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Assessing the Interplay Between Climatic Conditions and Olive Phenology Using the Growing Degree Day Model

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ABSTRACT

Rising temperatures, shifting precipitation patterns, and increasing frequency of extreme weather events across the Mediterranean, driven by climate change, present significant challenges for olive cultivation, particularly if traditional soil management practices are not adapted. Croatia, located at the northern edge of the Mediterranean olive-growing zone, represents the northernmost region where olives are cultivated. However, comprehensive agroclimatic studies in Istria (Croatia), especially those examining recent trends in olive tree phenology, remain scarce, providing the main motivation for this research. Our results indicate that rising minimum and maximum temperatures across Istria, particularly in spring, have increased growing degree day (GDD) accumulation during the growing season. This has advanced the onset of key phenological stages and shortened the overall growth period, with the Istarska Bjelica cultivar showing the most pronounced response. To further explore this, a simple GDD model was developed and tested as a prognostic tool for predicting the initiation of phenological stages. The model successfully captured the entire flowering period, performing best with a base temperature of 6°C. This highlights its strong potential for projecting the onset of olive flowering under future climate conditions and supporting more effective management decisions.

1 | Introduction

The evidenced tradition of olive growing in Istria (Croatia) spans over more than 2000 years, dating back to the ancient Romans who recognised the region's favourable conditions for olive trees (Šoštarić and Küster 2001; Essert et al. 2018). Today, Istria has become an olive-growing region planted by a great number of olive trees (*Olea europaea* L.), gradually increasing from 735,062 in 2011 to 1,074,117 in 2023 (Paying Agency for Agriculture, Fisheries and Rural Development (PAAFRD), official data). This represents an increase of 46% in the cultivated area, which reached around 4300 ha by 2023. This longstanding tradition owes its success to suitable climatic conditions, excellent soil

quality and timely processing of olives, all aimed at producing high quality oil (Benčić and Krapac 2009).

Quantifying the interplay between regional climate and the stages of olive phenology is essential for predicting the onset and duration of phenological stages (Krapac and Sladonja 2010). The latter depends on heat units accumulated from the end of the dormancy above a temperature threshold of 7°C, often measured as growing degree hours (GDH) or growing degree days (GDD) (Osborne et al. 2000; Vuletin Selak et al. 2018; Fraga, Pinto, et al. 2020). Temperature is a critical factor influencing olive phenology, and studies show that the flowering stage is particularly sensitive to temperature changes (Aguilera

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and Valenzuela 2012; Aguilera et al. 2015; Fraga, Moriondo, et al. 2020; Silveira et al. 2023). To end dormancy and begin accumulating heat for flowering, average daily air temperature must be above 7°C for at least a week.

Although Istria's climate has supported a longstanding olive-growing tradition, Croatia's climate has shifted over the last decade (Branković et al. 2013; Patarčić et al. 2014; Belušić Vozila et al. 2019, 2023; Tojčić et al. 2024). Climate projections for Istria indicate a gradual increase in air temperature (Sviličić et al. 2015; Radilović et al. 2020), and specifically up to 2.5°C during the growing season (April–October) by the middle of the 21st century. Thus, traditional Istrian olive orchards are facing new challenges and threats to their sustainability (Šimunić et al. 2021).

The Mediterranean region has already documented adverse climate change effects on olive cultivation. By 2040, Southern Iberia is projected to fall outside its current GDD range by 2040 (Fraga et al. 2019). Rising temperatures have caused earlier flowering and an extended growing season on the Iberian Peninsula (Pérez-López et al. 2008). In Crete, GDD increases may shorten the growing season after the middle of the 21st century, exceeding the needs of existing crops (Paparrizos and Matzarakis 2017). A trend analysis of olive phenological stages along the eastern Adriatic coast in the period 1956–2003 shows a statistically significant earlier onset of flowering, by 5 days in 100 years, and the first ripe fruits appearing 27 days over 100 years (Vučetić and Vučetić 2005).

Extreme weather events—such as heat, drought and storms—are expected to intensify across southern Europe (Bindi and Olesen 2011), potentially pushing climatically suitable areas for olive cultivation northwards (Tanasićević et al. 2014). By comparing GDD for the present climate (1981–2000) and the end of the 21st century (2081–2100) and using flowering maps, estimates by Orlandi et al. (2013) for southern Italy indicate a possible northward and altitudinal expansion of oil-growing areas. Similarly, Charalampopoulos et al. (2021) suggest that cultivation may extend to low-lying areas in the northern Balkans, including northern Serbia and Croatia, though some farmers in southern Europe may need to abandon cultivation if conditions become excessively warm and dry (Tanasićević et al. 2014; Ceglar et al. 2019).

In order to understand and quantify the impacts of climate change, models are increasingly being developed to describe olive phenology using machine learning (Oses et al. 2020; Azpiroz et al. 2021), deep learning (Miličević et al. 2020; Chacón-Maldonado et al. 2022) or other equations linking meteorological parameters to phenology. Indeed, predicting the timing of phenological stages is challenging. Garcia-Mozo et al. (2009) developed a model for predicting the onset and duration of flowering in Spain and Italy that combines forcing temperature with photoperiod. Aguilera et al. (2015) used partial least squares regression to create eight forecasting models across the Mediterranean, with flowering dates (date of flowering onset, date of full flowering) as dependent variables and meteorological and bioclimatic parameters (monthly and seasonal temperatures and precipitation) as predictors. These models proved to be effective, with deviations between

observed and expected flowering onset and full flowering dates ranging between 1%–7% and 1%–5%, respectively, across various regions.

The GDD model, based on heat accumulation, is another approach for predicting phenological stages (Orlandi et al. 2014; Zouari et al. 2017; Garrido et al. 2020; Didevarasl et al. 2023). This model has yielded reliable results for olive and similar crops, such as grapevine (García de Cortázar-Atauri et al. 2009; Omazić et al. 2023). In this model, the base temperature for GDD calculation is typically set at 7°C, the temperature at which olives end dormancy and begin to accumulate heat for flowering. However, recent studies indicate that optimal GDD model performance varies with location and cultivar, with best results in northern, central and southern Italy achieved at base temperatures of 7°C, 8°C, and 9°C, respectively (Orlandi et al. 2014). Didevarasl et al. (2023) found the best base temperature to range from 4.5°C to 7°C in Italy, depending on the growing stage and cultivar.

