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Climate change information tailored to the agricultural sector in Central Europe, exemplified on the region of Lower Franconia

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Abstract
There is a growing societal, economic, and political demand to translate available data on regional climate change into sector-specific, practice-oriented, and user-friendly information. The study presents a demand-driven approach to specify the impacts of regional climate change on agriculture, viticulture, and fruit and vegetable growing in Lower Franconia, southern Germany, a region with heterogeneous topography, diversified land use patterns, and intense activities in the sectors specified above. The approach is based on an ensemble of high-resolution regional climate model projections, a bias correction tool, and a large spectrum of meteorological (extreme) indicators that are crucial to the agricultural sector in Central Europe, as inferred from a stakeholder survey. For several decades, Lower Franconia represents a hotspot region of climate change with enhanced heat waves, prolonged droughts, and intermittent local flooding by heavy rainfall events. Results of the high-resolution regional climate model projections indicate an increase of hot days and tropical nights by a factor of 5 and 12, respectively, if greenhouse gas emissions continue to grow until 2100 according to the RCP8.5 emission scenario. At the same time, droughts will occur more frequently and last longer while rainfall intensity enhances. A longer growing period starting more than 40 days earlier (compared to the reference period 1970 to 1999) implies a higher risk of late frost damage for crops, fruits, grapes, and even some tree species. In contrast, the thermal prerequisites for viticulture will be satisfied across the entire region, even at higher-elevation sites. These facets of regional climate change are made accessible to users and the public via an interactive field-resolving web portal. Altogether, they gravely challenge the historically developed land use systems in Lower Franconia and require timely adaptation and mitigation strategies.

Keywords Climate change · Germany · Demand-driven research · Agriculture

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1 Introduction

There is growing evidence that man-made climate change cannot be defeated entirely, regardless of our future efforts in climate mitigation (IPCC 2021). Consequently, more scientific focus is currently oriented to strategies of timely adaptation to the inevitable extent of future climate change to reduce socioeconomic risks and/or benefit from potential positive implications. The basic challenge for the involved scientific disciplines consists in the diversity of processes and systems affected by global warming and in the complexity of the interactions between climate, human activities, societal, and individual interests. Thus, a science-guided way towards appropriate, sustainable, and beneficial adaptation measures requires sector-specific, practice-oriented, and user-friendly approaches. Recent examples for climate service dedicated to fostering necessary climate adaptations in the agricultural sector have been given by Cox (1996), Howden et al. (2007), and Wenkel et al. (2013). In the present study, we exemplify this challenge by translating raw output from future climate model projections into relevant information for agriculture and specialized crops in Central Europe.

Agriculture, in a broader sense, represents a paradigm for the manifold and reciprocal interactions between climate change and human activities. This has recently been highlighted by a special report of the Intergovernmental Panel on Climate Change on the nexus between climate change, land degradation, agriculture, and food security (IPCC 2019). With continuously increasing atmospheric greenhouse gas concentrations, the authors expect crop failure especially in the global South and the Mediterranean region, high damages due to meteorological extremes, pests, and plant diseases, dramatically increasing food prices as well as lower food quality and nutritional value. At lower warming rates during the next decades, some positive effects may occur in higher latitude regions, mainly related to a longer growing period. The same report alludes to the responsibility and potential of agricultural activities in terms of climate mitigation targets. Thus, mitigation potential and adaptation to the unavoidable implications of climate change are closely tied to each other in the agricultural sector, with mitigation failure implying substantially larger efforts in adaptation (IPCC 2019, cf. Paeth et al. 2009). As such, it is not surprising that many studies have pointed to the urgent and challenging needs of adjustment in the agricultural sector including forestry, fishery, and specialized crops such as grapevine, fruits, and vegetables (e.g. Easterling and Apps 2005, Howden et al. 2007, Perarnaud et al. 2005). In particular, the scientific community has been focusing on European viticulture, revealing a large spectrum of disturbances arising from issues of wine quality and ageing to the shift of the entire wine growing geography across Europe (Urhausen et al. 2011, Malheiro et al. 2012, Xu et al. 2012, Hannah et al. 2013, Moriondo et al. 2013, Boss et al. 2014, Fraga et al. 2016).

Some authors suggest a regionally heterogeneous pattern of vulnerability to climate change: in general, crop yield and food security are more affected in tropical and subtropical regions of rain-fed agriculture while higher income may be achieved in the countries of northern Europe, at least during the upcoming decades (Ferrara et al. 2010, Ruffault et al. 2014, Awoye et al. 2017). Our study is dedicated to a region in southern Germany that, according to common knowledge, has so far been less associated with crop failure and needs of adaptation in the agricultural sector. The study domain refers to the district of Lower Franconia in northern Bavaria, which covers an area of about 8500 km^2 and is centred at around 50 °N and 10 °E (cf. Fig. 1). It is characterized by a heterogeneous topography, diversified land use patterns, and intense activities in agriculture, viticulture, forestry, and fruit and vegetable growing. Soil patterns in the study area are extremely diverse due to variable geological and geomorphological conditions (Schäfer et al. 2020).

Furthermore, since Neolithic times, human impact provoked a massive change in the pedosphere and, thus, in soil functions such as soil fertility and hydrology (Meyer-Heintze et al. 2020). At the international level, Lower Franconia is famous for its tradition in growing a large variety of high-quality white wines (Maaß and Schwab 2011, Rauh and Paeth 2011).

Germany has experienced above-average warming rates in the past and is expected to sustain substantially higher temperatures in the future (IPCC 2021, Paeth and Pollinger 2021). At the same time, heat waves, droughts, and heavy rainfall events may intensify in amplitude, duration, and/or frequency (Paeth et al. 2015). This makes southern Germany a hotspot of regional climate change, emanating from a combination of increasing greenhouse effect, enhanced warm air advection, modified planetary wave activity, reduced snow cover in winter, and a relatively high level of population density and soil sealing (Grossmann-Clarke 2017, Paeth and Pollinger 2019, 2021, Kirchner et al. 2021). In the light of these apparent changes, several authors have emphasized the urgent need for adaptation in German agriculture and forestry (Köstner et al. 2014, Riediger et al. 2014, Troost and Berger 2015, Möller et al. 2019) to prevent crop failure and loss of income to farmers and forest owners (Lippert et al. 2009). Sufficient plant-available water, along with an adequate nutrient supply, is the basic prerequisite for vital, stable, and well-growing forest stands. Many forest sites suffer from drought stress as a result of limited plant-available water. Consequently, vulnerable tree stands either directly collapse or are no longer resilient to further sources of stress, like insect infestations (e.g. Netherer et al. 2019).

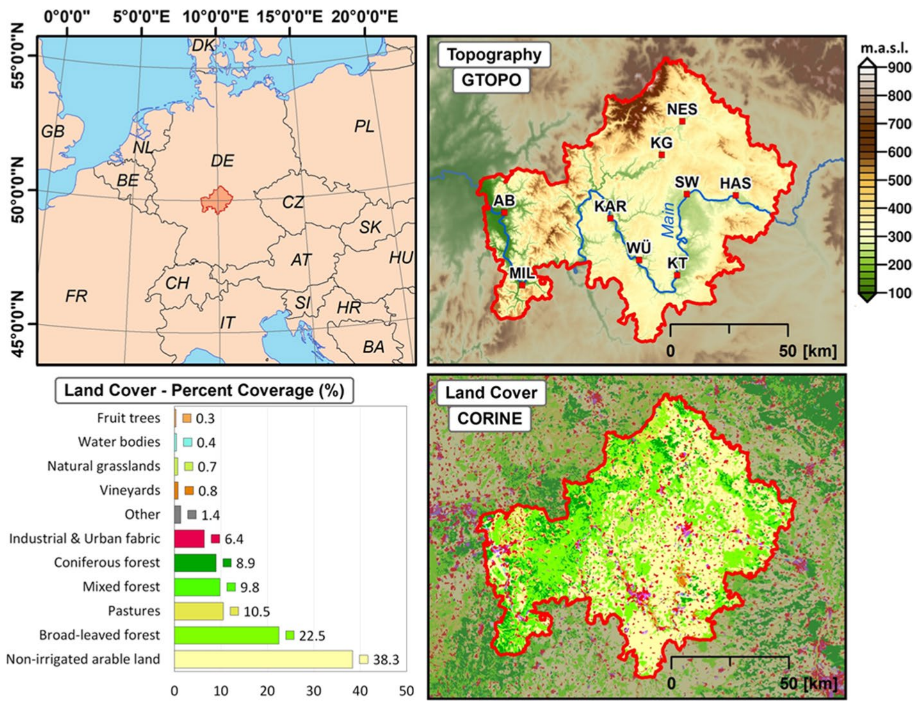

Fig. 1 Location, topography and land cover of Lower Franconia. The red squares indicate the location of the county seats in Lower Franconia. AB, Aschaffenburg; HAS, Haßfurt; KAR, Karlstadt; KG, Bad Kissingen; KT, Kitzingen; MIL, Miltenberg; NES, Bad Neustadt an der Saale; SW, Schweinfurt; WÜ, Würzburg

