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Climate change is implicating a two-fold impact on air temperature increase in the ripening period under the conditions of the Luxembourgish grapegrowing region

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ABSTRACT

Aim: Grape (*Vitis vinifera* L.) phenology is mainly temperature-driven. Consequently, the shift in thermal conditions due to climate change is supposed to have a distinct influence on grape phenology, grape maturity and wine typicity. This study aims to investigate (i) the future phenological development, as well as (ii) the consequences on the temperature conditions in specific phenophases under the conditions of the Luxembourg grapegrowing region.

Methods and Results: A budburst model and a phenological model were combined with an ensemble of ten regional climate change projections for Luxembourg. Analyses comparing four 30-year time spans (reference period: 1971-2000; present: 2001-2030; near future: 2031-2060; far future: 2061-2090) demonstrated that each of the 27 phenological stages according to BBCH code is projected to be reached significantly earlier than in the reference period. According to these projections, the length of phenophases at the early stages is not affected, whereas the ripening period length is significantly shortened. The air temperature increase in the ripening period (far future compared to reference period: + 4.6 °C to + 5.3 °C) is projected to be markedly higher than in the annual averages (+ 2.6 °C).

Conclusions: Since (i) air temperatures are generally projected to increase in the future and (ii) the ripening period will take place earlier (usually in the warmer parts of the season), climate change is implicating a two-fold impact on air temperature increase in the ripening period.

Significance and impact of the study: This two-fold impact potentially threatens the wine typicity of the traditional grapegrowing regions and therefore calls for specific adaptation strategies.

KEYWORDS

climate change, cumulative degree days, multi-model ensemble, phenology, ripening temperature

Additional tables can be downloaded from https://oeno-one.eu/article/view/2329

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INTRODUCTION

The grapevine (*Vitis vinifera* L.) is a perennial plant with an annual cycle that is highly dependent on environmental conditions (Parisi *et al.*, 2014). Among them, air temperature represents a central factor for the cultivation of grapevines. In cases where the water, nutrient and radiation requirements of the plants are fulfilled (Nendel, 2010, Webb *et al.*, 2007), thermal conditions control "with only minor other influences" (Gladstones, 2011) grapevine phenology and final grape maturity. Consequently, changes in thermal conditions are impacting grape phenology, grape maturity, wine typicity and, as a last consequence, the economic sustainability of many traditional grapegrowing regions such as Luxembourg, where the wine industry traditionally represents an economically important sector.

On the east- to south-faced vineyards along the Moselle River grapevines have been cultivated since the Roman times. The quality and the quantity of annual wine production in Luxembourg have been documented in a wine chronicle since the beginning of the 9th century A.C. (Molitor *et al.*, 2016b). Nowadays (2017), the total area of the Luxembourgish grapegrowing regions covers 1303 ha between Schengen and Rosport over approximately 42 km along the Moselle River (Anonymous, 2018). The position of the viticultural fields in the Luxembourgish grapegrowing region is depicted in Figure 1. In 2017, most cultivated cultivars were Müller-Thurgau (syn. Rivaner) (23.3% of the total acreage), Pinot gris (15.2%), Auxerrois (14.8%), Pinot blanc (12.6%), Riesling (12.5%), Pinot noir (9.7%) and Elbling (6.1%) (Anonymous, 2018). Total wine production of the region on average of the vintages 2008 to 2017 reached 109 092 hl (Anonymous, 2018).

Worldwide, thermal conditions have significantly changed during recent decades at both global and regional scale. According to the Intergovernmental Panel on Climate Change (IPCC), human influence, primarily the burning of fossil fuels, has been the dominant cause of global warming for several decades (IPCC, 2013). Based on regional climate change projections taken from the ENSEMBLES and the CORDEX projects, an air temperature increase of up to 4 °C – depending on the emission scenario – is projected for Luxembourg by the end of this century (Goergen *et al.*, 2013; Junk *et al.*, 2016). Also, changes in precipitation patterns towards drier summers and wetter winters are projected (Goergen *et al.*, 2013).

Since grape phenological development is predominantly air temperature-driven (e.g., Duchene and Schneider, 2005; Gladstones, 2011; Keller, 2015; Moncur *et al.*, 1989), the projected temperature increase due to climate change will have significant impacts on viticulture, particularly close to the climatic frontiers of viticulture where the dependence of grape phenology and maturity on climatic conditions is most pronounced (Brazdil *et al.*, 2008). Phenology represents a major factor in the distribution of the viticultural areas (Garcia de Cortazar-Atauri *et al.*, 2017). With ongoing climatic change, northern regions are expected to become more suitable (in terms of climatic conditions) for ripening grapes (Jones and Schultz, 2016). In contrast, regions where temperatures are already close to optimum for best wine quality might become too hot to produce high quality wines with balanced fruit in the future (Jones and Schultz, 2016). To assess the viticultural opportunities, risks and challenges related to climate change and furthermore to support the development of adequate adaptation strategies, numerical models simulating the effects of temperature conditions on plant development are helpful tools.

