THERMAL RISK ASSESSMENT FOR VITICULTURE USING MONTHLY TEMPERATURE DATA

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Abstract

Temperature extremes affect grapevine physiology, as well as grape quality and production. In most grape growing regions, frost or heat wave events are rare and as such conducting a risk analysis using robust statistics makes the use of long term daily data necessary. However, daily climate data suffers many constraints such as typically having a short-term history, with uneven spatial coverage worldwide, and their homogenization to account for changes in climate sensors or changes in site location are challenging. In contrast, monthly data sets offer a much more robust spatiotemporal coverage. Furthermore, data at monthly time steps is relevant for climate projection analyses over the 21st century. Therefore, the current study evaluates the relevance of estimating thermal risks for viticulture using monthly data. Daily minimum (Tmin) and maximum (Tmax) temperature data were collected from 369 weather stations in Europe (European Climate Assessment & Dataset) and 1218 weather stations in the USA (United States Historical Climatology Network) for the period from 1972 to 2008. For the whole period and for each station, the average yearly number of winter freeze days (Tmin < -17°C), spring frost days (Tmin < -1°C), and heat stress days (Tmax > 35°C) were calculated. In addition, frequencies of years with at least one spring frost event, the date of the last spring frost event at 90% probability (i.e. the quantile 0.9) and frequencies of years with at least one winter freeze event were calculated. These thermal risk indicators, analyzed on a daily time step, exhibited strong relationships with maximum and minimum monthly average temperatures during the 1972-2008 period. Winter freeze risk is strongly linked to January average monthly minimum temperature, while spring frost risk is related to April minimum monthly temperature. The average number of heat stress days is strongly correlated to July maximum temperature. Using WorldClim 5 arc-minute resolution climate grids, a winter frost risk map for the 1950-2000 period is proposed. The results suggest that grape growing region limits are strongly restrained by winter freeze risk hazards.

Keywords: Thermal risks, climate, viticulture, WFR, SFR, HST

1 INTRODUCTION

The expansion of viticulture worldwide is driven by many factors, amongst which temperature suitability is considered as a major driving factor (Schultz and Jones 2010). Higher temperatures reduce carbon assimilation (Luo et al. 2011), increase grape malate and anthocyanin content (Buttrose et al. 1971; Rienth et al. 2014), modify grape aromatic compounds (Marais 1998) and affects grape water status (which contributes as well to changes in grape physiology and grape physico-chemical features) via evaporative demand. Viticulture potential in constantly warm (e.g. in tropical humid climate) or desert areas for wine production are therefore limited and require specific efforts to cultivate grapevines. At higher latitudes or higher elevation, frost occurrence and timing prevent grape production, even if these boundaries are being expanded with climate change (Malheiro et al. 2010; Schultz and Jones 2010; Hannah et al. 2013). When evaluating viticulture potential based on climate suitability and risk, it is crucial to assess regional economic sustainability of grape or wine production. Developing an extreme temperature-related risk assessment requires long-term daily data records to provide a reliable metrics. However, daily time steps suffer several drawbacks, when compared to monthly averages: (1) there are generally fewer data series are available; (2) the spatial coverage is not even; (3) the large quantity of data can be challenging to manage; and (4) daily data homogenization to account for artificial temperature shifts introduced by changes in site, sensor or radiation shield throughout station history is challenging. To help address these issues, the current study proposes to estimate thermal risks for viticulture using long term averages of monthly minimum and maximum temperatures as proxies for daily data.

2 MATERIAL AND METHODS

Climate station data

Daily minimum and maximum temperature data was extracted from the European Climate Assessment (ECA) data set (Klein Tank et al. 2002) and the United States Historical Climatology Network (USHCN) daily temperature data set (Menne et al. 2013) for the 1972-2008 period. A total 1587 stations were used. These stations are located from 24.55 to 76.50°N. We thus consider that our study is valid for areas located between this range of latitudes (Figure 1). To evaluate the representativeness of this network of stations, we identified the Köppen-Geiger climate group for each station, using the updated classification map by Peel et al. (2007), which consists of a raster grid at 10’ resolution (i.e. about 17 km at equator). Stations used in the current study cover 20 of the 32 Köppen-Geiger climate classes worldwide. Most of the stations are located in “Cold” (747 stations), “Temperate” (515) and “Arid” (232) climate groups, while Tropical (3) and Polar (12) climates are have few stations. The Köppen climate classes of a few stations (78) could not be identified. This because they are located in areas which are not referenced by the Peel et al. (2007) dataset (mostly island or coastal locations). Grape growing regions worldwide are mostly located in areas with Köppen Climate types identical to those of the weather stations used in this study (Figure 1).