Trnka et al. (2011) have investigated agro-climatic conditions across Central Europe and suggested a dramatic shift of the status quo: 98 % of all agricultural production areas may experience a markedly different agro-climate towards the middle of the twenty-first century. Wine production in Germany, and specifically in Lower Franconia, is also prone to increasing risks and challenges such as late frost events, water stress, sunburn, new pests, fungal infestation, and reduced ageing capacity (Stock et al. 2007, Maaß and Schwab 2011, Rauh and Paeth 2011, Ziegler et al. 2020). This underlines the extensive and urgent adaptation challenges for all sectors of agriculture, forestry, and specialized crop production in our study domain.

Here, we present a comprehensive investigation of various aspects of regional climate change that are immediately relevant to agricultural, viticultural, and silvicultural activities in Lower Franconia, serving as an example of the climate change hotspot in Central Europe. Our approach is entirely demand-driven since the analyzed meteorological variables and indicators are derived from a survey among actors and stakeholders (i.e., traditional fruit and truck farmers, wine-growers, forest owners, and associated regional organizations). The novelty of the approach pertains to the broad spectrum of analyzed indicators, including issues of phenology and growing season, and the underlying data source referring to an ensemble of high-resolution bias-adjusted regional climate model projections until the end of the twenty-first century. This represents an advancement compared to former studies by Trnka et al. (2011) and Möller et al. (2019). The main objective of the present paper is to draw a picture of multivariate regional climate change tailored to the specific requirements of an economic sector that is specifically challenged by the implications of man-made climate change.

The next section is dedicated to the considered model and observational data sets and to their statistical processing, including the definition of specific meteorological indicators tailored to agriculture and specialized crops. The results are presented in Section 3, differentiated into aspects of climate change related to temperature, precipitation, and plant growth. The results are discussed in Section 4 with respect to findings from other studies and to their practical relevance. Section 5 provides the main conclusions and a brief outlook.

2 Data and methods

Figure 1 illustrates the geographical location, topography, and land use of the study domain. The outline marks the district of Lower Franconia in southern Germany (area of 8531 km^2). It is subdivided into nine counties. The meandering course of the River Main is clearly visible. Along the Main, partly steep hillsides with southerly exposition are cultivated by wine-growers. In total, vineyards cover less than 1% of the entire surface of 8531 km^2 but make an important contribution to the region's economic output. Higher-elevation sites in the west, north, and east are covered by forests (38.7% in total). In between, intensive agriculture with fruit and vegetable growing prevails (38.3%). The hilly terrain and relatively large topographic variance with elevations ranging between 80 and 930 m above sea level has led to a diversified pattern of land use systems, making Lower Franconia also attractive for hiking and cultural tourism.

Data on current and future climate change is derived from an ensemble of regional climate model (RCM) simulations that are provided in the framework of the Coordinated Regional Climate Downscaling Experiment (CORDEX). RCM datasets from CORDEX have become a benchmark for the assessment of regional climate change in practically all continental regions on Earth (e.g. Jacob et al. 2014, Aich et al. 2017, Choudhari et al. 2019). High-resolution RCMs favour the investigation of climate change implications at the landscape scale. In addition, Paeth and Mannig (2012) have demonstrated that RCMs exhibit an added value in detecting regional climate change signals against the background of internal climate variability. Here, we refer to the EURO-CORDEX domain that expands over the whole of Europe with Germany being in the centre of the downscaling region (Jacob et al. 2014). We applied the following two criteria on the large spectrum of available RCM experiments (cf. Table 1): (1) time series of daily mean, minimum and maximum temperature as well as daily precipitation sums are available over the 1970–2100 period at a horizontal resolution of 0.11° (~12 km). (2) For each RCM, a historical run with observed forcings between 1970 and 2005 and two transient projections using the RCP4.5 and RCP8.5 emission scenario, respectively, are provided during the 2005–2100 period (RCP = Representative Concentration Pathways; cf. van Vuuren et al. 2011). This selection results in six considered simulations from six different RCMs that are themselves driven by six different global climate models (GCMs). Unfortunately, EURO-CORDEX does not provide more simulations meeting the criteria required for our study. However, it is assumed that uncertainty ranges in the assessment of regional climate change are reasonably represented, although the ensemble size is relatively small (cf. Paeth et al. 2013). The RCP8.5 scenario follows a high-impact pathway that assumes barely any large-scale achievements in climate protection. It has been selected to assess the upper limit of regional climate change in Central Europe and the most severe implications the agricultural sector may have to cope with. The RCP4.5 scenario represents an intermediate scenario between a business-as-usual pathway and the full commitment to the Paris agreement. Most modeller groups contributing to CORDEX have addressed these two scenarios to span the corridor of more or less likely future emission pathways.

We refer to gridded observations from the German Weather Service (DWD) for model validation and model bias adjustment. For the DWD data the same four meteorological variables are available over the reference period 1970–1999. The spatial resolution is considerably higher while the time step is monthly (Table 1). This gridded dataset is derived from the relatively dense network of meteorological stations across Germany that is spatially interpolated using an inverse-distance weighting and height regression (Kaspar et al. 2013).

The study uses only standard methods of descriptive statistics to enhance the clarity of the results and to avoid inappropriate interpretations by end users. First, all datasets are statistically interpolated to the 1 km × 1 km grid of the DWD observations using a nearest-neighbour approach (Wilks 2006). Second, systematic model biases are removed by adjusting the mean seasonal cycle of each RCM simulation and each meteorological variable to the observed values during the 1970–1999 period. The difference between mean values is considered for the temperature variables, while for the precipitation the ratio between the precipitation sums is considered to avoid negative daily rainfall (cf. Ruffault et al. 2014, Ruiz-Ramos et al. 2016). This represents a first-order bias correction called “linear scaling” that retains the original temporal variability of the model run, including long-term changes. In addition, the portion of total model uncertainty, which arises from different climate sensitivities to the imposed radiative forcing and from different phases and amplitudes of internal model variations, is unaffected (cf. Paeth et al. 2013). Note that such univariate approaches of bias correction cannot guarantee that the physical consistency between the corrected meteorological variables is safeguarded (cf. Li et al. 2019, Paeth et al. 2019). However, it is assumed

Table 1 Considered model and observational data sets

		Horizontal resolution	Temporal resolution	Time period	Variables
Model data					
RCM	Driving GCM				
CCLM4-8-17	HadGEM2-ES	0.11° (~12 km)	Daily	1970–2100	T_{mean}, T_{min}, T_{max}, P
ALADIN53	CNRM-CM5	0.11°	Daily	1970–2100	T_{mean}, T_{min}, T_{max}, P
HIRHAM5	NorESM1-M	0.11°	Daily	1970–2100	T_{mean}, T_{min}, T_{max}, P
RACMO22E	EC-EARTH	0.11°	Daily	1970–2100	T_{mean}, T_{min}, T_{max}, P
REMO2009	MPI-ESM-LR	0.11°	Daily	1970–2100	T_{mean}, T_{min}, T_{max}, P
RCA4	IPSL-CM5A-MR	0.11°	Daily	1970–2100	T_{mean}, T_{min}, T_{max}, P
Validation data					
DWD gridded observations		1 km	Monthly	1901–2019	T_{mean}, T_{min}, T_{max}, P
DWD gridded observations		1 km	Annual	1951–2019	Frost days, ice days, summer days, hot days, strong precipitation days, heavy precipitation days (cf. Table 2)
DWD station Würzburg		-	Monthly	1961–2021	T_{mean}, P

T_{mean} daily mean temperature, T_{min} daily minimum temperature, T_{max} daily maximum temperature, P precipitation sum that this problem is of minor relevance for the outcomes of the present study as a direct combination of temperature and precipitation variables is only undertaken when computing the de Martonne aridity index (see below).