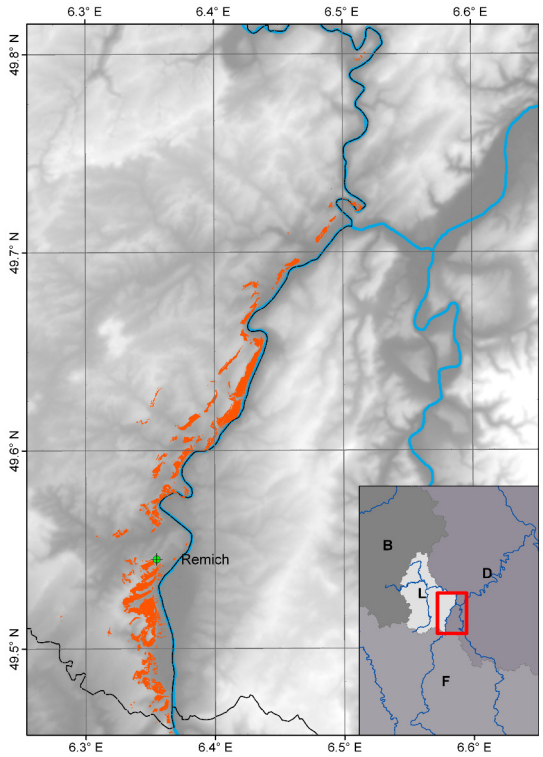


FIGURE 1. The Luxembourgish grapegrowing region. Vineyards are depicted in red, main rivers in blue and borders between countries in black. The weather station used for present investigations is located in Remich.

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Recently, Molitor *et al.* (2014b) developed a high-resolution phenology model covering all 27 BBCH (Biologische Bundesanstalt, Bundessor-tenamt und Chemische Industrie) plant phenological growth stages defined by Lorenz *et al.* (1995) from budburst to grape harvest (i.e., BBCH stage 89 describes "grapes ripe for harvest"). The incorporation of (i) an upper threshold temperature, above which a further increase of the temperature will not accelerate plant development, and (ii) a heat threshold, above which a further increase of the temperature will slow down plant development, in this model have been demonstrated to improve the precision of the model compared to commonly used un-capped cumulative degree day-based phenology models (e.g., Amerine and Winkler, 1944; Duchene *et al.*, 2010; Hoppmann, 2010; Nendel, 2010; Oliveira, 1998; Parker *et al.*, 2011; Schultz, 1992; Zapata *et al.*, 2015). Under increased air temperature, the improvement in precision gained through the incorporation of additional thresholds is expected to be even more pronounced (Molitor *et al.*, 2014b).

Since (i) air temperatures are expected to increase in the future due to climate change and (ii) the ripening period will likely take place earlier, usually in the warmer parts of the season due to faster phenological development driven by higher temperatures, a two-fold impact on air temperature increase in the ripening period could be expected (Duchene *et al.*, 2010), while little is known about the influence of climate change on the temperature conditions in other phenophases. In addition, a temperature increase in the ripening period is expected to alter the typicity of the wine (Jackson and Lombard, 1993).

Consequently, the aim of the present study was to investigate the future phenological development of the cultivars Müller-Thurgau, Riesling and Pinot noir, as well as the consequences on the air temperature conditions in specific phenophases, especially in the ripening period, based on (i) the budburst model of Molitor *et al.* (2014a), (ii) the high-resolution phenological model of Molitor *et al.* (2014b) and (iii) a multi-model ensemble of ten regional climate change projections under the conditions of the Luxembourgish grapegrowing region.

MATERIALS AND METHODS

1. Observation data: daily mean air temperatures Remich 1970-2016

Air temperature data were recorded from 1970 through 2016 by a weather station of the Luxembourgish national agricultural administration ASTA (Administration des services techniques de l'agriculture) located in the centre of the Luxembourgish grapegrowing region in Remich/Luxembourg (49.54° N, 6.35° E; 207 m a.s.l.) (Figure 1). Unventilated air temperatures were measured at 2 m above the ground. Daily mean air temperatures were calculated as averages of daily minimum and maximum temperatures.

2. Modelled data: daily mean air temperatures 1970-2090

Time series of daily mean air temperature between 1970 and 2090 were extracted from the online archives of the EU ENSEMBLES project (http://ensembles-eu.metoffice.com/). In order to assess the uncertainties related to climate change projections, a multi-model ensemble of ten regional climate change projections was used, based on the A1B emission scenario (Supplementary Table 1).

The A1B emission scenario describes anthropogenic emissions of a future world with rapid economic growth until the middle of this century and a balanced use of fossil and non-fossil energy resources (Nakicenovic and Swart, 2000). It is widely used in impact assessments for Central Europe (Junk *et al.*, 2015a; Junk *et al.*, 2015b; Junk *et al.*, 2016; Lokys *et al.*, 2015; Molitor *et al.*, 2014a).

The selected ensemble covers the overall range of the available regional climate models (RCMs) in terms of air temperature change signals and accounts for the most widely used European RCMs (van Pelt *et al.*, 2012). Time series of daily data for Remich were extracted from each RCM. Instead of using the information from just

TABLE 1. Optimized threshold temperatures for degree day accumulation as well as average coefficients of variance in the three cultivars Müller-Thurgau, Riesling and Pinot noir.

Cultivar	Lower threshold (°C)	Upper threshold (°C)	Heat threshold (°C)	Average coefficient of variance	Reference
Müller-Thurgau	5	20	22	0.1473	Molitor *et al.* (2014b)
Riesling	7	18	24	0.1465	Molitor *et al.* (2016)
Pinot noir	3	20	24	0.1572	

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one single grid cell of the model results, a spatial mean of 3 × 3 grid cells around that central point (Remich) was used (spatial resolution of 25 km × 25 km per grid cell) (Goergen *et al.*, 2013; Junk *et al.*, 2012; Matzarakis *et al.*, 2013) (Supplementary Figure 1). Regional climate models show systematic differences when compared to direct point measurements. In our study the impact models for budburst and the BBCH stages are both based on absolute values and therefore it is necessary to apply a bias correction. We used long-term measurements from the Remich site for the bias correction. The applied method of quantile mapping is described in detail in Molitor *et al.* (2014a) and Junk *et al.* (2015b). Correction factors were calculated for the period 1971-2000 and then applied to the period of investigation from 1970 to 2090.