The lack of comprehensive agroclimatic studies in Istria, particularly those focusing on recent trends in olive tree phenology and the creation of statistical models to predict future phenological stages, has been the key driving force behind this research. Furthermore, it is of great importance for Croatia, and Istria in particular, to raise awareness of the effects of climate change and consequently improve adaptation strategies for successful olive cultivation. To complement the existing studies over the Mediterranean region, the objectives of this study are twofold: first, to provide the very first calculations of the present-climate GDD values over Istria and recent trends for each phenological stage, and secondly, to develop and test a reliable statistical model for future GDD predictions.

2 | Data and Methods

2.1 | Climate and Phenological Data

The region of Istria (Croatia), located between 44.7° and 45.5° north latitude, is among the northernmost areas in the Mediterranean where olives are cultivated. Data from four meteorological stations in Istria (Figure 1) were obtained from the Croatian Meteorological and Hydrological Service (DHMZ). Three coastal stations, located on the west coast of Istria from south to north, are Pula, Rovinj and Poreč. These stations are situated less than 1 km from the sea and at elevations below 30 m above sea level. The fourth station, Čepić, is an inland station in the eastern part of Istria, approximately 8 km from the sea and 30 m above sea level, located in the valley at the bottom of the slope of mountain Učka. To determine the climatic characteristics during the study period, daily minimum (T_{\min}), maximum (T_{\max}) and mean (T) air temperatures (in °C) were analysed.

The start dates of five phenological stages (beginning of flowering, full flowering, end of flowering, fruit ripening, and harvest) were also obtained from DHMZ and recorded at the four stations, with the addition of a station in Sveti Lovreč, located halfway between Rovinj and Poreč (Figure 1), approximately 13 km from the sea and 196 m above sea level. All meteorological measurements are carried out right near the respective

orchards, except for Čepić. Phenological data for Čepić were observed 2 km from the meteorological station and at an elevation 37 m higher.

This study includes olive orchards of several varieties: Leccino in Poreč and Pula, Istarska Bjelica in Poreč, Rovinj and Čepić, Frantoio in Poreč, Pendolino in Pula and Sveti Lovreč, Buža in Pula and Sveti Lovreč, Oblica in Sveti Lovreč. Leccino and Pendolino are the most common introduced varieties in Istria, while Buža and Istarska Bjelica are the most widespread indigenous varieties. The olive cultivars investigated in this study exhibit distinct phenological patterns with respect to flowering and fruit ripening. Istarska Bjelica and Leccino are the earliest to enter the flowering phenological stage, followed sequentially by Buža and Oblica, whereas Frantoio and Pendolino start flowering later (Krapac and Sladonja 2010; Vuletin Selak et al. 2019). Regarding fruit development, Leccino is classified as an early-ripening cultivar (Barranco et al. 2000), Buža and Oblica as

mid-season cultivars, and Istarska Bjelica as a late-ripening cultivar (Bandelj et al. 2014). These cultivars are the most commonly grown in our region and, as such, serve as reference varieties for this area. The length of individual time series varies between stations (Table 1), with Pula-Buža having the longest uninterrupted record (1996–2021) and Sveti Lovreč-Oblica the shortest (2009–2016).

2.2 | GDD and a Statistical Model

The heat units accumulated up to the beginning of each phenological stage are calculated as GDD per year, following methodology established in previous studies on olive cultivation (Bonfiglio et al. 2008). To determine GDD, the daily T_{max} and T_{min} are averaged to obtain daily temperatures. From this value, the temperature threshold ($=7^{\circ}C$) for olive crops is subtracted (Equation 1). The resulting positive difference (active

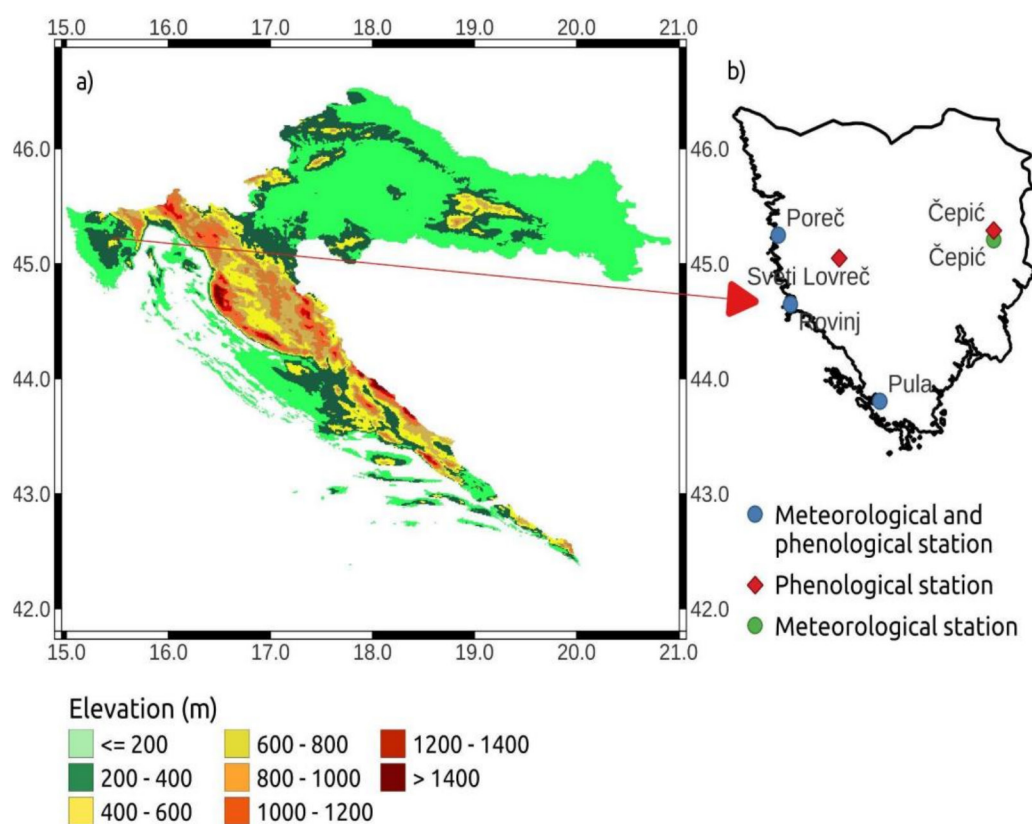


FIGURE 1 | (a) The position of Istria on the map of Croatia. (b) Spatial distribution of three agrometeorological stations (blue dots), two phenological stations (red) and one meteorological station (green).

TABLE 1 | Summary of phenological data availability per location and olive variety.

Location/Variety	Istarska Bjelica	Buža	Frantoio	Leccino	Oblica	Pendolino
Pula		1996–2021		1999–2021		2000–2021
Rovinj	2005–2021					
Poreč	2006–2021		2005–2021	2005–2021		
Sveti Lovreč		2008–2021			2009–2016	2003–2021
Čepić	2012–2021					

TABLE 2 | Summary of temperature conditions on selected stations in the analysed period.

