Vitis **55**, 23–30 (2016) DOI: http://dx.doi.org/10.5073/vitis.2016.55.23-30

Historical vintage descriptions from Luxembourg - an indicator for the climatic conditions in the past?

D. Molitor[1), 2)], T. Udelhoven[1), 3)], S. Ney[1)], L. Hoffmann[1)] and L. Pfister[1)]

[1)] LIST - Luxembourg Institute of Science and Technology, Environmental Research and Innovation (ERIN) Department, Belvaux, Luxembourg

[2)] University of Natural Resources and Life Sciences, Department of Crop Sciences, Division of Viticulture and Pomology, Tulln, Austria

[3)] University of Trier, Environmental Remote Sensing and Geoinformatics, Trier, Germany

Summary

Verbal vintage descriptions in a historical wine chronicle (809-1904) of the Luxembourgish winegrowing region were assigned to five wine quality and three wine quantity classes. To calibrate models describing the impact of the seasonal heat consumption on wine quality and quantity, instrumental records from Luxembourg-City in a reference period (1854-1885) and the associated vintage quality and quantity classes were correlated. Dummy regression models showed, that in the reference period the wine quality classes assigned were significantly correlated with the annual modified heliothermic index values (representing the heat consumption) ($R^2_{adj.}$ = 0.55, p = 0.0002); whereas, the incorporation of the wine quantity as additional predictor variable did not significantly improve model output. Based on linear correlations between annual thermal conditions and wine quality descriptions, average April-September temperatures were reconstructed for the period 1200-1904. Running averages calculated using LOESS smoothing showed that periods with cooler and warmer climatic conditions alternated in the past centuries. Even though a precise reconstruction of the annual temperature conditions solely based on vintage descriptions is not possible due to the broad set of potentially interfering effects, long-term climatic trends described in the literature such as the Medieval Climate Optimum and the Little Ice Age could be retrieved.

K e y w o r d s : climate change; climate of the past; heat consumption; historical climatology; viticulture; wine chronicle; wine quality.

Introduction

Systematic daily instrumental meteorological observations started in Europe in the 17th century (so-called Manley series in England beginning 1659 (Storchmann 2005)) and in Luxembourg in the 19th century (observations in Luxembourg-City beginning 1838 (Drogue *et al.* 2005)), respectively. For the periods prior to these first notations no direct information on the past climatic conditions is available. However, for the classification of present climate and its variability, information of climatic conditions prior to systematic notations is of highest interest especially in climate change research (Koch *et al.* 2009, Santos *et al.* 2015).

To overcome the temporal limitations of systematic instrumental climatic records, mainly biological and documentary proxy records ("proxies") retrieved from tree rings, corals, ice cores, pollen assemblages, sediments (Koch *et al.* 2009, Guiot 2012) or nature observations such as memoirs, diaries, chronicles, weather reports or logbooks (Santos *et al.* 2015) are used as means of historical climatology.

Grapevine phenology (e.g. Caffarra and Eccel 2009, Molitor *et al.* 2014a, Molitor *et al.* 2014b) and harvest dates (e.g. Chuine *et al.* 2004, Mariani *et al.* 2009, Meier *et al.* 2007, Kiss *et al.* 2011, Krieger *et al.* 2011, Koch *et al.* 2009) are highly determined by temperature conditions. Furthermore, investigations of Huglin (1978) showed that the grape (*Vitis vinifera*) sugar content, a parameter describing the maturation status, is strongly correlated (0.80 < r < 0.91) with temperature conditions between April, 1 and September, 30 (northern hemisphere). The dependence of grape development on climatic conditions is particularly pronounced close to the climatic frontiers of viticulture (Brazdil *et al.* 2008, Koch *et al.* 2009). Hence, records of grape maturation, phenology and harvest dates might be used for reconstructions of the temperature conditions in the past (Koch *et al.* 2009).

Analyses of Brazdil *et al.* (2008) as well as of Storchmann (2005) showed that the historical descriptions of wine quality are highly influenced by the weather conditions in the corresponding season. Consequently, Brazdil *et al.* (2008) proposed that the relations between wine quality and quantity notes and climatic conditions could build an additional proxy to reconstruct the temperature conditions in past times. However, neither Brazdil *et al.* (2008) nor Storchmann (2005) used the correlations obtained between the annual climatic conditions and the wine quality or quantity for the reconstruction of pre-instrumen-

Correspondence to: Dr. D. Molitor, LIST - Luxembourg Institute of Science and Technology, Environmental Research and Innovation (ERIN) Department, 41, rue du Brill, L-4422 Belvaux, Luxembourg. Fax: +352-47 02 64. E-mail: daniel.molitor@list.lu

tal climatic conditions. For the Luxembourgish winegrowing region, located at the northern frontier of viticulture in Europe (49.46- 49.80°N), such descriptions of vintage quality and quantity are recorded in an ancient vintage chronicle (Anonymous 1937). This chronicle initiates in the year 809, which documents the existence of viticulture in Luxembourg back to the beginning of the Middle Ages (Anonymous 1937).

Consequently, present analyses based on this chronicle aimed at investigating (i) the impact of the thermal conditions in the summer half-year (April to September) on the vintage quality and quantity descriptions and (ii) the appropriateness of this information to reconstruct the temperature conditions in Luxembourg in the centuries prior to the beginning of systematic weather records.