3. Phenological models

3.1. Budburst model

The budburst date (expressed as day of the year – DOY) was calculated for each ensemble member and each year based on the model developed by Molitor *et al.* (2014b) for the Müller-Thurgau cultivar. This model represents a parameterization of the DORMPHOT model (Caffarra *et al.*, 2011) simulating budburst for photoperiod-sensitive plant species. It considers (i) the dormancy induction process occurring in late summer-autumn; (ii) the action of chilling temperatures for dormancy release; and (iii) the promoting effect of a long photoperiod on bud development during dormancy release and bud development (Caffarra and Eccel, 2011).

2. High-resolution cumulative degree day-based models to simulate the phenological development

The dates of reaching all 27 phenological stages (according to the BBCH scheme (Lorenz *et al.*, 1995)) between budburst and harvest were calculated for the three *Vitis vinifera* cultivars Müller-Thurgau, Riesling and Pinot noir, according to the high-resolution cumulative degree day-based phenological model (Molitor *et al.*, 2014b). In contrast to linear cumulative degree day approaches, this model takes into consideration that the forcing effect of air temperature is limited at higher temperatures by incorporating (i) an upper threshold, above which a further increase of the temperature will not accelerate plant development, and (ii) a heat threshold, above which a further increase of the temperature will slow down plant development (Molitor *et al.*, 2014b). Investigations of Molitor *et al.* (2014b) demonstrated that optimized temperature thresholds for vegetative and generative development are almost identical with those determined for the whole phenological cycle. Hence, a single model covering the whole phenological development was used according to Molitor *et al.* (2014a). Most adequate temperature thresholds to simulate the phenological development were selected based on minimum average (average of all stages) coefficients of variation (CV; the standard deviation divided by the mean) of the cumulative degree days (Molitor *et al.*, 2014).

The optimized thresholds (leading to minimum coefficient of variation) for Müller-Thurgau and Riesling were taken from Molitor *et al.* (2014b) and Molitor *et al.* (2016), respectively (Table 1). For Pinot noir, a parameterization took place following the approach of Molitor *et al.* (2014b) based on 26 long-term phenological and meteorological observation data sets from Eltville (Germany), Kindel (Germany) and Remich (Luxembourg).

Threshold triplets (cardinal temperatures) with best predictive fit were determined based on the coefficients of variance on the average of all stages as described before (Molitor *et al.*, 2014b; Molitor *et al.*, 2016). For Pinot noir, best adaptation on the 26 long-term phenological data sets (lowest average coefficient of variation (0.1572)) was achieved using the threshold triplet 3°C, 20°C and 24°C.

An overview of the optimized thresholds for degree day accumulation in the different cultivars is given in Table 1.

Average (representing the average value of the 26 data sets) cumulative degree days reaching specific BBCH stages for all three cultivars are given in Supplementary Table 2.

The budburst date according to the budburst model represents the starting date of the high-resolution cumulative degree day-based model.

Analyses of multi-annual observation data recorded in Remich/Luxembourg (Supplementary Table 3) demonstrate that the DOYs of budburst (BBCH 09) of Riesling and Pinot noir do not differ significantly from the DOYs in Müller-Thurgau (according to non-parametric paired-sample t-test; $p \leq 0.05$). Hence, calculated dates of budburst for Müller-Thurgau according to Molitor *et al.* (2014b) were used for all three cultivars.

A 'phenophase' is defined as the time span between reaching a specific BBCH stage and reaching the subsequent stage (e.g., time span BBCH 09 to 11 = phenophase 09).

4. Determination of dates of reaching phenological stages

Based on (i) the budburst model, (ii) the phenological model and (iii) the ensemble of ten regional climate change projections, the DOYs for reaching each of the 27 phenological stages between budburst and harvest were calculated for each year, each of the ten ensemble members and each of the three cultivars. The average dates (30 years 10 projections - n = 300) of all stages in the subsequent 30-year time spans were computed for all cultivars:

- the reference period ("past") from 1971 to 2000,
- the "present" from 2001 to 2030,
- the "near future" from 2031 to 2060 and
- the "far future" from 2061 to 2090.

5. Determination of air temperatures in different phases

Every year, for each of the ten regional climate change projections and each of the three cultivars of investigation, the subsequent average air temperatures were calculated:

- annual and monthly temperatures,
- pre-bloom temperature (budbreak (BBCH 09) to beginning of flowering (BBCH 61)),
- bloom temperature (beginning of flowering (BBCH 61) to end of flowering (BBCH 69)),
- post-bloom temperature (end of flowering (BBCH 69) to veraison (BBCH 81)) and
- ripening temperature (veraison (BBCH 81) to berries ripe for harvest (BBCH 89)).

Air temperatures in the four phases defined above were calculated as mean air temperatures in the period between the DOY after reaching the starting stage (BBCH 09, BBCH 61, BBCH 69, BBCH 81, respectively) and the DOY of reaching the terminal stage (BBCH 61, BBCH 69, BBCH 81, BBCH 89, respectively) for each projection, each year and each cultivar. Average air temperatures (30 years 10 projections - n = 300) were calculated in the four 30-year time spans defined above and for the phases for each cultivar.

Additionally, the average number of years, in which the BBCH stage 89 "berries ripe for harvest" was not reached until 31/10, was computed for each 30-year time span. In the event that BBCH 89 ("berries ripe for harvest") was not reached by 31/10 (number of cases see Supplementary Table 4), the terminal date for ripening temperature calculation was fixed at DOY 304 (31/10) to avoid the impact of low temperatures after the vegetation period (such as in November or December) on the calculated average ripening temperature.

Moreover, the average daily air temperatures were computed for all four time spans. Their annual course was plotted (i) relative to 01/01 as well as (ii) relative to the date of budburst (BBCH 09).

