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# Performande of a Chill Overlap Model for Predicting Bud Break Prediction In Chardonnay Grapevines Over A Broad Range of Growing Conditions

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**Abstract:** Predicting phenological stages through modelling has significant applications for planning viticultural practices as well as for predicting climate change impacts on phenology. The Chill Overlap Model is based on an exponential declining curve to integrate the demonstrated compensatory relationship between chill and heat accumulation, and it incorporates recent research-based knowledge of physiological changes during dormancy. The aim of this work was to develop parameters for a Chill Overlap Model for predicting bud break in *Vitis vinifera* cv. Chardonnay grapevines and determine if using a Chill Overlap Model could be used to predict bud break better than previously developed models. The Chill Overlap Model that was developed also

incorporated the use of the Dynamic chill accumulation model for quantifying accumulation of chill exposure with a cultivar that has a relatively low chill requirement. Bud break data from Californian and Spanish wine grape regions representing a wide range of climates were used to parameterize a Chill Overlap Model for Chardonnay. The newly developed Chardonnay Chill Overlap Model did not succeed in predicting bud break better than previous efforts, but it did point out significant differences between the dynamics of chilling in grapevine compared to other species on which the Chill Overlap Model was developed. Further research is needed to account for environmental and vineyard management factors that influence bud break timing in order to further improve the model and better understand factors that influence completion of dormancy in grapevines.

**Keywords:** chill and heat requirements, chill portions, Dynamic chill accumulation model, modelling, phenology, temperature

## Introduction

Phenological models have relevant applications in viticulture, from planning viticultural practices (Williams et al. 1985, Caffarra and Eccel 2010) to modelling carbon dioxide fluxes (Richardson et al. 2013, Pope et al. 2014). Recent research has focused on predicting climate change impacts on plant phenology to develop strategies to mitigate its possible effects on crop behavior (Chuine 2000, Richardson et al. 2013, Darbyshire et al. 2016).

Bud break in grape indicates the onset of vegetative growth (Duchêne et al. 2010). Any delay during this stage can have impacts on the seasonal growth cycle, making it a key phenological stage with large site and cultivar variability (García de Cortázar-Atauri et al. 2009). Ambient temperature is widely considered to be the main

climatic driver responsible for phenological development (Williams et al. 1985, Martin and Dunn 2000, Jones 2003, García de Cortázar-Atauri et al. 2009, Caffarra and Eccel 2010, Duchêne et al. 2010, Nendel 2010). But other factors have been reported to modify grapevine phenology, such as soil temperature, soil texture (Jones 2003), photoperiod and water stress (Parker et al. 2013).

Dormancy is described as a temporary suspension of growth caused by physiological changes in buds (Lang et al. 1987). The timing of dormancy release depends on the exposure of buds to winter chill for ending endodormancy, followed by a period of spring heat to release ecodormancy and finally trigger bud break (Caffarra and Eccel 2010, Pope et al. 2014). Chill and heat are needed to release correspondent dormancy stages, resulting in specific temperature exposure requirements for different species and cultivars (Chuine 2000).

Grapevine growth models that predict bud break are mainly based on the computation of heat accumulation during spring, also known as Thermal Time (Cannell and Smith, 1983), from a set date until reaching a species-dependent threshold. These models are referred to as Spring Warming models (Hunter and Lechowicz, 1992). Under these models chilling requirements are assumed to be met every year (Pope et al. 2014), but these types of models may be inappropriate for Mediterranean climates, with occasional mild winters when minimum amounts of chill are not met (Pope et al. 2014) or for areas where climates are trending toward warmer winters (Luedeling and Brown, 2011). Other models, called sequential models, are structured with winter chill and spring heat accumulation being treated as independent phases fulfilled sequentially (Kramer 1994).

Complex sequential models, developed for Chardonnay and other cultivars, further integrate knowledge about developmental responses to environmental drivers.

Adding more biological and physiological explanations about grapevine crops into a phenological modelling framework, García de Cortázar-Atauri et al. (2009) developed the BRIN model. This was the first grapevine model to predict bud break based on physiological mechanisms as a framework for the heat accumulation approach. Caffarra and Eccel (2010) built the FENOVITIS model for the Chardonnay (*Vitis vinifera*) cultivar by adding complex model parameters to integrate a negative relationship between the chill and heat accumulation stages with set chilling requirements previously described by Cannell and Smith (1983), Chuine (2000) and Harrington et al. (2010).

It is often assumed in deciduous tree studies that chilling and heat accumulation requirements have to be fulfilled one after the other up to a fixed threshold, but this sequential fulfilment of chill and heat requirements is based on a simplified understanding of dormancy breaking processes (Luedeling et al. 2009). The measurement of the specific periods when buds are influenced by chilling and warming temperatures is challenging (Chuine 2000). Moreover, complex processes are likely to be involved in the transition from dormancy to bud break in grapevine (Fila et al. 2014). It is known that specific proteins appear to contribute to the induction and release of bud dormancy, but extensive molecular biological analyses are required to further understand the physiological, biochemical and genetic basis of grapevine bud dormancy (Lavee and May 1997, Nendel 2010).

Major changes in dormant buds occur when chilling requirements are fulfilled, such as changes in membranes or in the fatty acid ratios in phospholipids (Faust et al. 1997). Research has shown that the relationship between chilling, post-rest and bud break is complex. According to recent knowledge on genetic dormancy control (Horvath 2009, Leida et al. 2012) Pope et al. (2014) suggested that there could be a large overlap between chill and heat requirements because, after the minimum chill

requirement is met but before bloom in peach (*Prunus persica*), there was decreased expression of the genes responsible for response to cold with continued chill exposure (Yamane et al. 2011).

Following these principles, recently developed Chill Overlap Models attempt to integrate possible interactions between chill and heat accumulation by fitting an exponentially declining curve to describe decreasing requirements for post-chill heat accumulation in response to higher exposure to chilling temperatures, contemplating a partial compensatory relationship between chilling and post-chill heat requirements to finally trigger bud break (Pope et al. 2014). The conceptual basis for the model, compared with other recently developed models for Chardonnay, might help to increase understanding of the biological and physiological behavior of grapevines during the dormancy period. Chill Overlap Models have been developed for almond (*Prunus dulcis*) and apple (*Malus domestica*) deciduous trees, achieving a prominent improvement over previous model predictions (Pope et al. 2014, Darbyshire et al. 2016).

Furthermore, with the Chill Overlap Model, chill accumulation is calculated with the Dynamic chill accumulation model (Fishman et al. 1987), which has been found to perform either better, or equivalent, to other commonly used chill accumulation methods for various locations and cultivars (Erez 2000, Ruiz et al. 2007, Luedeling et al. 2009, Pope et al. 2014, Darbyshire et al. 2016). The negation of chill due to high temperatures that is imbedded in the Dynamic chill accumulation model has not been tested for grapevines but it could provide interesting perspectives for bud break predictions in warm climates (Dokoozlian 1999, Fila et al. 2014).

The aim of this work was to develop parameters for a Chill Overlap Model for predicting bud break of the Chardonnay grape cultivar and determine if such a model

would improve bud break prediction over a broad range of growing conditions. Bud break data across Californian and Spanish growing regions were used to develop and test model predictive capacity from observations over a range of diverse locations for evaluating the reliability of the model in different climates.

## **Materials and Methods**

### **Bud break and weather station data**

Bud break data of the Chardonnay cultivar were used to parameterize and validate the performance of the Chill Overlap Model (Pope et al. 2014). Wineries and research institutions across Californian (USA) and Spanish regions provided phenological data from different locations (Figure 1). Bud break was considered to be achieved when 50 % of buds were open, but a specific scale was not used in all data sources.

