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Research Article

Climate Change, Grape Phenology, and Frost Risk in Southeast England

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Background and Aims. The cultivation of grapevines in England is expected to benefit under climate change. Yet assessments of future wine climates remain undeveloped. Accordingly, this study assesses how climate change might modify frost risk for Chardonnay in the Southeast England viticulture region. *Methods and Results*. Cold-bias-corrected climate projections from the UKCP18 Regional (12 km) perturbed parameter ensemble (PPE) climate model under RCP8.5 are applied with phenological models to determine how frost risk and the timing of key grapevine phenophases might alter under climate change. Notwithstanding the uncertainties associated with projections of key viticulture-related bioclimate variables, the last spring frost was found to advance at a greater rate than budburst, indicating a general decrease in frost risk. *Conclusions*. Although projections point to an improving climate for viticulture across Southeast England, frost will remain a risk for viticulture, albeit at a reduced level compared to the present. Furthermore, the strong cold-bias found for temperature simulations used in this study needs to be given careful consideration when using the UKCP18 projections for viticulture impact assessments of climate change. *Significance of the Study*. This study highlights the present sensitivity of viticulture to climate variability and the inherent uncertainty associated with making future projections of wine climate under climate change.

1. Introduction

As a perennial crop, grapevines (*Vitis vinifera*) are particularly sensitive to short-term variability and long-term changes in climate [1]. Exposed to fluctuating weather conditions both within and between years, production of high-quality wines is associated with low frost damage at budburst, flowering during warm springs, and an optimal maturation period [2–5]. Previously, British wine production has been constrained by insufficient heat accumulation during the growing season, leading to a loss of bud fertility [6]. However, projected increases of average growing season temperature under future climate scenarios are expected to benefit the cultivation of grapevines in cool climate regions, thus presenting the opportunity for growth in the United Kingdom (UK) wine production sector [7–9]. Already, the hectarage planted in the UK has quadrupled since 2000, with wine producers expecting to accelerate investment in vineyard capacity within the current decade [10, 11].

Stakeholders of sparkling wine or "British bubbly" have generally reported the impacts of climate change to be positive with rising average maximum temperature designated a key external driver of industry growth [3, 10]. Yet, wine production in the UK is complicated by short-term climate variations, resulting in large fluctuations in vintage-to-vintage harvest quality [12]. Indeed, the potential for damage to grapevines from late spring frosts at the post-budburst cold-sensitive stages of shoot development continues to be of foremost concern to stakeholders [3, 13]. Adverse weather-related falls in wine production highlight the inherent volatility of the industry [10, 12, 14, 15].

In the wider context of learning to live with the uncertainty of climate change and the development of climate resilience, viticulture is an agricultural sector that will greatly benefit from the assessment of future climate risks to inform decisions on vineyard location, cultivar selection, and crop management [12]. Yet, for areas of the UK where vineyards are currently established, a combination of the long life time

(50+ years) and high capital investment of grapevines presents a "lock-in" to winegrape growers [2]. For English vineyards, this lock-in period reflects the payment of combined initial and establishment costs and is estimated to be 22 years [16]. Accordingly, the potential impact of climate change on vines currently, or being planted, demonstrates an immediate risk and/or opportunity to winegrape growers [2]. Previously, Mosedale et al. [9, 12] assessed the exposure of vineyards in Cornwall, Southwest England, to adverse weather conditions under different climate scenarios, finding an increased risk of frost damage in the future. The effects of climate change are, however, spatially heterogeneous, with projections for the same climate change scenario expected to have impacts on grapevine phenology that vary over short distances [17]. Therefore, it is crucial to consider the place-based occurrence of climate events in relation to the timing of phenological stages for "locked-in" vineyards [18]. This is particularly relevant to the winegrowing region of Southeast England, which has witnessed a rapid expansion in the area of vines planted since 2004 [3]. Increased cultivation of Chardonnay and Pinot Noir vines indicates a continued direction of the British viticulture industry towards sparkling wine production. Furthermore, the relative low cost of land in Southeast England has provided an incentive for investment by at least one Grand Marque Champagne house. Near-term investments from top Champagne houses are expected to continue in the future due to the region's geological similarity to Champagne [10]. While these developments are positive, the supplanting of hardy Germanic cultivars with Chardonnay vines is largely market-driven and indicates the industry's changing attitude towards climate risk. A reduction in frost days [19] has bolstered the perception that wine production will be relatively risk-free because of warming conditions under climate change. For successful grape growth, however, the timing of frost days and grape phenophases, specifically budburst, is critical to frost risk. This is highly pertinent in the case of Chardonnay and Pinot Noir, as these cultivars are not only early budding but also early ripening, rendering them sensitive to spring frosts [20]. Given that spring frosts remain very much a part of the climate character of Southeast England, a region perceived as offering great potential for sparkling wine production, the purpose of this study is to present an exploratory assessment of the degree to which future frost risk may alter under climate change for the grape cultivar Chardonnay. Associated with this overarching aim, this paper specifically assesses the current sensitivity of wine yield to interannual variations in grape bioclimate and phenology and the changing nature of viticulture suitability for Chardonnay. It also attempts to quantify the risk of potential frost damage in Southeast England for the near future period of 2021–2050.

2. Materials and Methods

This section describes the study area, viticulture yield data, and observed and projected climate data used, along with methods of analysis.

2.1. Study Area and Approach. The assessment of frost risk presented here focuses on a small area within the broader wine producing region of Southeast England, which contains several notable vineyards internationally recognised for the quality of their sparkling wine (Figure 1) and Chardonnay, which is the cultivar of interest for this study.

In undertaking an exploratory assessment of the implications of projected climate change for frost risk, this study applies output from the UKCP18 climate projections at a resolution of 12 km. Although considered high resolution in climate modelling terms, in the context of small-scale vineyards that typify the viticulture scape of the UK, the largest being 90 ha (0.9 km^2), climate estimates at the 12 km scale are essentially mesoscale in nature. This is because the topographic diversity of the Southeast England viticulture region is likely to create microclimate variations at the intravineyard scale [21], as found for vineyards in a wide range of other geographical settings [22–24]. Such subgrid scale variability is not captured by "high resolution" climate projections. As a result, the assessment presented here is one of the impacts of mesoscale to macroscale variations and change on viticulture-related frost risk. Furthermore, as observations for a single climate station (East Malling) and projections for just one grid cell from the UKCP18 output are applied (Figure 1), an assumption is made that the time series of climate values represent the wider Southeast England region. This is vindicated by the good level of correlation ($P > 0.05$) between climate variables observed at the East Malling climate station and regional time series of climate variables compiled by the UK Met Office for the wider Southeast England region (not shown here).

2.2. Yield Data. Yield data from individual vineyards were not available, with vineyards citing commercial sensitivity as a reason for nonprovision of data. Furthermore, regional yield data are currently unavailable in the UK. Consequently, and by default, this study relies on nationally aggregated yield data sourced from the Wine Standards Branch of the Food Standards Agency (FSA) for the period 2000–2019. Presented in the form of hectolitres per hectare (hL/ha), this is the only officially available yield data in the UK. Therefore, an underlying assumption is that national yield data are indicative of that for the study area. This appears to be a safe assumption, as vineyards in Southeast England contribute well over 50% of the total UK vineyard production [3].

2.3. Observed and Modelled Temperature Data. Daily minimum and maximum air (1.5 m above ground) and grass (25–50 mm above ground) temperature data were obtained from the MIDAS-Open archive of the UK weather data [25] for the East Malling UK Met Office station in Kent (Figure 1). Chosen to represent the wider study area based on its central position and high correlation with surrounding stations, the associated data from East Malling were used to analyse climate and yield associations, as input into grape phenology models, and for validation of climate model projections. Temperature data inhomogeneities prior to 2000 meant that the climate baseline period and that used for