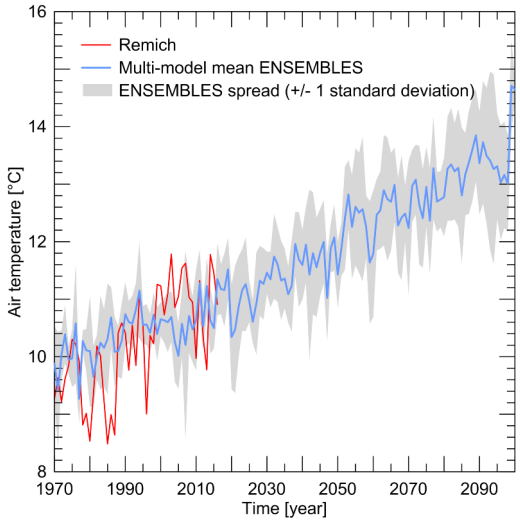


FIGURE 2. Observed annual average temperatures in Remich (red line) and projected (A1B emission scenario; ten ensemble-based regional climate change projections; multi-model mean) annual average temperatures (blue line) in the period 1970 to 2100. Ensemble spread (+/- 1 standard deviation) is indicated in grey.

6. Statistical analyses

Data sets consisting of 300 data per time span (30 years * 10 regional climate change projections) under present (2001-2030), near future (2031-2060) and far future (2061-2090) conditions were generally tested for significant differences compared to the reference period (past; 1971-2000) by non-parametric Mann-Whitney U-test ($p \leq 0.001$), using SPSS Statistics 19 (IBM, Chicago, IL, USA). For the phenological data sets, analyses were conducted separately for each cultivar.

RESULTS

1. Annual temperature evolution

Figure 2 shows the observed annual mean air temperatures for the weather station at Remich as well as the multi-model mean of the ten

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TABLE 2. Average (ten ensemble-based regional climate change projections) annual air temperatures, monthly air temperatures, as well as pre-bloom (BBCH 09-61), bloom (BBCH 61-69), post-bloom (BBCH 69-81) and ripening (BBCH 81-89) air temperatures in the Müller-Thurgau, Riesling and Pinot noir cultivars in the different 30-year time spans. Δ (°C) = temperature difference (in Kelvin) compared to the reference period (past; 1971-2000).

	Past (1971-2000)	Present (2001-2030)		Near future (2031-2060)		Far future (2061-2090)	
	T (°C)	T (°C)	Δ (°C)	T (°C)	Δ (°C)	T (°C)	Δ (°C)
Year (01/01-31/12)	10.3	**10.8**	0.5	**11.8**	1.5	**12.9**	2.6
January	2.3	2.9	0.6	**4.3**	2.0	**5.4**	3.1
February	3.0	**3.7**	0.7	**4.9**	1.9	**5.8**	2.8
March	5.9	**6.6**	0.7	**7.4**	1.5	**8.4**	2.5
April	9.6	**10.2**	0.6	**11.1**	1.5	**11.4**	1.8
May	13.8	14.2	0.4	**15.0**	1.2	**15.6**	1.8
June	16.8	**17.3**	0.5	**18.1**	1.3	**19.4**	2.6
July	18.9	**19.5**	0.7	**20.2**	1.3	**21.4**	2.5
August	18.3	**19.0**	0.7	**19.9**	1.7	**21.1**	2.8
September	15.2	**15.7**	0.5	**16.6**	1.4	**17.8**	2.6
October	10.8	11.2	0.4	**12.2**	1.4	**13.3**	2.5
November	5.6	**6.1**	0.6	**7.3**	1.8	**8.7**	3.2
December	2.7	2.9	0.2	**4.3**	1.5	**5.9**	3.1
Müller-Thurgau							
Pre-bloom (BBCH 09-61)	14.4	14.4	0.0	14.6	0.2	14.5	0.1
Bloom (BBCH 61-69)	17.6	17.8	0.1	18.2	0.5	18.3	0.6
Post-bloom (BBCH 69-81)	18.8	**19.3**	0.5	**19.7**	0.8	**20.7**	1.8
Ripening (BBCH 81-89)	16.3	**17.5**	1.2	**19.2**	2.9	**20.9**	4.6
Riesling							
Pre-bloom (BBCH 09-61)	14.5	14.6	0.0	14.7	0.2	14.7	0.1
Bloom (BBCH 61-69)	17.7	17.9	0.2	**18.4**	0.7	**18.4**	0.7
Post-bloom (BBCH 69-81)	18.7	**19.3**	0.6	**19.9**	1.2	**20.9**	2.2
Ripening (BBCH 81-89)	15.2	**16.6**	1.3	**18.4**	3.2	**20.3**	5.1
Pinot noir							
Pre-bloom (BBCH 09-61)	14.4	14.4	0.0	14.5	0.2	14.5	0.1
Bloom (BBCH 61-69)	17.5	17.6	0.1	18.0	0.5	18.2	0.6
Post-bloom (BBCH 69-81)	18.7	**19.3**	0.5	**19.8**	1.0	**20.7**	2.0
Ripening (BBCH 81-89)	15.0	**16.5**	1.5	**18.4**	3.3	**20.3**	5.3

Temperatures of the same phases that differed significantly according to the non-parametric Mann-Whitney U-test (p= 0.001) compared to the reference period (1971-2000) are marked in bold.

ensemble members (bias corrected). A significant increase in the annual air temperatures compared to the reference period is projected (Table 2).