Material and Methods

Data sets

A) Luxembourgish wine chronicle 809-1904: Historical annual vintage quality and quantity descriptions for the Luxembourgish winegrowing region during the period 809 to 1904 were compiled by anonymous authors in honour of the 25th anniversary of the Luxembourgish Viticulture Federation in the year 1937 (Anonymous 1937). A view into this chronicle is given in Fig. 1. Especially in the Middle Ages vintage descriptions were recorded discontinuously, whereas, more regular notations exist since the 14th century. In total, 427 notations concerning the vintage quality and 300 notations concerning the vintage quantity were available (Tab. 1).

LUXEMBURGER WEINCHRONIK 809–1904

Aufgestellt durch die Großherzogliche Weinbau-Kommission in Grevenmacher

Jahrgang	Quantität	Qualität	Witterung
809	völliger	Mißwachs	
820		hart und sauer	anhaltender Regen und kalt dabei.
860			strenger Winter, Reben verdorben.
882	viel	gut	gutes Weinjahr.
993	,,		heißes Jahr.
994	viel	und gut	heißer Sommer u. kalter Winter.
1000	viel	gut	heiß und trocken.
1043	wenig und	schlecht	Sommer kalt und regnerisch. Trauben nicht reif.
1044			gar kein Wein geraten.
1048			kalter Winter bis März; Mißjahr.
1056			sehr kalter Winter; Reben erfroren.
1063			Weinberge erfroren.
1077			strenger, kalter Winter; viele Stöcke erfroren.
1115		gut	
1125		schlecht	strenger Winter; Weinberge erfroren.
1130		gut	heiß.
1138	viel	gut	fruchtbares Jahr.
1151			Fehljahr, häufig Regen, Trauben halbreif.
1152	sehr viel	gut	wohlfeile Zeit, geringer Wein, wurde verschenkt.
1158	viel	gut	Sommer außerordentlich heiß und trocken.
1180	,,		
1181	,,	,,	wohlfeile Zeit.
1183	viel	,,	wohlfeile Zeit.
1186	viel	,,	im Januar blühten die Bäume, im August Weinlese.
1187	wenig	schlecht	kalt bis in den Juni, am 17. Mai noch Schnee.
1191	viel	gut	wohlfeile Zeit.
1210			strenger Winter; Wein erfroren.
1217	viel		
1232		gut	sehr heiß.
1236	sehr viel	mittelm.	kalter Winter, heißer Sommer.
1237	wenig		nicht sehr günstiger Sommer.
1254			Mißjahr.
1255	viel	schlecht	wohlfeile Zeit.
1259		gut	trocken.
1270		ebenso	ebenso.
1271	viel		
1272	wenig	schlecht	Mißjahr.
1273		gut	
1274		,,	
1275		schlecht	vom Mai bis Herbst anhaltender Regen.
1276		gut	heiß, im August schon reife Trauben.
1278	wenig		am 16. und 18. Mai Schnee und sehr kalt; Sommer gut, wohlfeile Zeit.
1279	wenig	gut	fruchtbares Jahr.
1280	viel		kalt, in Bayern fiel am 17. Juli viel Schnee.
1283	wenig		am 13. Mai in Stuttgart Reben erfroren.
1284	viel	gut	
1288	nichts		gelinder Winter, im Mai Reben erfroren.
1289	mittelm.	mittelm.	um Weihnachten trieben die Bäume, im April blühten die Trauben, Anfang Mai Frost und Schnee; vieles erfroren.
1290	viel		
1295	sehr viel	gut	
1297	viel	mittelm.	häufige Gewitter.
1303	,,	sehr gut	sehr warmer, trockener Sommer.
1310			begann eine 18jährige Teuerung, die bloß durch zwei fruchtbare Jahre unterbrochen wurde.

122

Fig. 1: First page of the Luxembourgish wine chronicle 809-1904 (Anonymous 1937).

Table 1

Number of notations in the different centuries concerning vintage quality and quantity in the Luxembourgish wine chronicle 809-1904 (ANONYMOUS 1937)

Time frame	Number of notations	
	Quality	Quantity
809-899	2	2
900-999	1	2
1000-1099	2	2
1100-1199	11	9
1200-1299	15	16
1300-1399	23	20
1400-1499	41	40
1500-1599	71	71
1600-1699	80	51
1700-1799	83	18
1800-1899	93	64
1900-1904	5	5
Total	427	300

B) Daily temperature observations in Luxembourg-City (1854 to 1885): Daily based air temperatures of Luxembourg-City (approximate distance to viticulture region along the Moselle river: 10-30 km; see Fig. 2) are available starting in 1854 based on the observations of François Reuter (REUTER 1867, REUTER 1874, REUTER 1887, REUTER-CHOMÉ 1890). Temperature measurements of François Reuter took place three times per day, at 07:30, 12:00 and 19:30.