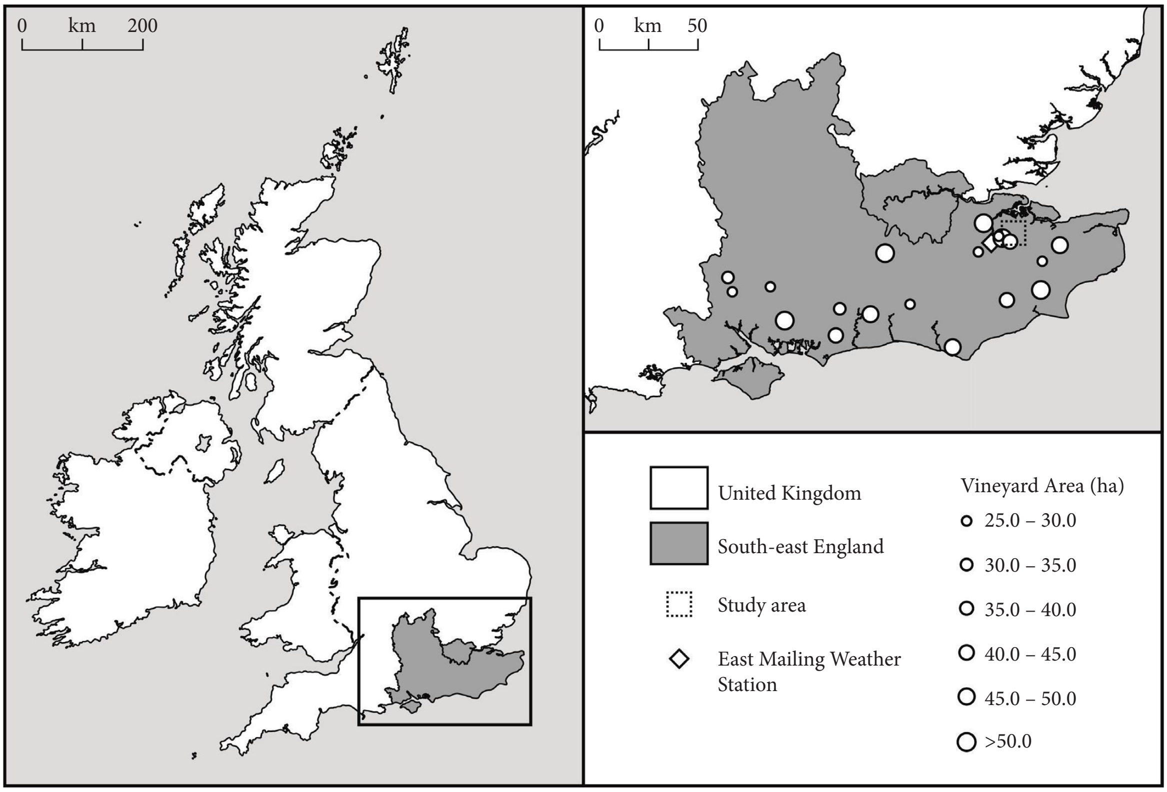

Figure 1: Map depicting the location of the study area in relation to the wider region of Southeast England with vineyards greater than 25 ha indicated. The position of the 12 km × 12 km grid from which climate projections have been extracted and the East Malling climate station which provided the observational data for the study.

assessing climate-yield associations had to be restricted to the period 2000–2019.

Measures of daily minimum and maximum temperature for the baseline period (2000–2019) and the near future (2021–2051) were derived from the latest (2018) UK Climate Projections (UKCP18). As regional projections (spatial resolution of 12 km) are only available for Representative Concentration Pathway 8.5 [26, 27], estimates of future grape phenology and frost risk are limited to this scenario [5, 28]. Referred to hereafter as RCP8.5, this scenario is considered relevant as an indicator of potential warming since global trends in greenhouse gas emissions up to the mid-21st century are generally consistent with those estimated under RCP8.5 [29, 30]. Furthermore, for temperature projections at the spatial scale used in this study, uncertainties caused by emissions are secondary to those resulting from the internal variability of models up until the mid-21st century [31].

In acknowledgment of the inherent uncertainty associated with climate projections, the UKCP18 projections apply a perturbed parameter ensembles (PPEs) approach [32]. This study utilises projections from the third strand of the UKCP18 projections, consisting of a 12-member PPE of projections at 12 km horizontal resolution, referred to as HadREM3-GA705 [26, 27]. All 12 PPE members are the outcomes of downscaling from the current family of Hadley Centre climate models (HadGEM3-GC3.05) to the British Ordinance Survey's National Grid [26]. Climate model data were downloaded from the UK Centre for Environmental Data Analysis (CEDA) archive in netCDF format as decadal files for the 12 km grid box shown in Figure 1.

In accordance with the guidance associated with the use of the UKCP18 land projections for climate change impact assessment, the degree to which systematic differences exist between observations and models and the need for any bias correction of climate model data were explored [33]. Usefully, the UKCP18 user guidance points to a possible strong cold-bias for PPE members 11 and 12, as these models depict an early collapse of the (AMOC) Atlantic meridional overturning circulation [26]. Indeed, density plots of raw daily minimum and maximum temperatures for the baseline period for each PPE member revealed a strong cold-bias for these two models relative to all other ensemble members. Accordingly, PPE members 11 and 12 were not included in the analysis. Notwithstanding this, bias correction was deemed necessary as the remaining PPE members also demonstrated a cold-bias, but to a lesser extent. A comparison of observed and simulated values for the baseline period 2000–2019 revealed the cold-bias to be greater for the growing season months of April to September compared to the dormant period centred on the Northern Hemisphere winter. Local model bias correction (i.e., grid cell-specific) of both daily minimum and maximum temperature was done using a linear scaling method, as described by Beyer et al. [34]. This method corrects for systematic bias in the mean. In doing so, it assumes that the temperature bias (i.e., grid cell-specific) is stationary with no changes over time in the variance [34]. Mathematically, local bias is represented by

$$\widehat{T_{\text{sim}}}(t) = T_{\text{sim}}(t) + \left(T_{obs}(0) - T_{\text{sim}}(0)\right), \tag{1}$$

with T_{obs} and T_{sim}, the observed and simulated data, respectively, for the baseline period of 2000–2019. All subsequent analyses used the bias-corrected climate model data.

2.4. Bioclimate Indicators. Two bioclimate indicators were applied in this study, namely, growing degree days (GDD) and the incidence of frost. The idea of GDD accords with the widely used Winkler Index. Since its first application in the 1940s [35], notwithstanding some criticism of the concept [36], GDD has been employed widely in the viticulture industry to approximate the amount of growth-relevant heat for a specified period by accumulating the degrees above the growing temperature threshold of 10°C [37–40]. Annual values of GDD for the growing season, defined as the period 1 April–31 October, were calculated using daily observed and projected temperature data. As noted by others [3, 9, 12], dates of budburst and harvest are the best indicators for defining the length of the growing season. As mentioned earlier, however, the requisite vineyard-based data were not available for this study for reasons of commercial sensitivity, hence the choice of the specified growing season period.

Frost represents a major hazard for the viticulture industry, especially during the "critical period," that is, the period between budburst and flowering, when exposure of photosynthetically active grapevines to frost can have a detrimental impact on yield [41, 42]. Defined in this way, the critical period sits within the wider growing season of April–October. To characterise the nature of frost as a hazard and thus its potential to injure or damage grapevines, this study, like others [3, 12, 42–44], defines frost days (FD) as those with a minimum air temperature ≤0°C. This definition aligns with that commonly used in the UK, as defined by the UK Met Office [19]. Although ground frosts are not an immediate risk to grapevines, they often precede air frosts, which are generally the main grapevine-damaging "culprits" [45]. As minimum grass temperature values were available as part of the MIDAS-Open data, the annual number of "baseline" ground frost days (GFD) was calculated. The time of the last spring frost (LSF) was also calculated as a frost index. This was defined as the Julian day number (DOY) from the beginning of the year (1 January) up until the last day before flowering when the minimum daily air temperature ≤0°C. This definition assumes no frost occurrence in the postflowering period, a safe assumption as for the reference period 2000–2019 no frost was recorded after flowering.

2.5. Grapevine Phenology. In the absence of empirical data for relatively new viticulture regions, such as England, and thus the calibration of models that predict the grapevine phenological stages of budburst, flowering, and veraison (onset of ripening), this study uses generic temperature-driven phenological models [46] to determine the timing of phenophases for Chardonnay. Often referred to as "spring warming models," these have been applied widely, including an analysis of Chardonnay phenophases for Southwest England [12].

Budburst represents the beginning of the growth cycle, with the budburst date a measure of the earliness and adaptability of cultivars to a warming climate [47]. The budburst model used here is that of De Cortázar-Atauri et al. [47], the parameters for which are presented in Table 1. This "spring warming," or growing degree day (GDD) model, is based upon the classical concept of thermal time such that daily responses to temperature (forcing units) are accumulated from a fixed starting date up to a critical threshold [12, 47]. Using the requisite temperature data, the annual budburst was modelled for the observed and projected baseline and future climate change time horizons. The simple process-based model of Parker et al. [48] was applied to the calculation of the annual timing of the growth stages of flowering and veraison (see Table 1 for the associated parameters). Developed from a wide range of cultivars and locations across northern, central, and southern Europe, the Parker et al. [48] model is driven by temperature summation from a defined date above a minimum temperature threshold (T_{base}). The timing of flowering and veraison is the date on which a set critical value for the forcing units is obtained (Table 1).

2.6. Statistical Analyses. To achieve an understanding of the degree of dependence of viticulture yield on climate and grapevine phenology, yield was correlated with the aforementioned bioclimate indicators and phenophase indices. The parametric Pearson product-moment correlation statistic was used with a significance level of $P = 0.05$. In addition, a P value of 0.06–0.10 was taken to indicate an association approaching statistical significance. In advance of the correlation analyses, all data were converted to standardised anomalies (z-scores) by finding the difference between the observed variable value and the variable mean and dividing this by the variable SD. In order to determine the rate of change of the climate indicators and phenophases under climate change, the associated indices were regressed against time for the simulation period 2021–2050. In addition to establishing how viticulture-relevant climate indicators and grapevine phenophases might alter under climate change, this study calculated exceedance probabilities [49, 50] for several key climate and phenology indicators for the baseline and future periods to assess how climate under RCP8.5 may modify frost risk.

