 7′E; 59°m a.s.l.; oceanic climate), Epernay (49° 3′N, 3° 57′E; 71°m a.s.l.; transition oceanic climate), Montpellier (43° 21′N, 3° 31′E; 5°m a.s.l.; Mediterranean climate), Bordeaux (44° 47′N, 0° 34′E; 25°m a.s.l.; oceanic climate with maritime tendency) and Colmar (48° 3′N, 7° 19′E; 193°m a.s.l.; continental climate). Each experimental site is equipped with a standard weather station (WMO protocol) that collects the data needed by our study: daily maximum and minimum temperatures.

The cultivars selected for the study span the scale of precocity according to the classification of McIntyre et al. (1982). Classification by earliness of the varieties present in the PHENOCLIM database using all the observations from different sites was: Chardonnay (1), Chasselas (2), Pinot Noir (3), Merlot (4), Riesling (5), Syrah (6), Sauvignon (7), Cabernet Sauvignon (8), Grenache (9) and Ugni blanc (10). Comparison of this classification with the classification of McIntyre et al. (1982) of 114 cultivars demonstrates a convergence for very early and very late cultivars. The mean values of budburst date for all the varieties were in accordance with data presented in Jones et al. (2005) (data not shown). In addition, a latitudinal effect in budburst precocity is observed: Montpellier is the earliest station, followed by Bordeaux, Champagne, Angers and Colmar. Note that, although it lies to the north of Angers and Colmar, Champagne displays before these two stations because Chardonnay and Pinot Noir (varieties present in this region) are early varieties.

The budburst date used corresponds to stage C according to Baggiolini's scale (stage 4 on Coombe's scale).

Phenological models

Growing degree day model

The growing degree day model (GDD; Eq. 1) is based on the classical thermal time concept (Bonhomme 2000), i.e. cumulative daily (n) mean temperatures minus a base (or threshold) temperature (T_0) (assumed constant), starting from 1 January. Budburst occurs when a critical sum of degree-days (G) is reached:

$$G_c = \sum_{n=1}^{N_{bb}} A_c(n) \quad (1)$$
$$with \quad A_c(n) = \max(T(n) - T_0, 0)$$

Table 2 Summary of the database used in our study: years and location (from PHENOCLIM database)

Site Varieties	Angers	Bordeaux	Epernay	Colmar	Montpellier	Total data
Cabernet Sauvignon	1982, 1984–1990	1970–1986, 1988, 1995–2002	*	1976–1985, 1988–1990	1973–1976, 1988–1997, 1999–2002	63
Chardonnay	*	1970–2002	1998–2002	1976–1985, 1988–1990	1974–1976, 1995–2002	60
Chasselas	1982, 1984–1986, 1990	1970–2002	*	1976–1985, 1988–1994 1996–2001	1972–2002	89
Grenache	1982, 1984–1986, 1990	*	*	1977–1985, 1988–1990	1978–1986, 1988 – 2002	40
Merlot	*	1970–1982, 1984–2002	*	1976–1985, 1987–1990	1981–1984, 1995–2002	54
Pinot Noir	*	1970–1982, 1984–2002	1998–2002	1976–1985, 1988–1990, 1992–1994 1996–2001	1973, 1988–2002	72
Riesling	1982–1986, 1990	1970–1982, 1984–2002	*	1976–1985, 1988–1994 1996 – 2001	1974–1976, 1989, 1996	64
Sauvignon	1982, 1984–1986, 1990	1970–1982, 1984–2002	*	*	1972–1974, 1978 –2002	63
Syrah	1982, 1984–1986, 1990	1970–1982, 1984–2002	*	1976–1985, 1987–1990	1988–2002	64
Ugni Blanc	1982, 1984–1986, 1990	1970–1982, 1984–2002	*	1976–1985, 1987–1990	*	47

where $T(n)$ is the daily mean temperature, n is the day and N_{bb} is the date of budburst. A base temperature (T_0) of 10°C, generally accepted for grapevine (Winkler 1962; Williams et al. 1985a, b; Carbonneau et al. 1992) was used (GDD_{10}).

Riou's model

Riou (1994) proposed an improvement of the model of Pouget (1968, 1988): Riou's model (RIOU). This model is based on the sum of daily actions (A_c) of temperature, which differs from degree-days. It uses hourly temperatures calculated from the daily minimum and maximum temperatures [$T_n(n)$ and $T_x(n)$], assuming a sinusoidal response of temperature during the daytime and a parabolic response during the night (see Fig. 1). Daylength is calculated with the astronomical formulae of Sellers (1965). Budburst occurs when a critical sum (G_c) of daily actions A_c is reached (Eq. 2):

$$G_c = \sum_{n=1}^{N_{bb}} A_c(n)$$
$$with \quad A_c = \sum_{h=1}^{24} \left(e^{0.07T(h,n)} - 1.91e^{-0.126T(h,n)} \right) \tag{2}$$

with $T(h,n)$ the hourly temperature of day n at time h.