Parameter/Location	Pula (south) (1996–2021)	Rovinj (2005–2021)	Poreč (north) (2005–2021)	Čepić (2012–2021)
Mean temperature	15.2°C	14.5°C	14.32°C	13.5°C
Mean temperature in July	25.2°C	24.7°C	24.7°C	23.2°C
Mean temperature in January	6.1°C	5.8°C	5.2°C	4.2°C
Max. temperature (year)	39°C (2017)	36.5°C (2013)	36.9°C (2013)	40°C (2017)
Min. temperature (year)	−7.1°C (2009)	−9.6°C (2016)	−9.8°C (2009)	−14.8°C (2012)
Mean max. temperature	19.34°C	19.12°C	19.06°C	20.38°C
Mean min. temperature	11.38°C	10.21°C	10.05°C	7.18°C

temperature, larger than 0°C) is assumed to contribute to the olive growth. Accumulated heat units are then summed for each day from February 1st to the day before the onset of the corresponding phenological stage following Equation (1) February was chosen as the starting point, as it marks the onset of olive bud differentiation (Jelović 2015). During February, buds begin to develop into either flower buds (which bear fruit) or vegetative buds (which produce new shoots), and from this point onward, the olive tree begins to accumulate active temperatures required for the initiation of flowering and the following phenological stages.

$$\text{GDD} = \sum_{\text{Feb}}^{\text{Oct}} \frac{T_{\min} + T_{\max}}{2} - T_{\text{base}} \quad (1)$$

To expand on previous studies, we performed a sensitivity test of GDD by changing the T_{base} in Equation (1) from 5°C (model A) to 8°C (model G) in increments of 0.5 (models B, C, D, E, F). Additionally, we incorporated the known response of olive trees to elevated temperatures, acknowledging that their photosynthetic activity diminishes once critical temperature thresholds are exceeded (Haworth et al. 2018; Didevarasl et al. 2023). Accordingly, we set a condition limiting GDD accumulation to a maximum of 20 units per day. Therefore, in our model, it could not exceed 25°C to 28°C, depending on the T_{base} model.

For each T_{base} model evaluation is conducted in the following steps at each station. First, the available dataset was divided into approximately equal numbers of training and testing years. The years selected for training and testing were chosen randomly using a random number generator—the details are provided in Table S1 in the Supporting Information. For each year, location and variety in the training period, GDD at the onset of a specific phenological stage was calculated. The median of these values was then used as the threshold for the phenological stage onset during the testing period. Statistical measures—including the correlation coefficient (Rcv, Equation (2)), root-mean-square error (RMSE, Equation (3)) and agreement index (d, Equation (4), Willmott et al. (2012))—were used to evaluate model performance during the testing years.

$$\text{Rcv} = \frac{\sum_{i=1}^n [(P_i - \bar{P})(O_i - \bar{O})]}{\sqrt{\sum_{i=1}^n (P_i - \bar{P})^2 \sum_{i=1}^n (O_i - \bar{O})^2}} \quad (2)$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^n (P_i - O_i)^2}{n}} \quad (3)$$

$$d = 1 - \left[\frac{\sum_{i=1}^n (P_i - O_i)^2}{\sum_{i=1}^n (|P_i - \bar{O}| + |O_i - \bar{O}|)^2} \right] \quad (4)$$

2.3 | Agroclimatic Conditions Over Istria During the Growing Seasons

The Istrian region exhibits typical characteristics of a Mediterranean climate (Table 2), with hot and dry summers, and mild and rainy winters, and an average annual temperature of about 14°C. The warmest month is July, with an average temperature of 24°C, while the coldest month is January, with an average air temperature of 5°C. In addition, temperature fluctuations between day and night are minimal throughout the year, creating highly favorable conditions for olive cultivation.

Olive flowering in the Istrian region typically begins in May and lasts until early June, with evident differences between the coastal and inland parts. To initiate flowering (Figure 2a), an average heat accumulation of about 400°C, with the base temperature of 7°C, is required in the interior (Čepić), compared to 450°C–510°C on the western coast of Istria (Poreč, Pula and Rovinj). Full flowering is reached after an additional accumulation of about 75°C (ranging from 510°C in Poreč to 620°C in Pula and 490°C in Čepić). An additional 113°C is needed to complete the flowering phenological stage (ranging from 610°C in Poreč to 750°C in Pula and 600°C in Čepić). The consistency of these heat accumulation requirements provides a solid basis for applying the GDD model (described in Section 2.2) to predict the onset of this phenological stage.

From the end of flowering to the beginning of fruit ripening, approximately 130 days are needed, during which the olive requires an additional 1700°C–1900°C of heat accumulation for the first fruits to ripen. As a result, the first fruits ripen when an average heat accumulation reaches 2230°C in the interior of Istria and 2500°C in the coastal region. On average, 150 days are needed from the beginning of flowering to harvest, depending on location and variety. Between fruit ripening and harvest, an additional 110°C–240°C is required, corresponding to an

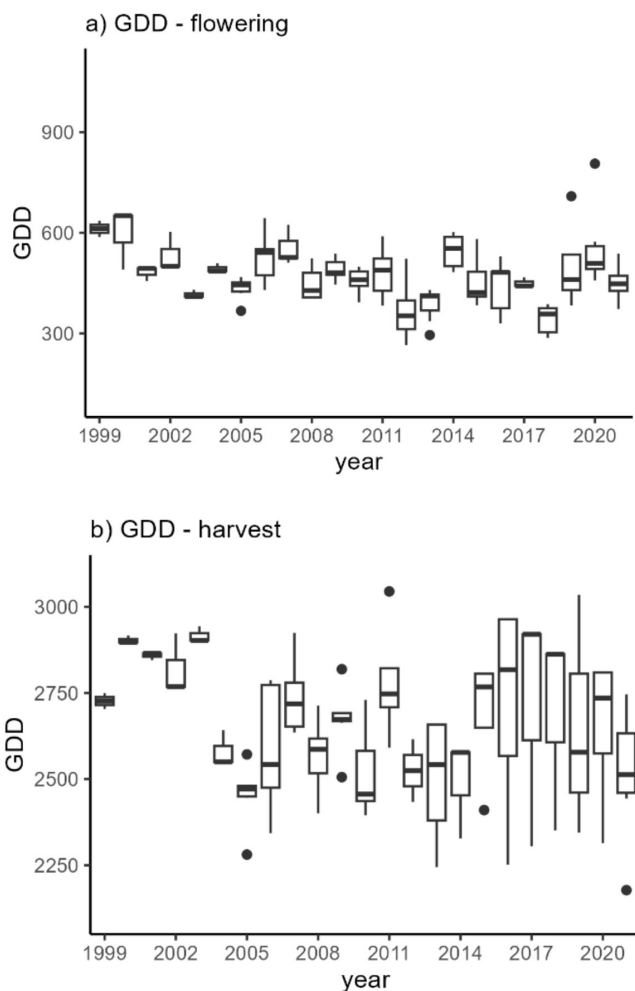


FIGURE 2 | Boxplot of GDD (°C, with base temperature 7°C) from four meteorological stations and available olive varieties (a) from February 1st to the beginning of flowering and (b) between February 1st and harvest. The range of the y-axis is set to 1000°C in all subplots.