Results of the RCM simulations are drawn for the period 1970 to 2100. The time series plots illustrated in Section 3 refer to the low-pass filtered multi-model ensemble means using a running 30-year average, which is typically used to highlight long-term climate changes against the background of internal noise (Santer et al. 2011). The ensemble range, however, stretches from annual minimum to maximum values within the ensemble to emphasize differences between models at shorter time scales. These are supposed to reflect internal variability. Note that this highlights the model uncertainty with respect to the changes in the ensemble mean (cf. Paeth et al. 2013). Thus, extending the ensemble range over 30-year low-pass filtered values would reduce the ensemble spread considerably.

Based on the four meteorological standard variables from climate models and observations (cf. Table 1), 18 indicators of meteorological conditions relevant to the agricultural sector in Lower Franconia are calculated (Table 2). This selection is based on a stakeholder survey among farmers, forest owners, and wine-growers which was conducted in 2018 and guides the scientific workflow of the project ever since. The survey was originally done in German, an English translation is accessible via the Electronic Supplemental Material (ESM 5). The naming of relevant indicators was completely open (free text), i.e. no list of predefined indicators was given because we did not want to predetermine the answers. Some of the considered indicators are typically addressed when the link between climate change and agricultural production is investigated (cf. Möller et al. 2019). Yet, our spectrum of indicators is substantially larger, relating to phenomena such as late frost events, heat stress, erosion and damage due to extreme rainfall events, water stress, dry spells, onset, and length of growing period as well as thermal comfort for grapevines. Most indicators listed in Table 2 are self-explanatory with the definitions provided. The thresholds correspond to the recommendations from the World Meteorological Organization and the World Climate Research Programme (Möller et al. 2019, ETCCDI 2022). The aridity index by de Martonne (1926) has originally been developed for relatively dry climates and is often applied to European climate types, especially in the Mediterranean region (e.g. Pellicone et al. 2019). Low values indicate a higher level of aridity. The Huglin index is based on degree days and describes the thermal comfort of grape varieties (Huglin and Schneider 1998). ESM 1 illustrates how categorized values of the Huglin index relate to recommended grape varieties in Lower Franconia and in other wine growing regions in Europe (cf. Stock et al. 2007). High values are favourable for thermophile grapevines (see Section 3.4 for more details).

Most indicators are based on counting statistics according to WMO standards (Möller et al. 2019, ETCCDI 2022), leading to annual time series (number of events per year) although the original temporal resolution is daily (see above). However, the seasonality of climate change is of crucial importance to the agricultural sector. In fact, the seasonality is implicitly included since cold (heat) events are confined to the cold (warm) season in Central Europe (e.g. frost days, hot days, and tropical nights). In addition, heavy precipitation events and long drought periods only occur during the summer half-year. The remaining indicators directly relate to the vegetation period during the summer half-year (e.g. onset and duration of vegetation period, late frost events, and Huglin index). Observed temperature and precipitation anomalies are presented in a monthly resolution to highlight the seasonality of recent changes.

Table 2 Analyzed meteorological indicators relevant to the agricultural sector in Lower Franconia

Indicator	Unit	Definition
Frost days	Number	$T_{min} < 0$ °C
Ice days	Number	$T_{max} < 0$ °C
Summer days	Number	$T_{max} \geq 25$ °C
Hot days	Number	$T_{max} \geq 30$ °C
Tropical nights	Number	$T_{min} \geq 20$ °C
Precipitation days	Number	$P \geq 1$ mm
Strong precipitation days	Number	$P \geq 10$ mm
Heavy precipitation days	Number	$P \geq 20$ mm
Dry days	Number	$P < 1$ mm
Dry spells	Number	≥ 6 consecutive dry days
Average drought duration	Days	Average duration of dry spell
Longest drought duration	Days	Longest duration of dry spell
de Martonne aridity index	mm/°C	$dMI = \frac{P_{\text{annual}}}{T_{\text{annual}}+10°\text{C}}$
Onset of vegetation period	Day of year	≥ 6 consecutive days with $T_{mean} \geq 5$ °C
Vegetation period	Days	Period between first 6 consecutive days in first half-year with $T_{mean} \geq 5$ °C and $T_{mean} \leq 5$ °C in second half-year
Last frost in spring	Day of year	Last frost day in first half-year
Late frost lag since vegetation onset	Days	Period between vegetation onset and last frost day in first half-year
Huglin index	Dimensionless	$HI = \kappa \bullet \sum_{d=91}^{273} \left(\frac{T_{\text{mean}}(d)+T_{\text{max}}(d)-20}{2} \right)$

T_{mean} daily mean temperature, T_{min} daily minimum temperature, T_{max} daily maximum temperature, P daily precipitation sum, T_{annual} annual mean temperature, P_{annual} annual precipitation sum, K day-length factor depending on geographical latitude

3 Results

3.1 Climatic characterization of the study domain

Figure 2 illustrates the mean climate in the study domain. The region is assigned to a temperate subcontinental climate type with annual mean temperatures stretching from below 6 °C to more than 10 °C, depending on elevation. Another regional peculiarity is given by the remarkable gradient of annual precipitation totals between less than 500 mm in the southeast and more than 1200 mm along the northern low mountain range, attributable to wind-ward and lee-ward effects. Compared with other regions in Germany, Lower Franconia is characterized by a relatively dry, warm, and sunny climate.

Especially during the last decade, our study domain has experienced very warm monthly temperature anomalies. In Fig. 3, this is illustrated for the DWD station Würzburg being the largest city and administrative seat of the district (top panel). Most months show positive temperature anomalies between 1 and 5 °C compared with a standard deviation of about 1 °C (1.5 °C) in summer (winter) months during the 1961–1990 climate normal period. Since 2015, months with deficient precipitation amount clearly prevail (Fig. 3, bottom panel). Meanwhile, the accumulated precipitation anomalies sum up to more than 550 mm, which is equivalent to the mean annual precipitation amount in Würzburg. In contrast to temperature,

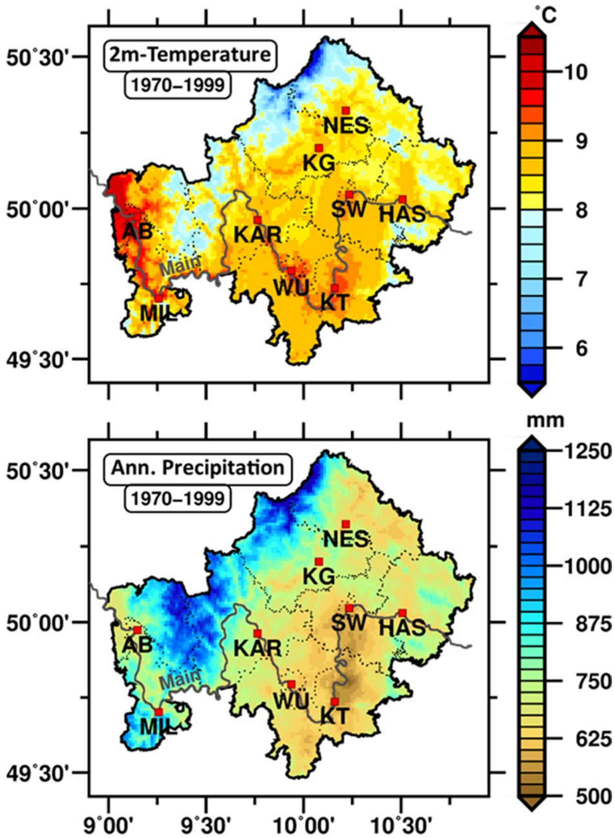

Fig. 2 Observed long-term mean temperature (top) and annual precipitation totals (bottom) during the 1970–1999 period