Daily maximum and minimum temperature data were acquired from the nearest weather station to each vineyard site (Table 1). Weather data for California (USA) were obtained from the California Irrigation and Management Information System (CIMIS, [www.cimis.water.ca.gov](http://www.cimis.water.ca.gov)). In Spain, weather data were retrieved from the Meteorological Service of the Catalanian Government (SMC, [www.ruralcat.net/web/guest/agrometeo.estacions](http://www.ruralcat.net/web/guest/agrometeo.estacions)) (Raïmat and Sant Sadurni d'Anoia locations) and the Irrigation advice network of Extremadura (REDAREX, [redarexplus.gobex.es/RedarexPlus/](http://redarexplus.gobex.es/RedarexPlus/)) (Badajoz location) (Figure 1). For occasional instances of periods of missing temperature data at a specific station, data from the nearest weather station were used as substitute data. In a few instances when several phenology observation sites were located near the same weather station (i.e. Windsor, Carneros), mean bud break data was calculated and used with temperature data from that station.

Phenology data were divided into two independent parameterization ( $n=42$ ) and validation ( $n=39$ ) subsets to cover the most representative climatic conditions, and to test the robustness of the model (Figure 2).

### **Chill Overlap Model description**

The Chill Overlap Model is based on an exponentially declining curve to represent the possible combinations of chill accumulation ( $C_a$ ), and heat accumulation ( $H_a$ ) that result in bud break (Harrington et al. 2010). Two sub-models were used to quantify winter chill and spring heat from the onset of the dormancy period until bud break (Pope et al. 2014).

Chill was determined with the Dynamic chill accumulation model (Fishman et al. 1987), and involved a two-step process. In the first step, a chill intermediate was formed or destroyed according to an hourly bell-shaped temperature relationship. There was an enhancement of formation of chill intermediates in cold temperatures with an optimal efficacy at 6-8 °C, and the negation of previously accumulated chill intermediates if there were temperatures above a specific threshold (24°C). In a second step, the chill intermediate was computed as one Chill Portion (CP), equivalent to 30 hours at continuous chill exposure at 6°C (Erez and Fishman 1998), where later warmer temperatures could not negate it. Heat was calculated using the Growing Degree Hour (GDH) ASYMCUR Model (Anderson et al. 1986). The acquisition of heat was an hourly asymmetric curvilinear model defined by two cosine equations with three threshold temperatures (base temperature=4°C, optimum temperature=25°C, critical temperature=36°C), which determined the accumulation of Heat Units (HU). A base temperature of 10°C it was also tested with this model.

Hourly temperatures were required as inputs to the Dynamic chill accumulation model and GDH ASYMCUR Model. Following Linvill (1990) equations, daily



maximum and minimum temperatures were interpolated into hourly data, with the specific parameters of each weather station location, for both the parameterization and validation datasets (Table 1).

The chilling requirement ( $C_r$ ) is the minimum amount of accumulated chill needed for bud break to be possible, and the heat requirement ( $H_r$ ) was the minimum accumulated heat required for bud break to be possible. According to Pope et al. (2014),  $C_r$  should be met before additional chill ( $C_a$ ) modifies a specific part of the heat accumulation ( $H_a$ ) phase resulting in an overlap between both phases, defined by Eq. (1) and (Figure 3):

$$H_a = \beta_1 + \frac{\beta_2}{e^{(\beta_3 \times C_a)}} \quad (1)$$

$H_a$ , heat accumulation from  $C_r$  to bud break

$C_a$ , chill accumulation after  $C_r$  is met

$\beta_1$ ,  $\beta_2$  and  $\beta_3$ , model parameters

The  $\beta_1$  model parameter, defined the lowest heat accumulation when bud break was possible, being equivalent to  $H_r$ . In fitted models it correlated with heat accumulations experienced in high chill years/climates.  $\beta_2$  corresponded to the difference of heat accumulation between the highest and the lowest observation values ( $\beta_2 = H_o - H_r$ ), estimated by data accumulated during mild winters.  $\beta_3$  parameter was related with the shape of the curve with values ranging between 0 and 1 defining that shape (Pope et al. 2014).

### **Model parameters development and parameterization**

The Chill Overlap Model parameters were fitted following Pope et al. (2014) and Darbyshire et al. (2016). The chilling requirement ( $C_r$ ) was estimated, since there were no previous experiments conducted to evaluate it. The onset of chilling was considered to occur on October 1 (Jarvis-Shean et al. 2015). The minimum value of

chill accumulation measured through the period across all sites and years (October 1 to March 31) was tested as the maximum  $C_r$  with 1 CP increments and a range of 1 to 31 CP (Spain - Sant Sadurni d'Anoia, 2012). The tested overlap interval values were from 10 % to 90 % with increments of 5% (Figure 3).

For each  $C_r$  tested, starting values to fit model parameters were estimated from parameterization datasets. The lowest value of  $H_a$  was used as an estimation of  $\beta_1$ , the difference between the highest and the lowest  $H_a$  values was estimated as  $\beta_2 = H_o - H_r$ , and the starting value for  $\beta_3$  was 0.0001 (Eq. 1).

Non-linear regression algorithms were applied to fit the model. The Levenberg-Marquart algorithm in the Curve Fitting Toolbox of MATLAB software (MATLAB and Statistics Toolbox Release 2014b, The MathWorks, Inc., Natick, Massachusetts, United States) was chosen instead of a trust-region algorithm, because it required fewer iterations to find properly fit values for the model. Negative values of  $\beta_1$  and  $\beta_2$  were dismissed for lack of biological sense, i.e. heat accumulation cannot have negative values (Pope et al. 2014).

### **Model parameter evaluation**

To obtain model parameter values, three indices were evaluated. The information-theoretic approach Akaike Information Criterion ( $AIC_C$ ) was evaluated comparing within each  $C_r$ , the model with the lowest value of  $AIC_C$  (Burham and Anderson, 2002). Models with different  $C_r$  could not be compared because of the change of the response variable that resulted in lower  $C_r$  to earlier heat accumulation (Pope et al. 2014). Candidate model parameters were also evaluated considering  $R^2$  and Root Mean Square Error (RMSE) values. Models with better model parameters were evaluated in the same way using the validation dataset.

## Results

Selected candidate models prioritized according to the lowest AIC<sub>C</sub>, high R<sup>2</sup> and low RMSE values using parameterization data are shown in Tables 2 and 3. Testing several overlaps (from 10 to 90% with increments of 5%) for the range of Chill Portions selected (from 1 to 31), the AIC<sub>C</sub> with a value of 346.62, a R<sup>2</sup> of 0.54 and a RMSE of 8.86 were achieved with a  $C_r$  of 9 CP and a 40 % overlap (Table 2) (Figure 4A, Figure 4B). The corresponding Chill Overlap Model parameter values were 6110, 9657 and 0.0463, for  $\beta_1$ ,  $\beta_2$  and  $\beta_3$ , respectively (Figure 4A). The evaluation of the same overlap with different chilling requirements is shown in Table 3. Changing the  $C_r$  value from 9 CP did not improve the performance of the model.

Validation of these parameters was conducted by applying the same model parameters to an independent dataset. The model fit for the validation data set was better than for the parameterization data set and, a  $C_r$  of 9 CP, and a chill-heat overlap of 40%, resulted in an R<sup>2</sup> = 0.69, and a RMSE of 7.32 days (Table 2 and Table 3) (Figure 5), thus indicating that the previously chosen model parameters were as valid as could be expected.