2. Projected average phenological dates

The DOYs of all 27 phenological stages are modelled to occur significantly earlier in all cultivars in the present, near future and far future compared to the reference period (Figures 3 to 5). This shift in time increases continuously from the present to the far future. The temporal difference compared to the reference period already exists at budburst (BBCH 09) and remains relatively constant until the beginning of the ripening period (Supplementary Tables 5 to 7). Consequently, in the time span 2001-2030, no significant changes in the length of the different phenophases between BBCH 09 and BBCH 77 were projected in comparison to the reference period. In contrast, the phenophase 85 (period between BBCH 85 and BBCH 89) is modelled to get significantly shorter in all three cultivars. The decrease in the length of this phenophase compared to the reference period is -3.9 (Müller-Thurgau), -3.5 (Riesling) and -5.7 (Pinot noir) days in the present, -7.7 (Müller-Thurgau), -7.7 (Riesling) and -10.2 (Pinot noir) days in the near future and -9.3 (Müller-Thurgau), -9.7 (Riesling) and -13.0 (Pinot noir)

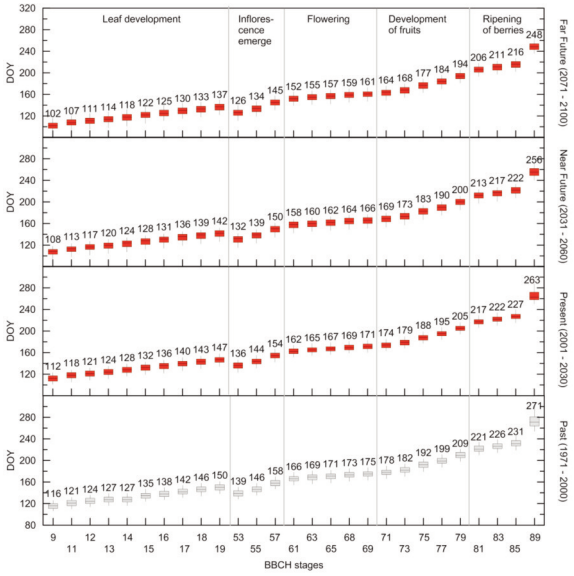


FIGURE 3. Days of the year (DOY) reaching the phenological stages 09 to 89 according to the BBCH scale (Lorenz *et al*., 1995) in the Müller-Thurgau cultivar in the four 30-year time spans. The box plots indicate the medians and the 25% and 75% percentiles, whiskers are limited to one standard deviation. Box plots of the days of the year of the same BBCH stage that differed significantly according to the non-parametric Mann-Whitney U-test (p= 0.001) compared to the reference period (1971-2000) are marked in red.

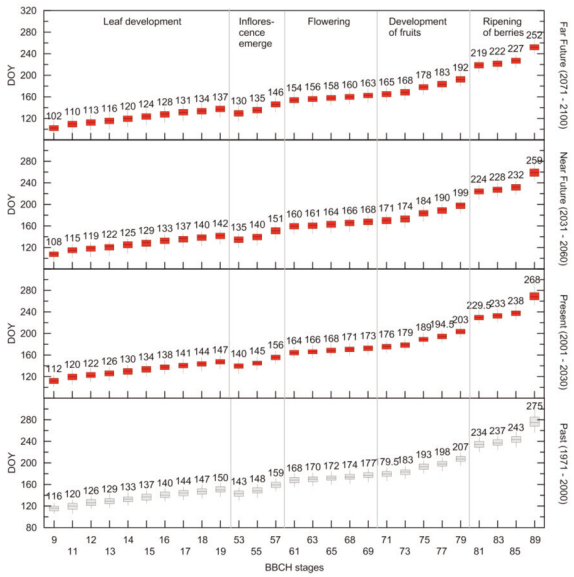


FIGURE 4. Days of the year (DOY) reaching the phenological stages 09 to 89 according to the BBCH scale (Lorenz *et al.*, 1995) in the Riesling cultivar in the four 30-year time spans. The box plots are indicating the medians and the 25% and 75% percentiles, whiskers are limited to one standard deviation. Box plots of the days of the year of the same BBCH stage that differed significantly according to the non-parametric Mann-Whitney U-test (p= 0.001) compared to the reference period (1971-2000) are marked in red.

days in the far future (Figures 3 to 5; Supplementary Tables 5 to 7).

The average number of years per 30-year time span, in which stage BBCH 89 was not reached until 31/10, is projected to decrease from 1.3 (Müller-Thurgau), 4.7 (Riesling), and 3.8 (Pinot noir) in the reference period to 0.1 (Müller-Thurgau), 1.2 (Riesling), and 1.1 (Pinot noir) in the present. In the near future and far future, no such cases were observed (Supplementary Table 4).

3. Temperature conditions in different phenophases

Annual and monthly average air temperatures (except for January, May, October and December) are modelled to be significantly higher in the 2001-2030 time span than in the reference period. In the near and the far future annual as well as all monthly temperatures are projected to be significantly higher than in the reference period. The computed annual temperature increase compared to the reference period is 0.5 °C (present), 1.5 °C (near future) and 2.6 °C (far future) (Table 2).

In all three cultivars, no significant differences were projected in the pre-bloom temperatures compared to the reference period. On the other hand, the post-bloom and ripening temperatures are modelled to increase significantly in the present, near future and far future. The projected increase (in comparison to the reference period) is most pronounced in the ripening period. Here, compared to the reference period, temperatures are modelled to increase from 1.2 °C (Müller-Thurgau), 1.3 °C (Riesling) and 1.5 °C (Pinot noir) in the present to 2.9 °C (Müller-Thurgau), 3.2 °C (Riesling) and 3.3 °C (Pinot noir) in the near future, to 4.6 °C (Müller-Thurgau), 5.1 °C (Riesling) and 5.3 °C (Pinot noir) in the far future (Table 2; Figure 6).

DISCUSSION

Present analyses revealed a constant increase of the annual **air temperature** in the Luxembourgish grapegrowing region in the future confirming previous studies (Junk *et al.*, 2015a, Junk *et al.*, 2015b, Junk *et al.*, 2016, Lokys *et al.*, 2015, Molitor *et al.*, 2014b).