TABLE 3 | Statistically significant ($p < 0.05$ by Student's t -test) trends in temperature (T_{mean} , T_{max} , T_{min} , °C/10 years during the monitoring period) at selected stations calculated on a monthly basis.

Parameter	Location	January	February	March	April	June	July	August	October
T_{mean}	Pula		0.7						
	Rovinj								
	Poreč		2.1					2.0	
	Čepić		3.2					1.5	
T_{max}	Pula						0.7		
	Rovinj	1.5	1.9	1.9	0.8			2.3	
	Poreč	1.3	1.8	1.7				2.1	
	Čepić								
T_{min}	Pula		0.8						
	Rovinj		2.3			1.6		1.8	
	Poreč		1.9			1.3			
	Čepić						-1.6		-3.9

Note: There were no statistically significant data for May, September, November and December.

average GDD of 2500°C in Poreč and Rovinj, 2800°C for Pula and 2300°C for Čepić. Still, year-to-year GDD fluctuations can be substantial, ranging between 2200°C and 3100°C (Figure 2b).

3 | Results and Discussion

3.1 | Observed Trends

We examined trends in temperature and the onset dates of each phenological stage for each site, identifying several statistically significant ($p < 0.05$) trends as listed below. All temperature trends in Table 3 are positive, except for the minimum temperature in July and October at the inland station Čepić. The main effect of temperature increase was observed for February and August, where both minimum and maximum temperatures show positive trends at most locations.

The rise in temperature also leads to an increase in temperature sums (GDD) during the growing season, from early February to the end of October. During the observed 30-year period (1992–2021), all stations show a positive trend in GDD (Figure 3). The most pronounced trend is recorded at Čepić, with an increase of +118°C units per decade. Remarkable positive trends are also observed in Poreč (+114°C units per decade) and Pula (+96°C units per decade). All these trends are significant at the 5% level. A positive GDD trend was observed in Rovinj (+39°C units per decade), though this trend is not statistically significant. Indeed, an increase in GDD indicates more heat availability for olive trees, leading to earlier fruit maturation.

Additionally, we analysed the GDD for corresponding phenological stages. However, statistical significance is confirmed only sporadically (using Student's t -test). For instance, the beginning of flowering for Leccino in Pula shows a trend of -59°C GDD per decade, indicating advances in the onset of flowering, and is the only statistically significant trend in the first phenological

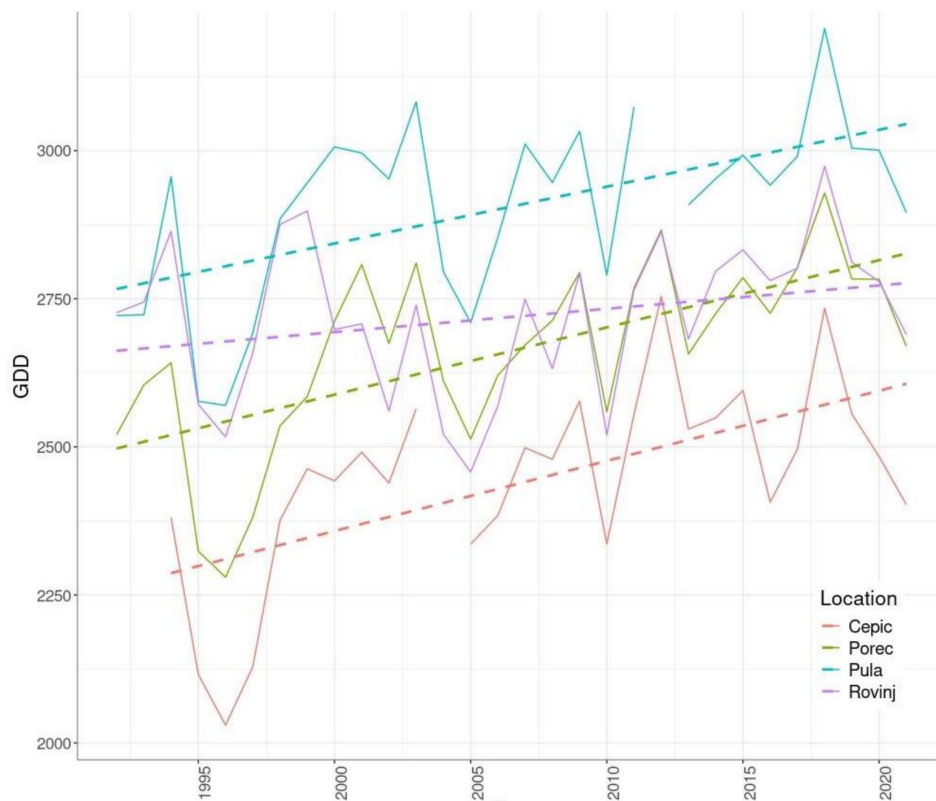


FIGURE 3 | Trends in GDD (°C units), with a base temperature of 7°C and in the growing season from February 1 to October 31 over a 30-year period (1992–2021) from four meteorological stations.

stage (Figure 4a). In the full flowering stage, statistically significant decreases in GDD are observed for the Leccino and Pendolino varieties in Pula, with declines of -67°C and -46°C per decade, respectively. No statistically significant trends are observed for the end of flowering. As GDD values continue to accumulate during the ripening period and the fall season, we observed a significant positive trend of $+160^{\circ}\text{C}$ per decade for fruit ripening and $+185^{\circ}\text{C}$ per decade for harvest (Figure 4b) in Rovinj. This is an indication that some olive varieties might accumulate higher GDD values preventing further advances in fruit ripening, as already seen for the onset of flowering documented in Fornaciari et al. (2025), indicating a flexible flowering of some cultivars and their adaptability to temperature and other environmental changes.