Model RMSE analysis was more accurate for data from the Central Valley (CA), with 7.09 and 6.13 days, for parameterization and validation, respectively. Model performance was less accurate in warmer winter locations such as the Central Coast (CA) (9.00 for parameterization and 10.00 days for validation) and South Central Coast (CA) (10.60 for parameterization and 8.49 days for validation) (Table 1). This may have been because fewer data points from these locations were available for initially fitting the model. (Figure 4B, Figure 5).

## Discussion

### Model approach

In accord with the structure of the Chill Overlap Model, in addition to  $C_r$ , colder locations accumulated more chill and decreased the heat needed to reach bud break, whereas warmer locations accumulated less chill, and more heat was required to trigger bud break. In our study, observations in cooler conditions presented later bud break (Spain), and warmer conditions presented earlier bud break (Central Coast and South Central Coast California locations) (Table 1). A delaying effect due to high temperatures during dormancy induction has been reported for Chardonnay, indicating mild temperatures might contribute to earlier dormancy during fall, whereas warm temperatures above 20°C delay it (Caffarra and Eccel 2010). But with Chardonnay low temperatures during the same period led to a more rapid chill accumulation, and earlier ecodormancy transition (Cragin et al. 2017).

The parameterizing dataset seemed to provide sufficient data with extreme values to approach  $C_r$ ,  $H_o$  and  $H_r$  to consequently fit model parameters. The estimated parameters presented some differences between the starting values and the fitted parameters (data not shown). The lower the  $\beta_3$  fitted value was, the more linear was the relation between  $C_a$  and  $H_a$ , and thus, the lower the value of  $\beta_1$  and the higher the value of  $\beta_2$ , but not in all the cases that were analyzed (Table 2, Table 3). These discrepancies were difficult to explain by the curved relationship between chill and heat, given numerous studies showing this relationship in temperate perennial species (Chuine 2000, Harrington et al. 2010). To gain further insights into an appropriate model, experimental determination of  $C_r$  could be used to fit the value directly rather than trying various  $C_r$  options and increasing model curvature to compensate for this lack of knowledge (Dennis 2003, Pope et al. 2014). To provide further insight into the accuracy

of fruit trees models, the addition of endodormancy break dates are needed to yield more robust projections of phenological changes (Chuine et al., 2016).

**Model performance**

The Chill Overlap Model developed in this research did not substantially improve bud break accuracy prediction considering previously developed phenological models for the Chardonnay cultivar, under specific locations and climatic conditions (García de Cortázar-Atauri et al. 2009, Caffarra and Eccel 2010), or comparing the accuracy improvement for the predictions in other species that have been tested (Pope et al. 2014 and Darbyshire et al. 2016). In this study the data used in model development covered a wider geographical area for the Chardonnay cultivar than in previous studies and this may have been one reason for the modest accuracy.

Varied phenological data sources may also have been an important reason for the limited accuracy of the developed model, because criteria for determining the exact onset of bud break was not uniform across sites and locations. Although bud break was generally considered when 50 % of buds were open, determination of the exact day of bud break likely varied depending on the days between observations and the person who was taking the data. Also, weather data was not recorded directly adjacent to the vines whose phenology was observed. There may have been differences between temperatures recorded at the weather stations and temperatures experienced in the vineyards, particularly due to differences in altitude (Nendel 2010) or aspect. Furthermore, maximum and minimum daily temperature data were used to estimate hourly chill and heat accumulation. The use of actual mean hourly temperature would have been more accurate for determining temperature accumulation but these data were not available for all sites.

Clonal behavior also likely varied in different locations, presumably affected by microclimates and soils, leading to diverse clonal performance under different conditions (Jones et al. 2014). In addition, it has been reported that yield and yield components differ among clones of Chardonnay depending on yearly clonal interactions (Fidelibus et al. 2006). It may be that there was some error in bud break prediction in this study due to unaccounted for clonal variability in the Chardonnay cultivar.

Variability of phenology in the same location may be explained by microclimate (Verdugo et al. 2016). Microclimate could affect phenological development as a consequence of particular changes in environmental conditions. California region phenology performance might have been affected by this phenomenon in the Central Valley and especially in the North Coast regions (Figure 4B, Figure 5). Another important factor may have been the distance between the weather stations and the observation vineyards (Table 1). Even though the Central Valley (CA) region is characterized as being flat, the distance between site and weather stations could be more than 10 km, and this could have been a source of error in model performance.

Air temperature has been widely described to be the main phenological driver. Depending on the net radiation, differences between air and bud temperature tend to be 0.5 – 2°C, but on foggy days the relationship changes to ~0.1 – 0.2 °C (Itier et al. 1987). Fog tends to decrease bud temperature and thus increases chill accumulation, but fog formation is highly variable on a year-to-year basis because of many complex and conditional meteorological factors. The general trend in the California region has been a decrease of winter fog events that are characterized by sustained periods of air temperatures below 7°C. Possible consequences of less fog are warmer air and an increment in the energy balance of buds, which amplifies their warming, and reduces their chill accumulation (Baldocchi and Waller 2014).

Orchard management might also have potential for influencing microclimate through small effects caused by planting density, pruning practices, cover cropping and irrigation regime (Luedeling et al. 2009). Grapevine management practices have been reported to influence bud break completion. In postharvest irrigation experiments, early cut off of irrigation have been reported to advance bud break stage with the Perlette cultivar (Williams et al. 1991). Similar responses were observed in an experimental vineyard of Chardonnay in Raïmat, Lleida, Spain, during spring 2016 (J. Marsal personal communication). Late pruning slightly delayed bud break with Cabernet Sauvignon (Martin and Dunn 2000) and Sauvignon Blanc grapevines (Trought et al. 2011).

#### **Chill and heat accumulation**

According to Faust et al. (1997) and Chuine (2000), specific changes in dormant buds do not occur until a minimum amount of chilling units are accumulated, and bud growth does not respond to warm temperatures during endodormancy. Over a range of temperatures chill accumulation in grapes was evaluated to be most efficient at 2.8 °C (Caffarra and Eccel 2010). A recent study conducted with Chardonnay canes indicated that -3 °C was also an effective temperature for endodormancy release after three weeks of cold exposure (Cragin et al., 2017). The Dynamic chill model, used to evaluate chill accumulation in the Chill Overlap Model, considered 6-8°C to be the optimum temperature range for chill accumulation. Furthermore, this model considers the effect of negation of chill due to a period of temperatures above 20°C. To our knowledge the Dynamic Chill Model has not been previously tested for grapevines species (Dokoozlian 1999). Even though chill models described in the literature are often not comparable because the amount of chilling units differ among sites, previously tested chill models and the experiments performed in grapevines provide some basis for

comparison (García de Cortázar-Atauri et al. 2009, Caffarra and Eccel 2010). The Dynamic chill accumulation model seemed to be appropriate for measuring chill in this study because of the range of climates present in the dataset.

For most plants, 10 °C is generally considered as the base temperature below growth does not occur. According with Williams et al. (1985), 10 °C was the base temperature for heat accumulation in grapevines, but several references show that it might be different for bud break prediction. In a study of phenological predictions Duchêne (2010) argued that a base temperature of 10°C might not be the most appropriate for bud break. Experimental studies found temperatures around 5°C to be the more appropriate for bud break predictions (Moncur et al. 1989) and García de Cortázar-Atauri et al. (2009) found better performance using 5°C as a base temperature for Chardonnay.