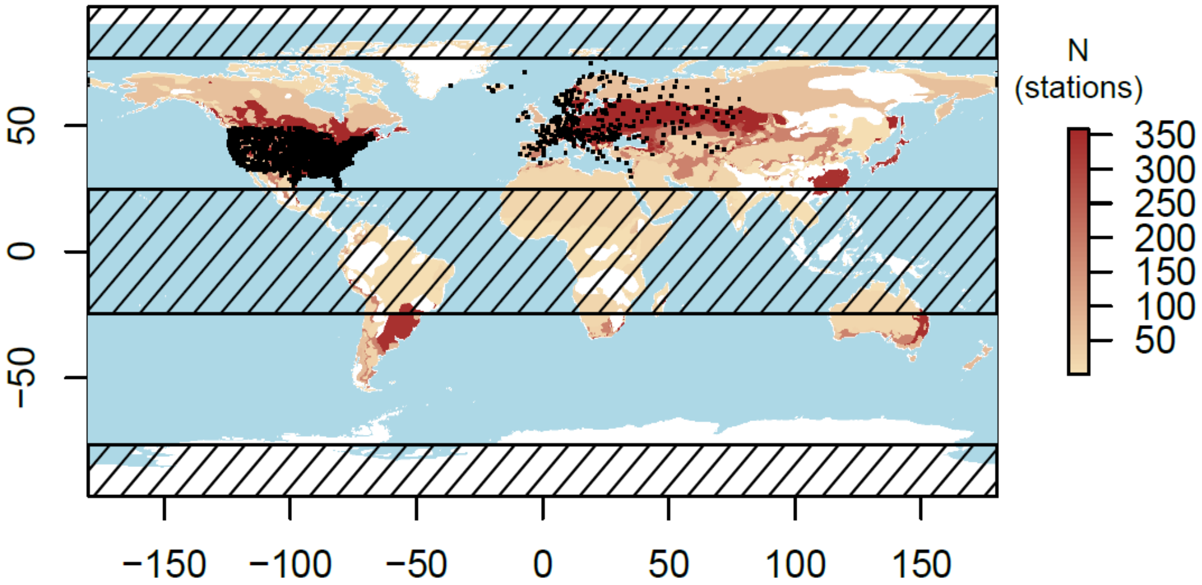

Figure 1: Location of the 1587 weather stations used in the current study. The background map corresponds to the Köppen-Geiger updated raster at 10’ resolution (Peel et al. 2007). Each Köppen climate group is colored as function of the number of climate stations belonging to the same climate group. The dashed areas indicate zones located beyond the latitude ranges of the climate stations used in this study.

Indices

For each station, a risks assessment from long term minimum and maximum temperature data averages was calculated. Table 1 indicates the acronyms used for all the indices and the calculation procedures. Each index is calculated for each of the 1587 stations.

Table 1: Indices used in the current study

Index	Acronym	Formula*	Period within the year
Monthly minimum temperature	TN*i*	$\frac{1}{n}\sum_{j=1972}^{2008} Tn_{i,j}$	month *i*
Monthly maximum temperature	TX*i*	$\frac{1}{n}\sum_{j=1972}^{2008} Tx_{i,j}$	month *i*
Annual monthly minimum temperature amplitude	ATN	max(TNi) – min(TNi)	
Average number of spring frost days per year	nSFR	$\frac{1}{n}\sum_{j=1972}^{2008}\sum_{k=91}^{151}\begin{cases}0 & if\ \ Tn_{k,j} < -1 \\ 1 & if\ \ Tn_{k,j} \geq -1\end{cases}$	April to May
Frequency of years with at least one spring frost event (Tmin < -1°C)	fSFR	$nSFR_j = \sum_{k=91}^{151}\begin{cases}0, & Tn_k < -1 \\ 1, & Tn_k \geq -1\end{cases}$ $\text{fSFR} = \frac{1}{n}\sum_{j=1972}^{2008}\begin{cases}0, & nSFR_j = 0 \\ 1, & nSFR_j < 1\end{cases}$	April to May