BRIN model

The BRIN model is derived from a combination of two models used for fruit trees (Liennard 2002; García de Cortázar-Atauri et al. 2005): the dormancy period is calculated using Bidabe's Cold Action model (Bidabe 1965a, b), and the post-dormancy period is calculated using sum of hourly temperatures (growing degree hours—GDH) obtained by the method of Richardson et al. (1974, 1975).

Budburst date (N_{bb}) occurs when a critical sum (G_c) of growing degree hours (A_c) is reached, starting from the breaking of dormancy (N_{db}) (Eq. 3).

$$G_c = \sum_{N_{db}}^{N_{bb}} A_c(n) \tag{3}$$

To calculate GDH, the hourly temperature of day n [$T(h, n)$] is estimated very simply by linear interpolation between $T_{nx}(n)$ and $T_n(n+1)$ by assuming a daylength of 12 h (Fig. 1) (Eqs. 4, 5).

$$\begin{aligned} &if\ h \leq 12 \quad then \quad T(h,n) = T_n(n) + h^* \left(\frac{T_x(n) - T_n(n)}{12} \right) \\ &if\ h > 12 \quad then \quad T(h,n) = T_x(n) - (h-12)^* \left(\frac{T_x(n) - T_n(n+1)}{12} \right) \end{aligned} \tag{4}$$

Two cardinal temperatures limit the function of the linear response: T_{0Bc} and T_{MBc}.

$$\begin{aligned} &A_c = \sum_{h=1}^{24} T(h,n) \\ &with \\ &if\ T(h,n) < T_{OBc} \quad then \quad T(h,n) = 0 \\ &if\ T_{OBc} < T(h,n) \leq T_{MBc} \quad then \quad T(h,n) = (h,n) - T_{OBc} \\ &if\ T(h,n) > T_{MBc} \quad then \quad T(h,n) = T_{MBc} - T_{OBc} \end{aligned} \tag{5}$$

We fixed T_{MBc}=25°C by referring to the work of Pouget (1968) and Moncur et al. (1989).

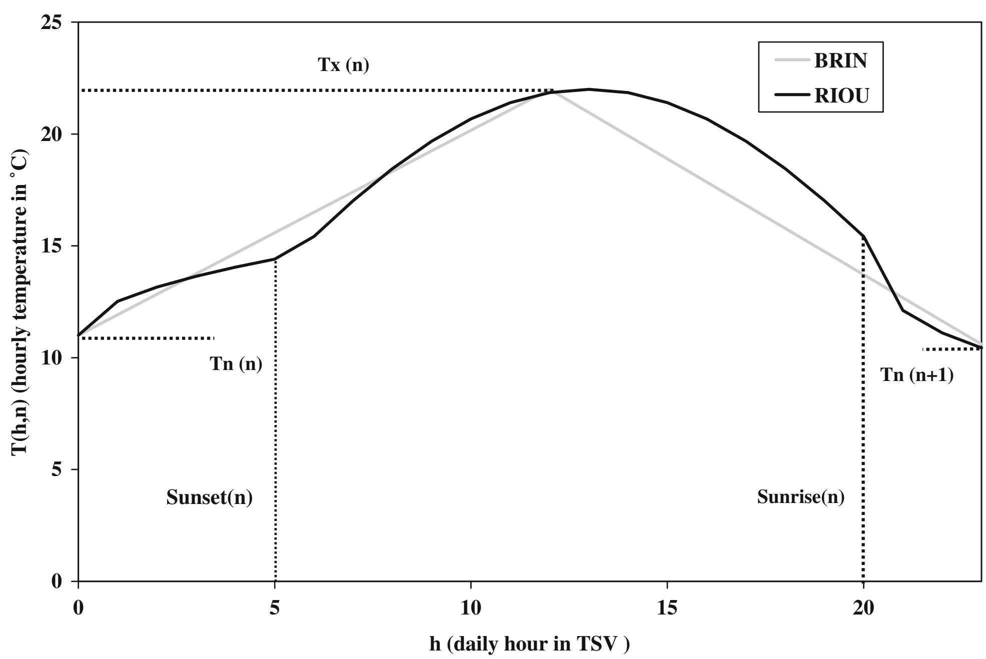

Fig. 1 Illustration of two methods of calculating the hourly temperature [$T(h,n)$] from daily minimum and maximum temperatures [$T_n(n)$, $T_x(n)$ and $T_n(n+1)$]. The method of Riou (1994) requires sunset and sunrise calculations (e.g. the example taken in 20 May in Montpellier, France). The method of BRIN consists of linear interpolation

Dormancy break occurs (N_{db}) when a critical amount of chilling units (C_U) is reached (C_c) (Eq. 6). Cold action is based on the Q_{10} concept: an arithmetic progression of 10°C in temperature causes an action with a geometric regression of ratio Q_{10}.

$$C_c = \sum_{n=1^{st}\ August}^{N_{db}} C_U \qquad (6)$$
$$with\ C_U = Q_{10c}^{\frac{-T_x(n)}{10}} + Q_{10c}^{\frac{-T_n(n)}{10}}$$

The accumulation of C_U started 1 August, based on numerous studies (Alleweldt 1963; Nigond 1967; Champagnol 1984; Pouget 1963, 1988) showing that buds become dormant around this date whatever the cultivar. Moreover, the hot summer period in the northern hemisphere has no influence on the accumulation.