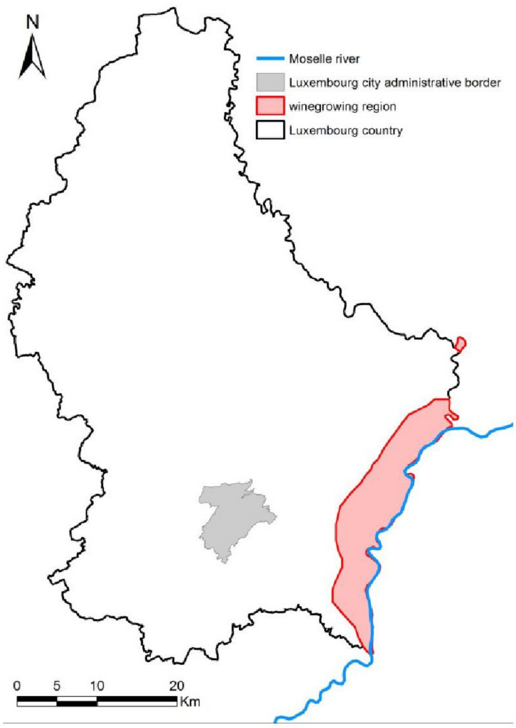

Fig. 2: Map of the present expansion of the Luxembourgish winegrowing region and the administrative borders of Luxembourg-City, the location of the temperature observations of François Reuter.

C) The homogenized monthly temperature data set for Luxembourg-City (1854 to 2010): Historical instrumental temperature observations in Luxembourg-City originating from different positions inside Luxembourg-City and different sources were compiled and homogenized by DROGUE *et al.* (2005) to the "homogenized monthly temperature data set for Luxembourg-City". In this data set, processed and homogenized monthly average temperatures are available for the time frame 1854 to 2010.

Calculation of the modified heliothermic index: According to the concept of the so called "Mannheimer Stunden / Mannheim hours" (FRICKE 1997), evening temperatures are considered twice in the approximation of the daily average temperature in case temperatures are recorded three times per day. Following this approach, in the present investigations daily average temperatures (T_{av}) were calculated based on the available temperature records of François Reuter as

$$T_{av} = (T_{07:30} + T_{12:00} + T_{19:30} + T_{19:30}) / 4 \qquad (1)$$

where T_{av} is the daily average temperature, $T_{07:30}$ the temperature at 07:30, $T_{12:00}$ the temperature at 12:00 and $T_{19:30}$ the temperature at 19:30.

Applying equation (1), it needs to be considered that calculated daily average temperatures are an approximation, which might be generally biased due to the time points of temperature records.

Adapting the heliothermic index proposed by HUGLIN (1978)) to the available data, the modified heliothermic index describing the temperature conditions in the summer half-year (1st of April to 30th of September) was calculated for every year in the time frame 1854 to 1885 (reference period) using the following equation (2):

$$HI_{mod} = \sum_{01.04.}^{30.09.} \left[\frac{(T_{av} - 10) + (T_{max} - 10)}{2} \right] * k \qquad (2)$$

where HI_{mod} is the modified heliothermic index, T_{av} is the daily average temperature, T_{max} is the maximum value of the three daily measurements of François Reuter at 07:30, 12:00 and 19:30, and k is the coefficient for the day length. Following HUGLIN (1978), k was fixed for the Luxembourgish winegrowing region (49.46-49.80°N) to 1.06.

In the event that the daily value of the HI_{mod} yielded a negative number, it was set to 0.0 as described by BACIOCCO *et al.* (2014). Due to the deviating input parameters (*i.e.* daily maximum temperature not necessarily equalling the maximum of the three temperature measurements) the values of the modified heliothermic index cannot be directly equated with the value of the heliothermic index according to HUGLIN (1978).

Transfer of verbal description into quality and quantity classes: Verbal description of all vintages were compiled and assigned to 5 quality classes (1-5) and 3 quantity classes (1-3). Original descriptions, English translations as well as classes assigned are given in Tabs 2 and 3. In case no vintage quantity was noted, quantity was assumed being average. In this case, the respective season was assigned to quantity class 2.

Table 2

Original descriptions of vintage quality for the Luxembourgish winegrowing region according to Anonymous (1937), English translations, as well as quality classes assigned

Original description	English translation	Quality class
Sehr schlecht, essigsauer, über die Massen sauer, so sauer, hart und sauer	Very poor, acetic, sour beyond measure, so sour, hard and sour	1
Schlecht, recht sauer, geringer Wein, mittelschlecht, recht schlecht	Poor, really sour, little wine, medium poor, really poor	2
Mittelmäßig, trinkbar, brauchbar, erträglich	Moderate, drinkable, useable, tolerable	3
Gut, ziemlich gut, sehr trinkbar, recht gut	Good, quite good, very drinkable, really good	4
Sehr gut, herrlich gut, delikat, köstlich, kostbar gut, Jahrhundertwein, (ganz) vortrefflich, extra gut	Very good, superb, fine, exquisite, sumptuous, wine of the century, (simply) excellent, exceptionally good	5

Table 3

Original descriptions of vintage quantity for the Luxembourgish winegrowing region according to Anonymous (1937), English translations, as well as quantity classes assigned

Original description	English translation	Quantity class
Sehr wenig, fast nichts, fast kein Wein, 1/8 Herbst, wenig, ziemlich wenig, 1/3 Herbst, kaum ½ Herbst, ¼ Herbst,	Very little, almost nothing, hardly any wine, 1/8 harvest, Little, quite little, 1/3 harvest, barely ½ harvest, ¼ harvest	1
Mittelmäßig, ½ Herbst, 2/3 Herbst, nahezu ¾ Herbst, mittleres Jahr	Moderate, ½ harvest, 2/3 harvest, almost ¾ harvest, medium vintage	2
Viel, ziemlich viel, ¾ Herbst, mehr wie 2/3 Herbst, gut, sehr viel, vollkommener Herbst, voller Herbst	A lot, quite a lot, ¾ harvest, more than 2/3 harvest, good, a great deal, complete harvest, full harvest	3

Model calibration: The period 1854-1885 (1854: initial records of François Reuter, 1886: first observation of grape downy mildew in Luxembourg (Anonymous 1937)) was selected as reference period for model calibration. Modified heliothermic index values in the reference period as well as vintage quality and quantity classes are given in Tab. 4.