The simulation of the future phenological development took place based on the high-

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resolution phenological model as proposed by Molitor *et al.* (2014b). Here, optimized threshold temperature triplets for phenology simulation are defined statistically per cultivar based on long-observation data. Even though these optimized thresholds are purely statistical, model validation for Müller-Thurgau over a broad range of locations in Europe showed a high accuracy (Molitor *et al.*, 2014). Using this cumulative degree day approach, in all three cultivars of investigation, all 27 **phenological stages** were computed to be reached significantly earlier in the future time spans than in the reference period confirming studies in other viticultural regions in recent years (e.g., Caffarra and Eccel, 2011; Duchene and Schneider, 2005; Duchene *et al.*, 2010; Fraga *et al.*, 2016; Garcia de Cortazar-Atauri *et al.*, 2017; Ramos, 2017; Sadras and Moran, 2013; Trought *et al.*, 2015). Differences in the extent of earlier appearance of phenological stages as well as in the length of phenophases observed by the different authors are supposed to be caused by differences in (i) the phenological models used (e.g., taking into account the effect above optimum temperatures or not), (ii) cultivars of investigation as well as (iii) the climatic conditions in the studied regions.

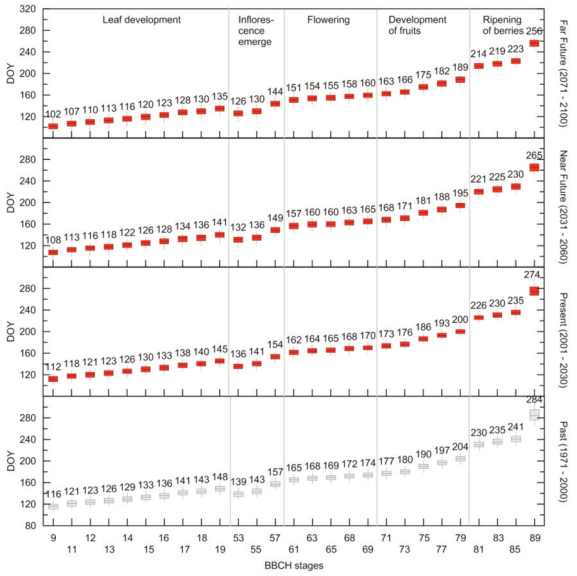


FIGURE 5. Days of the year (DOY) reaching the phenological stages 09 to 89 according to the BBCH scale (Lorenz et al., 1995) in the Pinot noir cultivar in the four 30-year time spans. The box plots are indicating the medians and the 25% and 75% percentiles, whiskers are limited to one standard deviation. Box plots of the days of the year of the same BBCH stage that differed significantly according to the non-parametric Mann-Whitney U-test (p= 0.001) compared to the reference period (1971-2000) are marked in red.

In the past, BBCH stage 89 ("berries ripe for harvest") was simulated not to be reached in all years in all three cultivars. This was especially the case for the (compared to Müller-Thurgau) relatively late ripening cultivars Pinot noir and Riesling. In the near as well as in the far future, heat summation will – according to present analyses – not be a limiting factor for full grape maturity – not even in Riesling or Pinot noir.

Due to generally increasing air temperatures, budburst (BBCH 09) is modelled to be reached significantly earlier in the future than in the past confirming previous analyses (e.g., Caffarra and Eccel, 2011; Fila *et al.*, 2012, Molitor *et al.*, 2014a). The consequences of the earlier budburst on the future late frost risk are controversially

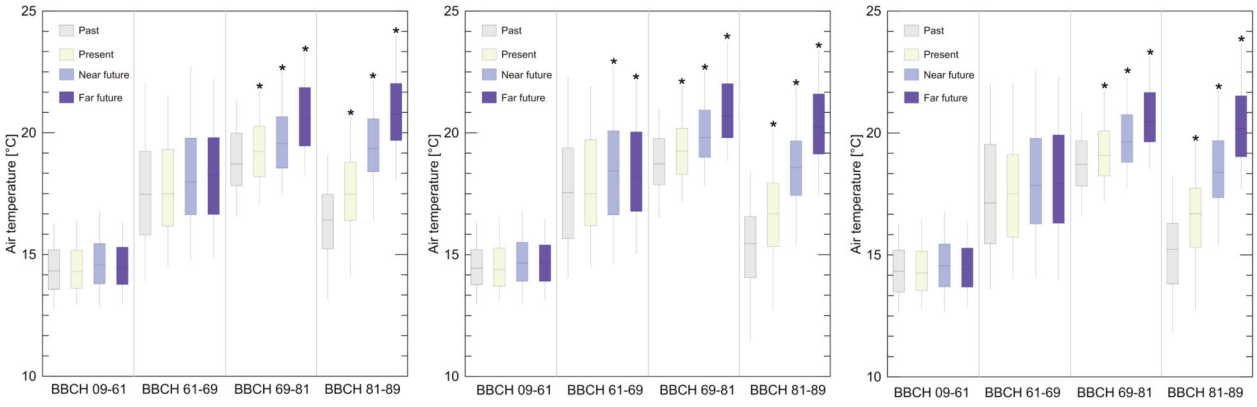


FIGURE 6. Average (ten ensemble-based regional climate change projections) pre-bloom (BBCH 09-61), bloom (BBCH 61-69), post-bloom (BBCH 69-81) and ripening (BBCH 81-89) air temperatures in the cultivars Müller-Thurgau (left), Riesling (centre) and Pinot noir (right) in the different 30-year time spans. *= temperatures of the same phases that differed significantly compared to the reference period (1971-2000) according to non-parametric Mann-Whitney U-test (p= 0.001).