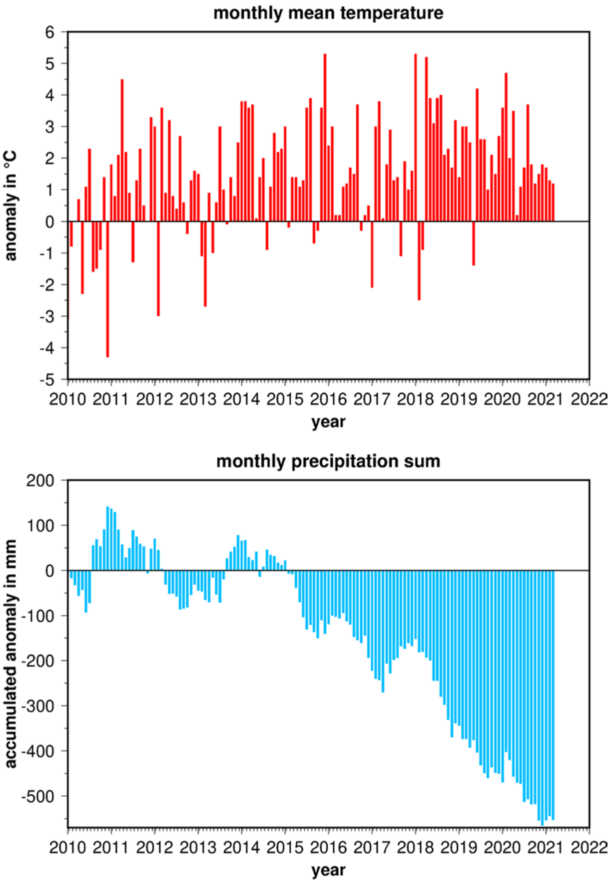

Fig. 3 Observed monthly anomalies of 2-m temperature and accumulated monthly anomalies of precipitation from 1961 to 1990 reference period at station Würzburg since January 2010

the precipitation changes exhibit a clear seasonal cycle with largely deficient rainfall in summer and slightly above-normal values in winter. Consequently, heat and water stress have become major issues in the public and political debate with special focus on viticulture, agriculture, and forestry as main pillars of economic activity in Lower Franconia.

3.2 Temperature related indicators of climate change

First, the attention is turned to changes in cold events. Figure 4 displays observed and simulated time series of ice days and frost days per year (for definitions see Table 2), averaged over the area of Lower Franconia. These events have been quoted in our stakeholder survey because they relate to frost damage during winter in vineyards and orchards, late frost events, phenology, ice wine production, and chilling phases being crucial for various tree species (cf. Stock et al. 2007, Maaß and Schwab 2011, IPCC 2019, Ziegler et al. 2020). When comparing observations and climate models with each other, it is obvious that the bias adjustment of the RCM output has successfully removed the offset between the time series during recent decades. Both meteorological indicators have experienced a steadily negative tendency since 1970, which is carried forward by the RCM projections until the end of the twenty-first century. The annual number of ice days decreases by 50% until the

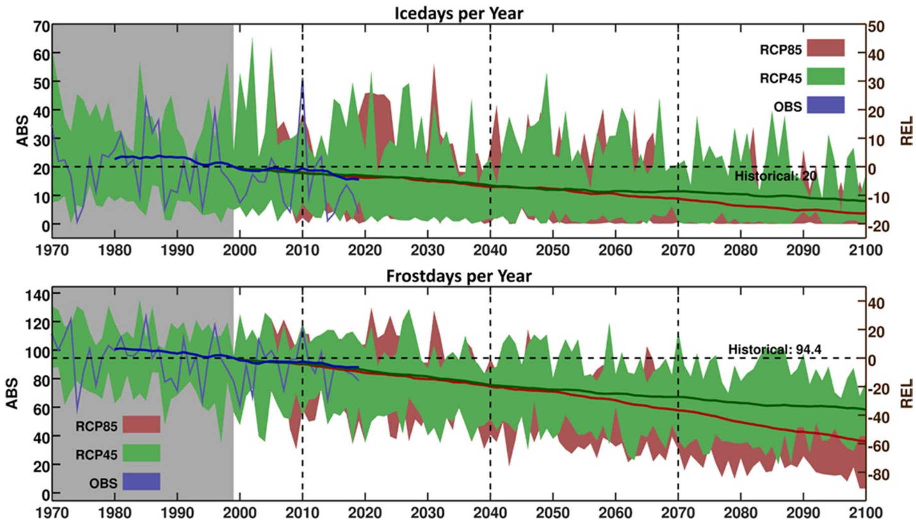

Fig. 4 Spatial-mean time series of ice days (top) and frost days (bottom) per year from observations (OBS: blue lines: annual means and 30-year low-pass filter) and RCM projections under the RCP4.5 (green) and RCP8.5 (red) emission scenario. For the definition of meteorological indicators refer to Table 2. For both scenarios the ensemble mean (30-year low-pass filtered) and spread (annual means) are plotted. The left y-axis denotes absolute values, and the right y-axis shows anomalies from 1970 to 1999 reference period (grey shading and dashed horizontal line). The dashed vertical lines separate 30-year time periods from each other that are referred to in subsequent figures

year 2100 under the RCP4.5 intermediate emission scenario and almost vanishes under the RCP8.5 “business-as-usual scenario” (top panel). Both emission scenarios are distinguishable only during the second half of the twenty-first century. The ensemble spread between annual lower and upper limits among the selected Euro-CORDEX simulations is comparable with the observed interannual fluctuations during the reference period, suggesting a rather homogenous long-term trend across the considered RCMs. A similar tendency is found for the annual number of frost days (bottom panel). Although they are reduced by one third or almost two thirds depending on the future efforts in climate change mitigation, they remain a common phenomenon in Lower Franconia with about 40 days per year in 2100, even under the RCP8.5 scenario.

Figure 5 illustrates the ensemble-mean spatial distribution of frost days per year across Lower Franconia, averaged over the 1970–1999 reference period (top panel) and over the last 30 years of the twenty-first century for the RCP4.5 and RCP8.5 scenario (middle and bottom panels). We display absolute means rather than relative changes because the latter do not exhibit noticeable spatial differences within this quite small study domain and as decision makers in the agricultural sector are more used to consult such absolute values. The comparison of the three maps leads to the following conclusions: (1) the occurrence of frost days is clearly a function of the elevation (cf. Fig. 1)—this still holds in the distant future, regardless of the emission scenario—and (2) there is a striking difference between both scenarios concerning the future frequency of frost days. In the business-as-usual scenario, no more than 70 frost days per year may occur towards the end of the twenty-first century, even at the highest elevations in the north (up to 928 m.a.s.l.), where they were observed more than 120 times per year on average in the reference period. Moreover, the future spatial maximum number of frost days in the North equals the present-day spatial minimum in the West. The frequency of