The years 1866 (incomplete or implausible temperature records), 1872 (incomplete or implausible temperature records), 1873 (nothing harvested) and 1880 (severe frost damage) were excluded in model calibration. In total, 28 data sets were available for wine quality, 24 for wine quantity and 24 for both wine quality and quantity.

A linear regression model was used to regress the two predictor variables, wine quality and quantity, against the modified heliothermic index values. Since both predictors represent categorical rather than numerical information, they were internally coded as dummy variables for the regression. Here, a k-category classification is represented by introducing k-1 dummy variables. Each dummy variable takes the values 1 or 0 to indicate the presence or absence of categorical effects. A value of 0 causes that the regression coefficient for that category has no influence on the dependent variable, whereas a value of 1 modifies the offset of the regression model for the respective category.

Two different calibration models were calibrated: The first model includes only the wine quality as predictor variable; the second model comprises both predictor variables (wine quality and quantity).

Statistical fit of both models was evaluated in terms of adjusted coefficients of determination ($R^2_{adj.}$) and leave-one-out cross validation. Based on the analysis of the residual plot and the Cook's distance, which is commonly used to measure the influence of individual data points in the regression model, one year (1869) was treated as an outlier and excluded from further analysis.

Reconstruction of past climatic conditions: Based on the best fitting model equations obtained to simulate the modified heliothermic index, annual index values were computed for the period 1200 to 1904.

Measured modified heliothermic index values in the reference period (1854-1885) were plotted against the recorded average temperatures in the period April to September originating from the homogenized monthly temperature data set for Luxembourg-City of the respective years (Drogue *et al.* 2005). Based on the obtained linear regression function, April to September average temperatures were re-calculated for the reconstruction period (1200-1904).

Running averages of both the reconstruction series (1200-1904) as well as the homogenized temperature data set for Luxembourg-City (1854-2010) were calculated using locally weighted scatterplot smoothing (LOESS; smoothing parameter: 0.1) and plotted against time (years 1200 to 2010). 95 % confidence levels of each prediction were smoothed in the same way (LOESS function).

Comparison with other climate reconstructions: To test their plausibility annual April

Table 4

Vintage quality and quantity classes according to ANONYMOUS (1937) as well as calculated modified heliothermic index values in the reference period 1854 to 1885. * = years not considered for model calibration

Year	Quality class	Quantity class	Modified heliothermic index
1854	2	1	1353.1
1855	3	1	1298.1
1856	2	2	1144.0
1857	5	2	1476.8
1858	4	2	1431.2
1859	4	1	1533.2
1860	1	2	1135.7
1861	5	2	1396.6
1862	4	1	1431.2
1863	4	2	1356.9
1864	3	1	1379.4
1865	5	3	1851.3
1866*			
1867	2	2	1409.5
1868	5	2	1836.4
1869	3	2	1624.2
1870	4	2	1431.2
1871	2	2	1386.1
1872*			
1873*			
1874	4	3	1464.8
1875	4	3	1528.5
1876	4	3	1301.0
1877	2	3	1153.8
1878	3	3	1276.6
1879	1	2	1040.9
1880*			
1881	3	2	1207.4
1882	1	2	1047.5
1883	3	3	1210.3
1884	5	3	1346.4
1885	3	1	1219.9

to September temperature reconstructions were compared with the temperature reconstructions for the months April to August for Burgundy (appr. 350 km south-west of Luxembourg) in the years 1370 to 1904 as well as with the reconstructed April to September temperatures for the grid point 6.250 °E / 49.750 °O (appr. 15 km west of the Luxembourgish winegrowing region) in the years 1659 to 1904. Data sets were provided by Dr. Isabelle Chuine (Burgundy) and Dr. Jürg Luterbacher (6.250 °E / 49.750 °O) and represent raw data of publications by CHUINE *et al.* (2004) as well as by LUTERBACHER *et al.* (2004). April to September temperatures for the grid 6.250 °E / 49.750 °O were calculated as averages of monthly reconstructions.

Linear correlation coefficients (r) between reconstruction temperatures of present investigations and the temperatures reconstructed by CHUINE *et al.* (2004) and LUTERBACHER *et al.* (2004), as well as respective p-values were computed.

Results and Discussion

Tabs 5 and 6 give the regression coefficients of dummy regressions for both models to reconstruct the annual modified heliothermic index. Each coefficient represents the partial offset from the reference level (quality class 1, quantity class 1), which is represented by the global intercept of the model.

Model results showed, that the annual modified heliothermic index value is significantly correlated with the wine quality ($p = 0.000192$), as well as with a combination of the wine quality class and the wine quantity class as predictor variables ($p = 0.00118$) (Tabs 5 and 6).