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discussed in scientific literature (Kartschall *et al.*, 2015, Kotremba *et al.*, 2014, Molitor *et al.*, 2014a, Mosedale *et al.*, 2015, Sgubin *et al.*, 2018). While the analyses of Molitor *et al.* (2014a) indicate that the late frost risk might decrease in the future, other analyses revealed inconsistent or even increasing late frost risks. These contrary results might be explained by the respective underlying budburst models used.

The total length of the period between BBCH 09 and BBCH 89 (season duration) is projected to be shortened in the future in all cultivars confirming projected data of Webb *et al.* (2007) for the Australian grapegrowing regions. Interestingly, the **length of the different phenophases** prior to veraison is projected not to change significantly in the future compared to the reference period. That is, the shift of the phenological development until veraison towards the beginning of the year is mainly the result of the earlier budburst. This is in accordance with observations of Duchene and Schneider (2005) in the Alsace region where the time span from budburst to flowering was constant between 1965 and 2003. In contrast, the phenophase 85 representing the period between BBCH 85 and BBCH 89 is projected to be up to 13 days shorter in the far future in the case of Pinot noir. The explanation for adverse effects on phenophase lengths in different phases of development can be attributed to the course of the daily average air temperatures in the four time spans. Figure 7 demonstrates that this increase is relatively constant in the course of the year (left) compared to the reference period. In contrast, when plotting the daily average air temperatures relatively to the date of budburst, comparable temperature conditions are projected in the period around BBCH 09 in all four time spans (Figure 7; right). As consequence of the relatively constant temperature conditions, the length of the phenophases (mainly determined by temperature conditions) is not significantly affected in the early stages but shifted towards the beginning of the year.

As a consequence, the computed **pre-bloom** air temperatures do not show any significant differences between the reference period and the future time spans. This is the case because this phase is shifted towards the earlier (usually colder) part of the year. In consequence, mainly temperature-dependent steps of grape physiology between budburst and bloom (such as inflorescence differentiation and flower initiation (Keller 2015; Molitor and Keller, 2016)) might not be systematically affected (even though there is an increase in spring temperatures).

While, according to present results, air temperatures are already increasing significantly in the **post-bloom** to veraison period, the length of the phenophase stays relatively constant until veraison. This apparent contradiction can be explained by the fact that the air temperature conditions in this period are situated in all time

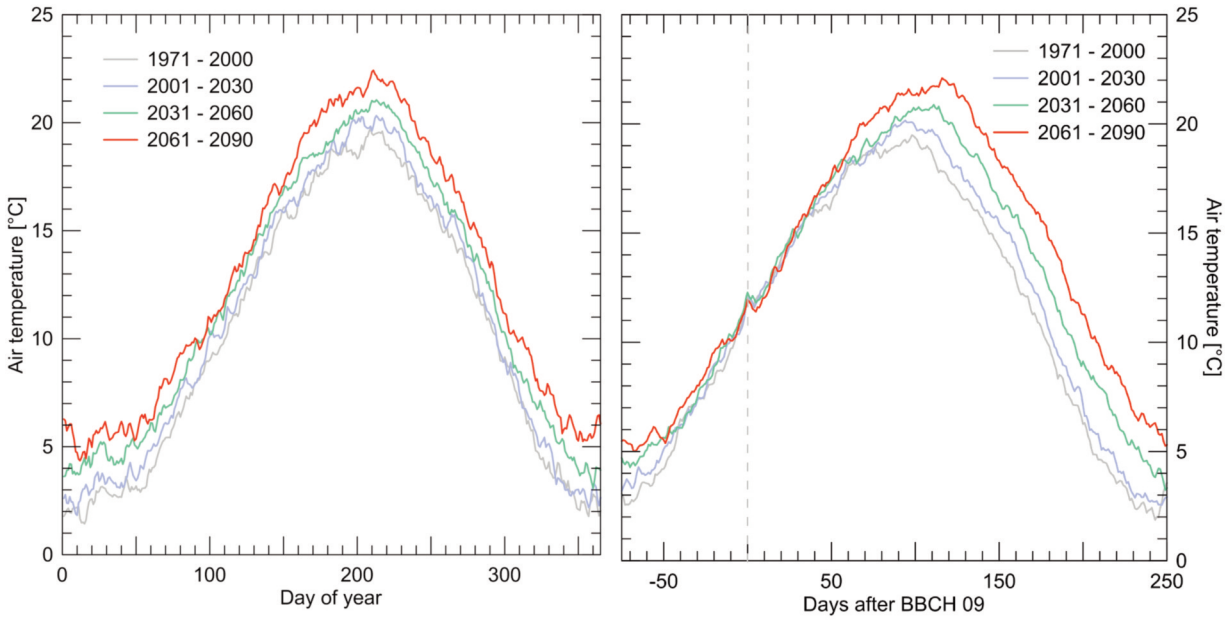


FIGURE 7. Course of daily average temperatures in the four time spans (past: 1971-2000; present: 2001-2030; near future: 2031-2060; far future: 2061-2090) (i) relative to 01/01 (day of the year – DOY; left) or (ii) relative to the date of budburst (BBCH 09; right).

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spans predominately in the optimum range for further phenological development (e.g., in the case of Riesling between 18 °C and 24 °C daily mean air temperature). Here, a further slight increase of daily average air temperatures does not influence the pace of the phenological development, if the heat threshold is not exceeded.

For practical viticulture under given climatic conditions, the relatively stable length of the phenophases prior to veraison means that consequences on the temporal distribution of the pre-veraison workload in the vineyard are expected to be relatively slight. That is, since phenological development is not accelerated in this period, spray intervals and time frames for canopy management measures, for example, might not be affected.