9th decile of last spring frost day of the year (10% risk of a frost event after this date)	q90	$Q(0.9)$	January to August
Average number of winter freezes (Tmin < -17°C)	nWFR	$\frac{1}{n}\sum_{j=1973}^{2008}\sum_{\substack{k=305\\j=j-1}}^{\substack{90\\j=j}}\begin{cases}0, & Tn_{k,j} < -17\\1, & Tn_{k,j} \geq -17\end{cases}$	November to March
Frequency of years with at least one winter freeze event (Tmin < -17°C)	fWFR	$nWFR_j = \sum_{\substack{k=305\\j=j-1}}^{\substack{90\\j=j}}\begin{cases}0, & Tn_{k,j} < -17\\1, & Tn_{k,j} \geq -17\end{cases}$ $\text{fWFR} = \frac{1}{n}\sum_{j=1973}^{2008}\begin{cases}0 & if\ nWFR_j = 0\\1 & if\ nWFR_j < 1\end{cases}$	November to March
Average number of heat stress days during summer (Tmax > 35°C)	nHST	$\frac{1}{n}\sum_{j=1972}^{2008}\sum_{k=152}^{243}\begin{cases}0, & Tx_{k,j} > 35\\1, & Tx_{k,j} \leq 35\end{cases}$	June to August

**Tn* is the minimum temperature, *Tx* is the maximum temperature, *i* is the month of the year, *n* is the number of *j* years, *k* is the day of the year, *Q(0.9)* stands for the 9th decile of the last spring frost event (Tn_k < -1) during the January to August period, calculated on using the type 7 approach as given by Hyndman and Fan (1996).

3 RESULTS AND DISCUSSION

Monthly minimum and maximum temperatures are relevant indicators for thermal risk evaluation

The link between each minimum / maximum temperature of each month and the thermal risk indices were evaluated by means of a correlation coefficient analysis (results not shown). Spring frost related indices (nSFR, fSFR and Q90) exhibit the strongest relationship with the average minimum temperature of April (TN4). Winter freeze indices (nWFR and fWFR) are strongly correlated to January average minimum temperature (TN1). The highest correlation for heat stress days (nHST) was reached with July average maximum temperature (TX7).

Spring frost event counts during spring (nSFR, Figure 2a) decreases in an exponential manner as TN4 increases. This decreasing exponential shape reaches an asymptote (no frost event) when TN4 is around 10°C. When April average minimum temperature falls below 0°C, nSFR increases linearly as minimum April temperature decreases (Figure 2a) and at least one April-to-May-frost event occur each year (fSFR = 1, Figure 2b).

Figure 2b clearly shows two groups of data, presenting similar decreasing sigmoid relationships between fSFR and TN4, but with a shift in the x-axis (TN4) of about 3°C. The first group (yellow dots, Figure 2a-c) corresponds to climate stations where the yearly range of monthly minimum temperature (ATN) is below 20°C. For these locations, frost events after April are very rare when TN4 is around 8°C (or more). At such TN4 values that combined into the second group (blue dots, Figure 2a-c), many climate stations still exhibit a considerable frequency of spring frost years (fSFR from 0 to 0.9). This second group includes climate stations with considerable annual minimum temperature range (over 20°C), exhibiting a “continental” thermal regime, whereas group 1 corresponds to more temperate areas. For group 1the date of the latest spring frost (at 10% risk level, as expressed by Q90) decreases more rapidly as TN4 rises (Figure 2c). For almost every location, whatever the ATN value, Q90 (date at which spring frost risk is 10% or lower) is reached by April 1st (or before) when TN4 rises over 12°C. As budburst generally occurs during April or later in most of the northern hemisphere grape growing regions, we can consider that little damage caused by spring frost can be expected in such areas. Where TN4 is below -5°C, the 10% frost risk level is reached by the beginning of June (or later), which makes the spring frost hazard considerable in these areas, with probably little chances of a sustainable grape production.

Winter freeze (when minimum temperature reaches -17°C or lower) exhibits similar relationships with January average minimum temperature, as spring frost does with April average minimum temperature. The relationships are homogenous for the entire set of climate stations (no distinction according to climate stations annual minimum temperature amplitude). The average number of winter freezes starts increasing when TN1 falls below 0°C (Figure 2d). A January average minimum temperature of -11°C (or less) indicates that winter freeze occurs every year (Figure 2e). When TN1 is 4°C and over, winter freeze events are very rare (fWFR below 4%). Between -11°C and 4°C, the winter freeze frequency starts increasing rapidly when TN1 falls below 0°C.

Heat stress day counts are strongly related to July average maximum temperature (Figure 2f). When TX7 rises over 30°C, the average number of days during which temperature exceeds 35°C increases linearly (nHST). When TX7 is below 25°C, the average number of heat stress days per year goes to zero.