As a result, we found a statistically significant shift in the timing of flowering and veraison at some sites (Figure 5). Flowering onset (Figure 5a) has advanced significantly for Istarska Bjelica in Poreč by approximately 10 days per decade, for Leccino in Poreč by 15 days per decade, and for Leccino in Pula by 8.5 days per decade. This statistical analysis demonstrates that spring temperature trends (Table 3) are closely linked to olive flowering patterns through their influence on bud development, a result consistently reported in numerous previous studies (Galán et al. 2004; Orlandi et al. 2005, 2009). These effects, combined with the increased risk of extreme events during sensitive phenological stages, may have substantial negative impacts on both final yield and fruit quality (Moriondo and Bindi 2007; Knežević et al. 2017). In contrast, flowering in Čepić starts approximately 13 days later over the past decade. The delay may be related to more frequent temperature fluctuations and late frosts in inland

areas, as previously reported by Mycking (1997) and Orlandi et al. (2005). However, since this result is based on a short-term period and data from a non-local meteorological station, it should be interpreted with caution.

The olive fruit ripening has also started earlier: up to 20 days earlier for Leccino in Poreč and Buža in Pula (Figure 5b), and approximately 10 days earlier for Istarska Bjelica in Poreč and Leccino in Pula over the past decade. When comparing trends in flowering and fruit ripening, and consistent with rising temperatures, olive fruit development is expected to accelerate: phenological stages will occur earlier, and the overall growth period will be shorter. This is consistent with the findings of Moriondo and Bindi (2007) and Didevarasl et al. (2025), and aligns with previous studies conducted in Portugal (Fraga et al. 2019), Italy (Di Paola et al. 2023), Montenegro (Knežević et al. 2017), and Dalmatia, Croatia (Vučetić and Vučetić 2005).

We conclude that the relationship between plant phenology, temperature trends, and geographical features is indeed very strong. The results further emphasise the importance of long-term data series to prevent partial interpretations or misleading conclusions regarding such complex dynamics, as also noted by Orlandi et al. (2009). Harvest dates were not included in this analysis, as no statistically significant trends were found. It is essential to note that the timing of harvest is highly dependent on the chosen maturity level, available olive oil processing facilities, the capacity for processing plants at any given time, and the weather leading up to harvest. In other words, the start of the harvest is highly dependent on human decision.

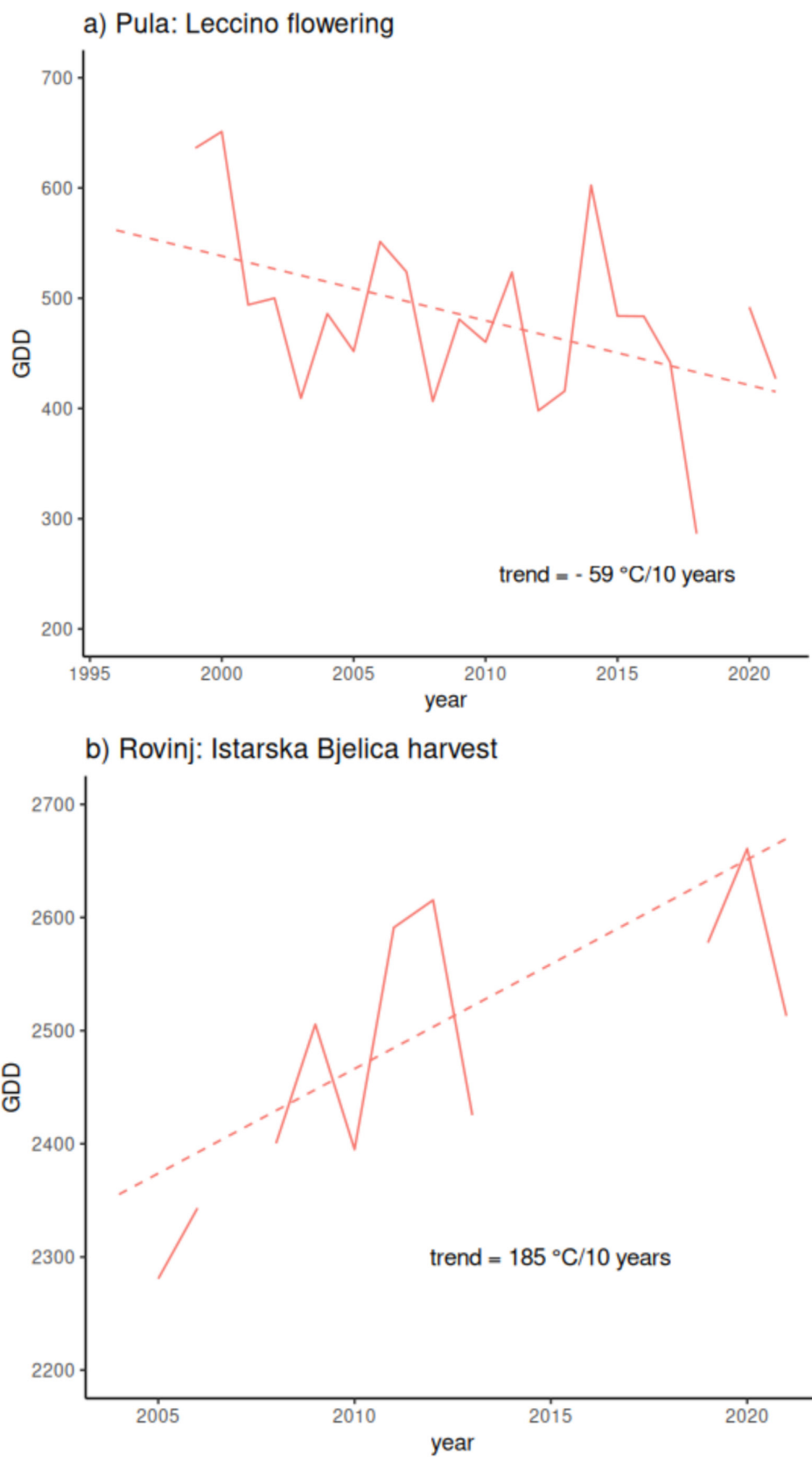


FIGURE 4 | Time series of GDD (°C) and their statistically significant ($p < 0.05$) trends, calculated for two varieties. (a) From February 1st until flowering of Leccino in Pula and (b) from February 1st until harvest for Istarska Bjelica in Rovinj. Student's t -test was performed at the significance level of 0.05. Note that the extension of the y-axis is the same for both figures (500°C).