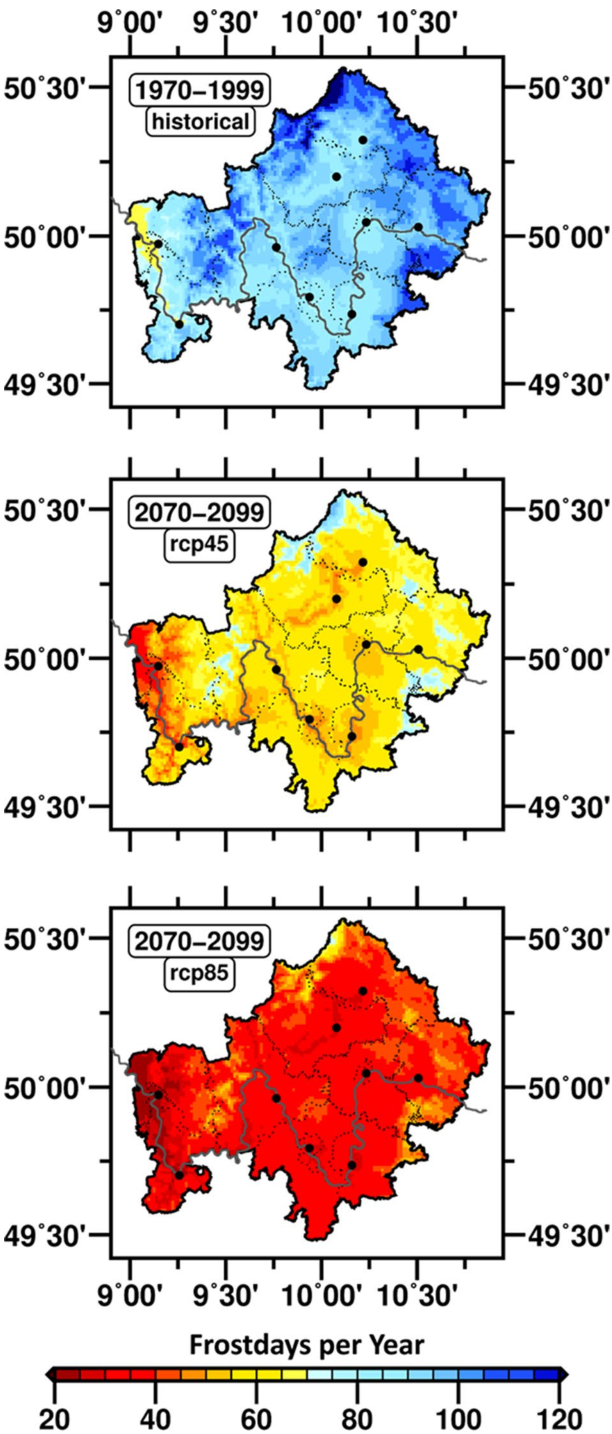

Fig. 5 Frost days per year across Lower Franconia averaged over the historical period 1970–1999 (top), the future period 2070–2099 under the RCP4.5 scenario (middle) and the same future period under the RCP8.5 scenario (bottom), as represented by the ensemble mean over all considered RCM projections. Black circles refer to the county seats in Lower Franconia (cf. Fig. 1)

frost days may fall below 20 per year in the westernmost fringe of Lower Franconia, possibly offering a new spectrum of agricultural crops, e.g. from the Mediterranean region (cf. Trnka et al. 2011, Malheiro et al. 2012, Moriondo et al. 2013).

Figure 6 shows the RCM projections for warm temperature extremes during the day and night. Summer days and hot days are typically addressed when it comes to the nexus between climate change, agriculture, and food security because these indicators represent heat stress, water shortage, and high UV exposure (e.g. Perarnaud et al. 2005, Lippert et al. 2009, Ruffault et al. 2014, Fraga et al. 2016). Tropical nights denote situations that are physiologically relevant to plants which require chilling factors at night-time to cope with heat stress during the day (IPCC 2019, Rahman et al. 2020), equivalent to their effect on humans (Artmann 2016, Grossmann-Clarke et al. 2017). In addition, cold nights before the vintage period are crucial for wine quality and ageing capacity (Hannah et al. 2013, Boss et al. 2014). All three meteorological indicators exhibit a substantial increase in their annual frequency. Under the business-as-usual scenario, the amount of summer days rises by a factor of 1.4, for hot days it is a factor of 5, and for tropical nights even a factor of 60 until the year 2100. The fact that some models project up to 110 summer days, 85 hot days, and 60 tropical nights in individual years after 2070 is even more alarming, although future summers with barely any of these events may also occur sporadically. Under the RCP4.5 scenario, the ensemble mean time series ends up with noticeably smaller changes in the frequency of warm temperature events, but the scenario effect is not visible before 2060.

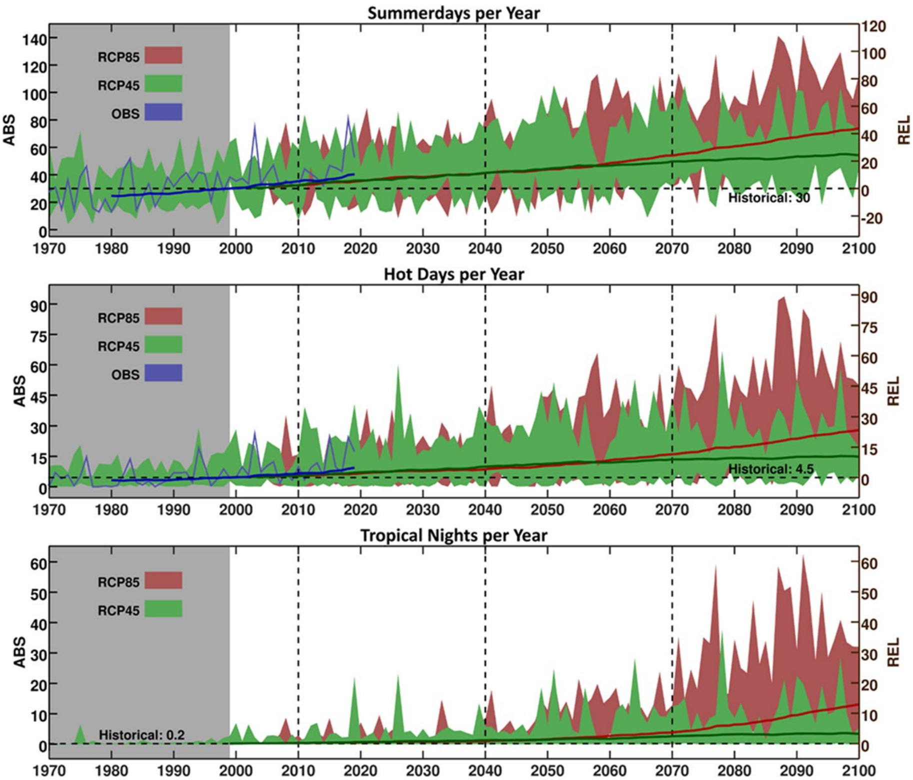

Fig. 6 Same as Fig. 4 but for summer days (top), hot days (middle) and tropical nights (bottom) per year

As for all temperature-related variables, the present-day and future occurrence of hot days and tropical nights across Lower Franconia strictly depends on elevation (Fig. 7). The largest threat by heat stress is given along the Main valley, especially in the westernmost stretch with lowest elevation. Towards the end of the twenty-first century, the coldest region in the north will experience the same number of hot days per year as the warmest region in the west under present-day conditions (left panels). Thus, the latter may serve as a present-day climate analogue for what to expect in the future along the low-mountain range of the Rhön Mountains with elevations being 800 m higher than in the analogue region. In the past, tropical nights have barely occurred in the whole of Lower Franconia (top right panel). Yet, they may become a quite normal phenomenon in most parts of the study domain if greenhouse gas concentrations continue to increase unrestrictedly. The political scope of action, as reflected by the difference between the RCP4.5 and RCP8.5 scenario, is quite large in terms of both heat-related meteorological indicators.