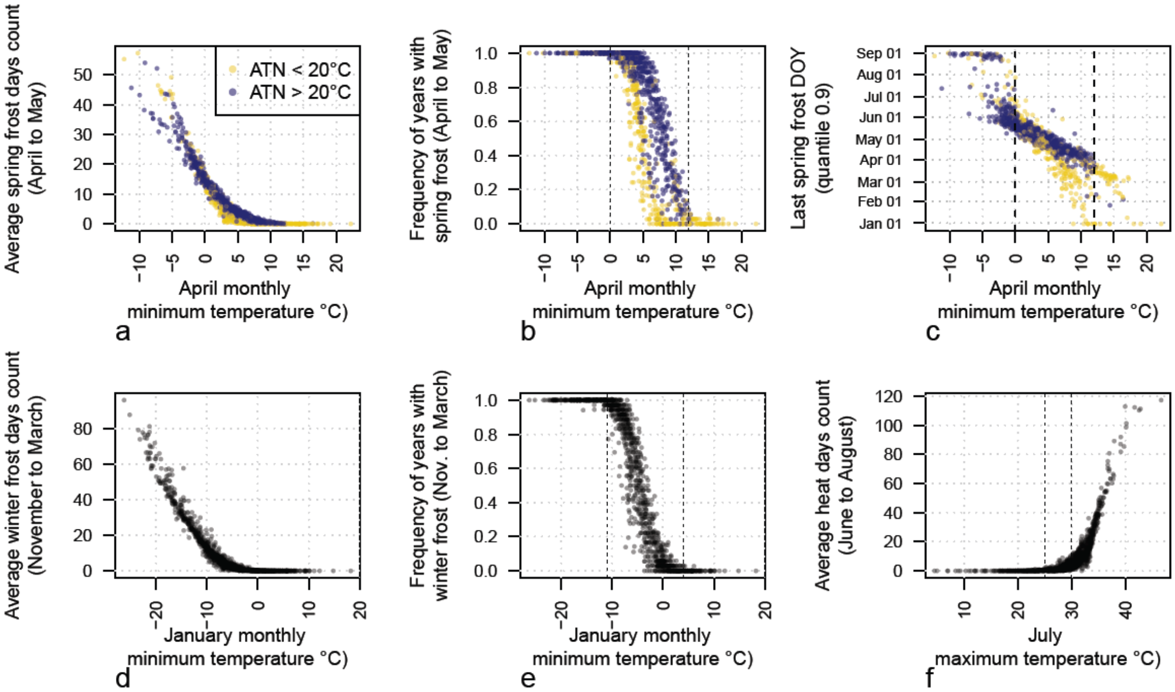

Figure 2: Relationships between monthly temperature averages and thermal risk indices. a: TN4 vs nSFR; b: TN4 vs fSFR; c: TN4 vs Q90; d: TN1 vs nWFR; e: TN1 vs fSFR; f: TX7 vs nHST (see text for acronym definitions).

Exploring the thermal hazard for viticulture worldwide

The relationships between monthly temperature and thermal risks are strong and rather homogenous within the large range of climatic types covered by the data sets used in this study. Considering that similar thermal conditions are reached in the southern hemisphere with a 6 month shift, we propose to use TN7, TN10 and TX1 to evaluate winter freeze, spring frost and heat stress risks, respectively, between 24.5°S and 76.5°S. Therefore, we introduce three thermal indices that could be used as indicators of frost and heat risks for viticulture, within the mid-latitudes (Table 2). These indices would likely require specific adaptations to tropical or equatorial areas because (1) climate data below 24.5° latitude was not used in the current study, (2) thermal characteristics might make it possible to shift the grapevine growth cycle during the year making the reference to minimum and maximum temperature averages of specific months for these areas irrelevant.

Table 2: Thermal risk indices and their specific thresholds

			Key values	
Index Name	Acronym	Details	Low risk	High risk
Winter freeze risk index	WFR	Average of minimum temperature of January (Northern hemisphere) or July (Southern hemisphere)	> 4°C	< -11°C
Spring frost risk index	SFR	Average of minimum temperature of April (Northern hemisphere) or October (Southern hemisphere)	> 12°C	< 0°C
Heat stress index	HST	Average of maximum temperature of July (Northern hemisphere) or January (Southern hemisphere)	< 25°C	> 30°C

The “key” values proposed in Table 2 (see also vertical dotted vertical lines in figure 2b, c, e and f) are derived mostly from the analysis of fSFR, fWFR and nHST. For frost or freeze risks, the low risk values correspond to temperatures over which frost/freeze events are very rare or never occur. On the contrary, one or more frost/freeze events might occur when SFR or WFR exceed the high risk value. In such areas, outdoor grape production requires specific technical adaptations, such as trunk burying during the winter (for winter freezes) or sprinkler-like irrigation systems (for spring frosts). For heat stress, below the low risk value, daily temperature (almost) never exceeds 35°C during summer. The average heat stress day counts vary from 1 to 12 when the heat stress index reaches 30°C. Over this limit, it increases dramatically, and might induce dramatic increases in water conservation strategies and/or affect grapevine carbon assimilation.