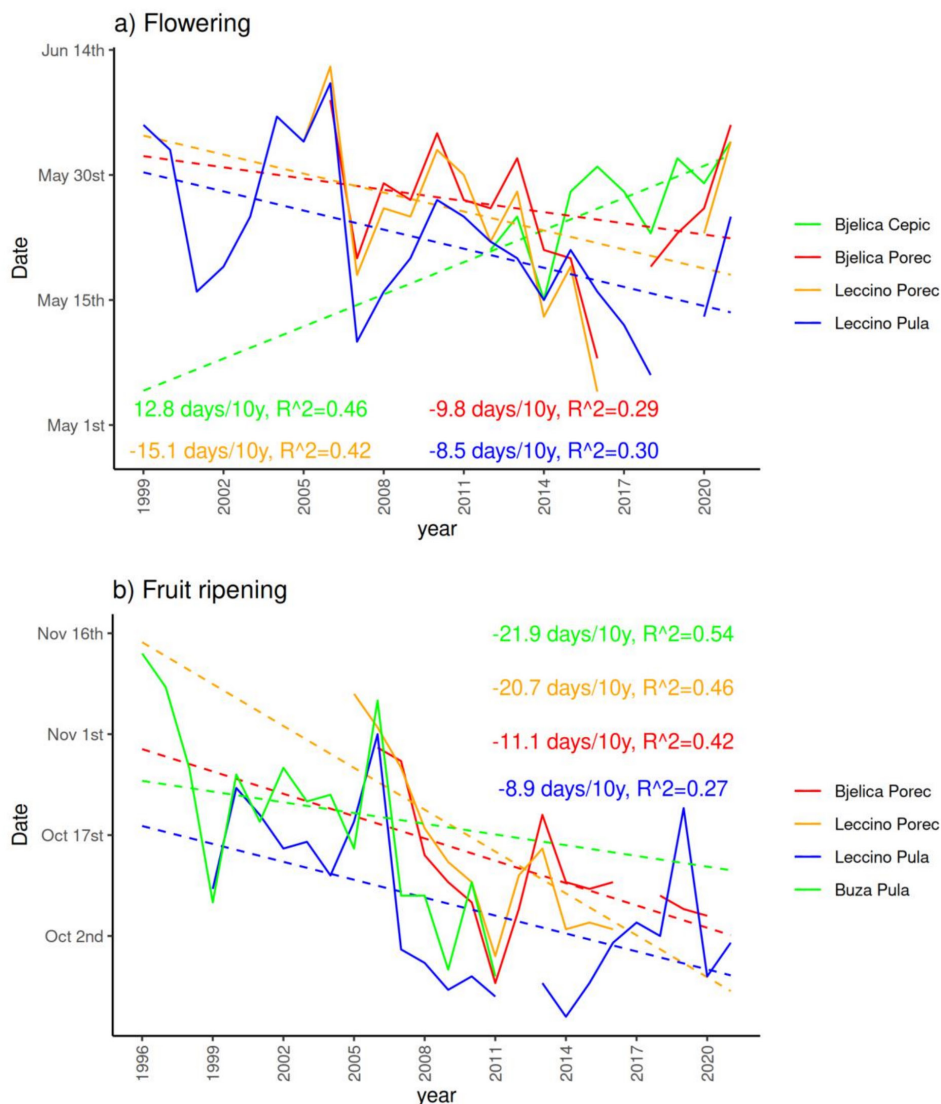


FIGURE 5 | Statistically significant (by Student's t -test, $p < 0.05$) trends in the observed data for (a) flowering onset and (b) ripening onset.

3.2 | Evaluation of the GDD Model

The presented GDD model performs well in predicting phenological stages, especially the flowering period (Figures 6, S1 and S2). Results for the beginning of flowering (Figure 6 and Table S2) show the best performance for Istarska Bjelica at Čepić (0.96), followed by Istarska Bjelica at Pula (0.8) and Poreč (0.78). Adjusting the T_{base} within the same variety and location leads to changes in the agreement index by a maximum of 6%. The largest discrepancies with observations, and thus the lowest agreement index, are found for Istarska Bjelica at Rovinj ($d = 0.63$). For this phenological stage, we found that adjusting T_{base} has the most significant effect for Istarska Bjelica at Čepić, Pendolino at Pula, and Istarska Bjelica and Leccino at Poreč. Therefore, the best agreement is obtained at $T_{\text{base}} = 7^{\circ}\text{C}$ for the first two, and at $T_{\text{base}} = 5^{\circ}\text{C}$ for the latter two. For all other varieties and locations, differences are negligible.

For the full flowering (Figure S1 and Table S3), the highest agreement index is found for Istarska Bjelica at Čepić ($d = 0.97$), followed by Istarska Bjelica at Poreč and Frantoio

Poreč. The lowest agreement is obtained for Istarska Bjelica at Rovinj ($d = 0.64$). The variations of T_{base} resulted in the best model performance for Istarska Bjelica at Čepić and Rovinj at $T_{\text{base}} = 6.5^{\circ}\text{C}$, Buža at Pula, Istarska Bjelica and Frantoio at Poreč at $T_{\text{base}} = 6^{\circ}\text{C}$, and Leccino at Poreč at $T_{\text{base}} = 5^{\circ}\text{C}$. The agreement index for the end of flowering (Figure S2 and Table S4) varies between 0.62 (Istarska Bjelica at Rovinj) and 0.95 (Istarska Bjelica at Čepić), followed by Istarska Bjelica at Poreč, and Istarska Bjelica at Pula. The best fit to the observations is found at $T_{\text{base}} = 5^{\circ}\text{C}$ for Buža at Pula, Istarska Bjelica and Leccino at Poreč, and at $T_{\text{base}} = 6^{\circ}\text{C}$ for Istarska Bjelica at Čepić, Poreč and Rovinj.

The further the olive growth progresses, the less the GDD model can describe the phenological stages as for initial stages. This is due to the fact that meteorological indicators (i.e., temperature) play the most important role for flowering while, in later phenological stages, other factors (such as disease infestation, fertilisation, that is the application of technologies that are not included in the GDD model) are taking the effects. Nonetheless, the largest agreement with observations for the onset of fruit

