Frost risk projections in a changing climate are highly sensitive in time and space to frost modelling approaches

Catinca Gavrilescu[1], Sebastien Zito[1], Yves Richard[1], Thierry Castel[1], Guillaume Morvan[2] and Benjamin Bois[1,3]

[1] Centre de Recherches de Climatologie – UMR Biogeosciences, Université Bourgogne Franche-Comté / CNRS, 6, Bd Gabriel, 21000 Dijon, France
[2] Chambre d'Agriculture de l'Yonne, *14 bis rue Guynemer*, *89000 Auxerre*, France
[3] Institut Universitaire de la Vigne et du Vin, Université Bourgogne Franche-Comté, rue Claude Ladrey, 21000 Dijon, France

***Catinca Gavrilescu:** catinca.gavrilescu@u-bourgogne.fr

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Abstract

Late spring frost is a major challenge for various winegrowing regions across the world, its occurrence often leading to important yield losses and/or plant failure. Despite a significant increase in minimum temperatures worldwide, the spatial and temporal evolution of spring frost risk under a warmer climate remains largely uncertain. Recent projections of spring frost risk for viticulture in Europe throughout the 21st century show that its evolution strongly depends on the modelling approach used to simulate budburst. Furthermore, the frost damage modelling methods used in these projections are usually not assessed through comparison to field observations and/or frost damage reports. The present study aims at comparing frost risk projections simulated using six spring thermal stress models based on two approaches: a) models considering a fixed damage threshold after the predicted budburst date (BRIN, Smoothed-Utah, Growing Degree Days, Fenovitis) and b) models considering a dynamic frost sensitivity threshold based on the predicted grapevine winter/spring dehardening process (Ferguson model). The capability of each model to simulate an actual frost event for the *Vitis vinifera* cv. Chardonnay B was previously assessed by comparing simulated cold thermal stress to reports of events with frost damage in Chablis, the northernmost winegrowing region of Burgundy. Models exhibited scores of $\kappa > 0.65$ when reproducing the frost/non-frost damage years and an accuracy ranging from 0.82 to 0.90. Spring frost risk projections throughout the 21st century were performed for all winegrowing subregions of Bourgogne-Franche-Comté under the RCP8.5 concentration pathway using statistically downscaled 8x8 km daily air temperature and humidity of 14 Global Climate Models (GCM). Contrasting results with region-specific spring frost risk trends were observed. Four out of six models show a decrease in the frequency of frost years across the whole study area while the other two show an increase that is more or less pronounced.

Introduction

Unlike other phenological stages of the vegetation season, which are fairly well simulated by a straightforward modelling approach such as the cumulation of degree days (Parker et al., 2011), the simulation of the budbreak date is improved by the use of complex models that integrate both cold and heat effects (García de Cortázar-Atauri et al., 2009). Accurate predictions of the budbreak date are essential when assessing whether climate change is causing the risk of spring frost to increase, maintain or decrease. Contrasting results regarding the expected evolution of spring frost risk by the end of the 21st century have been observed in large parts of the French winegrowing regions (Sgubin et al., 2018). This change seems to be sensitive to the choice of the budburst model but also to the present and future regional climate conditions. In some regions, such as Champagne, the risk projections for spring frost seem to be reversed (either an increase or decrease in risk are being projected by the end of the 21st century) depending on the chosen phenological model. The accuracy of the forecasted budbreak date is all the more crucial as, to our knowledge, all late grapevines spring frost projections (Molitor et al., 2014; Mosedale et al., 2015; Sgubin et al., 2018) are using a binary approach when considering their sensitivity to subzero temperatures. On one hand, sensitivity to low temperatures before budbreak isn't taken into account and therefor no damage to the plant is conceivable, while on the other hand damage to the vine after budbreak is considered as soon as the minimum temperature alone (Molitor et al., 2014) or the minimum and the average temperatures get below a given threshold (Mosedale et al., 2015). These approaches have two limitations: first, the binary aspect of the pre- and post-budbreak exposure to risk of frost simplifies the field reality. The sensitivity of grapevines to cold during eco-dormancy is indeed gradual and albeit its rapid increase as budbreak approaches damage to the vines can nevertheless occur at relatively high negative temperatures prior to budbreak (Itier et al., 1991). And second, these approaches have never been confronted to any field data for validation purposes: the simulated budbreak date is compared with observed budbreak dates, but not the simulated damage.