3. Results

This section describes the outcome of the analysis of the association between yield and a range of climate/bioclimate and phenophase drivers derived from the MIDAS observational record and the impact of climate change on GDD, FD, and the timing of budburst, flowering, and veraison under RCP8.5.

Table 1: Grapevine phenology model parameters for the *Vitis vinifera* cultivar Chardonnay. The same equation with the associated base temperature was used to calculate all three phenological stages.

Parameters[†]	Budburst	Flowering	Veraison
Initial day (t_0) of forcing	1	60	60
Forcing state (FS) on day t		$\sum_{t_0}^{t} \max[(T_{\text{mean}} - T_{\text{base}}), 0]$	
T_{base} used to calculate FS	5°C	0°C	0°C
FS at which phenophase occurs	220.1	1217	2547

[†]Table and parameter expressions are adapted from Mosedale et al. [12]. T_0, the day of the year (julian day); FS, the daily sum of the rate of forcing and is a measure of heat accumulation in degree days [48].

3.1. Wine Yield and Climate and Phenophase Associations. For the period 2000–2018, the average wine yield for the UK was 21.9 hL/ha. This figure masks considerable interannual variation, as manifest by a SD of 9.27 hL/ha and a range from 5.98 (2012) to 48.0 hL/ha (2018). Undoubtedly, a consequence of the short 19-year record used in this study, no statistically significant trends in FD, GFD, LSF, and GDD were detected, as was the case for monthly temperature (mean, maximum, and minimum) values. Correlation analyses revealed varying degrees of dependence of yield on a range of bioclimate, temperature, and phenophase indicators (Table 2). Of the bioclimate indicators, the number of frost days (FD) and growing degree days (GDD) appear to have the greatest influence on yield, with significant inverse and positive associations, respectively. Although the correlation results for ground frost days indicate an association with yield, this is not the case for the date of last frost (LSF). Noteworthy is the association of yield with the number of days between budburst and LSF (Budburst DOY-LSF DOY), indicating that frost occurrence postbudburst has been instrumental in reducing yield for several years (Figure 2).

Given the significance of the bioclimate indicators FD and GDD, the association between yield and several standard measures of monthly and seasonal temperature was also investigated, revealing a high dependence of yield on warm conditions in the months of June and July as well as the summer (July-August) season as a whole (Table 2). In many ways, this corroborates the importance of GDD. Amongst the phenophases, there is a hint of an association between yield and budburst ($P = 0.07$), such that later budburst and thus avoidance of the frost season is likely to provide conditions conducive to a higher yield, as supported by the association presented in Figure 2. No association between yield and flowering or veraison was found.

An appreciation of the degree of interannual variability of yield in relation to some of the bioclimate and phenophase variables can be gained from Figure 3, which plots a time series of standardised anomalies (z-scores) for the period 2000–2018. Taking a standardised anomaly value of +1/−1 as an indicator of strong positive/negative yield years, identified 2006, 2014, and 2018 as good years while 2002 and 2012 are poor. Compared to 2006 and 2014, 2018 is a standout year for yield, with anomalously high July maximum temperature values, strong positive GDD, anomalously low FD, and budburst occurring well after the LSF (Figure 3), all working in concert to produce this outcome. The year 2018 is also noteworthy as the late winter/early spring conditions preceding the growing season were in the form of some of the harshest cold weather experienced for the last two to three decades, colloquially referred to as the “Beast from the East,” a consequence of an anomalous circulation pattern associated with the stratospheric polar vortex [51]. This highlights the importance to yield of heat accumulation in the early to mid-summer months of June and July despite harsh thermal conditions in the pregrowing season. The positive FD anomalies and anomalously cool conditions for the critical period are a feature of the poor yield years 2002 and 2012, as well as being part of a group of years in which budburst preceded LSF by many days (Figure 2). In the case of 2002, it would appear the coincidence of an anomalously early budburst and the strongest positive anomalies of FD recorded for the study period were the main drivers of poor yields, with frost exacting a heavy toll on grapevine buds while heat-related variables displayed only mild negative anomalies for this year. For 2012, while an unusual number of frost days is a feature, the earliness of budburst is not as extreme as in the case of 2002. Notwithstanding the possible importance of frost-related damage to grapevine buds, the poor yield for 2012 may also relate to the lack of heat accumulation, as manifested by the strong negative anomalies for GDD and July maximum temperature (Figure 3).

3.2. Changes in GDD and Phenophases. Figure 4 presents a time series of seasonal GDD for the period 2021–2050, with GDD for the baseline period of 2000–2019 displayed for both observation and bias-corrected UKCP18 PPE-based values. The observed GDD values reveal that all years, bar 2015, fall within the range deemed suitable for high-quality production of early ripening.

Vitis vinifera cultivars, such as Chardonnay, albeit with the current levels of GDD broadly falling within the lower third of Amerine and Winkler’s Region 1 range of 850–1380 thermal units. While the general level of observed and PPE-based GDD values align for the baseline period, the interannual variability for the aggregate PPE series is relatively supressed due to averaging, as indicated by the GDD SDs for the observed and PPE series of 101 and 54, respectively. Furthermore, for several years, there is low agreement on an interannual basis with observed and simulated warmer and colder years not necessarily lining up with each other. On an individual ensemble member basis, only one ensemble member (EM8) comes close to simulating the observed interannual variability. For the reference period 2000–2019, there is no difference in the trend of observed and simulated

Table 2: Correlation and associated levels of significance for yield in relation to bioclimate indicators, standard monthly and seasonal temperature variables, and phenophase day of the calendar year.

Variable	Correlation coefficient (r)	Level of significance (P)
Bioclimate indicators		
FD	−0.53	0.02
GFD	−0.45	0.05
LSF	−0.14	NS
Days budburst precedes LSF	0.45	0.05
GDD	0.56	0.01
Temperature variables		
June T_{max}	0.55	0.02
July T_{max}	0.78	0.001
July T_{ave}	0.75	0.001
JJA T_{max}	0.64	0.002
JJA T_{ave}	0.60	0.01
Phenophase		
Budburst	0.42	0.07
Flowering	−0.09	n.s.
Veraison	−0.36	n.s.

n.s., not significant ($P > 0.1$). FD, number of frost days; GDD, growing degree days; GFD, number of ground frost days; JJA, June, July, and August; LSF, Julian day of last spring frost; T_{max} and T_{ave}, maximum and average temperature, respectively.

GDD as established by the application of an analysis of covariance (ANCOVA) test. Beyond the reference period, however, there is a progressive growth of GDD, with growing season heating units projected to increase at a statistically significant ($P = 0.01$) rate of 79°C per decade (Figure 4). By mid-century, the seasonal GDD level for the study area is projected to move comfortably into the upper third of the "Region 1" range, with some years possibly recording values that accord with the lower third of the range associated with the Amerine and Winkler Region 2 wine climate types.

Projections of DOY for budburst, flowering, and veraison under RCP8.5 are shown in Figure 5, with associated statistics for the baseline and near future periods presented in Table 3. All ensemble members (EMs) project an advance of the three phenophases over the period 2021–2050, relative to the 2000–2019 baseline. Apparent from the time series plots is the considerable interensemble spread of phenophase values for any one year. This is especially so for budburst, as exemplified by the decadal DOY phenophase SD values. Given the spread of projected values, we undertook three separate ANOVA tests in order to establish whether significant interdecadal differences in the mean level of each phenophase of the DOY exist. The decades compared were 2021–2030, 2031–2040, and 2041–2050. This assessment revealed an overall interdecadal difference in the mean DOY for all three phenophases at the $P = 0.01$ level or better. The associated F values for the three ANOVA tests were budburst (22.7), flowering (54.8), and veraison (101.1). Furthermore, a posthoc honestly significant difference test (HSD) confirmed that the majority of decades were significantly different from each other for each phenophase, despite the large interensemble range in DOY (Table 4 a–d). Only budburst and flowering displayed no decade-to-decade difference for the period 2021–2030 to 2031–2040. Summarising the information presented in Table 3 and the complementary HSD tests in Table 4 a–c, there are projected advances of budburst, flowering, and veraison by 12, 7, and 14 days, respectively, under RCP8.5 by 2041–2050. Table 4 d also shows the HSD results for an ANOVA of interdecadal differences in GDD, indicating a statistically significant progression of the difference in mean decadal GDD over the analysis period, with GDD projected to increase by 295 thermal units (95% confidence range of 256–332 thermal units) beyond the baseline period by the mid-21st century.