Table 5

Regression coefficients (± standard error) obtained by dummy regression analysis using only quality class as predictor variable. Dependent variable: annual modified heliothermic index value

Factor	Value	Standard error	*p*-value
Intercept	1074.7	75.6	< 0.00001
Quality class 2	214.6	95.6	0.03521
Quality class 3	190.6	92.6	0.05159
Quality class 4	360.1	88.6	0.00052
Quality class 5	506.8	95.6	< 0.00001
		adjusted R^2	0.55
		p	0.000192

Table 6

Regression coefficients (± standard error) obtained by dummy regression using quality and quantity classes as predictor variables. Dependent variable: annual modified heliothermic index value

Factor	Value	Standard error	*p*-value
Intercept	1140.6	108.8	< 0.00001
Quality class 2	202.4	100.8	0.0583
Quality class 3	159.3	107.9	0.1556
Quality class 4	345.4	98.0	0.0021
Quality class 5	508.8	101.3	< 0.00001
Quantity class 2	-65.9	76.5	0.3989
Quantity class 3	-70.9	75.8	0.3605
		adjusted R^2	0.53
		p	0.00118

Adjusted coefficients of determination (R^2) were 0.55 for the model based on the quality classes as single predictor variable and 0.53 for the model based on both, the quality class, as well as the quantity class as predictor variables (Tabs 5 and 6). In the combined model none of the quantity classes added significant information to the model ($p > 0.36$). An ANOVA confirmed that the two models do not differ significantly ($F = 0.5$, $p = 0.61$) (Tabs 5 and 6).

Even though weather conditions are generally supposed to impact the annual yield, in fact, the consideration of the wine quantity as predictor variable did not improve the model performance. Consequently, in the present investigations only the simple, quality class based model was used for the reconstruction of the temperature conditions in the past. Leave-one-out cross validation of this model resulted in a coefficient of determination of 0.54. Scatterplots between observed and (cross-validated) predicted heliothermic index values are depicted in Fig. 3.

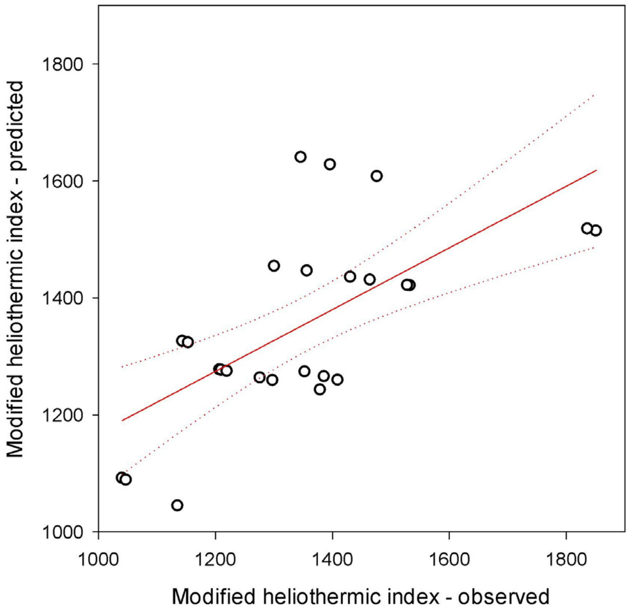

Fig. 3: Leave-one-out cross validation. Scatterplot of observed and predicted modified heliothermic index values (based on the model using wine quality as single input parameter). Solid line represents the linear regression, dotted lines the borders of the 95 % confidence bands.

Tab. 5 shows that besides quality class "3" all other local offsets differ significantly from quality class "1" (5 % significance level). In fact, present investigations demonstrate that under the climatic conditions (reference period) in the Luxembourgish wine growing region (located on the northern border of viticulture in Europe) a higher heat consumption due to higher temperature conditions during the vegetation period was generally linked to a higher wine quality. Consequently, present analyses confirm that moderate global warming due to climate change is likely to improve the quality of wines of the northern winegrowing regions (Storchmann 2005), where the heat consumption presently represents a limiting factor for grape maturity. In contrast, recent investigations (Molitor *et al.* submitted) indicate that in case the variety dependent minimum demand of heat consumption ensuring full grape maturity is already fulfilled a further increase of temperatures does not necessarily further improve wine quality. Once the heat consumption exceeds the optimum range for a specific variety even a decline of wine quality is likely (Jones 2007) .

Observed modified heliothermic index values in the reference period proved were highly correlated ($R^2 = 0.9581$; $p < 0.0001$) with the average April to September temperatures based on the homogenized monthly temperature data set for Luxembourg-City. Based on the linear regression equation $y = 0.0051x + 6.7147$ the modified heliothermic index values of the years 1200 to 1904 (x) were converted into the average April to September temperatures (y).

The observed adjusted coefficient of determination between the modified heliothermic index and the annual wine quality of 0.55 suggests that the annual temperature conditions represent the major influence factor on the wine quality. Potential additional factors that might have affected the vintage quality (or its perception by the chroniclers) not considered in the regression analysis might consist of (i) the annual precipitation and its distribution during the vegetation period, (ii) atypical weather conditions (frost, snow, hail), (iii) the occurrence of plant diseases or pests (Kiss *et al.* 2011), (iv) the harvest date influenced for example by the grape health status (Molitor *et al.* 2012, Molitor *et al.*, submitted), (v) anthropogenic effects, such as health-medical (epidemics, e.g. the plague) or social-political (wars, troop movements, mobilisation of grape growers, church regulations, infrastructure) impacts (Garnier *et al.* 2011, Kiss *et al.* 2011, Maurer *et al.* 2011), (vi) technical improvements, (vii) changes in cultural practices, wine styles or customers' tastes or (viii) adaptations in grape varieties cultivated (Maurer *et al.* 2011, Garcia de Cortazar-Atauri *et al.* 2010).