As an example of applying the results to mapping these risks globally, we used WFR applied to the WorldClim 1950-2000 monthly temperature gridded data (raster with a resolution of 5' resolution, i.e. about 8 km over the equator, Hijmans et al. 2005). Figure 3 shows that most of the grape growing regions were historically located within "medium" freeze risk areas during the second half of the twentieth century. When compared to the current geography of the winegrowing regions worldwide (see for example the world vineyard map in Schultz and Jones 2010) we observe strong similarities between the actual "world vineyard" extensions and "medium" winter freeze risk region limits (for the 1950-2000 period). Finally, only a few grape growing regions have been located in areas without winter freeze hazards. In eastern Australia, as well as Portugal and southern Italy, winter frost hazard does not occur. In contrast, most of the Canadian vineyard areas have been historically exposed to frequent winter freeze events, where specific cultivars and techniques are developed to adapt grape growing to low winter temperatures.

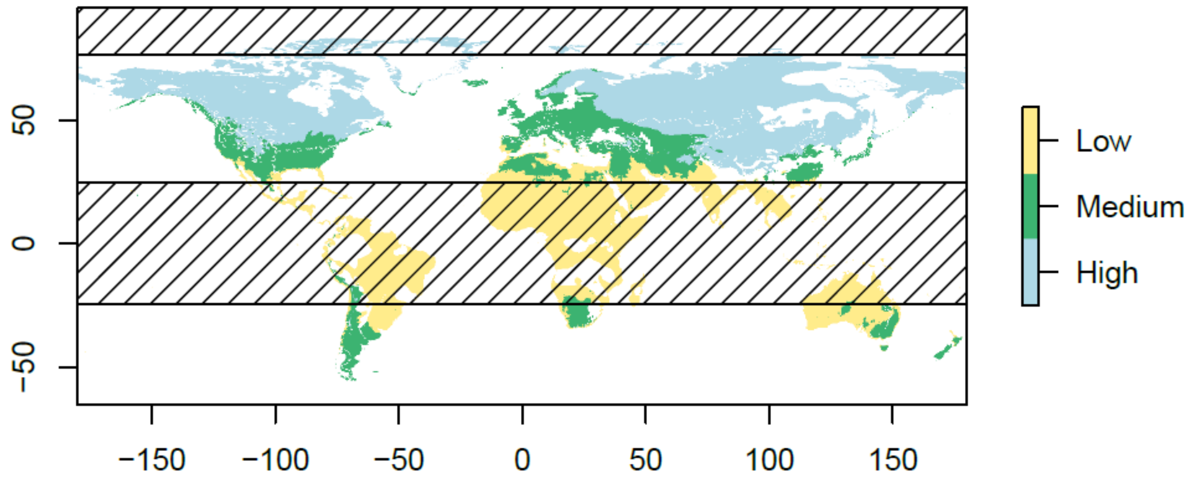

Figure 3: WFR classes as delimited by "key" values presented in Table 2. Low risk areas with WFR > 4°C and high risk areas where WFR < -11°C. WFR values were calculated using the WorldClim 1950-2000 5' resolution gridded database (Hijmans et al. 2005). Zones with climate conditions (Köppen groups) not covered by the 1587 stations used in this study are left blank (e.g. white areas such as a large part of Greenland). Dashed areas correspond to zones outside the latitude ranges cover by the climate stations.

4 CONCLUSIONS

The current study concludes that freeze, frost and extreme heat statistics at the daily time scale are related to monthly temperature averages. Monthly minimum and maximum temperature normals are widespread, have been largely homogenized, and are easy-to-use data. Herein we propose three indices based upon monthly minimum temperatures during winter (WFR) and spring (SFR) and monthly maximum temperatures during summer (HST) to evaluate the potential climatic risks for grape growing regions worldwide. Whereas considerable literature proposes thermal indicators concerning potential grapevine development rate and grape harvest dates, thermal risk indices have not been addressed extensively. Further analysis will propose general equations to more precisely retrieve frequencies, the average number and quantiles of extreme temperature events, based upon long term monthly temperature averages.

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