Statistical criteria

One of the aims of this work is to obtain a single set of parameters that can be used over France for each cultivar, which leads us to ignore any possible regional peculiarities in our analysis and to partition our dataset purely by cultivar. Giving the heterogeneity of our dataset it is difficult to split it into two independent calibration and validation subsets. Consequently, we used cross validation as proposed by Wallach and Goffinet (1987) and Wallach (2006). Cross validation, applied to each cultivar, is based on partitioning the set of N data values into a sub-sample ($N-1$) on which parameters are calibrated, and 1 individual (i) on which the resulting model is evaluated. The root mean square error of prediction (RMSEP) was used to evaluate the performance of the models. This represents the quadratic distance between the observed (N_{bbo}) and the simulated (N_{bbs}) budburst dates (Eqs. 7, 8).

$$N_{bbs}(i) = f(X(i), \theta(i)) \qquad (7)$$

$$RMSEP = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(N_{bbs}(i) - N_{bbo}(i))^2} \qquad (8)$$

where f represents the model and $X(i)$ and $\theta(i)$ are the vectors of input data and parameters for observation i.

Quasi-Newton algorithm (Matlab software) using the least square cost function was used to fit the parameters. Finally, the definitive values of the parameters of each model were obtained by carrying out an optimisation on the entire sample. A summary of the different parameters to be calculated for each model is presented in Table 3. Parameters considered cultivar-dependent are indicated with "c" index.

One of the interests of the BRIN model was to introduce calculation of dormancy into budburst modelling. However, the number of parameters in the BRIN model may be disadvantageous for generalising its use (four parameters against one or two parameters for the other models) (Cesaraccio et al. 2004). A sensitivity analysis was thus carried out to reduce the number of cultivar-specific parameters (Q_{10c}, C_c, T_{0Bc}, G_{hc}). The BRIN model may present structural correlations between parameters, which should enable only two of the four cultivar-specific parameters to be retained: one for the dormancy phase and the other for the post-dormancy phase. We used bootstrapping (sampling with replacement) (Manly 1991) to create 30 different random samples of the dataset of each variety. The principle of bootstrapping is sampling with replacement, with the purpose of approximating what would happen if the population was resampled. For the analysis, the data populations were grouped by cultivar, and we then performed the optimisation of the four parameters on each sample of the 30 samples.

General procedure

We estimated the predictive quality of the GDD_{10} and RIOU models for grapevine as well as the cultivar parameter sets for each model using the method described above.

Next we compared the BRIN model performance to that of the best model found previously (hereafter called "the reference model"). Previously, we carried out a sensitivity analysis to reduce the number of cultivar parameters in the BRIN model (Q_{10c}, C_c, T_{0Bc}, G_{hc}): one for the dormancy phase and the other for the post-dormancy phase.

Table 3 List of parameters of the phenological models used. The *c* index means that the parameter is cultivar-dependent. *GDD* Growing degree days, *RIOU* Rious's model (1994), *BRIN* combination Bidabe-Richardson, *GDH* growing degree hours

Model	Parameter name	Parameter meaning
GDD	T_0	Base temperature
	G_c	Cumulative GDD between 1 January and bud break date
RIOU	G_c	Cumulative thermal daily actions between 1 January and bud break date
BRIN	Q_{10c}	Rate of the geometric progression of the thermal dormancy response
	C_c	Cumulative cold actions between 1 August and the dormancy break
	T_{0Bc}	Base temperature for post-dormancy period
	G_c	Cumulative GDH between dormancy break and bud break

Lastly, we sought an explanation of the performance of the BRIN model by testing several intermediate models by progressive introduction of specific features of BRIN compared with the reference model. These tests were done with an analysis of variance (ANOVA) on the predictive model error (RMSEP). To evaluate the cultivar effect, we fitted the best model obtained with this analysis on the whole dataset (all cultivars confounded) and we tested the cultivar effect with an *F* test.

Results and discussion

Test of the GDD_{10} and RIOU models

Although the performance of the GDD_{10} and RIOU models (Fig. 2) varies between cultivars, the GDD_{10} model showed the best results (9 days < RMSEP <18 days). Results obtained with the GDD_{10} and RIOU models thus showed poor performances when applied over a very large dataset, in agreement with Pouget (1988).