In this study, the Growing Degree Hour (GDH) ASYMCUR Model (Anderson et al. 1986) was used for heat accumulation determination considering a base temperature of 4°C. A base temperature of 10°C during the endodormancy release period was also tested, but no improvements in model predictions were achieved. Thus, it seems that a base temperature below 10°C may be suitable for bud break prediction, as it has been used in previously developed models for the Chardonnay cultivar (García de Cortázar-Atauri et al. 2009).

The point of this research was not the determination of the threshold temperature values for chill and heat accumulation, thus the most common or apparently most suitable temperature values available from the literature at the time of the study were used. Further research is clearly needed on the evaluation temperatures for the perception of chill and heat by buds during dormancy, but because of other limitations



on the dataset used in this study it was not appropriate to pursue this objective in this study.

Other factors like a lack of synchrony in bud growth, where apical buds open before than lateral buds because they meet heat requirements earlier (Martin et al. 2000), differences in bud vigor, and amounts of carbon and nitrogen in reserves might also affect the perception of chill and heat temperatures by buds (Ben Mohamed et al. 2010).

In this study Chardonnay was found to need ~9 CP compared with 13, 21 and 23 CP for the Sonora, Mission, Nonpareil almond cultivars, respectively (Pope et al. 2014), and 34 CP for the Crisp Pink apple cultivar (Darbyshire et al. 2016). Compared with other deciduous fruit crops, Eshghi et al. (2010) reported that grapevines in Iran do not have high chilling requirements and need relatively little exposure to chill. Our results are consistent with this report. Considering that 1 CP is equivalent to 30 hours at continuous chill at 6°C (Erez and Fishman 1998), the evaluated chilling requirement for Chardonnay might be similar to a chill exposure of 270 hours (9 CP x 30 hours/CP). Previous research using chill hours accumulated between 0 and 10 °C found that 200 hours was the minimum chilling exposure required for normal bud grape growth for the Perlette cultivar (Dokoozlian, 1999), and 336 hours at temperatures below 6°C for Cabernet Sauvignon (Botelho et al. 2007). Chill hour requirements for Nonpareil almond have been reported to be 360 hours (Ramírez et al. 2010), while the requirements for Gala and Sweetheart apples have been reported to be 973 and 687 chill hours under 7.2 °C, respectively (Guak and Neilsen, 2013).

Although there is no exact equivalency between Chill Hour and Chill Portion quantification because they are not constant in time or space, it is reassuring that the differences in chill requirements ( $C_r$ ) between species are consistent with different chill

models, accentuating biological species differences. Some studies have suggested that the Dynamic chill accumulation model is more accurate for quantifying winter chill, reducing location and year-to-year variability and performing better in warmer areas (Luedeling et al. 2009).

Differences among species can be highlighted by comparing values of the Chill Overlap Model parameters. Emphasizing the low chill necessity in grapevines, the overlap defined by the period with a compensatory relationship between chill and heat requirements appeared to be lower in grapevines (40 %) than almonds and apples (75 %) (Pope et al. 2014 and Darbyshire et al. 2016). As hypothesized by Pope et al. (2014), the amount of overlap might vary by species. Grapevines appear to be less demanding of chill even in the compensatory stage between both requirements. On the other hand, along with a low chill demand, Chardonnay appeared to need the perception of more heat, as shown in the  $\beta_I$  fitted model parameter. This suggests that grapevines may be a species in which additional heat may be more effective than additional chill above the minimum chill requirement ( $C_r$ ).

Based on the Chill Overlap Model, the contribution of chill and heat to bud break differs between grapevines and apples. Once  $C_r$  is met in both species, cool locations with considerable accumulation of chill and subsequent decrease of heat demand presented later bud break observations in grapevines, but earlier bloom in apples. In warmer locations more heat was required to meet bud break conditions and grapevines had earlier bud break, while with apples it took additional time for flowering, delaying this stage (Darbyshire et al. 2016).

Values of  $\beta_3$  defined similar curves of roughly the same shape, but with different chill and heat requirements among species. Additionally, a more precise estimation of chilling requirements by forcing or growth-room experiments could increase model

curvature (Dennis 2003, Pope et al. 2014). A previous study demonstrated that models calibrated with growth room data provided good accuracy when tested on two different field-based datasets (Fila et al. 2012). The integration of data obtained by growth room experiments combined with field observation data may yield more accurate model estimates (Fila et al. 2014). Other aspects like the addition of the time of pruning into the models might also improve model performance (Martin and Dunn 2000).

More research to improve phenology models for making accurate predictions is necessary considering the potentials impact of climate change on the suitability of specific grape cultivars for specific future growing regions. The results of the Chill Overlap Model for Chardonnay grapevine did not significantly improve bud break predictions over previous more simple models (García de Cortázar-Atauri et al. 2009, Caffarra and Eccel 2010). But the fact that the model attempted to integrate the overlapping effect of chill accumulation on the subsequent heat accumulation requirements, that have been empirically observed in the field, indicates that it would be worthwhile to try to improve the model by accounting for several of the sources of potential non-temperature related variability in bud break pointed out in this work.

## **Conclusion**

This study provided a new set of parameters for modelling bud break in Chardonnay grapevines using the Chill Overlap Model. Even though model performance did not show substantial predictive improvements over previous bud break models, the model obtained can be considered as an approach for taking into consideration the synergistic interactions between chill and heat accumulation requirements prior to bud break in grapevines. The results were acceptable considering the wide range of climates involved and potential sources of inaccuracy in the data sets

used. Knowledge of the possible influences of environmental factors and management practices in specific locations, should help in reducing inaccuracies of the predictions obtained, and lead to further model improvement.

The study confirmed the apparent low chill requirement of Chardonnay, and that temperatures below 10°C seemed to be effective in fulfilling the chill requirement. On the other hand, Chardonnay is known to be a cultivar that needs substantial amounts of warm temperatures to achieve bud break, and this should be carefully considered in order to understand how the rise of temperatures due to climate change could affect its behavior and adaptability.

This model includes potential interactions between cold and warm temperatures that could help to further understand the physiology and crop behavior during dormancy and bud break. Even though all phenological models present simple interpretations to predict complex realities, the basis of this model presents enough complexity and does not need expensive experiments for evaluating its performance.

Fitted model parameters differ greatly among species and emphasize the relevance of phenological data collection for individual species and cultivars, and the importance of sharing information over different climatic conditions and locations, to provide more reliability and improvement of phenological model performance. The low percent overlap in chill and heat accumulation with Chardonnay, compared to the high overlap in the models for almond (Pope et al. 2014) and apple (Darbyshire et al. 2013) point to potential differences in how much chill accumulation beyond the minimum chill requirement can impact heat accumulation necessary for bud break.