3.3. Changes in Frost. Given the previously established significance of frost occurrence as a determinant of yield, this section explores projected changes in this critical bioclimate characteristic under RCP8.5. Figure 6 presents a time series of observed and simulated values of the annual number of frost days (FD) for the critical growing period. The simulated time series is the mean for all ensemble members. As noted earlier, there is no statistically significant trend in observed FD, most likely because of the shortness of the record. That aside, observed FD demonstrates considerable interannual variability, with 8 years recording no frost between 2000 and 2019, equivalent to a 40% probability of no frost during the critical period for the baseline period. A visual comparison of observed and simulated FD for the baseline period (2000–2019) reveals a poor association between the actual FD and the ensemble mean. Bivariate correlations between FD for the individual ensemble members and East Malling for the baseline period confirm this, with only one ensemble member (EM7) demonstrating near-significant associations with the observed record of FD. Overall, when regressed against time, the ensemble means for the entire 2000–2050, time series fail to demonstrate a statistically significant decreasing trend in FD. Only three of the ten ensemble members demonstrate trends suggestive

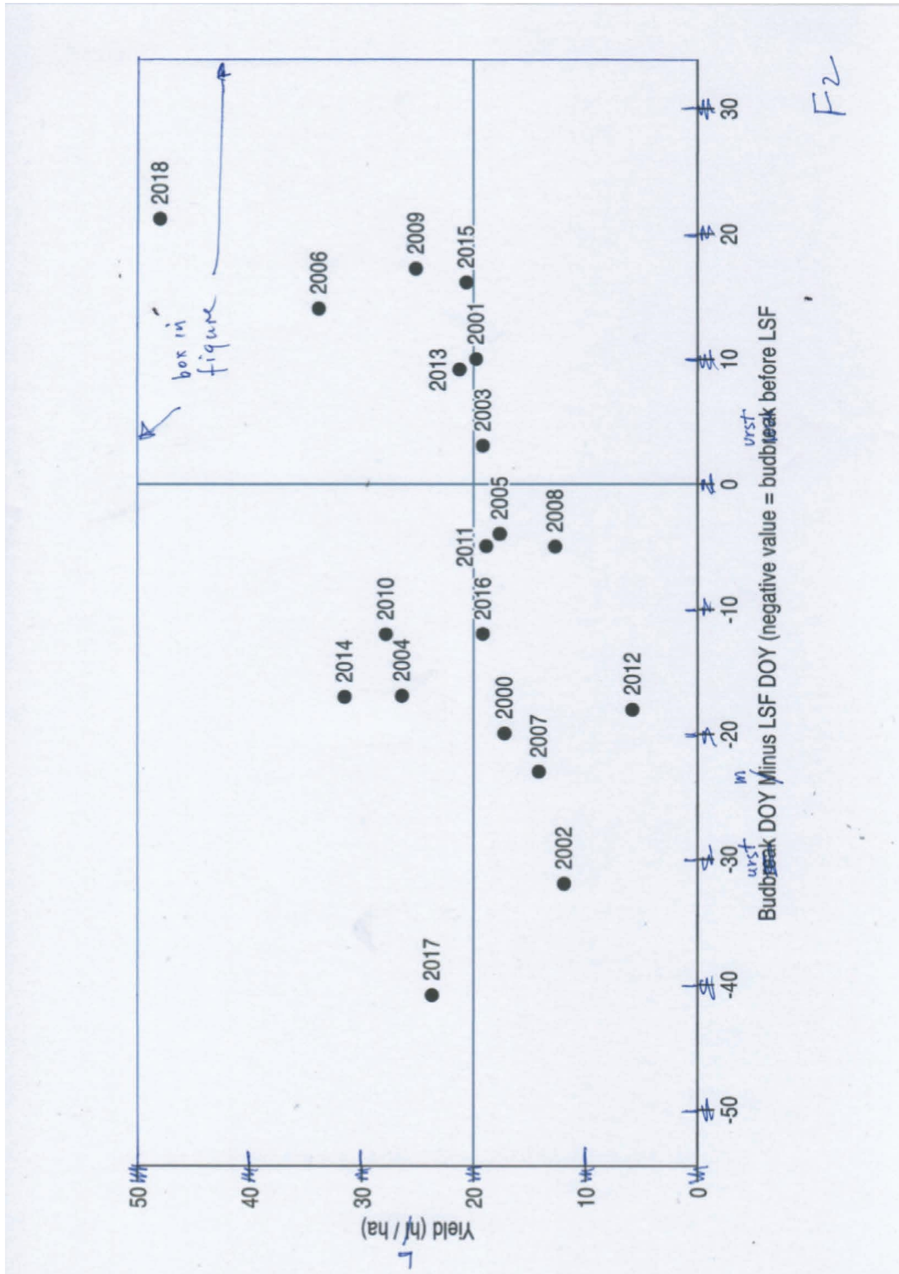

Figure 2: Association between yield and the number of days that budburst occurs before and after the last spring frost (LSF) ($r = 0.45$, $P = 0.05$). The vertical reference line at zero indicates the transition boundary between budburst preceding or following the LSF. The horizontal reference line represents the mean yield 2000–2018. Observed temperature values from the East Malling climate station were used to calculate budburst and last spring frost dates.

of a FD decrease, with statistical significance (P value) lying between 0.06 and 0.08. As can be seen in Figure 6, there is a considerable spread in the projected FD values. Years for which there is no spread are associated with an ensemble mean value of zero FD.

Although there is a considerable difference within the PPE spread of projected FD, we take the 50-year simulated time series to be homogeneous/internally consistent, thus facilitating interdecadal comparisons of frost frequency and the assessment of any shift in the timing of the last day of frost within the critical period. Based on a comparison of the baseline and near future periods, FDs are projected to decrease on average by 35% by the mid-21st century. This figure does mask some decadal variability in the magnitude of FD reduction, with the average projected decreases for 2021–2030 and 2031–2040 being 18% and 50%, respectively. At a reduction of 36%, the figure for 2041–2050 matches closely the overall mean reduction in FD.

To assess whether a shift in the likelihood of the timing of important bioclimate/phenophase events might occur under RCP8.5, we calculated DOY exceedance probability curves (EPC) for the baseline (2000–2019) and near future

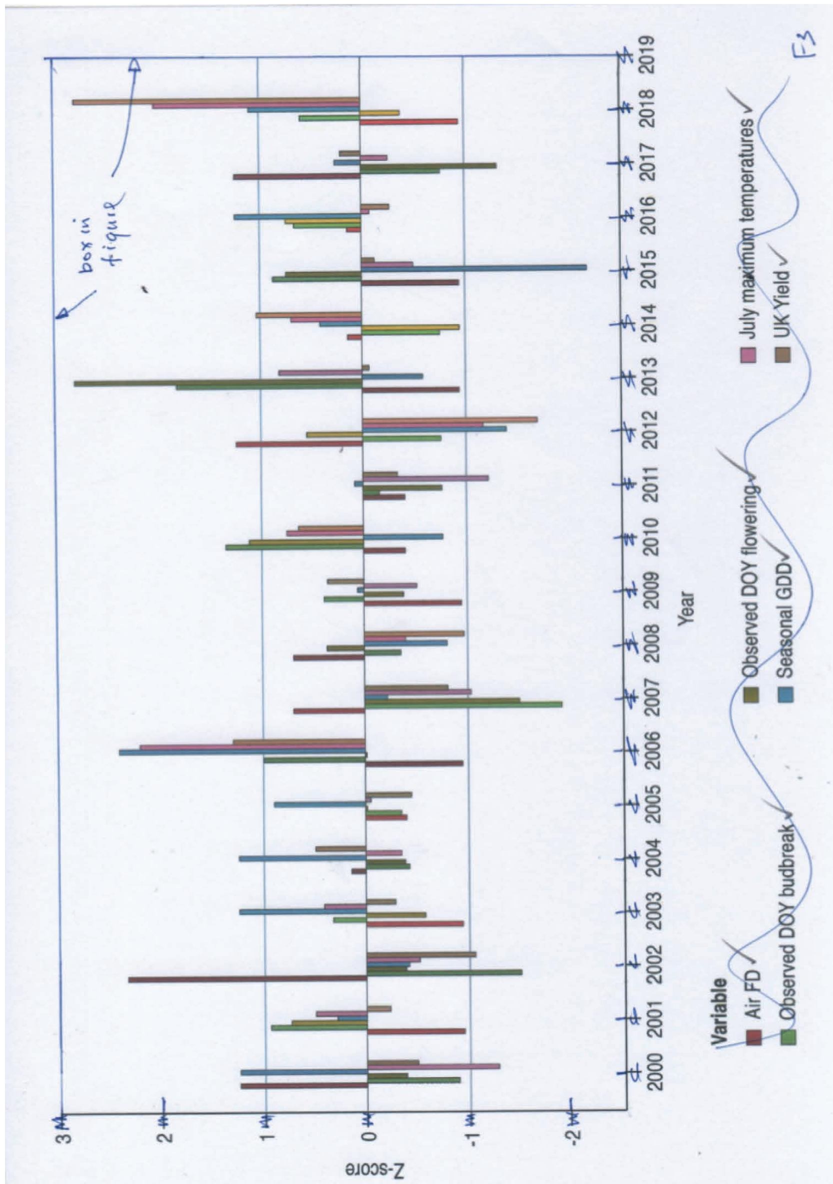

Figure 3: Time series of standardised anomalies (z-scores) for yield (■), bioclimate (air frost days (FD) (■), seasonal GDD (■), July maximum temperature (■)), phenophase variables (observed day of the calendar year (DOY), budburst (■), and observed DOY flowering (■)). The horizontal lines for ±1 SD indicate points beyond which strong positive/strong negative anomalies occur. For yield, note the strong positive (strong negative) anomalies for 2006, 2014, and 2018 (2002 and 2012).