Due to this broad set of potentially interfering effects, a precise reconstruction of the temperature conditions in a specific season purely based on the vintage descriptions is not possible. However, the fact that present annual temperature reconstructions were highly significantly positively correlated with the reconstructions of Chuine *et al.* (2004) and Luterbacher *et al.* (2004) (Tab. 7) confirmed their general plausibility. Correlations coefficients between present reconstructions and reconstructions in the literature were higher in case of the multiproxy reconstructions of Luterbacher *et al.* (2004) (time frame 1659 to 1904; grid point 6.250 °E, 49.750 °N, located close to the Luxembourgish winegrowing region; r = 0.60) than in case of the grape harvest date based reconstructions of Chuine *et al.* (2004) (time frame 1370 to 1904; Burgundy winegrowing region; r = 0.44).

Table 7

Linear correlation coefficients between present temperature reconstructions and temperature reconstructions for Burgundy (Chuine *et al.* 2004) or for the the grid point 6.250 °E, 49.750 °N (Luterbacher *et al.* 2004) and respective *p*-values

	Burgundy	Grid point 6.250 °E, 49.750 °N
Time range	1370-1904	1659-1904
Correlation coefficient r	0.44	0.60
p-value	< 0.0001	< 0.0001

To balance the uncertainties of annual temperature reconstruction and to detect long-term trends in the thermal conditions, reconstructed summer half-year temperatures, as well as observed April to September temperatures in the years 1854 to 2010 (homogenized monthly temperature data set for Luxembourg-City), were smoothed using the LOESS function (Fig. 4). Fig. 4 shows that periods of higher and periods of lower temperatures altered in the past cen-

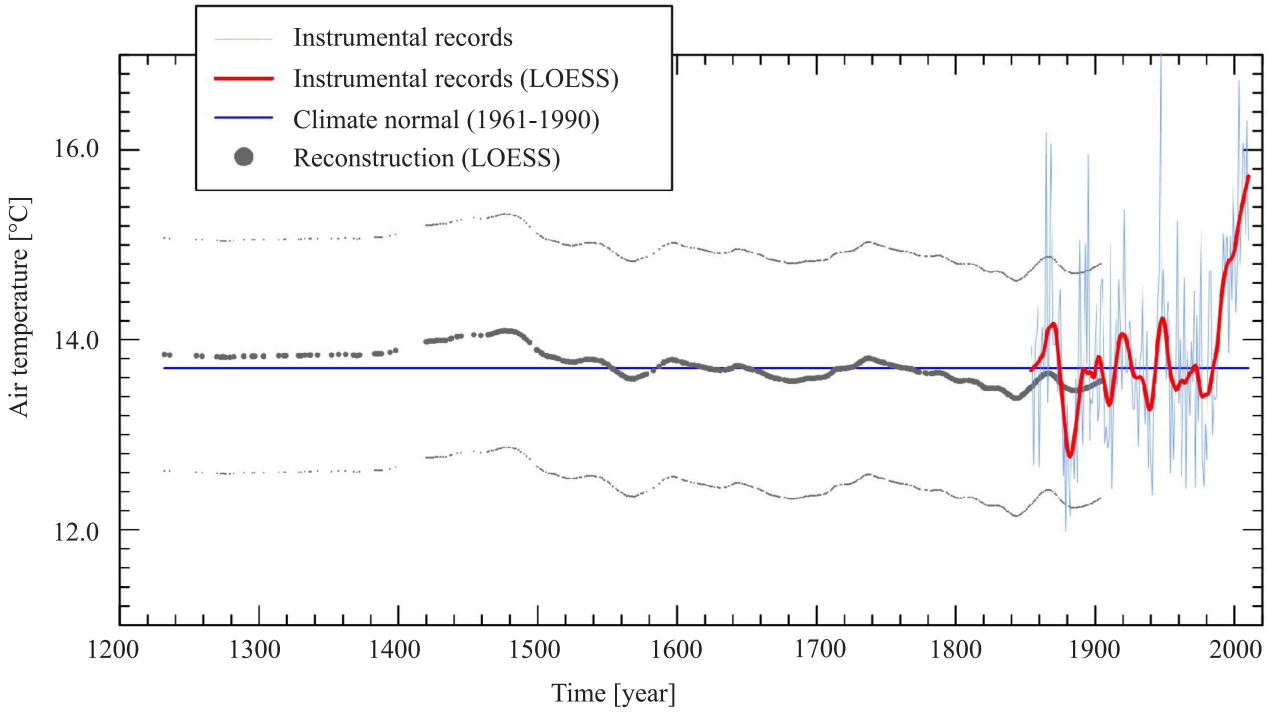

Fig. 4: Average April to September air temperatures in the time frame 1200 to 2010. Continuous lines represent instrumental records (light blue), LOESS smoothed instrumental records (smoothing factor: 0.1) (red) and climate normal conditions (1961-1990) (dark blue line) according to the homogenized monthly temperature data set for Luxembourg-City. Dark dots indicate LOESS smoothed curves (smoothing factor: 0.1) of temperature reconstructions based on wine quality notations (bold dots) as well as the respective 95 % confidence band (small dots).