## Literature Cited

- Anderson J.L., Richardson E.A. and Kesner, C.D. 1986. Validation of chill unit and flower bud phenology models for “Montmorency” sour cherry. *Acta Hort.* 184:71-78.
- Baldocchi D. and Waller E. 2014. Winter fog is decreasing in the fruit growing region of the Central Valley of California. *Geophys. Res. Lett.* 41:3251-3256.
- Ben Mohamed H., Vadel A.M., Geuns J.M.C. and Khemira H. 2010. Biochemical changes in dormant grapevine shoot tissues in response to chilling : Possible role in dormancy release. *Sci. Hort.* 124: 440–447.
- Botelho R.V., Pavanello A.P., Pires E.J.P., Terra M.M. and Muller M.M.L. 2007. Effects of chilling and garlic extract on bud dormancy release in Cabernet Sauvignon cuttings. *Am. J. Enol. Vitic* 58:402–404.
- Burham K.P. and Anderson R.A. 2002. Model Selection and Multimodel Inference: A practical Information-Theoretic Approach. Burnham, K.P. and Anderson, D.R., eds. Information theory and loglikelihood models: a basis for model selection and inference, pp. 32– 74. Springer, Berlin
- Caffarra A. and Eccel E. 2010. Increasing the robustness of phenological models for *Vitis vinifera* cv. Chardonnay. *Int. J. Biometeorol.* 54:255–267.
- Cannell M.G.R. and Smith R.I. 1983. Thermal time, chill days and prediction of budburst in *Picea sitchensis*. *J. Appl. Ecol.* 20:951–963.
- Chuine I. 2000. A Unified Model for Budburst of Trees. *J. Theoret. Biol.* 207:337–347.
- Chuine I., Bonhomme M., Legave J.M., García de Cortázar-Atauri I., Charrier G., Lacointe A. and Améglio T. 2016. Can phenological models predict tree phenology

508 accurately in the future? The unrevealed hurdle of endodormancy break. *Global Change*  
509 *Biol.* 22:3444-3460.

510 Cragin J., Serpe M., Keller M. and Shellie K. 2017. Dormancy and Cold Hardiness  
511 Transitions in Wine Grape Cultivars Chardonnay and Cabernet Sauvignon. *Am. J. Enol.*  
512 *Vitic.* 68:195-202.

513 Darbyshire R., Webb L., Goodwin I. and Barlow E.W.R. 2013. Evaluation of recent  
514 trends in Australian pome fruit spring phenology. *Int. J. Biometeorol.* 57:409–421.

515 Darbyshire R., Pope K. and Goodwin I. 2016. An evaluation of the chill overlap model  
516 to predict flowering time in apple tree. *Sci. Hort.* 198:142–149.

517 Dennis F.G. 2003. Problems in standardizing methods for evaluating the chilling  
518 requirements for the breaking of dormancy in buds of woody plants. *HortScience.*  
519 38:347–350.

520 Dokoozlian N. K. 1999. Chilling temperature and duration interact on the budbreak of  
521 “Perlette” grapevine cuttings. *HortScience.* 34:1054–1056.

522 Duchêne E., Huard F., Dumas V., Schneider C. and Merdinoglu D. 2010. The challenge  
523 of adapting grapevine varieties to climate change. *Clim. Res.* 41:193–204.

524 Erez A. and Fishman S. 1998. The dynamic model for chilling evaluation in peach buds.  
525 *Acta Hort.* 465:507–510.

526 Erez A. 2000. Bud Dormancy; Phenomenon, Problems and Solutions in the Tropics and  
527 Subtropics. A. Erez, ed. *Temperate Fruit Crops in Warm Climates.* pp. 17–48.  
528 Dordrecht, Springer, Netherlands

529 Eshghi, S., Rahemi, M. and Karami, A. 2010. Overcoming Winter Rest of Grapevine  
530 Grown in Subtropical Regions Using Dormancy-Breaking Agents. Iran Agricultural  
531 Research 29:99-109.

532 Faust M., Erez A., Rowland L.J., Wang S.Y. and Norman H.A. 1997. Bud dormancy in  
533 perennial fruit trees: physiological basis for dormancy induction, maintenance, and  
534 release. HortScience. 32:623–629.

535 Fidelibus M.W., Christensen L.P., Katayama D.G. and Verdenal P.T. 2006. Yield  
536 components and fruit composition of six “Cabernet Sauvignon” grapevine selections in  
537 the Central San Joaquin Valley, California. J. Am. Pomol. Soc. 60:32–36.

538 Fila, G., Gardiman, M., Belvini, P., Meggio, F. and Pitacco, A. 2014. A comparison of  
539 different modelling solutions for studying grapevine phenology under present and future  
540 climate scenarios. Agric. For. Meteorol. 195–196:192–205.

541 Fishman S., Erez A. and Couvillon G.A. 1987. The Temperature Dependence of  
542 Dormancy Breaking in plants: Mathematical Analysis of a Two-Step Model Involving  
543 a Cooperative Transition. J. Theor. Biol. 124:473–483.

544 García de Cortázar-Atauri I., Brisson N. and Gaudillere J.P. 2009. Performance of  
545 several models for predicting budburst date of grapevine (*Vitis vinifera* L.). Int. J.  
546 Biometeorol. 53:317–326.

547 Guak S. and Neilsen D. 2013. Chill unit models for predicting dormancy completion of  
548 floral buds in apple and sweet cherry. Hortic. Environ. Biote. 54:29–36.

549 Harrington C.A., Gould P. J. and St. Clair J. B. 2010. Modeling the effects of winter  
550 environment on dormancy release of Douglas-fir. For. Ecol. Manage. 259:798–808.

551 Horvath D., 2009. Common mechanisms regulate flowering and dormancy. *PlantSci.*  
 552 177:523–531.

553 Hunter A. and Lechowicz M. 1992. Predicting the timing of budburst in temperature  
 554 trees. *J. Appl. Ecol.* 29:297–604.

555 Itier B., Huber L. and Brun O. 1987. The influence of artificial fog on conditions  
 556 prevailing during nights of radiative frost. Report on an experiment over a Champagne  
 557 vineyard. *Agric. For. Meteorol.* 40:163-176.

558 Jarvis-Shean, K., Da Silva, D., Willits, N. and DeJong, T.M. 2015. Using Non-  
 559 Parametric Regression to Model Dormancy Requirements in Almonds. *Acta Hortic.*  
 560 1068:133-140.

561 Jones G.V. 2003. Phenology: an integrative environmental science. M.D. Schwartz, ed.  
 562 Wine grape phenology. pp. 523–539. Kluwer Press, Milwaukee, MA, Boston.

563 Jones J.E., Kerslake F.L., Close D.C. and Damberg R.G. 2014. Viticulture for  
 564 sparkling wine production: A review. *Am. J. Enol. Vitic.* 65:407–416.

565 Kramer K. 1994. Selecting a model to predict the onset of growth of *Fagus sylvatica*. *J.*  
 566 *Appl. Ecol.* 31:172-181.

567 Lang G.A., Early J.D., Martin G.C. and Darnell R.L. 1987. Endo-, para-, and  
 568 ecodormancy: physiological terminology and classification for dormancy research.  
 569 *HortScience.* 22:371–377.

570 Lavee S. and May P. 1997. Dormancy of grapevine buds-facts and speculation. *Aust. J.*  
 571 *Grape Wine Res.* 3:31-46.



572 Leida C., Conesa A., Llacer G., Luisa Badenes M. and Rios G. 2012. Histone  
 573 modifications and expression of DAM6 gene in peach are modulated during bud  
 574 dormancy release in a cultivar-dependent manner. *New Phytol.* 193:67–80.

575 Linvill D.E. 1990. Calculating chilling hours and chill units from daily maximum and  
 576 minimum temperature observations. *Hortscience.* 25:14–16.

577 Luedeling E., Zhang M., McGranahan G. and Leslie C. 2009. Validation of winter chill  
 578 models using historic records of walnut phenology. *Agric. For. Meteorol.* 149:1854–  
 579 1864.

580 Luedeling E. and Brown P.H. 2011. A global analysis of the comparability of winter  
 581 chill models for fruit and nut trees. *Int. J. Biometeorol.* 55:411–421.

582 Martin S.R. and Dunn G.M. 2000. Effect of pruning time and hydrogen cyanamide on  
 583 budburst and subsequent phenology of *Vitis vinifera* L. variety Cabernet Sauvignon in  
 584 central Victoria. *Aust. J. Grape Wine Res.* 6:31–39.