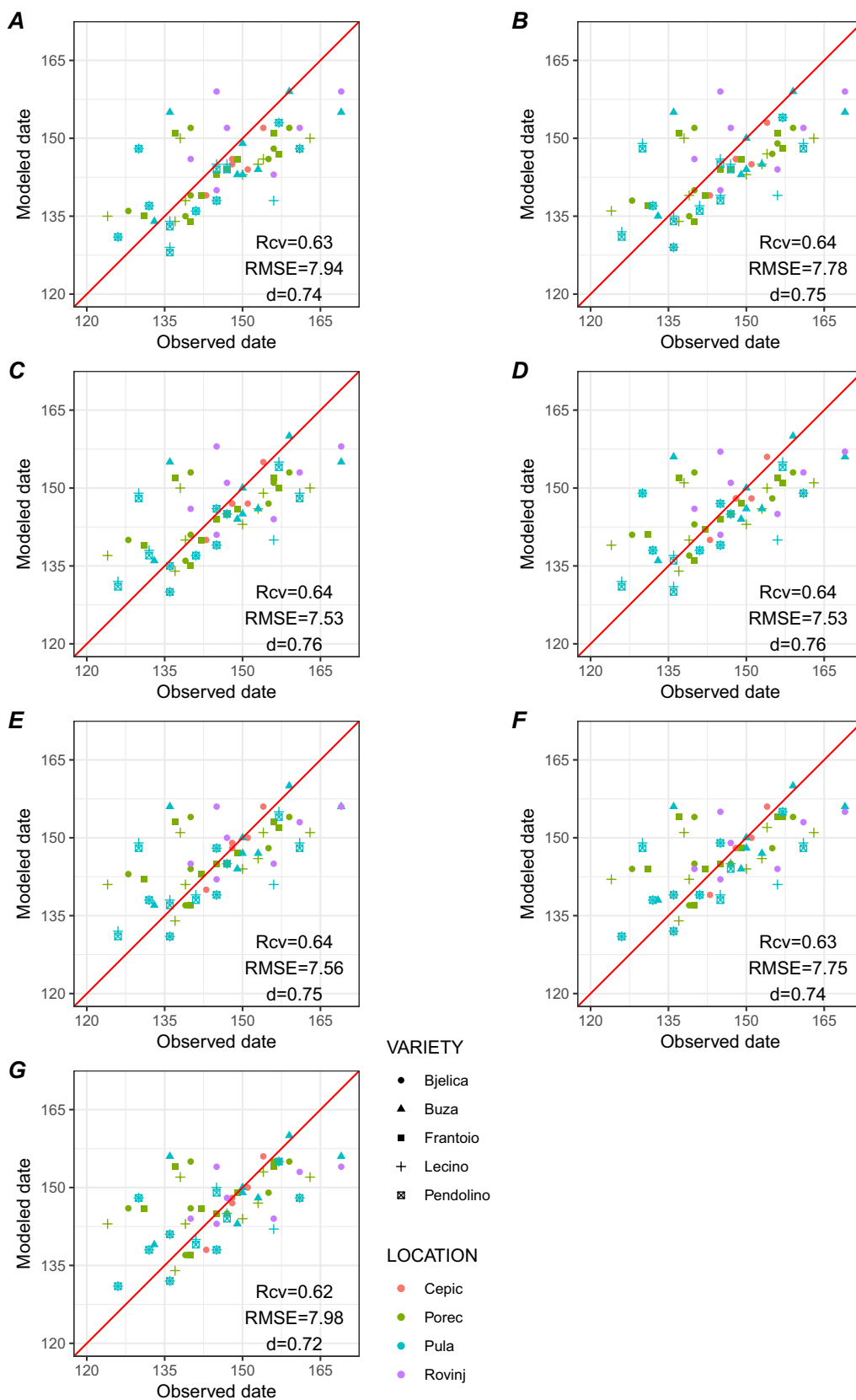


FIGURE 6 | Comparison of the predicted (y-axis) and observed (x-axis) dates for the onset of flowering. From model a to g the T_{base} increased by 0.5°C starting from 5°C (a) to 8°C (g). The Rcv, RMSE and d values are the mean values over all varieties (symbols) and locations (colours). The solid red line is a 1:1.

ripening (Figure S3 and Table S5) was found for Leccino Poreč ($d=0.92$), followed by Istarska Bjelica at Poreč and Frantoio Poreč. The worst agreement was found for Istarska Bjelica at Rovinj ($d=0.4$). Changing T_{base} indicates optimal $T_{\text{base}}=5^{\circ}\text{C}$ for Istarska Bjelica at Čepić and Poreč, Frantoio and Leccino at Poreč, while $T_{\text{base}}=7^{\circ}\text{C}$ is optimal for Istarska Bjelica, Buža and Pendolino at Pula.

The GDD model shows a poor fit for harvesting at most stations, as the agreement indices are below 0.55 for 63% of the data analysed. The only exception is the harvest data for all varieties at Poreč, where the agreement index exceeded 0.7, even reaching 0.9 for Istarska Bjelica. These less accurate results for harvest are likely also due to subjective harvesting criteria and inconsistent GDD accumulation by harvest date (Figure 2b), as explained earlier.

The presented GDD model for Istria has a strong potential for predicting the onset of flowering of olive crops. Similar results were obtained for four olive varieties in Italy using a comparable GDD model (Didevarasl et al. 2023). For all investigated varieties and locations studied here, the best fit during the flowering period was documented at $T_{\text{base}}=6^{\circ}\text{C}$, and the model robustly simulated Istarska Bjelica at all sites with the highest agreement index for all phenological stages. The use of the GDD model to determine the most suitable threshold temperature has been widely reported. For instance, in California, a threshold temperature interval of 10°C – 13°C was identified for olive trees grown in a greenhouse (Snyder et al. 1999). Alcalá and Barranco (1992) and Galán et al. (2001) determined a threshold of 12.5°C for the World Collection of Olive Cultivars in Córdoba, Spain. Orlandi et al. (2005) reported that most Spanish inland olive orchards exhibited threshold temperatures between 7°C and 9°C . The fact that Istria represents the northernmost region where olives are cultivated within the sub-Mediterranean bioclimatic zone may explain the lower threshold temperatures obtained in this study compared with the aforementioned works, a finding already noted by Galán et al. (2005).

Recent research using regional climate models indicates that the mean air temperature in the growing season (from April to October) in the period 2041–2070 in Istria will increase by 2°C – 2.25°C compared to the period 1971–2000, and that GDD (with a base temperature of 10) will increase by 500°C – 525°C units in the same period (Omazić et al. 2020). Therefore, this GDD model can serve as a useful tool for predicting flowering under future climate conditions, in order to make more effective management decisions. Still, one should be cautious on the use of the GDD model due to a higher-than-average temperature increase in the Mediterranean than globally (Giorgi 2006), which may induce plasticity and adaptability of some olive cultivars to different climatic conditions (Fornaciari et al. 2025; Tedeschini et al. 2025; Li et al. 2025). Further, beyond GDD, there is a possible influence of other meteorological parameters on later phenological stages (such as wind, precipitation, number of hot days, etc.), suggesting that advanced methods (such as machine learning) may be needed in the future to achieve accurate predictions throughout the entire growth cycle, in particular during later phenological stages such as fruit ripening and harvesting.