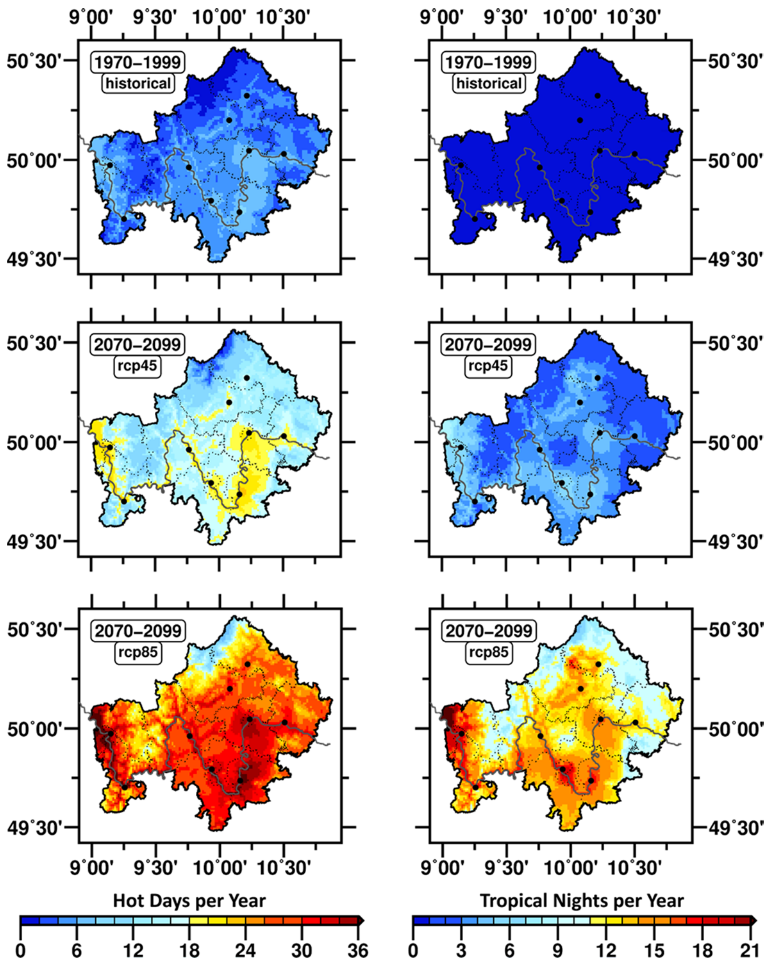

Fig. 7 Same as Fig. 5 but for hot days (left panels) and tropical nights (right panels) per year

3.3 Precipitation related indicators of climate change

The three indicators displayed in Fig. 8 refer to the total number of precipitation days and the frequency of strong and heavy precipitation events per year. The comparison among these indicators allows for assessing changes in the rainfall distribution, which is crucial for damages in cropping systems and forests due to hail, thunderstorms with downbursts and lightning, as well as local flooding (cf. Lippert et al. 2009, Möller et al. 2019, IPCC 2019). The total number of precipitation days is 152 per year during the 1970–1999 reference period and is not influenced at all by the radiative forcing, at least on a regional average. Precipitation events occur on more than 41% of all days during the year, being typical for a sub-continental area in the mid-latitudes. However, this occurrence is lower than in most other regions of Germany. Days with precipitation totals of more than 10 mm and, especially, more than 20 mm are quite seldom in Lower Franconia. Under the RCP8.5 scenario, their number increases by 38% and 77%, respectively. However, they remain rare but potentially damage-prone events. Altogether, daily precipitation may change in intensity but not in frequency. Note that the ensemble spread is large compared with the mean changes as to be expected in the context of precipitation extremes (cf. Paeth et al. 2015). Heavy precipitation is projected to occur more frequently in the entire study region whereas the basic pattern does not change from present-day to future periods (cf. ESM 2). Note that steep slopes and exposed mountain

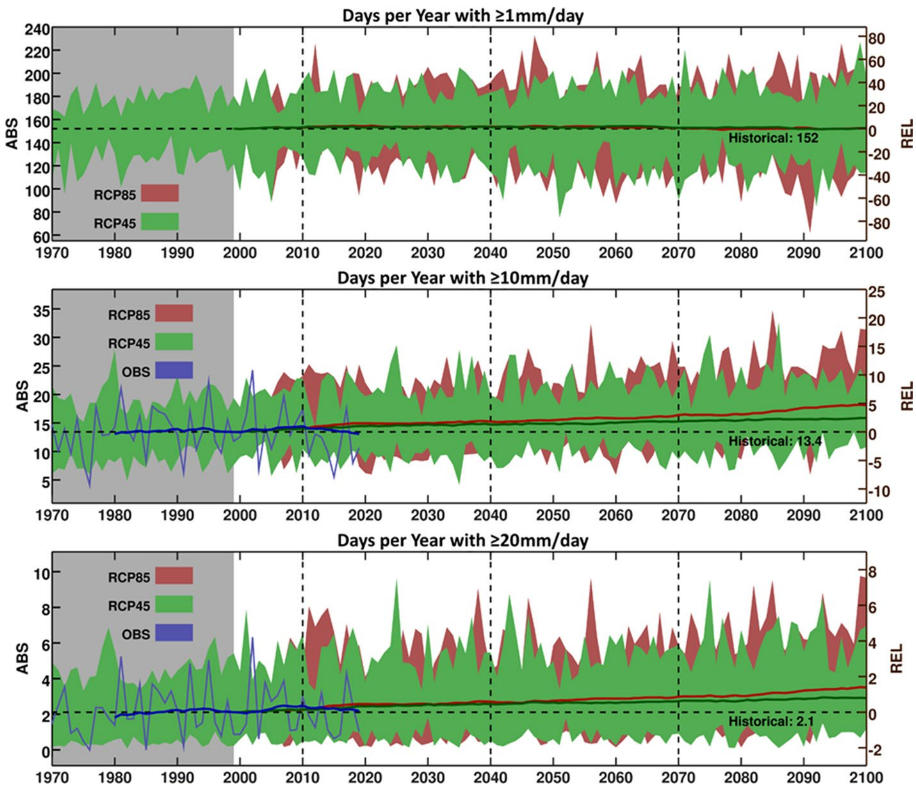

Fig. 8 Same as Fig. 4 but for precipitation days per year with ≥1 mm/day (top), ≥10 mm/day (middle) and ≥20 mm/day (bottom)

tops are particularly prone to erosion, landslides, and rolled lumber if heavy precipitation is accompanied by strong wind gusts during thunderstorms and extratropical cyclones (Easterling and Apps 2005, Perarnaud et al. 2005, IPCC 2019).

Figure 9 is dedicated to indicators of water scarcity in Lower Franconia. Colour bars are arranged such that the brownish colours denote enhanced drought conditions. The first indicator refers to the number of dry spells per year (left panels), defined as more than five subsequent dry days (see Table 2). It is more or less unaffected by the radiative forcing in either of the imposed greenhouse gas scenarios. Thus, the quantity of dry spells is not projected to change. Though, qualitatively there may be important changes until the year 2100 as average and maximum duration will increase substantially, according to the analyzed RCM simulations (second and third column). In fact, the extension is a matter of less than 4 days in most parts of our study domain, which, however, can be crucial for water stress and crop failure in Germany (cf. Lippert et al. 2009, Riediger et al. 2014, Möller et al. 2019). The de Martonne aridity index is composed of annual precipitation amount and temperature (see Table 2). It is less sensitive to enhanced greenhouse conditions (right panels) because annual precipitation totals do barely change in Lower Franconia (not shown). Rather the precipitation signal pertains to changes in inter- and intra-seasonal variability (i.e. longer dry spells interrupted by heavier rain events, cf. Fig. 8).