(2021–2050) periods for LSF, budburst, and flowering (Figure 7). All EPC point to a clear decrease in the probability associated with the DOY of LSF, budburst, and flowering for the near future compared to the baseline period. For example, the probability that LSF will occur on DOY 80 (20 March) changes from about 62% for the baseline period to about 12% for the period 2021–2050 (Figure 7(a)). Similarly, for budburst, there are marked shifts in DOY probability as demonstrated for DOY 100 (9 April), with a reduction of the probability of budburst on this day from circa 80% for the baseline to 25% in the future under RCP8.5 (Figure 7(b)).

As current evidence suggests the association between the timing of budburst and the last spring frost is important for yield (Figure 2), the relative changes in DOY probabilities for budburst and LSF are considered here. Taking a 50% probability event as a reference, under RCP8.5, there is a shift in budburst DOY by around 9 days, from DOY 106 to DOY 97. For LSF, the associated shift in DOY for a 50% probability event is 14 days, from DOY 82 to DOY 68. This makes for a greater advance in LSF compared to budburst and thus a decrease in frost risk. In the case of flowering, the magnitude of the DOY advance for a 50% probability event is similar to that for budburst at 8 days, from DOY 173 to DOY 165.

While the EPC analysis indicates a clear change in the relationship between budburst and LSF, the EPC is based on the mean for all ensemble members. This masks the

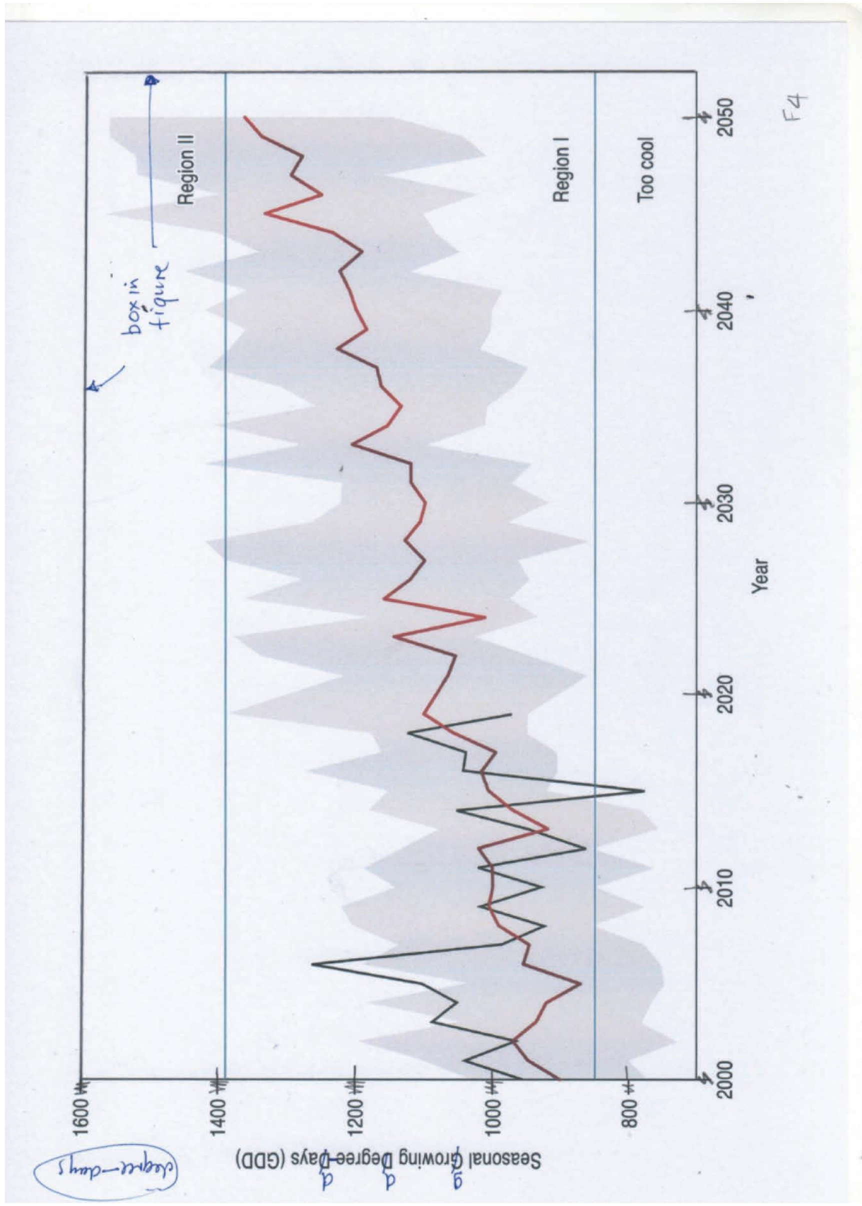

Figure 4: Time series of observed (——) and simulated perturbed parameter ensemble (PPE) mean values (——) for seasonal growing degree days (GDD). Shaded region indicates the PPE spread. Horizontal reference lines correspond to threshold values of the Amerine and Winkler [35] wine climate regions.

ensemble member-to-member variability in predicted frost risk. To shed light on this, the predicted change in the crucial gap between LSF and budburst over the period of the analysis is graphed in Figure 8. This shows the difference in timing between DOY for budburst and LSF for each ensemble member by decade. The 1 : 1 line in each plot indicates an identical shift in budburst and LSF relative to the reference period. That is, the temporal relationship between budburst and LSF is preserved into the future. Points located beneath the 1 : 1 line indicate an increase in risk compared to the baseline period while points located above the reference line indicate a decrease in risk. While some ensemble members project similar shifts for both budburst and the LSF with points located close to the 1 : 1 line, there is considerable interdecadal variability in the rate of change. For example, EMs 15 and 7 were the only models to indicate a later than average budburst for the decades 2021–2030 and 2031–2040, respectively. Notably, for the decade 2031–2040, a substantial decrease in frost risk compared to 2021–2030 is projected, with 8/10 EMs projecting the LSF to advance at a greater rate than that of budburst. The EM that predicted the greatest decrease in risk of frost damage for the entire near future (2021–2050) was EM 10, while EM 8 consistently predicted a greater advance of budburst and an increased risk of frost damage for 2021–2040 with convergence between budburst and LSF occurring for 2041–2050. Taking the output for all ten ensemble members by decade (100 sample points per decade), the likelihood that LSF will occur