585 Moncur M.W., Rattigan K., Mackenzie D.H. and McIntyre G.N. 1989. Base  
 586 temperatures for budbreak and leaf appearance of grapevines. *Am. J. Enol. Vitic.*  
 587 40:21–26.

588 Nendel C. 2010. Grapevine bud break prediction for cool winter climates. *Int. J.*  
 589 *Biometeorol.* 54:231–241.

590 Parker A., García de Cortázar-Atauri I., Chuine I., Barbeau G., Bois B., Boursiquot J.  
 591 M., ... van Leeuwen C. 2013. Classification of varieties for their timing of flowering  
 592 and veraison using a modelling approach: A case study for the grapevine species *Vitis*  
 593 *vinifera* L. *Agric. For. Meteorol.* 180:249–264.

594 Pope K.S., Da Silva D., Brown P.H. and DeJong T.M. 2014. A biologically based  
 595 approach to modeling spring phenology in temperate deciduous trees. *Agric. For.*  
 596 *Meteorol.* 198-199, 15-23.

597 Ramírez L., Sagredo K.X. and Reginato G.H. 2010. Prediction models for chilling and  
 598 heat requirements to estimate full bloom of almond cultivars in the Central Valley of  
 599 Chile. *Acta Hortic.* 872:107–112.

600 Richardson A.D., Keenan T.F., Migliavacca M., Ryu Y., Sonnentag O. and Toomey M.  
 601 2013. Climate change, phenology, and phenological control of vegetation feedbacks to  
 602 the climate system. *Agric. For. Meteorol.* 169:156–173.

603 Ruiz D., Campoy J.A. and Egea J. 2007 Chilling and heat requirements of apricot  
 604 cultivars for flowering. *Environ. Exp. Bot.* 61:254–263.

605 Trought M.C.T., Bennett J. S. and Boldingh H.L. 2011. Influence of retained cane  
 606 number and pruning time on grapevine yield components, fruit composition and vine  
 607 phenology of Sauvignon Blanc vines. *Aust. J. Grape Wine Res.* 17:258–262.

608 Verdugo-Vásquez N., Acevedo-Opazo C., Valdés-Gómez H., Araya-Alman M., Ingram  
 609 B., García de Cortázar-Atauri I. and Tisseyre B. 2016. Spatial variability of phenology  
 610 in two irrigated grapevine cultivar growing under semi-arid conditions. *Precis.*  
 611 *Agric.* 17:218–245.

612 Williams D.W., Andris H.L., Beede R.H., Luvisi D.A., Norton M.V.K. and Williams  
 613 L.E. 1985. Validation of a model for the growth and development of the Thompson  
 614 Seedless grapevine. II Phenology. *Am. J. Enol. Vitic.* 36:283–289.

615 Williams L.E., Neja R.A., Meyer J.L., Yates L.A. and Walker E.L. 1991. Post harvest  
 616 irrigation influences budbreak of “Perlette” grapevines. *Hortscience* 26:1081.

617 Yamane H., Ooka T., Jotatsu H., Hosaka Y., Sasaki R. and Tao R. 2011. Expressional  
618 regulation of PpDAM5 and PpDAM6, peach (*Prunus persica*) dormancy-associated  
619 MADS-box genes, by low temperature and dormancy-breaking reagent treatment. J  
620 Exp. Bot. 62:3481–3488.

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**Table 1** Database summary for parameterizing and validating data from Californian (CA, United States) and Spanish locations. Weather station descriptors are latitude, longitude, number of observation sites associated with each climatic station and mean distance between them are shown from Californian ([www.cimis.water.ca.gov](http://www.cimis.water.ca.gov)), and Spanish ([www.ruralcat.net/web/guest/agrometeo.estacions](http://www.ruralcat.net/web/guest/agrometeo.estacions) and [redarexplus.gobex.es/RedarexPlus/](http://redarexplus.gobex.es/RedarexPlus/)) weather stations. CP, are the average value of the Chill Portions accumulated from October 1 to March 31 of the observation years.

Location	Weather stations					Observation years	CP
	Station name	Latitude (°)	Longitude (°)	Number of observations sites	Mean distance to observations (Km)		
Central Valley (CA)	Manteca	37.83	-121.22	1	13	2009-2014	55
	Modesto	37.65	-121.19	1	13.5	2009-2011, 2013, 2014	57
	Kesterson	37.23	-120.88	1	18.5	2009-2014	52
	Oakdale	37.73	-120.85	1	7	2009-2014	57
North Coast (CA)	Santa Rosa	38.40	-122.80	1	8	2012-2015	46
	Winsdor	38.53	-122.83	2	15.5	2007-2013, 2015	55
	Carneros	38.22	-122.35	3	1.5	2004- 2011, 2014, 2015	55
	Oakville	38.43	-122.41	1	1.5	2010, 2012-2016	50
	San Benito	36.85	-121.36	1	2.5	2014	35
South Central Coast (CA)	Nipomo	35.03	-120.56	1	16	2010, 2011, 2014-2016	47
Spain	Raïmat	41.68	0.45	1	5.4	2013	49
	Sant Sadurni	41.43	1.79	1	5	2006, 2012, 2014, 2015	42
	d'Anoia	35.51	-6.39	1	0.5	2014-2016	59
	Badajoz						

**Table 2** Example of model fit and performance for overlap estimates at one potential  $C_r$ .  $AIC_C$  was used for evaluation of models for parameterization data set.  $R^2$  and RMSE were used for evaluating the relation with observed and predicted bud break values applying fitted model parameters for parameterization and validation datasets. Only significant ( $p$ -value  $< 0.05$ ) models are shown.

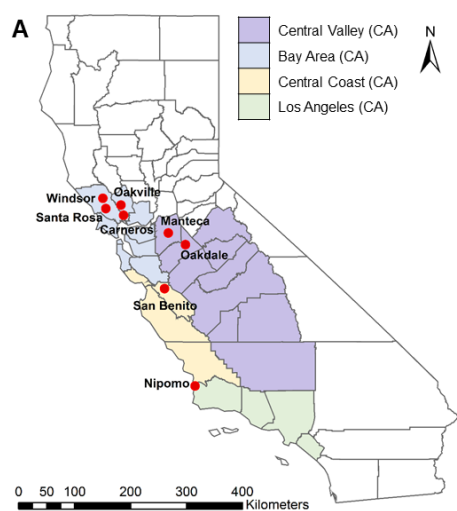
$C_r$ (CP)	Overlap (%)	Model parameters			Parameterization			Validation	
		$\beta_1$	$\beta_2$	$\beta_3$	$AIC_C$	$R^2$	RMSE (days)	$R^2$	RMSE (days)
9	25	6992	8152	0.0729	352.28	0.53	9.45	0.68	7.87
9	30	7800	7751	0.0813	359.77	0.47	10.33	0.64	9.50
9	40	6110	9657	0.0463	346.62	0.54	8.86	0.69	7.32
9	50	2141	14041	0.0252	400.53	0.56	16.78	0.62	16.44
9	75	8856	11358	0.0636	386.61	0.44	14.17	0.42	14.47

$AIC_C$ , Akaike Information Criterion;  $R^2$ , R-square; RMSE, Root Mean Square Error measured

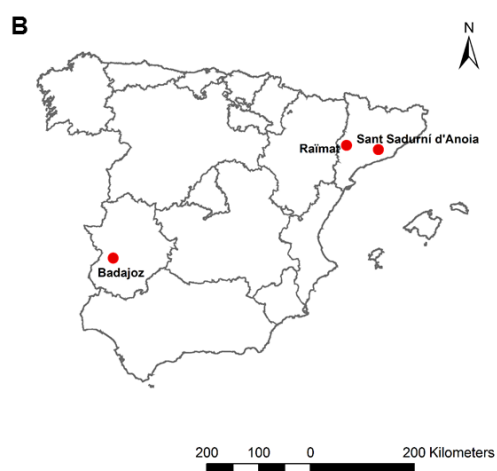
**Table 3** Model fit and performance for chilling requirement estimates at the same 40% overlap. Evaluation of  $R^2$  and RMSE for parameterization and calibration datasets evaluating the relation with observed and predicted bud break values applying fitted model parameters. With  $p$ -value  $< 0.05$ , all model fits were significant.