The purpose of this study is to bridge these two limitations by (1) proposing a frost model that simulates a dynamic sensitivity of grapevine to frost and (2) integrating a historical database of observed frost damage. This database makes it possible to optimize and evaluate the performance of these models while considering the resistance/sensitivity of the vine before and after budbreak.

Materials and methods

Study area and data

The study was carried out in the Burgundy and Jura winegrowing regions which are located in the central-eastern part of France as illustrated in figure 1. The frost risk simulations were carried out exclusively for the *Vitis vinifera* Chardonnay variety as it is the most cultivated grape throughout all the 6 different subregions of the above-mentioned study area.

In order to parametrize and assess the agroclimatic modelling of spring frost risk a historical database of frost events having occurred in the Chablis subregion (4820 ha spread across 30/40 km east-west/north-south

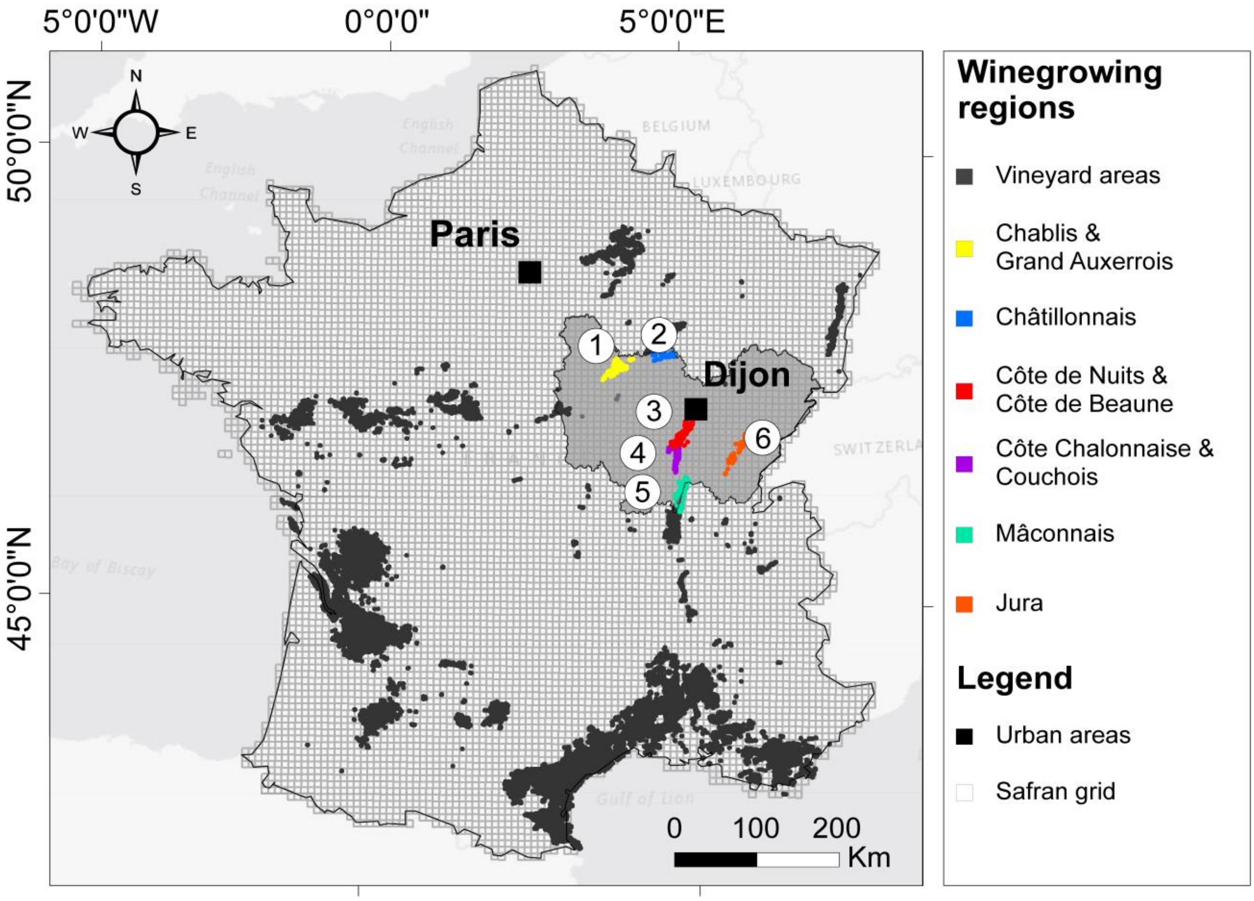

Figure 1. The geographical location of Burgundy and Jura winegrowing regions (colored) among French vineyards (black). The encircled numbers as well as the different colors corresponds to one of the 6 winegrowing subregions considered for this study: 1) Chablis (yellow); 2) Châtillonnais (blue); 3) Côte de Nuits & Côte de Beaune (red); 4) Côte Chalonnaise (violet); 5) Mâconnais (cyan); 6) Jura (orange). The SAFRAN grid (gray fine lines) corresponds to the same 8 x 8 km spatial resolution in the 14 GCMs used in this study for the future projections of frost risk.

approximately, Figure 1) was compiled. The information relative to spring frost occurrences was mostly collected from public institutions such as the Chambre d'Agriculture but also from winegrowers/historians that have documented and later archived all details in regards to historical spring frost events that have caused more or less damage to the vineyards. This allowed us to develop a database spanning a total of 150 years, from 1872 to 2021.

This database was confronted with the frost stress simulated by the agroclimatic models using as input daily minimum and maximum temperatures collected at a Météo France station (47°49' N, 3°47' E) located in the very core of the Chablis vineyard. The temperature data recorded by the station covers the period 1964-2020. The relative humidity data was extracted from the nearest grid-point from the the SAFRAN-Isba-Modcou SIM database (Vidal et al., 2010) as data for this variable was limited to only a handful of years for the in-situ Chablis station.