The parameters obtained for the RIOU model were compared to those given by the author. For the RIOU model (Table 4), an over-estimate of the parameter value G_c was noted, while the ranking of the cultivars in terms of precocity seems to be confirmed. This over-estimate may be explained because parameters of original Pouget's model were calculated for stage B of Baggioloni's scale and not for stage C as we have done. The GDD_{10} model showed the best results, but with very strong variability of parameters among cultivars, as stressed by other authors (Moncur et al. 1989; Jones 2003). Nevertheless, in view of its performance, the GDD_{10} model was used as the reference model for the rest of the study.

Table 4 Comparison between the G_c values of the RIOU model provided by the author (Riou 1994) and calculated in the present study

	G_c parameter	
	Present study	Riou (1994)
Chardonnay	53	38
Chasselas	61	47
Sauvignon	75	60
Merlot	61	56
Pinot Noir	61	51
Riesling	61	55
Ugni Blanc	65	64
Cabernet Sauvignon	80	72
Grenache	76	59
Syrah	67	53

Parameterisation and evaluation of the BRIN model

The distribution of parameters averaged over all cultivars is shown in Fig. 3. The statistics of the parameters (Table 5) show that parameters C_c and G_c have the highest coefficients of variation. Correlation coefficients between the parameters were not very high, but they were highly significant (Table 6). Therefore, the parameters Q_{10c} and T_{0Bc} were fixed for all cultivars (hereafter called Q_{10} and T_{0B}). Parameter Q_{10} was fixed to the mean value of its distribution, i.e. 2.17 (Table 5). To estimate T_{0B}, with Q_{10} fixed at 2.17, we tested seven values (0, 2, 4, 5, 6, 8 and 10). RMSEP varied from 10.96 (T_{0B}=6) to 11.27 (T_{0B}=10), with the second lowest RMSEP of 11.01(T_{0B}=8) and 11.02 (T_{0B}=5). We chose T_{0B}=5°C, because several authors have shown experimentally that the base temperature for bud-

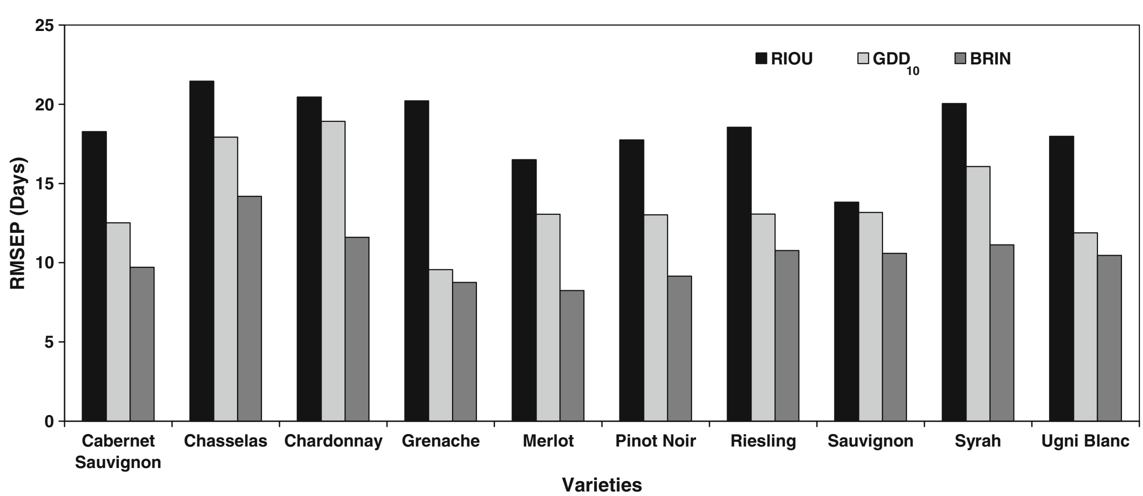

Fig. 2 Root mean square error of prediction (RMSEP) of the three grapevine models tested (RIOU, GDD_{10} and BRIN) for all varieties

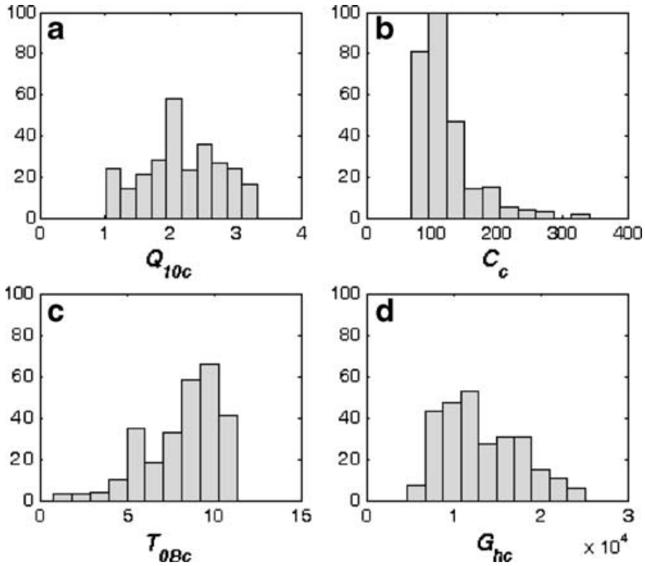

Fig. 3a–d Distribution of BRIN model parameter estimates (optimisation on 30 bootstrap samples per variety; 300 estimates per parameter in total). **a** Q_{10c}, **b** C_c, **c** T_{0Bc}, **d** G_{hc}

