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The risk of tardive frost damage in French vineyards in a changing climate

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ABSTRACT

Tardive frosts, *i.e.* frost events occurring after grapevine budburst, are a significant risk for viticultural practices, which have recently caused substantial yield losses over different winegrowing regions of France, *e.g.* in 2016 and 2017. So far, it is unclear whether the frequency of late frosts events is destined to increase or decrease under future climatic conditions. Here, we assess the risk of tardive frosts for the French vineyards throughout the 21st century by analyzing temperature projections from eight climate models and their statistical regional downscaling. Our approach consists in comparing the statistical occurrences of the last frost (day of the year) and the characteristic budburst date for nine grapevine varieties as simulated by three different phenological models. Climate models qualitatively agree in projecting a gradual increase in temperature all over the France, which generally produces both an earlier characteristic last frost day and an earlier characteristic budburst date. However, the latter notably depends on the specific phenological model, implying a large uncertainty in assessing the risk exposure. Overall, we identified Alsace, Burgundy and Champagne as the most vulnerable regions, where the probability of tardive frost is projected to significantly increase throughout the 21st century for two out of three phenological models. The third phenological model produces opposite results, but the comparison between simulated budburst dates and observed records over the last 60 years suggests its lower reliability. Nevertheless, for a more trustworthy risk assessment, the validity of the budburst models should be accurately tested also for warmer climate conditions, in order to narrow down the associated large uncertainty.

1. Introduction

The development of the grapevine (*Vitis vinifera* L.) follows three main phenological stages, *i.e.* budburst, flowering, veraison, whose timing can significantly determine both the yield and the quality of the crop. The achievement of each phenological stage is predominantly a temperature-driven process (Jones and Davis, 2000; van Leeuwen et al., 2008; Parker et al., 2011, 2013), and the on-going climate change (IPCC, 2013) is currently accelerating all the developmental stages of grapevine in most of the winemaking regions of the globe (Jones et al., 2005; Mira de Orduña 2010; Webb et al., 2011). Future projections suggest that the global warming trend will continue throughout the 21st century (IPCC, 2013), thus potentially further anticipating grapevine phenological phases (Webb et al., 2007; Fraga et al., 2016). Concerning French vineyards, Duchêne et al. (2010) showed that by the end of the 21st century phenological stages in Alsace may advance from by 8–11 days for budburst and up to 16–24 days for veraison of Riesling and Gewurztraminer varieties. Xu et al. (2012) estimated that within the next 30 years flowering and veraison dates may respectively occur 8 and 12 days earlier than present for Pinot noir in Burgundy. Cuccia et al. (2014) assessed that climate conditions 3–5 °C warmer than present may advance the characteristic date of veraison by 3–5 weeks for Pinot noir in Burgundy, while a similar precocity was found for the typical varieties of southern France under an increase of 2–4 °C (Lebon, 2002). In general, the contraction of each phenological phase may yield a precocity of the harvest over France, whose characteristic dates at the end of the 21st century may fall up to 40 days earlier than the current ones (Pieri, 2010; Ollat and Touzard, 2014).

The grapevine budburst process is mainly regulated by the temperature (Garcia de Cortazar-Atauri et al., 2009). Bud development is preceded by a "rest" phase, called endodormancy, during which vegetative growth is physiologically blocked, and by a "quiescence" phase, called ecodormancy, during which unsuitable temperature conditions inhibit the vegetative growth (Sarvas, 1974). Thus, new buds are able

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to grow after the endodormancy break when environmental conditions become favorable (Chuine, 2000). We classically consider that after a certain exposure to cold temperature (chilling state), the endodormancy status is broken and the action of the accumulated heat (forcing state) starts to be effective for the bud development (Chuine et al., 2003; Garcia de Cortazar-Atauri et al., 2009). Then, after a certain exposure to warm temperatures, this phase culminates with the budburst. Budburst is therefore a key stage for grapevine as it marks the beginning of the growth cycle after dormancy, thus influencing the overall yield and the timing of subsequent phenological stages. In the northern hemisphere, depending on the grape variety and on the local climate, buds commonly break between late winter and early spring. In this phase, the new growing shoots, characterized by high water content, become much more susceptible to freezing temperature than during the winter (Trought et al., 1999). Therefore, an anticipated budburst due to the expected global warming raises the issue of *tardive frosts*, *i.e.* cold events occurring after bud break. A premature budburst may indeed increase the risk to expose the growing tissues to critical cold temperature under which the young shoots may be destroyed. The critical temperature at which a chill injury occurs depends on the growing stage reached as well as on the type of cold event, *i.e.* hoar frost, black frost or freeze (Perry, 1998; Poling, 2008). During budburst, a temperature of −2.2 °C is considered to be lethal for 50% of the buds (Perry, 1998), although temperature around 0 °C can already kill young grape tissues (Trought et al., 1999; Poling, 2008).