$C_r$ (CP)	Overlap (%)	Model parameters			Parameterization		Validation	
		$\beta_1$	$\beta_2$	$\beta_3$	$R^2$	RMSE (days)	$R^2$	RMSE (days)
7	40	8591	9236	0.0833	0.48	11.67	0.49	11.72
8	40	7096	9242	0.0577	0.48	10.80	0.65	8.84
9	40	6110	9657	0.0463	0.54	8.86	0.69	7.32
10	40	2836	12225	0.0292	0.60	12.63	0.61	11.78
11	40	7275	8615	0.0662	0.55	10.17	0.61	9.99

$R^2$ , R-square; RMSE, Root Mean Square Error measured



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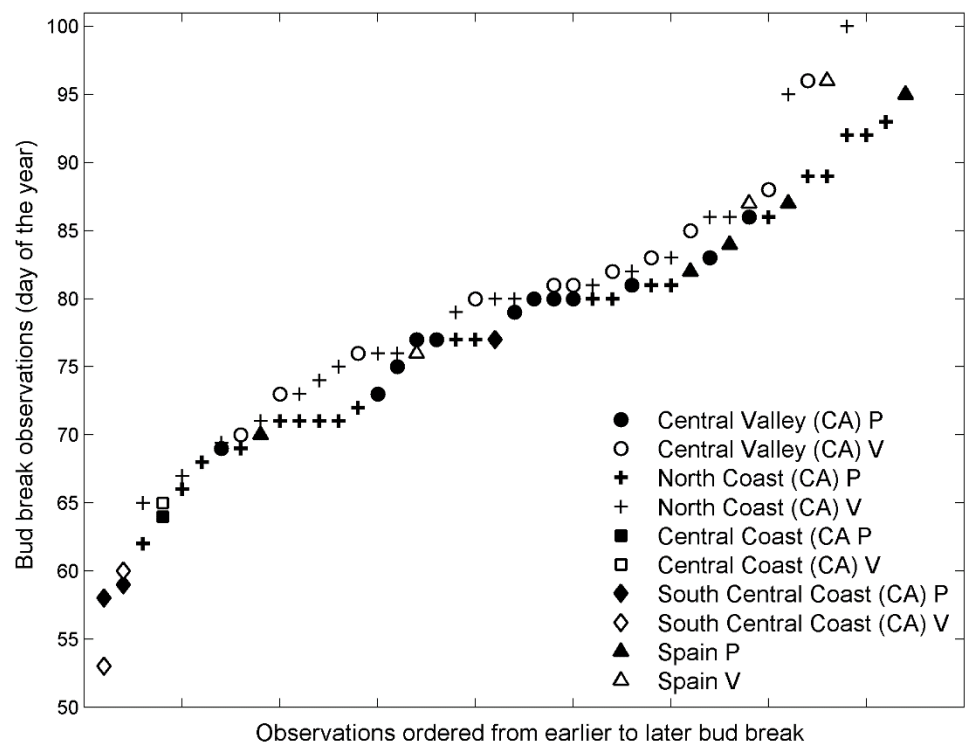
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646 **Figure 1** Location of the weather stations (red dots) used in the study in California (A)  
 647 (USA) and B Spain (B).

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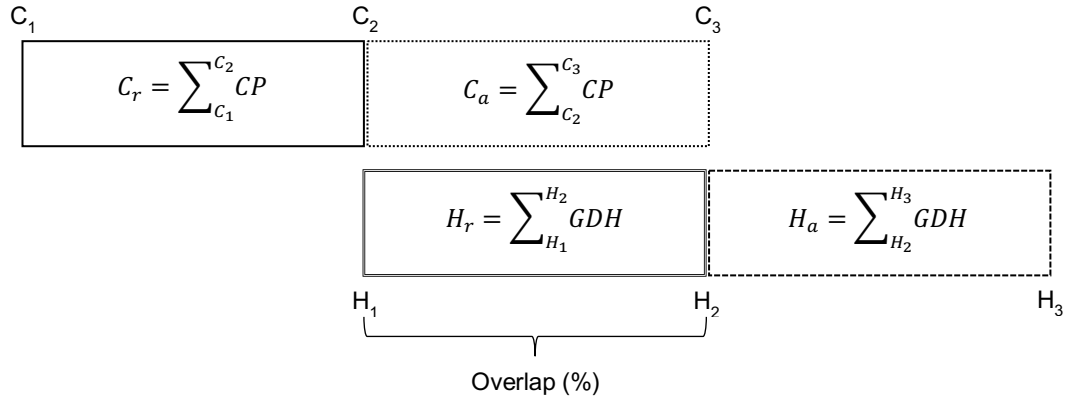
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652 **Figure 2** Chardonnay bud break day of the year subsets, ordered from earlier to later bud  
653 break observations, for parameterizing, P (42 observations, filled symbols) and  
654 validating, V (39 observations, open symbols) the Chill Overlap Model.