burst is around this value for several cultivars (Pouget 1968; Moncur et al. 1989). We fixed Q_{10} to 2.17 and T_{0B} to 5 and fitted parameters C_c and G_c for each cultivar. For all cultivars, the BRIN model provided better predictions than any other model tested in this study (RMSEP from 8 to 14 days) (Fig. 2) (Table 8).

Moreover, BRIN provides extra information, i.e. an estimate of the date of dormancy break. In this study, the date of dormancy break provided by the BRIN model occurs always before 1 January, which is consistent with the hypothesis of Pouget (1988) that dormancy is always broken by that date.

Performance analysis of the BRIN model

Differences between the BRIN and GDD_{10} models involve (1) using a varied dormancy break date as the start of the quiescence phase, instead of an arbitrary start on 1st January; (2) using hourly temperatures for the course of post-dormancy development instead of the mean daily temperature; and (3) using a base temperature of 5°C instead of 10°C. Those three differences can be regarded as three various options to set up a budburst phenological model. In addition, Jones (2003) showed that soil texture and soil temperature may have an impact in grapevine phenology. However, although the introduction of this information into phenology models could improve their performance, the difficulty and complexity of accessing instrumental measurements of these variables do not allow easy extrapolation and use in “operational” models. For this reason, soil temperature was not introduced in this study.

Consequently, we constructed eight intermediate models between the GDD_{10} model and the BRIN model by introducing these three options independently of each other (Fig. 4). Each model was characterised by a combination of the three options (dormancy vs no dormancy, hourly vs daily temperature, T_0 =5°C vs T_0=10°C). An analysis of variance of the predictive quality (RMSEP) of the models was performed to test the effect of the three factors. An analysis was performed for each cultivar and at the level of the whole species in order to test the cultivar factor. The results of ANOVAs (Table 7) showed that the “base temperature” factor (T_0=5°C vs T_0=10°C) was significant for all cultivars. On the contrary the “dormancy” factor was never significant, while the daily/hourly temperature factor was significant for four of the ten cultivars. The “cultivar” factor was highly significant, showing, unsurprisingly, that there cannot be any accurate “generic” parameterisation for the grapevine (*Vitis vinifera* L.) as noted by previous authors (McIntyre et al. 1982; Pouget 1988; Moncur et al. 1989; Riou 1994).

The accuracy of the predictions of the date of budburst was not affected when the dormancy break date was used as

Table 5 Mean, standard deviation and coefficient of variation of the four parameters of the BRIN model

	Q_{10c}	C_c	T_{0Bc}	G_{hc}
Mean	2.17	119	8.19	13,236
Standard deviation	0.59	43.99	2.13	4,520.10
Variation coefficient	0.27	0.37	0.26	0.34

Table 6 Linear correlations between the four parameters of the BRIN model

	Q_{10c}	C_c	T_{0Bc}	G_{hc}
Q_{10c}	1			
C_c	0.41 ***	1		
T_{0Bc}	−0.28 ***	−0.27 ***	1	
G_{hc}	−0.12 *	−0.46 ***	−0.17 **	1

* $P<0.05$, ** $P<0.01$, *** $P<0.001$

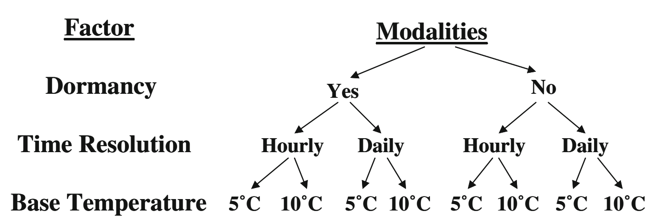

Fig. 4 Synthesis of the eight combinations used to construct intermediate models between GDD and BRIN: the left combination corresponds to BRIN and the right combination corresponds to GDD

Table 7 Results obtained from the analysis of variance (probability of the Fisher test) of the root mean square error prediction (RMSEP) of the different combinations of models tested, taking into account the three factors used to develop the model (Fig. 4) and the genetic factor. To test the cultivar factor, the GDD_5 model was used