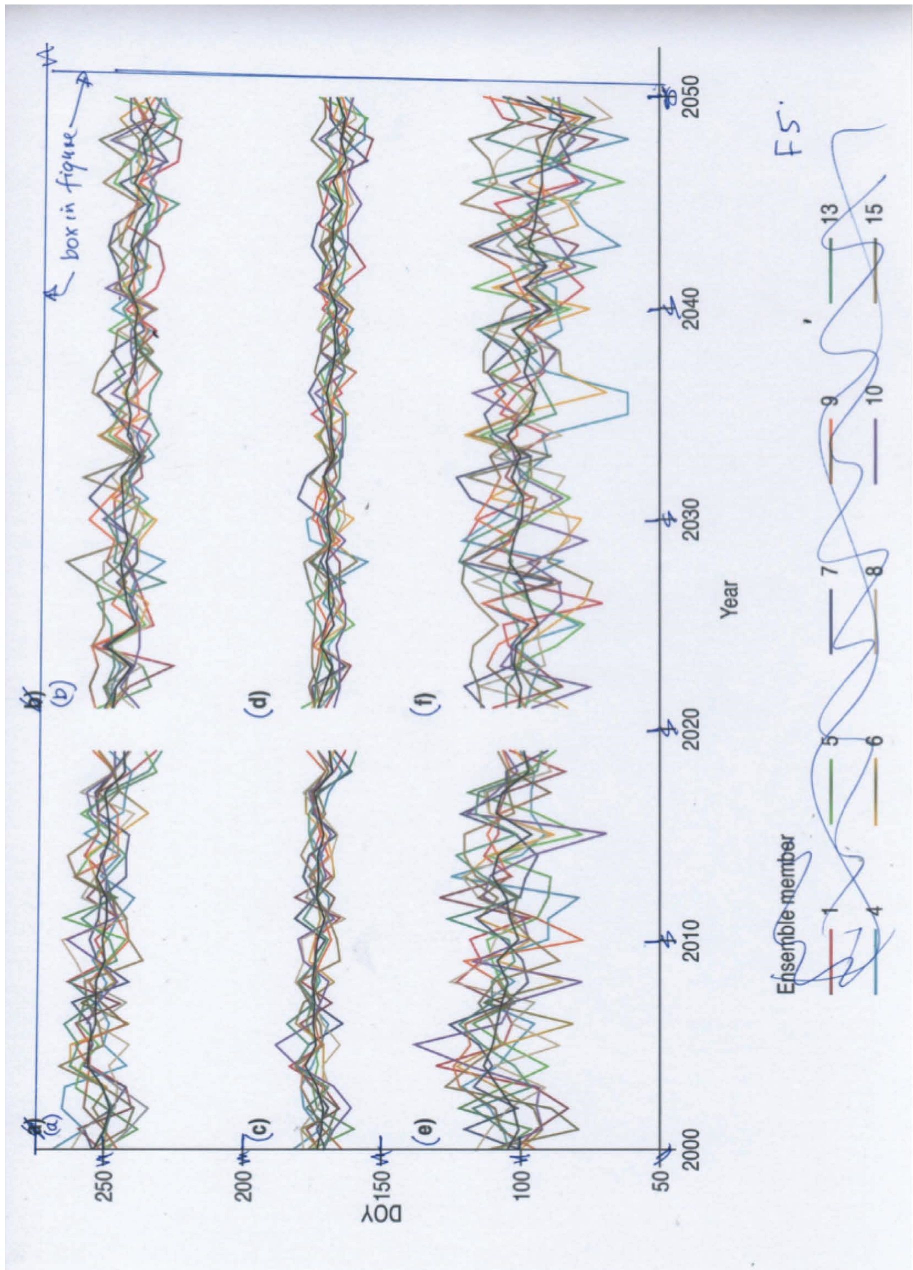

Figure 5: Modelled day of year (DOY) at which Chardonnay (e, f) budburst, (c, d) flowering, and (a, b) veraison occur for the (a, c, e) baseline (2000–2019) and (b, d, f) near future (2021–2050) periods for each ensemble member. The solid black line in each plot indicates the position of the perturbed parameter ensemble (PPE) mean. Ensemble member (EM) 1 (——), EM 5 (——), EM 7 (——), EM 9 (——), EM (——), EM 13 (——), EM 4 (——), EM 6 (——), EM 8 (——), EM 10 (——), and EM 15 (——).

Table 3: Mean and SD day of the calendar year statistics for modelled baseline and near future periods by Chardonnay phenophase.

Decade	Budburst		Flowering		Veraison	
	Mean	SD	Mean	SD	Mean	SD
2000–2019	105	4.63	173	2.20	250	3.54
2021–2030	100	3.01	169	1.73	243	3.18
2031–2040	98	4.67	168	1.47	240	2.31
2041–2050	93	4.26	166	2.10	236	3.09

Table 4: Results of honestly significant difference test following ANOVA of interdecadal difference in day of calendar year for Chardonnay budburst, flowering, veraison, and growing degree days.

	2021–2030	2031–2040	2041–2050
Budburst			
2000–2019	5.1* (1.3–9.0)	6.8* (2.8–10.6)	12.1* (8.2–16.0)
2021–2030		1.5 (−2.9–6.0)	7.0* (2.5–11.4)
2031–2040			5.4* (0.95–9.9)
Flowering			
2000–2019	3.2* (1.7–4.7)	4.8* (3.4–6.9)	7.0* (5.5–8.5)
2021–2030		1.5 (−0.16–−3.3)	3.8* (2.1–5.6)
2031–2040			2.3 (0.5–4.0)
Veraison			
2000–2019	7.0* (4.7.7–9.1)	10.1* (7.9–12.3)	13.8* (11.6–16.0)
2021–2030		3.1* (0.5–5.7)	6.8* (4.4–9.4)
2031–2040			3.7* (1.1–6.2)
Growing degree days			
2000–2019	122* (86–159)	190* (152–228)	295* (256–332)
2021–2030		68* (25–111)	172* (128–215)
2031–2040			101* (60–146)

Starred values indicate interdecadal differences are statistically different at the $P = 0.01$ level or better. Values designate the mean ensemble difference between decades and complement the differences shown from Table 3. Bracketed numbers are the upper and lower bounds for the 95% confidence interval for the mean difference. That is, there is 95% confidence that the mean difference ranges between the upper and lower values in brackets. Negative values appear for cases when the mean difference is close to zero and there is no significant difference. These indicate that although the mean difference is positive, there is a chance that the difference between the two decades could vary between earlier and later phenophase dates.

after budburst for each successive decade beginning 2021–2030 is 13, 7, and 11%.

4. Discussion

The primary goal of this study has been to assess the extent to which spring frost risk for the wine industry in Southeast England might alter under climate change. Drawing on the general frost risk classification system developed by Webb et al. [17] for temperate climate regions, the study region presently falls within the high frost risk category. This is because the observed likelihood of frost occurring within any one year for the critical period is 60% (>1 in 2 years). This is somewhat vindicated by the observed impact of growing season climate variability on UK wine production, with some years severely impacted by frost occurrence (Figure 3). Under RCP8.5, the study region is projected to transition from a frost risk regime generally considered unsuitable for viticulture (>1 LSF every 2 years: >50%) to a state of moderate frost risk and viticulture suitability (<1 LSF every 2 years: <50%) by the mid-21st century. The frost probability does not, however, systematically decrease under RCP8.5, as projections point to a possible higher frost risk for 2021–2030 compared to the present, with 8 out of 10 years projected to experience a LSF (Table 5). This may indicate that climate variability at interannual to decadal timescales will continue to be a feature of the Southeast England viticulture region. This assertion is supported by the results from recent climate projections for England, which show that while the frequency of cold weather extremes may reduce under climate change, their elimination is not total, even under a global warming of 4°C [52].

These results resonate with those of Mosedale et al. [9] for Cornwall, where under a RCP8.5 future, an increase in the risk of late spring frosts for Chardonnay between 2010–2039 and 2040–2069 is projected. Furthermore, the projections of budburst and LSF presented here point to a general preservation of the temporal relationship between these two critical events, although there is a marginally greater rate of the advance of LSF compared to budburst with climate change. The continuation of such a relationship into the future for the study area contrasts with that found for elsewhere, such as Poland, where Molitor et al. [44] demonstrated a widening temporal gap between the last frost event and budburst post-2025. For New Zealand's Marlborough wine region, Sturman and Quénol [53] have demonstrated the unexpected increase in frost risk despite a warming climate, driven by an increased frequency of frost conducive anticyclonic weather regimes. Such geographical contrasts in the relationship between budburst and LSF and frost conditions in general highlight the importance of place-based assessments of future frost risk given intraregional to interregional contrasts in climate.

While the information presented in Table 5 is useful for establishing the annual likelihood of LSF occurrence for a given decade (e.g., 8 out of 10 years are projected to experience at least one LSF, hence an 80% probability), of greater relevance to viticulturists is the evolution of risk for periods associated with grapevine growth. With this in mind, the temporal evolution of frost probability for the spring months of March and April and the critical period is presented in Table 6 for each decade. The probability calculations are based on the ensemble mean number of projected frost days for the month/period of interest, such that for the month of March and for any one decade, the total number of frost days are counted and divided by the total number of March days (310). The "shoulder months" of March and April demonstrate the largest downward shifts in frost risk, with the critical period revealing relatively small changes as this period generally spans the months of April to