turies. Highest temperature conditions were reconstructed for the period prior to the end of the 15th century (absolute LOESS maximum reached in 1483), which virtually fits with the supposed end of the so called Medieval Climate Optimum or Medieval Warm Period (Brazdil *et al.* 2005). The relative warm temperature conditions in Europe during this period are documented by the extension of grape cultivation in Europe into northern Germany, England and Poland (Schultz and Jones 2010). In the following centuries, reconstructed April to September temperatures decreased, which is in line with the Little Ice Age (generally assumed to be located between 1550 and 1850 (Brazdil *et al.* 2005)). In fact, this cool period is supposed to have caused many winegrowing regions to be abandoned and it established the 50th degree latitude as the reference northern limitation for the geographical extension of viticulture in Central Europe (Schultz and Jones 2010). Overall lowest LOESS values were observed in the middle of the 19th century (1843). This is in line with the observations of Luterbacher *et al.* (2004) that the 19th century was the coldest century in Europe in the last 500 years. In addition, the long cool period starting in the 1750s observed in Burgundy by Chuine *et al.* (2004) was retrieved in the present data set.

However, in interpreting present data, it has to be taken into account that reconstructed temperatures are purely based on wine quality classes assigned and hence shifted into the direction of average conditions of the respective wine quality class. Consequently, extreme temperature conditions in single seasons or even multi-annual periods of exceptionally warm or cold conditions might not be expressed to its complete extent in the present reconstruction data sets.

In general, instrumental records and their LOESS smoothing curve (Figure 4) illustrate the exceptional character of the recorded temperatures in the last decade of the 20th and the first decade of the 21st century. In fact, present data from Luxembourg confirm the observation of Luterbacher *et al.* (2004) that the late 20th and the early 21st century was in Europe very likely warmer than any period in the last 500 years.

Conclusion

Significant positive correlations between historical vintage descriptions regarding the annual quality of wines originating from Luxembourg and the temperature conditions in the summer half-year (April to September) were obtained; the additional inclusion of the wine quantity as predictor variable did not significantly improve the model output. Investigations showed that an increase of temperatures during the vegetation period was generally linked to a higher wine quality – at least under the climatic conditions of the Luxembourgish winegrowing region in the reference period (1854-1885).

Reconstructions of April to September temperatures indicate that periods with cooler climatic conditions and periods with warmer conditions alternated in the past centuries in Luxembourg. Even though a precise reconstruction of the annual temperature conditions solely based on vintage descriptions is not possible due to the broad set of potentially interfering effects, long-term climatic trends described in the literature such as the Medieval Climate Optimum and the Little Ice Age could be retrieved.

Acknowledgements

This work was carried out in the framework of the research projects "REMOD" and "Terroir2" and partially funded by the Institut Viti-Vinicole in Remich/Luxembourg. The authors would like to acknowledge N. Baron, R. Rausch, L. Giustarini, L. Stockes and Dr. I. Trebs (LIST – Luxembourg Institute of Science and Technology) for their support in data compilation, visualisation, translation and GIS, as well as Dr. I. Chuine (Centre d'écologie fonctionnelle et évolutive, Montpellier) and Dr. J. Luterbacher (Justus Liebig University, Giessen) for providing temperature reconstruction data sets.

References

Anonymous; 1937: Luxemburger Weinchronik 809-1904. In: Anonymous (Eds.): 25e Anniversaire de la Fédération Viticole du Grand-Duché de Luxembourg. 122-128. Imprimerie Saint-Paul, Luxembourg.

Baciocco, K. A.; Davis, R. E.; Jones, G. V.; 2014: Climate and Bordeaux wine quality: identifying the key factors that differentiate vintages based on consensus rankings. J. Wine Res. **25**, 75-90.

Brazdil, R.; Pfister, C.; Wanner, H.; Von Storch, H.; Luterbacher, J.; 2005: Historical climatology in Europe - the state of the art. Clim. Change **70**, 363-430.

Brazdil, R.; Zahradnicek, P.; Dobrovolny, P.; Kotyza, O.; Valasek, H.; 2008: Historical and recent viticulture as a source of climatological knowledge in the Czech Republic. Geografie-Sbornik CGS **113**, 351-371.

Caffarra, A.; Eccel, E.; 2009: Increasing the robustness of phenological models for *Vitis vinifera* cv. Chardonnay. Int. J. Biometeorol. **54**, 255-267.

Chuine, I.; Yiou, P.; Viovy, N.; Seguin, B.; Daux, V.; Ladurie, E. L.; 2004: Grape ripening as a past climate indicator. Nature **432**, 289-290.

Drogue, G.; Hoffmann, L.; Pfister, L.; 2005: Les archives climatiques quantitatives de Luxembourg-ville: analyse primaire des longues séries chronologiques (1838-2003). In: C. Ries (Ed.): Ferrantia 43: Contribution à la climatologie du Luxembourg. Analyses historiques, scénarios futurs, 43-84. Musée National d'Histoire Naturelle, Luxembourg.