Source of variation	Dormancy yes/no	T_0 5°C or 10°C	Daily/hourly	Variety
Cabernet Sauvignon	0.629	$<10^{-3}$ ***	0.013*	0.001**
Chasselas	0.707	0.006**	0.063*	0.024*
Chardonnay	0.304	0.004**	0.060*	0.009**
Grenache	0.270	0.003**	0.042*	$<10^{-3}$ ***
Merlot	0.220	$<10^{-3}$ ***	0.082*	$<10^{-3}$ ***
Pinot Noir	0.568	0.002**	0.044*	0.001**
Riesling	0.074*	0.006**	0.165	$<10^{-3}$ ***
Sauvignon	0.054*	0.016*	0.229	0.002**
Syrah	0.535	$<10^{-3}$ ***	0.011*	0.002**
Ugni Blanc	0.509	0.001**	0.194	$<10^{-3}$ ***
All varieties	0.658	$<10^{-3}$ ***	$<10^{-3}$ ***	$<10^{-3}$ ***

* $P<0.05$, ** $P<0.01$, *** $P<0.001$

the starting date of the accumulation of forcing units. This result questions one of the principal assumptions of this study, since introducing dormancy break into the model was useless in forecasting grapevine budburst date under current climate conditions. However, the starting date of forcing units accumulation, although arbitrary, is important. The use of 1 February as a start date resulted in a substantial drop in the model's predictive quality, demonstrating also the influence of temperatures in January (data not shown). However, some authors consider that it is important to simulate the date of dormancy break in the context of global warming because warmer winter temperatures may have a substantial impact on the date of dormancy break (Hänninen et al. 2007). Recent modelling studies on grapevine phenology have shown the importance of dormancy break in climate change conditions in different vineyards in Australia (Webb et al. 2007) and in France (García de Cortázar-Atauri 2006). In these studies, dormancy break was delayed in expected future climate conditions, which in turn sometimes delayed budburst.

Among the eight models tested, the GDD model with a base temperature of 5°C and BRIN model gave the best results in terms of RMSEP (RMSEP of BRIN; RMSEP of GDD_5). Since the GDD_5 model has fewer parameters, it can be considered as the best model so far to predict grapevine budburst date in France under current climatic conditions (Table 8).

Conclusions

In this work, we tested several models to predict grapevine budburst date. Our results showed that calculation of the dormancy period was not a critical factor for improving model performance under current climate conditions, while the base temperature to calculate GDD and cultivar specificity were most important. Nevertheless, modelling of dormancy may take on more importance given the upcoming climate conditions, which may affect dormancy release.

Table 8 Values of parameter sets and RMSEP for the various models used in the study: RIOU, GDD (with T_0=5°C and T_0=10°C) and BRIN

		RIOU		GDD (10°C)		GDD (5°C)		BRIN		
	Observations	G_c	RMSEP	G_c	RMSEP	G_c	RMSEP	C_c	G_c	RMSEP
Cabernet Sauvignon	63	80	18.3	52.5	12.5	318.6	9.8	106.8	9,169.4	9.7
Chasselas	89	61	21.5	37.2	17.9	257.8	14.6	106.3	6,971.8	14.2
Chardonnay	60	53	20.5	33.3	18.9	220.1	12.6	101.2	6,576.7	11.6
Grenache	40	76	20.2	57.0	9.6	321.3	8.2	102.2	9,174.3	8.8
Merlot	54	61	16.5	38.7	13.1	265.3	7.4	105.7	7,595.5	8.2
Pinot Noir	72	61	17.7	38.6	13.0	258.4	9.8	103.6	7,468.9	9.1
Riesling	64	61	18.6	39.7	13.1	257.7	9.2	108.2	7,471.3	10.8
Sauvignon	63	75	13.8	50.2	13.2	294.4	10.9	103.9	8,352.8	10.6
Syrah	64	67	20.0	39.2	16.1	265.3	11.0	99.2	7,818.6	11.1
Ugni Blanc	47	65	18.0	48.0	11.9	284.7	8.8	94.3	9,145.4	10.5

Nevertheless one should not forget that our approach is purely mathematical and statistical, and that although we have made use of elements of grapevine physiology, we have no way of controlling the precision of the estimated date of dormancy break. Field observations of real dormancy break date are urgently required to test the reliability of phenological models under future climatic conditions.