The risk of spring frost was projected over the 1976-2100 period for the various agroclimatic models supplied by daily temperatures and relative humidity extracted from the downscaled climate projections database (Zito, Sébastien et al., 2021). This database contains climate data generated for multiple general circulation models (GCM) under different representative concentration pathways (RCP) as part of the CMIP5 exercise (Taylor et al., 2012, p. 5) that was statically downscaled at a spatial resolution of 8 x 8 km across the whole metropolitan France using as a basis the SAFRAN database. Data corresponding to one given pathway (RCP8.5) was extracted from a total of 14 GCMs that integrated both air temperature and humidity.

Frost models

Two approaches to simulate spring frost have been confronted. The first assumes that grapevines are sensitive to below zero temperatures only after budbreak and that damage appears on green tissues only when the minimum air temperature at 2 m falls below this threshold. Four budburst models were compared using this approach. One of the models, the GDD5, is based on a simple cumulation of degrees days greater than 5°C (García de Cortázar-Atauri et al., 2009) while the other three combine sums of cooling units to simulate the dormancy rise and then sums of warming action to simulate the budbreak date. Among these models we mention BRIN (García de Cortázar-Atauri et al., 2009), Fenovitis (Caffarra & Eccel, 2010) and Smoothed-Utah/Wang and Engel models (hereafter referred to as SU). The later was adapted to the physiology of grapevines by Morales-Castilla et al. (2020). The threshold value for these models is -1°C.

The second approach is to dynamically simulate the Hc resistance threshold on a daily basis. For this we used the thermal time model proposed by Ferguson et al. (2011, 2014). This model simulates a cold resistance Hc value (also known as hardiness) for each day between the months of July of year j and June of year $j+1$ and whose response decreases to the daily temperature of the previous day (hardening of the buds). Once a certain amount of cold units has been reached (dormancy break) Hc then starts increasing as fast as the temperature rises. The first simulations showed that during vintages with milder winter conditions dormancy was never reached in our study area. For these specific years the dormancy is forced to break with the SU model.