A comprehensive analysis of the risks of future tardive frosts in France is missing so far. In particular, it is unclear whether the date of the last frost, which is also expected to recoil under global warming, will advance more than the date of budburst, *i.e.* whether the possibility of damage induced by tardive chill will increase or decrease in the future. Previous studies in other winemaking regions show contrasting results. White et al. (2006) envisaged a general decrease of late frost risks over the United States of America, while Poling (2008) assessed an increased risk in its eastern and mid-west regions. Molitor and Junk (2011) found a widening time gap between the mean last frost and budburst over the last decades in Luxemburg, thus suggesting that the risk of late frost damage has recently decreased under the influence of global warming. It has also been shown that such a local trend is to likely continue for future projections (Molitor et al., 2014). On the contrary, Orlandini et al. (2009) reported that the future earlier budburst is expected to increase the odds of tardive chill in Tuscany (Italy). Also, Mosedale et al. (2015) estimated an increased frequency of late frost events for future projections over the south-west of England. However, these results can be strongly sensitive to the choice of the phenological model for the budburst (Mosedale et al., 2015).

The present work aims at assessing the potential risk of tardive frosts for future climate conditions over France by means of a set of 8 global climate models' projections downscaled at the regional scale. Results are based on a statistical comparison between future trends in budburst and last frost timing. In particular, budburst dates have been calculated by adopting three different phenological models based on the temperature evolution provided by climate model simulations. Overall, our results reveal the qualitative possibility for tardive frost events to increase in the future, notably in the continental regions of France, while in coastal regions this risk is estimated to remain very low or to vanish throughout the 21st century. However, we also show that our assessment strongly depends on the choice of the budburst model, and, to a lesser extent, on the climate model considered.

2. Methods and material

To estimate the risk of tardive frosts in future projections at regional scale, we calculated (*i*) the budburst day and (*ii*) the date of last frost for each single year of climate model projections over France. The method for their calculation can be divided into three main steps:

- Simulation of future climate by means of 8 ocean-atmosphere general circulation climate models (GCM) under RCP8.5 scenario, *i.e.* ACCESS1-3, bcc-csm1-1-m, CanESM2, BNU-ESM, CSIRO-Mk3-6-0, IPSL-CM5A-MR, MIROC5, Nor-ESM1-M.
- Downscaling of the GCM outputs over France.
- Coupling of the downscaled air temperature data with phenological models for budburst stage.

All these procedures imply the use of different climatic and phenological datasets.

2.1. Climate data

For the scope of the present work, we used both past climate data and future projections. Global and regional historical data were necessary to identify statistical relationship for the downscaling process (Section 2.2). For the large scale, we used European Center for Medium-Range Weather Forecast (ECMWF) reanalysis (ERA-Interim) data (Dee et al., 2011), which cover the period from 1979 to present.

We also used higher resolution data from the Safran analysis (Quintana-Segui, 2008; Vidal et al., 2010), which are based on surface observations collected by Météo-France over the period 1959–2015. This dataset consists in hourly and daily temperature data projected on an 8 × 8 km regular grid over France computed through an optimal interpolation algorithm. Safran data have been also used to validate the budburst phenological models (Section 2.3).

Climatic projections are based on simulations of 8 climate models participating to the fifth Coupled Model Intercomparison Project (CMIP5), which provide daily data from 1979 to 2100. Model simulations take into account different emission scenarios from 2006 to 2100, *i.e.* RCP scenarios (Meinshausen et al., 2011), and include a common historical period. However, CMIP5 models run at coarse spatial resolution (around 100 km), which does not allow solving important subgrid scale processes such as those associated with the orography (typically at a scale of a few kilometers).

2.2. Statistical downscaling data

Low-resolution CMIP5 outputs have been projected on a finer grid through statistical downscaling, thus allowing an impact analysis at the regional scale over France. The rationale behind the statistical downscaling stems from the idea that the regional climate depends on the interaction between large-scale meteorological state and local features. Methods of statistical downscaling (see Goodess et al., 2009; Maraun et al. 2010 for a review) consist in establishing an empirical statistical relationship between large-scale variables (predictors) and regional scale variables (predictants) from a set of observational data over a common period called training period. Once the statistical relationships have been established for this period, these can be transferred over a different period and for a different set of low-resolution data, *e.g.* CMIP5 projections as in this study. Thus, statistical downscaling assumes the temporal transferability of the observed statistical relation.

Here we used the *analog* method (Lorenz, 1969), which consists in a re-sampling of the observed atmospheric states. In its formulation proposed by Dayon et al. (2015), statistical relationships between predictors and predictants have been built by comparing low-resolution ERA-Interim data and regional scale Safran data. According to this method, the combination of 7 predictors (sea-level pressure, surface air temperature, air temperature at 500 hPa and 850 hPa, dew point temperature at 850 hPa, specific humidity at 850 hPa and module of moisture flux at 850 hPa) enables to estimate the 2 m air temperature (predictant) over France at finer spatial scale, *i.e.* at a resolution of 8 km for a total of 9892 grid points.

The analog method has the main advantage of maintaining the inter-variable and spatial consistency. Yet, this method may be limited by its inability to reproduce atmospheric states that have not been