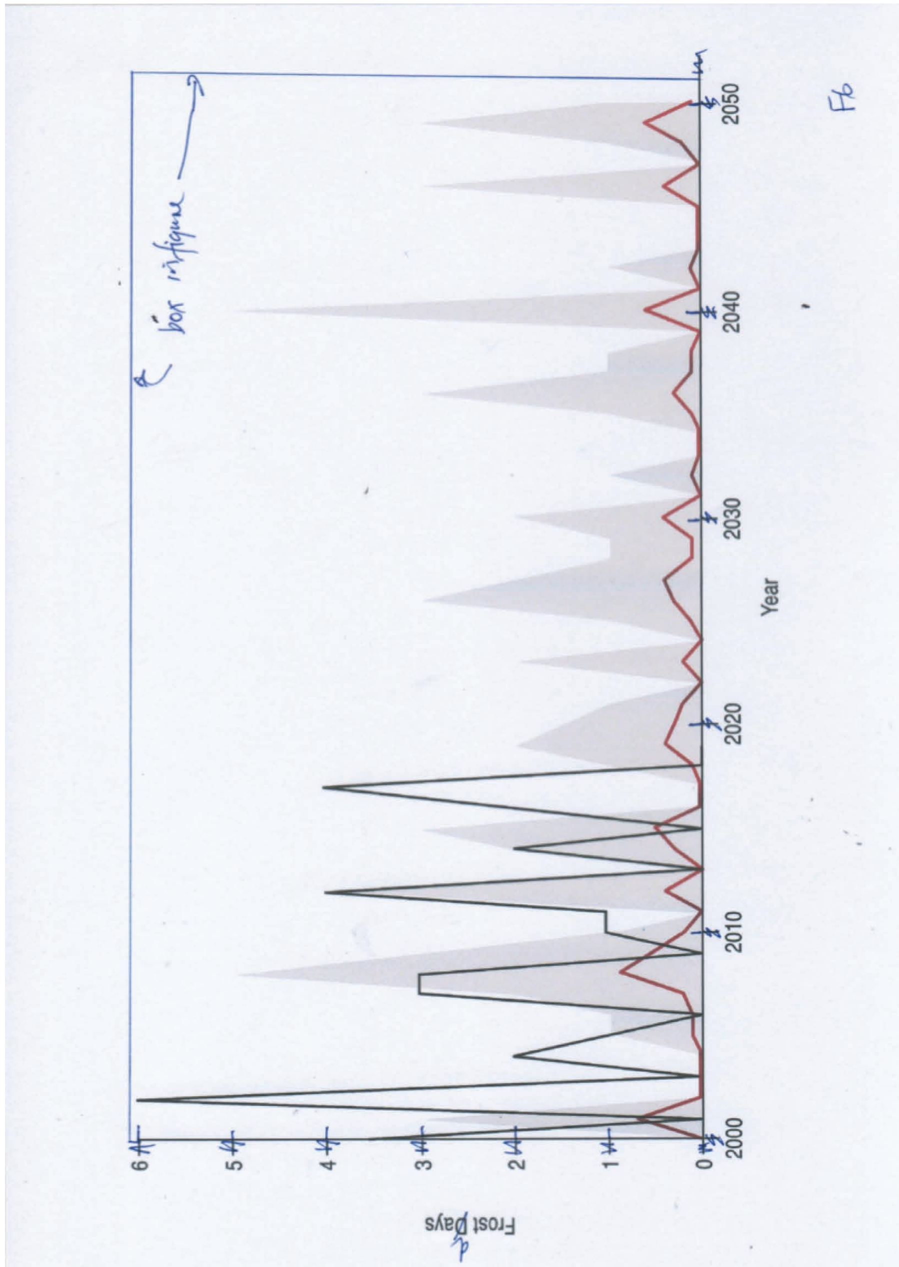

Figure 6: Time series of observed (——) and simulated perturbed parameter ensemble (PPE) mean values (——) for seasonal frost days. Shaded region indicates the PPE spread.

June, which are commonly frost-free. For the majority of years over the period 2000–2050, spring warming models place budburst in the month of April, when frost risk is greater than that for the multimonth and generally warm critical period but less than March. This makes April of special interest to viticulturists, with the dwindling likelihood of frost in this month acting to reduce the number of "dangerous" frost days per year and lengthen the growing season. That said, for temperature-limited ecosystems such as grapevines, the uncertainties surrounding the prediction of the date of budburst need to be borne in mind. The same applies to the projection of the number and timing of days of frost. For this reason, and as noted elsewhere [12, 41], the risk of frost in March and early April will remain relevant as an overall viticulture suitability factor because of the coincidence of these "frost months" with the timing of budburst.

While this study has focused on frost as one of the widely known threats to grape growth and wine production in England [3, 9], our analysis indicates frost frequency explains only 28% of the interannual variability of wine yield. In contrast, seasonal GDD and maximum July temperature account for a higher proportion of yield variance at 31.2 and 61.2%, respectively. These findings point to maximum temperature and heat accumulation as potentially more important at the overall level than frost occurrence and the

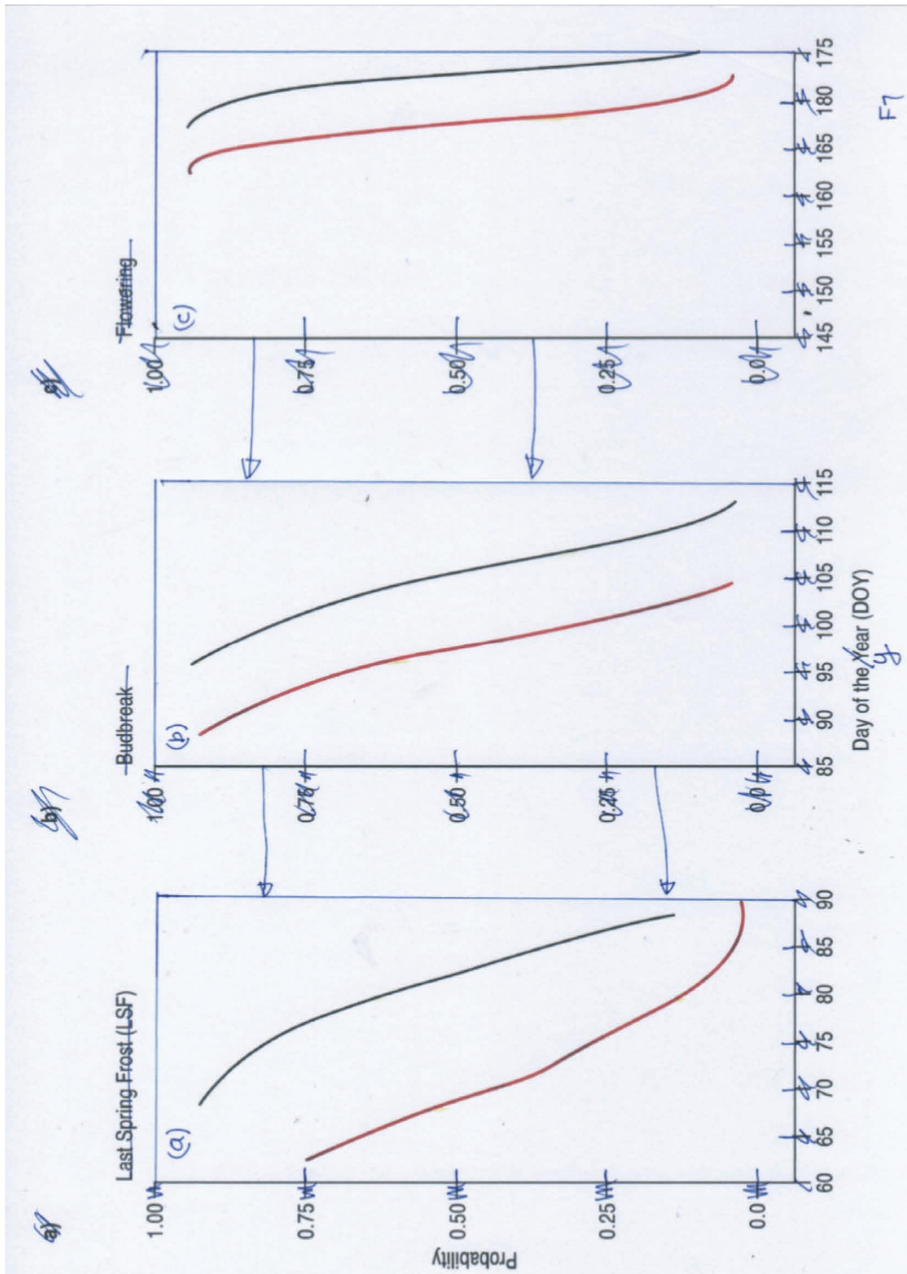

Figure 7: Exceedance probability curves for the (a) last spring frost event, (b) Chardonnay budburst, and (c) Chardonnay flowering, as a function of the day of the calendar year (DOY), for the baseline (2000–2019) (——) and overall, near future (2021–2050) (——) periods.

general view that rising average maximum temperature is increasing viticulture suitability in the UK. Such a supposition, however, may be misleading. While the requisite number of heat units is critical for grapevine success, extreme heat can pose a significant threat to grapevine health, something becoming increasingly evident in some grape-growing regions across Europe [54]. This raises the question of the impact of climate change on the complementary risk of acute heat events for UK viticulture, a matter that invites future research given that the best sparkling wine is produced in regions with moderate heat accumulation [55]. Increased heat may therefore pose a threat to grape health [56, 57], with the prospect that some wine regions may become unsuitable for viticulture in the future due to heat extremes [7]. This is important in the context of the wider Southeast England region, as although the average climate may become more conducive to wine production and agriculture in general, heatwaves will double in frequency, with the likelihood of heat stress affecting crops projected to increase by a factor of five with a global warming of 2°C, as pointed out by Arnell et al. [52].

Although maximum temperature may explain a great deal of current yield variability, around 40% remains unexplained, indicating other critical climate variables, such as