Before budbreak, moistened vine buds are more sensitive to frost (Itier et al., 1991). We therefore shifted the Hc value simulated using the Ferguson model by 3.5°C on days with more than 85 % maximum relative humidity, a threshold proposed by Zito et al. (2020) for the estimation of leaf wetness. However, Hc cannot exceed the maximum value of Hc corresponding to the maximum sensitivity (-1.2°C) of the vine as measured by Ferguson et al. (2014). We, therefore, propose two versions of the same model for comparison: FergSU, ignoring the effect of relative humidity and FergSUwet, simulating a greater sensitivity as a function of relative humidity.

For the 6 models used (GDD5, BRIN, Fenovitis, SU, FergSU, FergSUwet), we calculate, for each day of the period between March 1st and June 30th, the daily thermal stress S_d which the grapevines are exposed to as follows:

$$Sd = Hc, d - Tnd - dT$$

In the above equation $H_{c,d}$ is the cold resistance threshold of the vine on day d, set at 0°C after budbreak for models GDD5, BRIN, Fenovits, SU, and varying daily for FergSU and FergSUwet. Tn_d is the minimum daily temperature at 2 m and dT is the difference between the air temperature at the vegetation level and that recorded at 2 m. This parameter was estimated in average at a value of 1°C following the analysis of a long time series climate data measured at several heights (results not shown). S_n is the sum of the daily cold thermal stress caused by frost events between March and June of the current year. Frost damage occurs when S_n is higher than the damage threshold T_d. Several values of this threshold have been tested by comparing them to the actual occurrence of damage reported in the Chablis region. The T_d value with the highest ratio of reproducing the occurrence/absence of observed years with frost damage is considered as the optimum threshold T_{opt}.This parameter was later used to simulate frost damage occurrence in other regions/periods.

Results and discussion

Models' optimization

For each year of the 1964-2020 period, frost years with grapevine damage were identified when $S_n > T_d$ was simulated with the Chablis weather station data and compared to the observed frost damage years reported in Chablis. Several thresholds T_d (incrementally increasing by 0.5°C, starting from 0.5 up to the maximum value simulated by each frost model with Chablis climate data have been tested as depicted in Table 1. T_{opt} is the optimal threshold above which the yearly frost stress cumulation S_n best reproduces the occurrence/absence of a frost year with damage. The performance of each frost model with each T_d has been assessed by Cohen's kappa coefficient (Cohen, 1960). Table 1 provides the T_{opt} value and the corresponding maximum κ_{max} for each of the 6 frost models optimized with the Chablis climate and frost damage report data.

Table 1. Optimization of grapevine thermal stress models. The optimal cumulated stress threshold T_{opt} corresponds to T_d for which Cohen's kappa value reaches its maximum value. The number of thresholds tested depends on the frost stress range simulated by each model as well as the interval of variation which in this case was set every 0.5°C.

	κmax	***Topt***	***Frost stress range***	***No. thresholds***
GDD5	0.68	6.50	0.0 - 42.5	86
BRIN	0.79	6.50	0.0 - 55.5	109
Fenovitis	0.72	9.50	0.2 - 47.5	94
SU	0.69	5.50	0.0 - 38.0	75
Ferg.SU	0.65	0.10	0.0 - 18.0	37
Ferg.SUwet	0.65	3.50	0.0 - 34.5	70

The highest value of κ_{max} was obtained using the BRIN model. That is, BRIN is the model to reproduce frost occurrence/absence in Chablis with the highest success ratio. GDD5 and SU reached similar performances when simulating frost damage years despite SU having been reported to simulated budburst more accurately than BRIN (Morales-Castilla et al., 2020) while GDD5 doing so less accurately (García de Cortázar-Atauri et al., 2009). Dynamic modelling (i.e., FergSU and FergSUwet) optimization led to a poorer performance in comparison to binary approaches. Nevertheless, and keeping in mind that a value of 1 of kappa's coefficient corresponds to a perfect agreement while a value of 0 is an agreement reached by chance, all models simulate frost damage occurrence/absence with *substantial* agreement (kappa ranging from 0.6 to 0.8 ; see Sun, 2011). T_{opt} varies according to each model, ranging from 0.1 (Ferguson dynamical approach without accounting for bud wetness Ferg.SU) to 9.5 (binary approach using Fenovitis budburst model). Binary approaches all show that frost events occur when enough frost-related thermal stress is reached. Prior studies simulating grapevine spring frost usually consider that damage occurs only when minimum (and average in some cases) temperature after budburst gets below a given threshold often in the case of a onetime event (Molitor et al., 2014; Sgubin et al., 2018). However, from a physiological point of view frost damage can occur as a result of the multiple cumulated cold stresses that can be reached in one or more days, as shown for winter pea by Castel et al. (2017).