Garcia de Cortazar-Atauri, I.; Daux, V.; Garnier, E.; Yiou, P.; Viovy, N.; Seguin, B.; Boursiquot, J. M.; Parker, A. K.; Van Leeuwen, C.; Chuine, I.; 2010: Climate reconstructions from grape harvest dates: Methodology and uncertainties. Holocene **20**, 599-608.

Garnier, E.; Daux, V.; Yiou, P.; de Cortazar-Atauri, I. G.; 2011: Grapevine harvest dates in Besançon (France) between 1525 and 1847: Social outcomes or climate evidence? Clim. Change **104**, 703-727.

Guiot, J.; 2012: A robust spatial reconstruction of April to September temperature in Europe: Comparisons between the medieval period and the recent warming with a focus on extreme values. Global Planet. Change **84-85**, 14-22.

Huglin, M. P.; 1978: Nouveau mode d'évaluation des possibilités héliothermiques d'un milieu viticole. Comptes Rendus des Séances de l'Académie d'Agriculture de France **64**, 1117-1126.

Jones, G. V.; 2007: Climate change: Observations, Projections, and General Implications for Viticulture and Wine Production. Working paper no. 7. Whitman College Economic Department, Walla Walla, WA.

Jones, G. V.; Davis, R. E.; 2000: Climate influence on grapevine phenology, grape composition, and wine production and quality for Bordeaux, France. Am. J. Enol. Vitic. **51**, 249-261.

Kiss, A.; Wilson, R.; Bariska, I.; 2011: An experimental 392-year documentary-based multi-proxy (vine and grain) reconstruction of May-July temperatures for Kõszeg, West-Hungary. Int. J. Biometeorol. **55**, 595-611.

Koch, E.; Maurer, C.; Hammerl, C.; Hammerl, T.; Pokorny, E.; 2009: BACCHUS grape harvest days and temperature reconstruction for Vienna from the 16th to the 18th century, 2632-2638. In: Proc. 18th IMACS / MODSIM Congress, 13-17 July 2009, Cairns, Australia.

Krieger, M.; Lohmann, G.; Laepple, T.; 2011: Seasonal climate impacts on the grape harvest date in Burgundy (France). Clim. Past **7**, 425-435.

Luterbacher, J.; Dietrich, D.; Xoplaki, E.; Grosjean, M.; Wanner, W.; 2004: European seasonal and annual temperature variability, trends, and extremes since 1500. Science **303**, 1499-1503.

Mariani, L.; Parisi, S.; Failla, O.; Cola, G.; Zoia, G.; Bonardi, L.; 2009: Tirano; (1624-1930): A long time series of harvest dates for grapevine. Ital. J. Agrometeorol. **14**, 7-16.

Maurer, C.; Hammerl, C.; Koch, E.; Hammerl, T.; Pokorny, E.; 2011: Extreme grape harvest data of Austria, Switzerland and France from A.D. 1523 to 2007 compared to corresponding instrumental/reconstructed temperature data and various documentary sources. Theor. Appl. Climatol. **106**, 55-68.

Meier, N.; Rutishauser, T.; Pfister, C.; Wanner, H.; Luterbacher, J.; 2007: Grape harvest dates as a proxy for Swiss April to August temperature reconstructions back to AD 1480. Geophys. Res. Lett. **34**, L20705.

Molitor, D.; Behr, M.; Hoffmann, L.; Evers, D.; 2012: Impact of grape cluster division on cluster morphology and bunch rot epidemic. Am. J. Enol. Vitic. **63**, 508-514.

Molitor, D.; Caffarra, A.; Sinigoj, P.; Pertot, I.; Hoffmann, L.; Junk, J.; 2014a: Late frost damage risk for viticulture under future climate conditions: a case study for the Luxembourgish winegrowing region. Aust. J. Grape Wine Res. **20**, 160-168.

Molitor, D.; Junk, J.; Evers, D.; Hoffmann, J.; Beyer, M.; 2014b: A high resolution cumulative degree day based model to simulate the phenological development of grapevine. Am. J. Enol. Vitic. **65**, 72-80.

Reuter, F.; 1867: Observations Météorologiques faites à Luxembourg (1854-1863). Imprimerie V. Buck, Luxembourg.

Reuter, F.; 1874: Observations Météorologiques faites à Luxembourg, Deuxième volume (1864-1873). Imprimerie V. Buck, Luxembourg.

Reuter, F.; 1887: Observations Météorologiques faites à Luxembourg, Troisième volume (1874-1883). Imprimerie V. Buck, Luxembourg.

Reuter-Chomé, F.; 1890: Observations Météorologiques faites à Luxembourg de 1884-1888. Imprimerie V. Buck, Luxembourg.

Santos, J. A.; Carneiro, M. F.; Correia, A.; Alcoforado, M. J.; Zorita, E.; Gomez-Navarro, J. J.; 2015: New insights into the reconstructed temperature in Portugal over the last 400 years. Clim. Past Discuss. **11**, 1-25.

Schultz, H. R.; Jones, G. V.; 2010: Climate induced historic and future changes in viticulture. J. Wine Res. **21**, 137-145.

Storchmann, K.; 2005: English weather and Rhine valley wine quality: An ordered probit model. J. Wine Res. **16**, 105-119.

Received July 23, 2015