However, higher air temperatures in the time frame between bloom and veraison might have an impact on annual yield. Recent studies have demonstrated negative correlations between yield and temperatures, especially maximum temperatures, over the first three weeks after bloom for the Riesling cultivar (Molitor and Keller, 2016). Hence, higher air temperatures in this period might lead to a decrease in annual yield in the future while in other periods the effect of higher temperatures on the annual yield was observed to be mainly positive (Molitor and Keller, 2016). To clarify the overall effect of climate change on yield formation, in a further step, the present data on future temperature and phenological conditions will be combined with the temperature- and precipitation-driven yield models for the Müller-Thurgau and Riesling cultivars developed based on the multi-annual yield records for the Luxembourgish grapegrowing region (Molitor and Keller, 2016).

The most distinct influences on the temperature conditions as well as on the length of the phenophases are modelled for the **ripening period** between veraison and harvest. The increase in the ripening temperature is most pronounced in late ripening cultivars such as Riesling and Pinot noir. Here, the grapes are ripening at a later stage of the year where temperature differences compared to the reference period temperatures are most distinct (temperature decrease in the autumn), while in case of Müller-Thurgau, the ripening period is closer to the summer plateau of air temperatures. The projected increase in the ripening temperatures in the near future is 1.9 °C (Müller-Thurgau; 2.9 °C), 2.1 °C (Riesling; 3.2 °C) and 2.2 °C times higher (Pinot noir; 3.3 °C) than the temperature increase in the month of September (1.5 °C). This phenomenon is the result of two additional effects: (i) the general temperature increase and (ii) the shift of the phenology towards the earlier, generally warmer period of the year.

In fact, this two-fold effect demonstrates that changes in temperature conditions in calendar-based (=anthropogenic) time frames (such as in the "Cool Night Index" (Tonietto and Carbonneau, 2004), taking into account minimum temperatures in the month of September (northern hemisphere)), might not completely reveal the real temperature changes in specific developmental stages.

More generally, this fact is indicating a general limitation of calendar-based climatic indices used in viticulture such as the Winkler index (Amerine and Winkler 1944), the heliothermic index of Huglin (1978) or the average growing season temperature according to Jones (2007) since they do not take into account the plant response to climate (Caubel *et al.*, 2015) and, hence, might not perfectly reflect the real vegetation period of specific cultivars (Holzkämper *et al.*, 2010).

Present results furthermore demonstrate that the length of the ripening period (BBCH 81-89) is projected to decrease in the future (e.g., Riesling, past: 44.6 days; far future: 33.9 days). This is confirming the results of the analyses of Tomasi *et al.* (2011) in Northern Italy. Authors observed a significant decrease of the length of the period between veraison and harvest in the period 1964 to 2009 caused by increasing temperatures (Tomasi *et al.*, 2011). Due to the fact that the harvest date might under practical conditions be influenced by several factors (Garcia de Cortazar-Atauri *et al.*, 2010) the impact of temperature on the length of the ripening period is controversially discussed in the literature. For example, van Leeuwen and Destrac Irvine (2017) found opposite trends in the length of the period between veraison and harvest. However, based on present results we assume that the temperature-sum approach proposed here might, at least under the climatic conditions of the Luxembourgish grapegrowing region, better reveal the real average temperature conditions in the simulated ripening period (since its length is assumed to be influenced by temperature conditions) than approaches which calculate the temperature conditions in this period as the average temperatures between veraison and a temporally fixed date such as (i) 35 days thereafter (Duchene *et al.*, 2010) or (ii) 60 days thereafter (Schultz and Hofmann, 2017).

The strong air temperature increase in the ripening period as described above is presumably

linked to distinct changes in the wine typicity of a specific region.

In fact, higher temperatures are leading to altering fruit ripening rates (Martinez-Lüscher *et al.*, 2015), changes in flavour and aroma profiles (Trought *et al.*, 2015) as well as decoupled anthocyanin and sugar syntheses in berries (Sadras and Moran, 2013). Expected higher sugar concentrations are leading to higher alcohol contents (Jackson and Lombard, 1993) in the wines, and an acceleration of the degradation of organic acids (Duchene *et al.*, 2010), threatening both the freshness and lightness that is especially exemplary for white wines in (former) cool climate grapegrowing regions, such as Luxembourg. Furthermore, the fruitiness and aroma of grapes and wines is expected to be negatively affected by high ripening temperatures (Duchene *et al.*, 2010). To maintain the wine typicity of the region, potential adaptation strategies to mitigate the consequences of climatic change in general and higher ripening temperatures in particular might consist of measures leading to a temporal delay of the maturation period. This might be achieved by a shift towards cooler sites (e.g., with higher elevations or lower exposition) or regions (e.g., at higher latitudes), cultivars or clones with a later ripening characteristic, maturity-retarding rootstocks, the application of antitranspirants (Gatti *et al.*, 2016) or specific crop cultural measures including training systems (Molitor *et al.*, 2019), delayed winter pruning (Friend and Trought, 2007) and adapted canopy management (Parker *et al.*, 2016, Stoll *et al.*, 2013, Trought *et al.*, 2015).

CONCLUSIONS

Present analyses demonstrated that under the climatic conditions in the Luxembourgish grapegrowing region each of the 27 phenological stages according to BBCH code are projected to be reached significantly earlier in the future than in the reference period. While significant changes in the phenophase lengths are absent in early stages, the ripening period length is significantly shortened in the future according to these projections. Since (i) air temperatures are generally projected to increase in the future and (ii) the ripening period will take place earlier (usually in the warmer parts of the season), climate change is implicating a two-fold impact on ripening period air temperature increase. Consequently, the air temperature increase in the ripening period (far future compared to reference period: + 4.6 °C to + 5.3 °C) is projected to be markedly higher than in the annual averages (+ 2.6 °C). This significant increase of the ripening period air temperatures potentially threatens the wine typicity of the traditional grapegrowing regions and therefore calls for specific adaptation strategies.

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