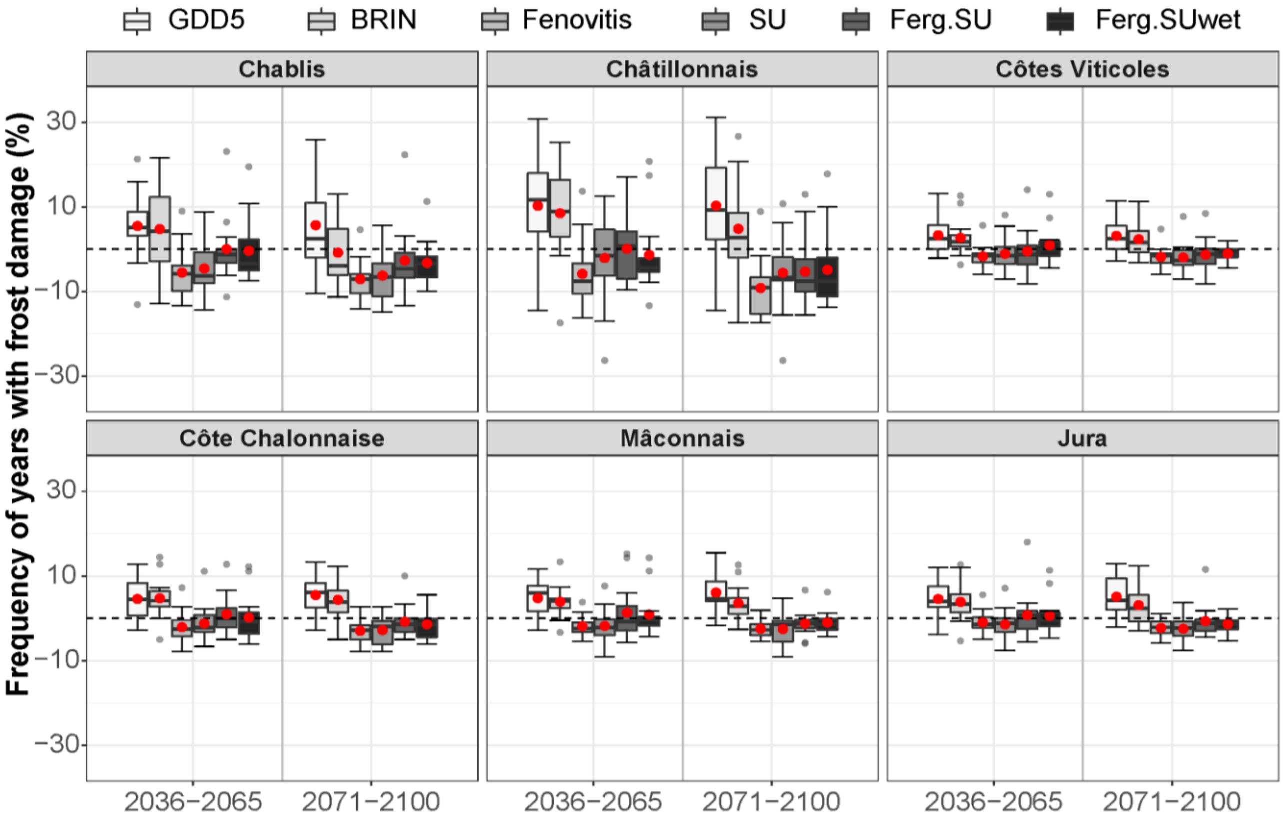

Figure 2. Percentage change of the frequency of years with grapevines frost damage in the 6 winegrowing subregions of Burgundy and Jura for 2036-2065 and 2071-2100, relative to 1976-2005. Simulations were computed under the RCP8.5 pathway based on temperature and humidity data derived from 14 GCMs. Each of the 6 boxplots corresponds to one of the following thermal stress models (from lighter to darker grays): GDD5, BRIN, Fenovitis, SU, Ferg.SU and Ferg.SUwet. The red dots indicate the mean value of the percentage change for the 14 GCMs by winegrowing subregion, thermal stress model and time period.

Projections

Using T_{opt} allowed us to calculate the frequency of frost years when damage to grapevines occurs for the 1976-2005, 2036-2065 and 2071-2100 time periods. Figure 2 compares the distributions and asymmetries of frost frequency anomalies simulated under the RCP8.5 concentration pathway for the middle and end of the century based on data derived from an ensemble of 14 GCMs. Both GDD5 and BRIN thermal stress models point, almost systematically, to an increase in the frequency of frost years regardless of winegrowing location. This is equally reflected in the response of climate models that, despite them exhibiting different percentages of change, indicate an upward general trend in frost years frequency with grapevine damage. In the case of GDD5 significant changes ranging in average from 3.3 to 10.3% are to be expected across the whole study area by the end of the 21st century. Furthermore, the northern and southern most winegrowing subregions (corresponding to 1, 2 and 5 on figure 1) seem to be the most vulnerable as the frequency in frost years indicates the largest increase (10.3, 5.7 and 6.1%, respectively). BRIN, on the other hand, shows a strong but less pronounced increase compared to GDD5 for 2036-2065 and that, in average, tends to either slow down or maintain by 2100 throughout all subregions.

In regards to the evolution of grapevines frost years frequency for the remainder thermal stress models, all of them indicate either a decrease or a maintenance of frost risk levels for the late 21st century. GCM intermodel variably is limited in most winegrowing subregions compared to the two frost models previously mentioned with the exception of the north-northwestern part of the study area. According to Fenovitis and SU, models