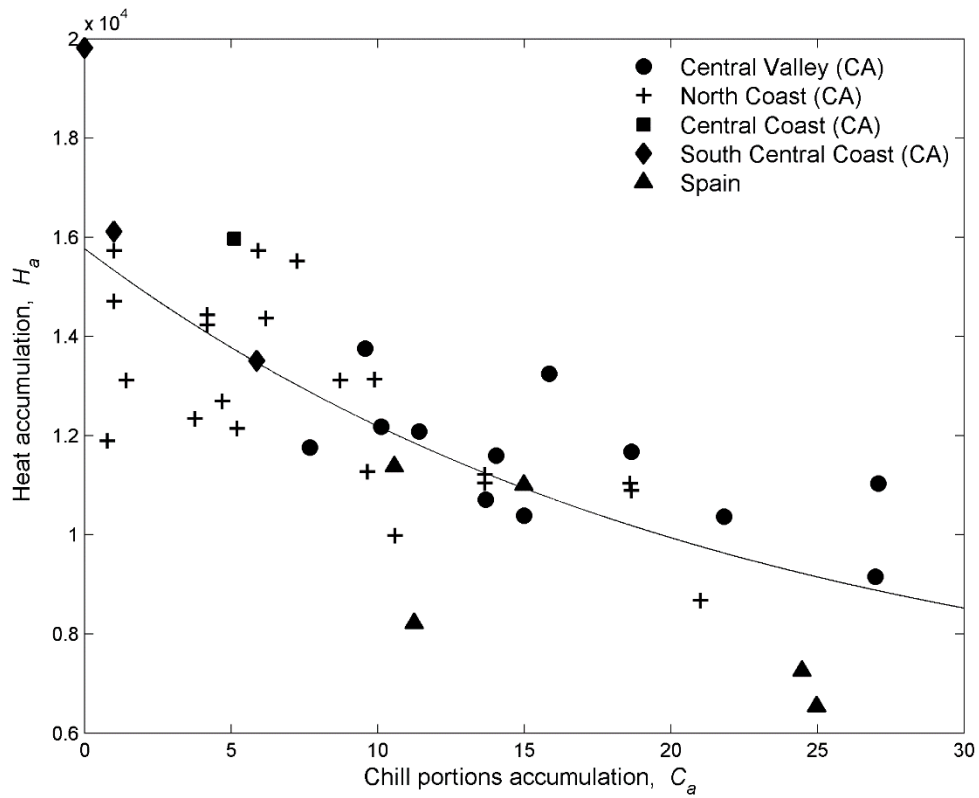
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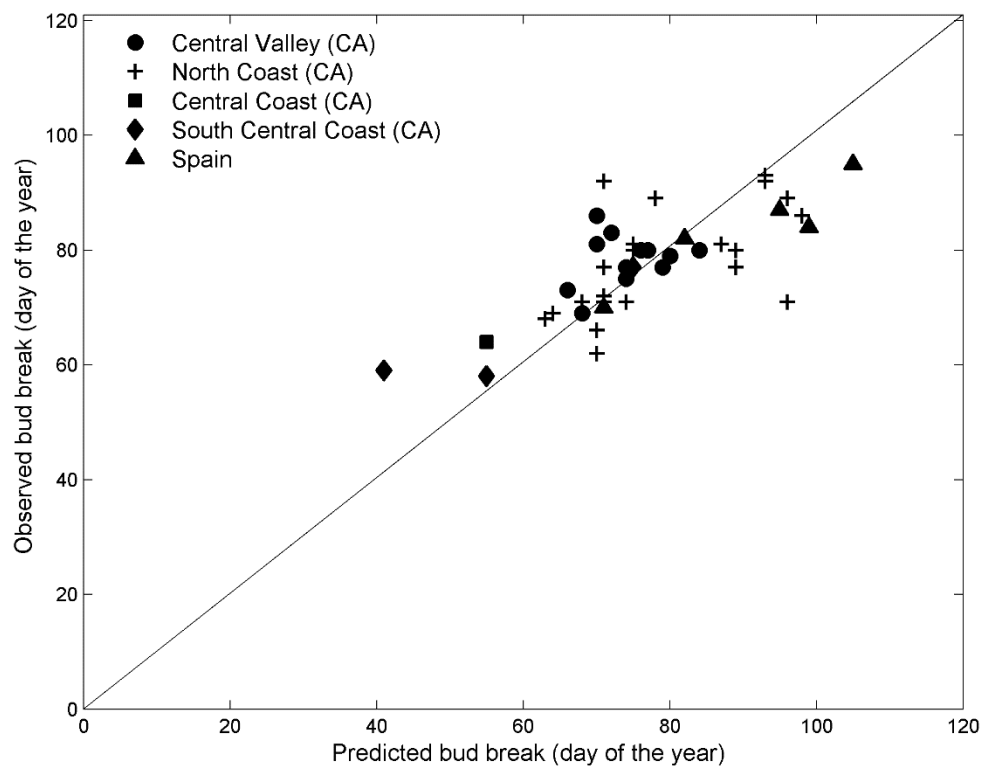




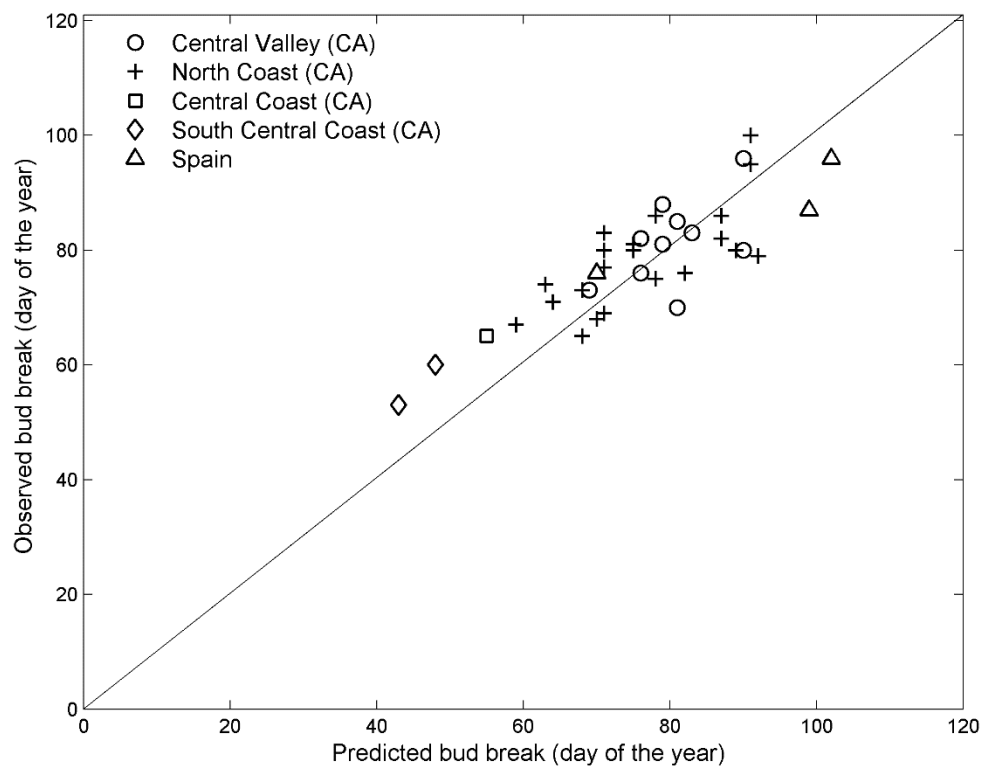
**Figure 3** Drawing to explain the overlapping between the chill and heat phases implied in the Chill Overlap Model.  $C_1$ ,  $C_2$  and  $C_3$  exemplify the different accumulation times for chill, and  $H_1$ ,  $H_2$  and  $H_3$  the different accumulation times for heat. Rectangles with solid lines show fixed chill/heat amounts, and rectangles with dashed lines show not fixed chill/heat accumulated amounts. The overlap where additional accumulated chill (CP, Chilling Portions calculated with Dynamic Chill Accumulation Model) that reduce heat sum (GDH, Growing Degree Hour determined with GDH ASYMCUR Model) is when  $C_a$ , chill accumulated from  $C_2$  to  $C_3$ , and  $H_r$ , heat accumulated from  $H_1$  to  $H_2$ , are determined simultaneously for the same period.



**Figure 4A** Chill Overlap Model fit parameterization. Chill requirement ( $C_r$ ) are 9 CP and an overlap of 40 % between the chill accumulation ( $C_a$ ) and the Heat Accumulation ( $H_a$ ) phases. Model accuracy was evaluated with AIC<sub>C</sub> obtaining a 346.62 value.



**Figure 4B** Predicted and observed bud break day of the year from the Chill Overlap Model using parameterizing data, obtaining  $R^2=0.54$  and  $RMSE=8.86$  days statistics. Fitted values were determined after 9 CP corresponding to the chill requirement ( $C_r$ ) are meet, and an overlap of 40 %.



681

682 **Figure 5** Predicted and observed bud break day of the year evaluated with the best  
 683 performance fit model parameters with the validating dataset, obtaining  $R^2=0.69$  and  
 684 RMSE=7.32 days statistics. 9 CP were the chill requirements ( $C_r$ ), and 40 % the overlap.

685