References

Alleweldt G (1963) Einfluss von klimafaktorem die zahl der inflorescenzen bei Reben. Wein-Wiss 18(2):61–70

Baggiolini M (1952) Les stades repères dans le développement annuel de la vigne et leur utilisation pratique. Rev Romande Agric Vitic Arbor 8:4–6

Bernstein Z (1984) L'amélioration de la régulation de débourrement dans les régions à hiver doux. Bull OIV 57:478–488

Bidabe B (1965a) Contrôle de l'époque de floraison du pommier par une nouvelle conception de l'action de températures. C R Acad Agric Fr 49:934–945

Bidabe B (1965b) L'action des températures sur l'évolution des bourgeons de l'entrée en dormance à la floraison. 96 Congrès Pomologique, pp 51–56

Bindi M, Miglietta F, Gozzini B, Orlandini S, Seghi L (1997a) A simple model for simulation of growth and development in grapevine (*Vitis vinifera* L.). I. Model description. Vitis 36(2):67–71

Bindi M, Miglietta F, Gozzini B, Orlandini S, Seghi L (1997b) A simple model for simulation of growth and development in grapevine (*Vitis vinifera* L.). II. Model validation. Vitis 36(2):73–76

Bonhomme R (2000) Bases and limits to using "degree-day" units. Eur J Agron 13:1–10, doi:10.1016/S1161-0301(00)00058-7

Brisson N, Gary C, Justes E, Roche R, Mary B, Ripoche D, Zimmer D, Sierra J, Bertuzzi P, Burger P, Bussière F, Cabidoche YM, Cellier P, Debaeke P, Gaudillère JP, Maraux F, Seguin B, Sinoquet H (2003) An overview of the crop model STICS. Eur J Agron 18:309–332, doi:10.1016/S1161-0301(02)00110-7

Carbonneau A, Riou C, Guyon D, Riom J, Schneider C (1992) Agrométéorologie de la vigne en France. EUR-OP, Luxembourg, p 168

Cesaraccio C, Spano D, Snyder RL, Duce P (2004) Chilling and forcing model to predict bud-burst of crop and forest species. Agric For Meteorol 126:1–13, doi:10.1016/j.agrformet.2004.03.010

Champagnol F (1984) Eléments de physiologie de la vigne et viticulture générale. Champagnol, Saint-Gely-du-Fesc, France

Chuine I (2000) A unified model for budburst of trees. J Theor Biol 207:337–347, doi:10.1006/jtbi.2000.2178

Chuine I, Kramer K, Hänninen H (2003) Plant development models. In: Schwartz MD (ed) Phenology: an integrative environmental science. Kluwer, Milwaukee, pp 217–235

Chuine I, Seguin B (2008) The history and current status of the French Phenology Networks. In: Nekovar J, Koch E, Kubin E, Nejedlik P, Sparks T, Wielgolaski FE (eds) The history and current status of plant phenology in Europe. COST Office, Vammalan Kirjapaino Oy, pp 76–79

Coombe BG (1995) Adoption of a system for identifying grapevine growth stages. Aust J Grape Wine Res 1:104–110, doi:10.1111/j.1755-0238.1995.tb00086.x

Crepinsek Z, Kajfez-Bogataj L, Bergant K (2006) Modelling of weather variability effect on fitophenology. Ecol Model 194:256–265, doi:10.1016/j.ecolmodel.2005.10.020

De Melo-Abreu JP, Barranco D, Cordeiro AM, Tous J, Rogado BM, Villalobos FJ (2004) Modelling olive flowering date using chilling for dormancy release and thermal time. Agric For Meteorol 125:117–127, doi:10.1016/j.agrformet.2004.02.009

Eichhorn KW, Lorenz DH (1977) Phönologische entwicklungsstadien der rebe. Nachrichtenbl Dtsch Pflanzenschutzdienst Braunschweig 29:119–120

Galet P (1976) Précis de Viticulture. Dehan, Montpellier, France

García de Cortázar-Atauri I, Brisson N, Seguin B, Gaudillere JP, Baculat B (2005) Simulation of budbreak date for vine. The BRIN model. Some applications in climate change study. In: Proceedings of XIV International GESCO Viticulture Congress, Geisenheim, Germany, 23–27 August, 2005, pp 485–490

García de Cortázar-Atauri I (2006) Adaptation du modèle STICS à la vigne (*Vitis vinifera* L.). Utilisation dans le cadre d'une étude du changement climatique à l'échelle de la France. PhD thesis of Ecole Supérieur Nationale d'Agronomie de Montpellier. Available at: [http://www.inra.fr/ea/sources/index.php?page=detail_these&id=200]

Gilreath PR, Buchanan DW (1981) Rest prediction model for low-chilling Sungold nectarine. J Am Soc Hortic Sci 106(4):426–429

Gutierrez AP, Williams DW, Kido H (1985) A model of grape growth and development: the matematical structure and biological considerations. Crop Sci 25:721–728

Hänninen H, Slaney M, Linder S (2007) Dormancy release of Norway spruce under climatic warming: testing ecophysiological models of bud burst with a whole-tree chamber experiment. Tree Physiol 27(2):291–300 2007

Jones GV (2003) Winegrape phenology. In: Schwartz MD (ed) Phenology: an integrative environmental science. Kluwer, Milwaukee, pp 523–540