3.4 Indicators related to growing season, phenology, and thermal comfort

Finally, five indicators are considered that relate to the length and onset of the growing season, to late frost events, and to the thermal comfort for grape varieties in Lower Franconia

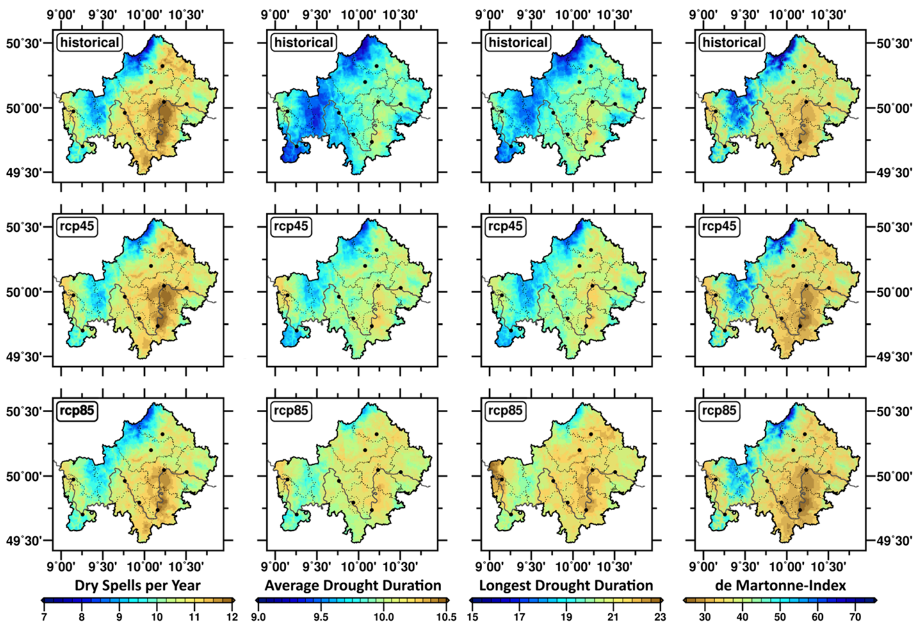

Fig. 9 Same as Fig. 5 but for dry spells per year (left column), average drought duration (second column), longest drought duration (third column) and de Martonne aridity index (right column). Historical 1970--1999, rcp45 and rcp85 2070-2099

(Fig. 10, see Table 2 for definitions). In the ensemble mean, the onset of the vegetation period may start 44 days earlier under the RCP8.5 scenario (top panel). This means that the onset shifts from the end of March to the beginning of February, while under the RCP4.5 scenario, the onset would be at the end of February. The duration of the vegetation period may lengthen by 70 days (second panel from top), implying that it extends from early February until mid-November and, hence, retains only a short chilling phase in winter. There is a noticeable difference between both emission scenarios. The last frost event in springtime occurs 15 (RCP4.5) and 30 (RCP8.5) days earlier (third panel). At first sight, this suggests a mitigation of late frost damages. However, the time span between the onset of the vegetation period and the last frost event in springtime increases by about 15 days until the end of the twenty-first century (fourth panel). In this case, the difference between the business-as-usual and mitigation scenario is minor. This can be explained by the shifts in the onset and in the last frost in springtime, which, combined with each other, come up with the same future risk by late frost events. The Huglin index may increase by more than 700 points (bottom panel), which equals a shift over six to seven thermal comfort zones and pushes the viticultural climate from a cold white wine regime to a typical red wine regime (cf. ESM 1).

Note that wine-growing is confined to a relatively small area in Lower Franconia, especially along the Main valley. Therefore, the consideration of the regional-mean Huglin index is not useful because it underestimates the real thermal comfort in existing vineyards. The spatial pattern of the Huglin index (ESM 3) follows the topography since this index is strictly temperature-guided. During the reference period, the western and southern stretches of the Main valley are characterized by the highest Huglin index with values between 1400 and 1700. This favours the cultivation of traditional grape varieties in Lower Franconia such as Müller-Thurgau, Bacchus, Kerner, and Silvaner (cf. Maaß and Schwab 2011, Rauh and Paeth 2011). Under the RCP8.5 scenario, practically the entire district of Lower Franconia may be utilized for viticulture after 2070 and almost everywhere the regime may have shifted from white to red grape varieties with the Huglin index beyond 2000. Though, it must be noted that the Huglin index does not account for water-related issues that also play a crucial role in the local climate comfort of vineyards (Stock et al. 2007). The present-day and future patterns of late frost risk are illustrated in ESM 4. In the reference period, the lag time between vegetation onset and last frost event is spatially rather homogeneous, amounting to around 30 days. For the last 30 years of the twenty-first century, the largest lag time of more than 50 days is expected in the central and southeastern parts of Lower Franconia where orchards and vineyards dominate the landscape. This enhances the risk of crop failure and, hence, the economic and psychological stress for fruit- and winegrowers.

4 Discussion of results

The present study contributes to the nexus between climate change, implications for the agricultural sector, and resulting needs for adjustment. We exemplify this important issue on the region of Lower Franconia in southern Germany where agriculture, wine-growing, and fruit and vegetable farming have a long tradition and contribute substantially to the regional economic output (Maaß and Schwab 2011, Rauh and Paeth 2011). The study domain is characterized by a relatively dry and warm midlatitude climate and has experienced above-average warming rates and severe water shortage during recent decades (IPCC 2021). We have tailored the output of high-resolution RCMs to the specific needs of the agricultural sector as inferred from

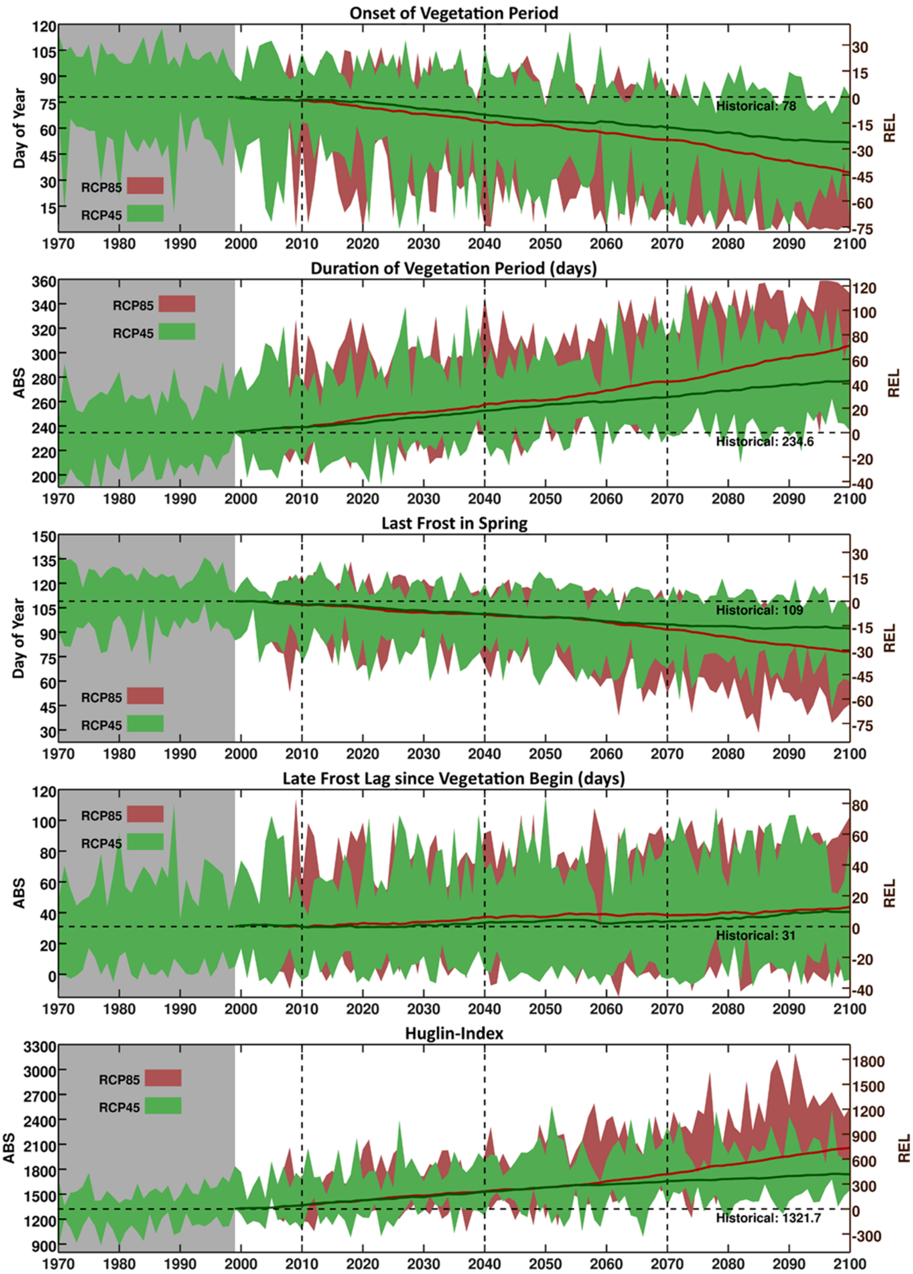

Fig. 10 Same as Fig. 4 but for onset of vegetation period (top panel), duration of vegetation period (second panel), last frost event in spring (third panel), lag of last frost event after onset of vegetation period (fourth panel) and Huglin index (bottom panel)

a stakeholder survey among actors and experts in Lower Franconia (cf. section 2 and ESM 5). This has resulted in a broad spectrum of analyzed meteorological indicators that represent the major threats of a warmer, dryer, and more extreme climate to agricultural operations in Central Europe. The novelty of the approach pertains to the comprehensiveness of the addressed aspects of regional climate change and to the high-resolution database from state-of-the-art RCMs (cf. Trnka et al. 2011, Riediger et al. 2014, Troost and Berger 2015, Möller et al. 2019).