with the largest decrease projected, a significant difference ranging from 1.8 (2.0) to 9.2% (6.2%) depending on subregion is expected for 2071-2100. Winegrowing areas such as Chablis and Châtillonnais seem to be yet again the most sensitive to the evolution of frost frequency under warmer conditions, registering a decrease of 7.1 and 9.2% as projected by Fenovitis and 6.2 and 5.6%, respectively using SU. The dynamical models, for their part, show no significant evolution of frost years frequency at mid-century. However, a significant but less notable decrease in 2100 for the model integrating the relative humidity (Ferg.SUwet) is only observed in the Chablis, Châtillonnais, Côtes Viticoles and Jura subregions while this is valid only for the Châtillonnais in the case of Ferg.SU.

Conclusion

In this study we examined the historical and future impacts of spring frost occurrence on grapevines using two modeling approaches: binary and dynamical. 21st century frost risk projections were simulated based on six field validated thermal stress models that integrated both air temperature and humidity derived from 14 GCMs. Our results show uncertainties in the projected frequency of frost years with damage on grapevines steaming from the variability among thermal stress and climate models. Projected changes show a downward trend for four frost stress models, dynamical ones included, while the other two show an increase independently of winegrowing subregion. The models BRIN and GDD5 that integrate a binary approach to frost risk simulation, although highly evaluated by the kappa coefficient (0.79 and 0.68), display an evolution marked by a strong climate intermodel variability. Furthermore, in spite of being a widely used statistical measure, the kappa coefficient may prove sensitive to imbalance distribution among classes (i.e. marginal probability) and therefor be difficult to interpret (Cohen, 1960). Despite these uncertainties the range of changes in frost risk is substantially larger, be it an increase or a decrease, in the parts of our study area that are presently among the most impacted by the occurrence of spring frost. As suggested by the recent frost events, spring frost risk evolution that might lead to grapevine damage is not unambiguous suggesting subtle balance between climate change pattern and grapevines vulnerability.

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