Jones GV, Duchene E, Tomasi D, Yuste J, Braslavksa O, Schultz H, Martinez C, Boso S, Langellier F, Perruchot C, Guimberteau G (2005) Changes in European winegrape phenology and relationships with climate. In: Proceedings of XIV International GESCO Viticulture Congress, Geisenheim, Germany, 23–27 August, 2005, pp 55–62

Lang GA, Early JD, Martin GC, Darnell RL (1987) Endo-, para-, and ecodormancy: physiological terminology and classification for dormancy research. HortScience 22(3):371–377

Liennard ME (2002) Contribution à l'étude de la prévision de la précocité de floraison et du déterminisme climatique des nécroses florales de l'Abricotier, *Prunus armeniaca* L., dans le contexte des changements climatiques. Institut National d'Horticulture, Angers

Manly BFJ (1991) Randomization, bootstrap and Monte Carlo methods in biology. Chapman and Hall, London

McIntyre GN, Lider LA, Ferrari NL (1982) The chronological classification of grapevine phenology. Am J Enol Vitic 33 (2):80–85

Moncur MW, Rattigan K, Mackenzie DH, McIntyre GN (1989) Base temperatures for budbreak and leaf appearance of grapevines. Am J Enol Vitic 40(1):21–26

Nigond J (1967) Recherches sur la dormance de la vigne. Ann Amelior Veget 9:I:107–152 II:197–232; III:273–338

Oliveira M (1998) Calculation of budbreak and flowering base temperatures for *Vitis vinifera* cv. Touriga Francesa in the Douro Region of Portugal. Am J Enol Vitic 49(1):74–78

Pouget R (1963) Recherches physiologiques sur le repos végétatif de la vigne (*Vitis vinifera* L.): la dormance des bourgeons et le mécanisme de sa disparition. PhD Thesis Bordeaux University & Ann Amelior Plantes 13 Special Issue

Pouget R (1968) Nouvelle conception du seuil de croissance chez la vigne. Vitis 7:201–205

Pouget R (1972) Considérations générales sur le rythme végétatif et la dormance des bourgeons de la vigne. Vitis 11:198–217

Pouget R (1988) Le débourrement des bourgeons de la vigne: méthode de prévision et principes d'établissement d'une échelle de précocité de débourrement. Conn Vigne-Vin 22(2):105–123

Rea R, Eccel E (2006) Phenological models for blooming of apple in a mountainous region. Int J Biometeorol 51:1–16, doi:10.1007/s00484-006-0043-x

Richardson EA, Seeley SD, Walker DR (1974) A model for estimating the completation of rest for Redhaven and Elberta peach trees. HortScience 9(4):331–332

Richardson EA, Seeley SD, Walker RD, Anderson J, Ashcroft G (1975) Pheno-climatography of spring peach bud development. HortScience 10:236–237

Riou C (1994) The effect of climate on grape ripening: application to the zoning of sugar content in the european community. CECA-CEE-CECA, Luxembourg

Sarvas R (1974) Investigations on the annual cycle of development of forest trees. II. Autumn dormancy and winter dormancy. Commun Inst For Fenn 84:1–101

Schultz HR (2000) Climate change and viticulture: a European perspective on climatology, carbon dioxide and UV-B effects. Aust J Grape Wine Res 6:2–12, doi:10.1111/j.1755-0238.2000.tb00156.x

Sellers WD (1965) Physical climatology. University of Chicago Press, Chicago, IL

Shaultout AD, Unrath CR (1983) Rest completion prediction model for Starkrimson Delicious apples. J Am Soc Hortic Sci 108 (6):957–961

Wallach D, Goffinet B (1987) Mean squared error of prediction in models for studying ecological and agronomics systems. Biometrics 43:561–573

Wallach D (2006) Evaluating crop models. In: Wallach D, Makowski D, Jones JW (eds) Working with dynamic crop models. Evaluating, analyzing, parameterizing and using them. Elsevier, Amsterdam, pp 6–37

Webb LB, Whetton PH, Barlow EWR (2007) Modelled impact of future climate change on the phenology of winegrapes in Australia. Aust J Grape Wine Res 13:165–175, doi:10.1111/j.1755-0238.2007.tb00247.x

Wermelinger B, Baumgärtner J, Gutierrez AP (1991) A demographic model of assimilation and allocation of carbon and nitrogen in grapevines. Ecol Model 53:1–26

Williams DW, Williams LE, Barnett WW, Kelley KM, Mckenry MV (1985a) Validation of a model for the growth and development of the Thompson seedless grapevine. I. Vegetative growth and fruit yield. Am J Enol Vitic 36:275–282

Williams DW, Andris HL, Beede RH, Luvisi DA, Norton MVK, Williams LE (1985b) Validation of a model for the growth and development of the Thompsom Seedless grapevine. II. Phenology. Am J Enol Vitic 36:283–289

Winkler AJ, Cook JA, Kliewer WM, Lider LA (1962) General viticulture. University of California Press, Berkele