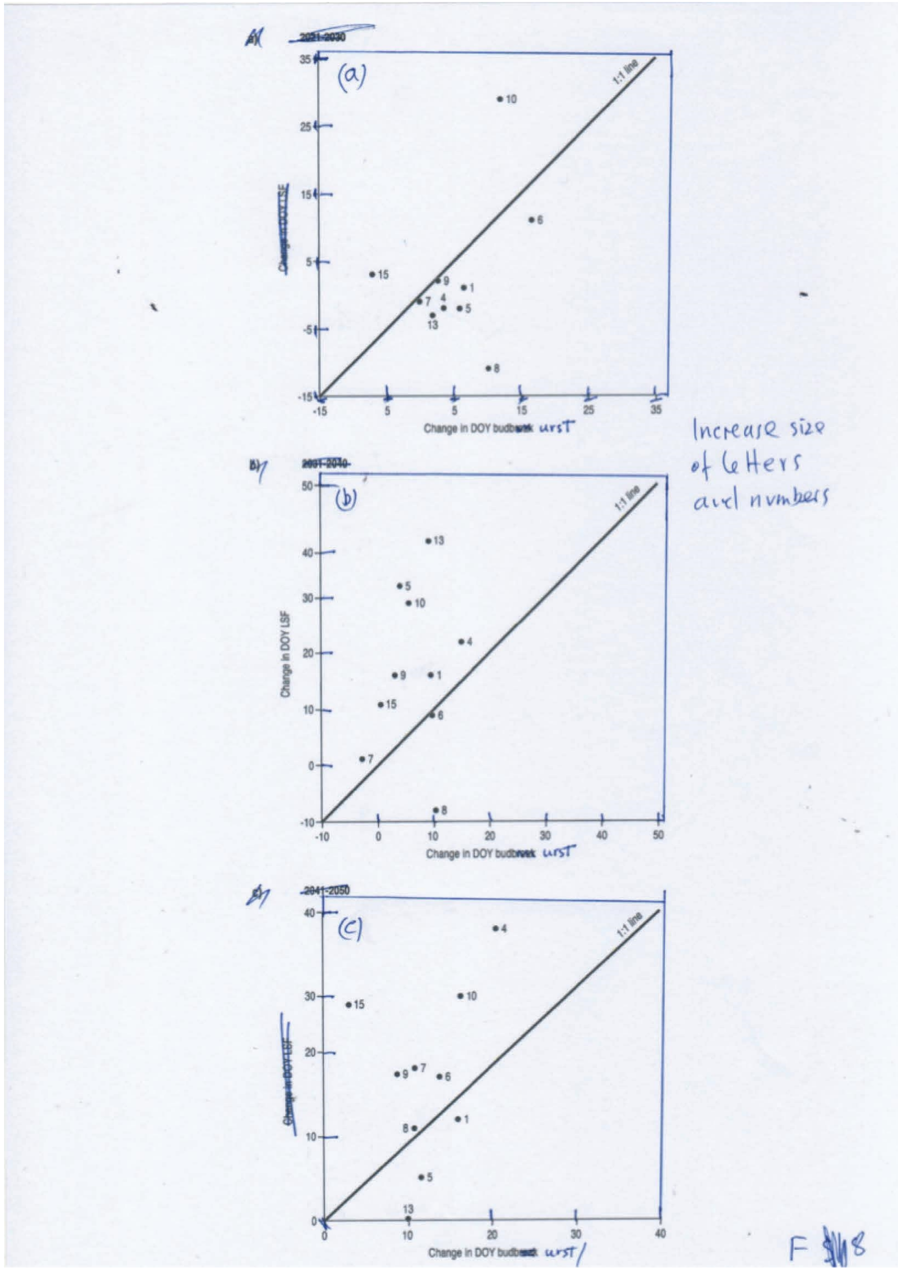

Figure 8: Relationship between the mean change in day of the calendar year (DOY) for Chardonnay budburst and last spring frost (LSF) for each ensemble member for (a) 2021–2030, (b) 2031–2040, and (c) 2041–2050. Numbers refer to the individual PPE ensemble members. Change is measured from the baseline (2000–2019) average for each ensemble member, respectively. Points located beneath the 1 : 1 line indicate an increase in risk from the baseline period, while points located above the reference line indicate a decrease in risk for each decade, respectively.

Table 5: Probability that the last spring frost will occur in the critical period for any one year by decade, with the critical period defined as the time between Chardonnay budburst and flowering.

Period	Frost risk (%)	Class of frost risk†
2000–2009	60	High
2010–2019	60	High
2021–2030	80	High
2031–2040	60	High
2041–2050	50	Moderate

Probability was calculated as the number of years for which an LSF occurred divided by 10 years. †The risk classes are those developed by Webb et al. [17].

Table 6: Decadal trend in frost risk for March, April, and the critical period.

Period	Frost risk (% probability)		
	March	April	Critical period
2000–2009	20	11	3
2010–2019	13	7	2
2021–2030	11	7	2
2031–2040	12	3	1
2041–2050	9	2	1

precipitation, soil moisture, and sunshine hours [58–60], may be important as well as weather conditions during flowering and harvest [61], which have not been considered here. Consequently, their role is worth exploring in future studies of contemporary yield sensitivity, along with the types of large-scale weather patterns that might be pivotal in influencing annual wine yield and frost occurrence, as found elsewhere, for example in Sturman and Quénol [53]. Vineyard management practices as a driver of yield variability remain unexplored in England to date but may also play an important role in determining grape yield, as found in several regions [3, 4].

Because of the relatively short history of commercial wine production in England and the lack of requisite phenological datasets for developing robust phenological models, studies of grapevine phenology in England are reliant on models developed elsewhere. This represents a potential and important source of uncertainty in any study that attempts to assess the impact of future climate change on viticulture because accurate estimates of budburst are required for assessing potential frost risk. The timing of and weather conditions during other phenophases, such as flowering, veraison, and harvest, are also known to determine grape yield and are expected to be impacted by future climate change [62, 63]. There is a wide-ranging and unresolved debate as to which model type provides the most reliable estimates of phenophase timing [12, 47, 48, 64]. Mosedale et al. [12] have highlighted the implications of phenological model choice. Focusing on the Southwest England grape-growing region of Cornwall, they found that winter chilling models produce different trends in budburst timing when compared to spring warming models [12], as used in this study. Additionally, they suggest that the warmer winter conditions projected under climate change might work to impede the commencement of the vegetative period in the future, compensating for any advance in the date of budburst. Further reduced winter chilling is likely to have physiological effects on the grapevine beyond just impacts on date of budburst and frost risk [65]. Consequently, in addition to investigating the effects of strong observational evidence of a continued increase in winter temperature for England [19], future studies should examine the influence of winter chilling and spring warming models on the potential under- or overestimation of budburst date.

Further to the uncertainty associated with phenological model choice is that related to climate modelling [12, 66]. This study has applied the output from a set of perturbed parameter ensembles (PPE) comprising the UKCP18 climate projections to frost risk estimation. In doing so, it has revealed the mismatch between the observed and PPE-based simulated values for several key bioclimate and phenophase variables, which bears implications for uncertainty in model predictions for viticulture. Put simply, as shown in this study, the simulations are "too cold," which accords with the findings from other studies that apply UKCP18 simulations [67]. This raises the possibility that the scale of bias correction applied in this study to the overall ensemble mean value was not sufficient from the outset. Given that some individual ensemble members match the observations more closely than others, a more ensemble member-specific approach to bias correction could have involved bias correction for each individual ensemble member, as opposed to the application of a single value for increasing the overall ensemble mean closer to the observed mean. This approach, plus the inclusion of bias correction for variance as well as the mean, is worthy of consideration in future studies and may lead to improved convergence between observed and modelled values. Regarding the significant variability between the individual ensemble members, this may arise from errors introduced in the global climate model that are carried through to the regional climate model [68], from which the climate variables for this study have been extracted. This gives rise to the prospect that PPEs underrepresent the structural uncertainties of climate projections, something that could be reduced by combining PPE projections with multimodel ensembles [32]. Given this, we suggest that future climate change and viticulture impact studies for the UK adopt a blended approach that combines output from both perturbed ensembles and models from several different modelling centres. As suggested by Sexton et al. [32]; benefits should accrue from such an approach, as sampling modelling uncertainties from climate simulation ensembles of both types will be possible. Moreover, consideration needs to be given to the extent to which modes of interannual to decadal climate variability, possibly important for influencing viticulture success, are captured by the individual PPE members making up the UKCP18 projections.

5. Conclusions

The results presented here suggest that climate change and a warmer wine climate should provide a positive future for viticulturists in England. Specifically, projected temperatures under climate change should lead to both a substantial reduction in spring frosts for the critical growth period and an increase in growing degree days/heating units. In addition, the greater advance of the date of the last spring frost relative to budburst should decrease frost risk for the Chardonnay grape, providing a distinct improvement in prospects for the UK sparkling wine industry. Notwithstanding these potential positives, there is a distinct prospect that frost risk will remain a threat into the future, a key factor that should be recognised as it only takes a single frost occurrence after budburst to cause significant losses. This is because this study suggests that the possibility of frost occurrence after budburst will remain at least until the mid-21st century, although at decreasing levels, as shown by the consistent downward decadal trend in LSF probability for the critical growing period between budburst and flowering.

As the success of the viticulture industry in the wider study region is likely to depend on climate factors other than temperature, such as moisture supply and timing and levels of solar radiation/cloudiness, future assessments of viticulture in the Southeast England region under climate change need to take this complexity into consideration. Given the differences identified between observations and model projections for temperature and thus key temperature and related bioclimate and phenological variables noted in this study, work is required to understand the origin of these differences, especially as temperature generally possesses greater model-based predictability compared to other climate variables. In particular, the cold-bias detected for the PPE simulations of the baseline period (2000–2019) needs careful consideration in any future work that applies the UKCP18 simulations to the assessment of changes in wine climate under climate change. There are therefore several potential uncertainties inherent in climate-wine projections based on the UKCP18 projections. These constitute a clear challenge for making unequivocal statements about how climate in all respects will affect future viticulture across the wider study region. Grappling with this challenge and assessing how grape cultivars other than Chardonnay may respond to climate change provides a clear direction for future programs of climate and wine research in England.

Data Availability

The data supporting the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

The authors contributed significantly to the production of this manuscript.

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