The negative implications of climate change in the study region are manifold. (1) The number of frost and ice days will decrease remarkably and the recovery phase during winter will become much shorter. Under the high-emission scenario, the present-day winter climate characteristics in the warmest part of Lower Franconia serve as an analogue for the future winter climate in the coldest area whose elevation is 800 m or higher. This represents an enormous shift along topographic gradients that has also been reported by other authors (Ferrara et al. 2010, Trnka et al. 2011). For agriculture, viticulture, and also forestry reduced winter frostiness implies a deficient or missing chilling phase and lower pest control, often leading to limited biomass production and crop failure (Stock et al. 2007, Maaß and Schwab 2011, IPCC 2019, Rahman et al. 2020, Ziegler et al. 2020).

(2) Another challenge for the agricultural sector relates to a critical enhancement of heat stress at day and night. Days with maximum temperatures above 30 °C may increase by a factor of up to 5, for tropical nights it is even a factor of 60, depending on the emission scenario. Such events are also associated with increased evapotranspiration and loss of soil water, as well as more intense UV radiation. Several studies have pointed to the negative consequences of heat stress for crops and trees (e.g. Perarnaud et al. 2005, Lippert et al. 2009, Ruffault et al. 2014, IPCC 2019). Temperature-related indicators also typify the northward and/or topographic shift of wine-growing regions across Europe (cf. Malheiro et al. 2012, Xu et al. 2012, Moriondo et al. 2013, Fraga et al. 2016), including issues of wine taste, quality, and ageing capacity (Hannah et al. 2013, Boss et al. 2014). The considerable changes in the Huglin index across Lower Franconia also imply a dramatic modification of favoured grape varieties from psychrophilic white grapes to thermophilic red grapes (cf. Stock et al. 2007).

(3) Dry spells may not change in number but extend over a noticeably longer period. Reduced synoptic and intra-seasonal variability of planetary waves in relation to a weakening jet stream over the North Atlantic may serve as an explanation for longer time spans without precipitation in summer and winter (Paeth and Pollinger 2019). Water stress for crops, trees, and grapes increases exponentially with every additional dry day during summertime heat waves (Ruffault et al. 2014, IPCC et al. 2019, Möller et al. 2019, Pellicone et al. 2019). In fact, water shortage has been supposed to be another major threat to the agricultural sector in Germany, implying new investments in irrigation systems all over the country (cf. Köstner et al. 2014, Riediger et al. 2014, Troost and Berger 2015).

(4) In Lower Franconia, the total number of precipitation days per year appears to be unaffected by radiative heating. Yet, the statistical distribution may move towards more intense rainfall. The phenomenon of longer dry spells interrupted by isolated heavy rain events is a common companion of climate change in many regions of the globe (IPCC 2021), including Germany (Paeth et al. 2015, Möller et al. 2019). The combination of drought and heavy rainfall is particularly detrimental because, after long dry spells, soils are characterized by a higher wetting resistance and reduced infiltration and percolation, making fields and vineyards more prone to erosion, local flooding, and soil dryness (e.g. Easterling and Apps 2005, Perarnaud et al. 2005, IPCC 2019).

(5) The projected extension of the vegetation period in springtime and autumn may be interpreted as being beneficial for biomass production, crop yield, and new crops from producing regions in the south (cf. Ferrara et al. 2010, Trnka et al. 2011, IPCC 2019). However,

it also implies another major risk to crops, orchards, and grapes in Lower Franconia (i.e. the lengthening of the time span between vegetation onset or blossom and the last frost event in springtime). While farmers and winegrowers formerly expected the last frost event about 1 month after onset, this period may extend over 46 days at the end of the twenty-first century, when greenhouse gas concentrations follow the business-as-usual scenario. Indeed, damage due to late frost has occurred in vineyards and orchards almost every year during recent decades (Maaß and Schwab 2011, Rauh and Paeth 2011, Ziegler et al. 2020).

On the one hand, all these aspects of regional climate change, as projected by state-of-the-art RCMs, foreshadow a tremendous need of adjustment in all sectors of agricultural activity. On the other hand, it is noteworthy that the issue between climate change and agriculture is reciprocal because extensive land use contributes to greenhouse gas emissions and other effects on climate via land and soil degradation (e.g. Paeth et al. 2009). Several authors have suggested that a climate adapted sustainable land management may support our efforts in climate protection and mitigation of local climate change (Artmann et al. 2016, Rahman et al. 2020, Kirchner et al. 2021), although the overall effect may be low compared with ongoing radiative forcing (Hirsch et al. 2017).

5 Conclusions

Our study has demonstrated that the agriculture and specialized crops in Germany face tremendous challenges in response to regional climate change. The study domain of Lower Franconia has already experienced above-average warming rates and severe water shortage for many years and is supposed to become a hotspot of climate change in Central Europe. The climatic threats will be manifold as are the needs for adjustment. Future cultivation practices as well as selections of crops, grapes, and trees must cope with enhanced heat stress and drought, heavier precipitation events and erosion, earlier stages of phenology, and increasing late frost damage. Therefore, timely adaptation measures are required to counteract crop failure and income losses in the German agricultural sector (Lippert et al. 2009). Our study was dedicated to this goal by quantifying the various aspects of climate change relevant to the traditional land use systems in Lower Franconia and by making this information available to stakeholders and the public via a user-friendly web portal. Thus, the study is mainly focused on the adaptation aspect of the agricultural sector. However, climate-adapted land use also holds the prospect of climate mitigation in the form of enhanced carbon storage (IPCC 2019) and positive effects on the hydrological cycle (Paeth et al. 2009).

The approach holds the prospect of being extended to other risks and challenges related to climate change in Germany, e.g. with respect to health issues, the energy supply sector, traffic management, assurance industry, and touristic potential. (cf. Aich et al. 2011, Paeth et al. 2012). However, there is also room for improvement concerning the assessment of regional climate change: the effect of urban climate and soil sealing needs to be implemented in RCMs (cf. Ng et al. 2012, Han et al. 2014, Kirchner et al. 2021), processes related to land use changes are often underrepresented in RCMs (Paeth et al. 2009), and model resolution still needs to be enhanced further to meet the requirements of actors making decisions at the scale of fields and vineyards, for instance by applying very high-resolution models of intermediate complexity (Paeth et al. 2017). Another aspect that our study lacks is the translation of information on climate change into recommended actions such as sewing dates, cultivation practices, crop and site selection, as well as economic and income-relevant aspects (cf. Köstner et al. 2014, Troost and Berger 2015)—a matter of future research in a potentially subsequent project phase.

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Author contributions All authors contributed to the study conception and design. The first draft of the manuscript was written by Heiko Paeth. Roland Baumhauer, Andreas Hotho and Birgit Terhorst supervised the PhD students and Postdocs. All other co-authors provided the scientific results and figures. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability The datasets analysed during the current study are publicly available through the Euro-CORDEX and DWD web sides. We have implemented an open-access interactive web portal where users can choose 1 km × 1 km grid boxes or larger areas, time periods, emission scenarios, meteorological variables, and extreme indicators to display the corresponding time series (https://bigdata-at-geo.eu/klimaatlas, in German language).

Declarations

Competing interests The authors declare no competing interests.

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