4 | Conclusions

In this study, we investigated thoroughly the effects of climate conditions over Istria on the phenological stages of olive cultivation. Furthermore, we tested a simple but reliable statistical model for future projections of GDD for each phenological stage. The main conclusions are as follows.

- i. *The rising minimum and maximum temperatures over Istria, particularly pronounced in spring, contributed to an increase in GDD in the growing season during the observed period and, consequently advancing the onset of phenological stages.* The onset of flowering showed a statistically significant trend, advancing by approximately 10 days per decade. In addition, the onset of fruit ripening has advanced by up to 20 days over the past decade, particularly for Leccino, Buža and Istarska Bjelica varieties, thereby shortening the overall growth period.
- ii. *The presented GDD model shows strong potential for predicting the onset of flowering under future climate conditions, providing valuable support for more effective management decisions.* Our statistical model performed best for the flowering period for Istarska Bjelica with the index of agreement up to 0.96. Overall, the index of agreement for the whole flowering period was 0.75. Adjusting the T_{base} revealed the optimal fit at 6°C for most locations and varieties over Istria.

Rising temperatures, changing precipitation patterns, and extreme weather events across the Mediterranean, driven by climate change, pose significant challenges, particularly if traditional soil management and olive cultivation practices are not adapted. However, as the northernmost region for olive cultivation, Croatia may be affected in two ways due to the olive's well-known ability to tolerate and adapt to varying environmental conditions. First, increasing temperatures may expand the potential cultivation range, especially in areas with favorable precipitation patterns. Second, the adoption of cultivars better suited to projected changes in temperature and water availability will be necessary to maintain productivity. The Intergovernmental Panel on Climate Change (IPCC) in its Sixth Assessment Report (AR6, IPCC 2022) has pointed out that adaptation challenges are likely to continue for the next generations. Therefore, as a next step to complement this study, we recommend investigating the sensitivity of olive cultivation to the projected climate changes, following a variety of high-resolution climate projection ensembles available through Euro-CORDEX and Med-CORDEX programmes (Jacob et al. 2014; Ruti et al. 2016).

Author Contributions

Andreina Belušić Vozila: conceptualization, data curation, formal analysis, investigation, methodology, software, validation, visualization, writing – original draft, writing – review and editing. **Branimir Omazić:** conceptualization, methodology, software, validation, visualization, writing – review and editing. **Maja Telišman Prtenjak:** conceptualization, supervision, writing – review and editing. **Marijan Bubola:** validation, writing – review and editing. **Marin Krapac:** validation, writing – review and editing. **Ivica Vilbić:** conceptualization, validation, writing – review and editing. **Smiljana Goreta Ban:** writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the Croatian Meteorological and Hydrological Service. Restrictions apply to the availability of these data, which were used under licence for this study. Data are available from the author(s) with the permission of the Croatian Meteorological and Hydrological Service.

References

- Aguilera, F., M. Fornaciari, L. Ruiz-Valenzuela, et al. 2015. "Phenological Models to Predict the Main Flowering Phases of Olive (*Olea europaea* L.) Along a Latitudinal and Longitudinal Gradient Across the Mediterranean Region." *International Journal of Biometeorology* 59: 629–641. <https://doi.org/10.1007/s00484-014-0876-7>.
- Aguilera, F., and L. R. Valenzuela. 2012. "Microclimatic-Induced Fluctuations in the Flower and Pollen Production Rate of Olive Trees (*Olea europaea* L.)." *Grana* 51: 228–239. <https://doi.org/10.1080/00173134.2012.659203>.
- Alcalá, A. R., and D. Barranco. 1992. "Prediction of Flowering Time in Olive for the Cordoba Olive Collection." *American Society for Horticultural Science* 27, no. 11: 1205–1207. <https://doi.org/10.21273/HORTSCI.27.11.1205>.
- Azpiroz, I., N. Osés, M. Quartulli, I. G. Olaizola, D. Guidotti, and S. Marchi. 2021. "Comparison of Climate Reanalysis and Remote-Sensing Data for Predicting Olive Phenology Through Machine-Learning Methods." *Remote Sensing* 13, no. 6: 1224. <https://doi.org/10.3390/rs13061224>.
- Bandelj, D., E. Bešter, M. Bučar-Miklavčič, et al. 2014. *Factsheet on the Olive Variety 'Istrska Belica'*, 16. Univerza na Primorskem, Znanstveno-raziskovalno središče.
- Barranco, D., A. Cimato, P. Fiorino, et al. 2000. *World Catalogue of Olive Varieties*. International Olive Oil Council.
- Belušić Vozila, A., D. Belušić, M. Telišman Prtenjak, et al. 2023. "Evaluation of the Near-Surface Wind Field Over the Adriatic Region: Local Wind Characteristics in the Convection-Permitting Model Ensemble." *Climate Dynamics* 62, no. 6: 4617–4634. <https://doi.org/10.1007/s00382-023-06703-z>.
- Belušić Vozila, A., I. Güttler, B. Ahrens, A. Obermann-Hellhund, and M. Telišman Prtenjak. 2019. "Wind Over the Adriatic Region in CORDEX Climate Change Scenarios." *JGR-Atmospheres* 36, no. 1: 110–130. <https://doi.org/10.1029/2018jd028552>.
- Benčić, Đ., and M. Krapac. 2009. "Influence of Olive Growing Location on the Quality of the Varieties 'Leccino' and 'Buža' Extra Virgin Olive Oil in Istria (In Croatian)." *Glasnik Zaštite Bilja* 32: 27–42. <https://hrcak.srce.hr/163469>.
- Bindi, M., and J. E. Olesen. 2011. "The Responses of Agriculture in Europe to Climate Change." *Regional Environmental Change* 11, no. Suppl 1: 151–158. <https://doi.org/10.1007/s10113-010-0173-x>.
- Bonofiglio, T., F. Orlandi, C. Sgromo, B. Romano, and M. Fornaciari. 2008. "Influence of Temperature and Rainfall on Timing of Olive (*Olea europaea*) Flowering in Southern Italy." *New Zealand Journal of Crop and Horticultural Science* 36, no. 1: 59–69. <https://doi.org/10.1080/01140670809510221>.
- Branković, Č., I. Güttler, and M. Gajić-Čapka. 2013. "Evaluating Climate Change at the Croatian Adriatic From Observations and Regional Climate Models' Simulations." *Climate Dynamics* 41, no. 9: 2353–2373. <https://doi.org/10.1007/s00382-012-1646-z>.
- Ceglar, A., M. Zampieri, A. Toreti, and F. Dentener. 2019. "Observed Northward Migration of Agro-Climatic Zones in Europe Will Further Accelerate Under Climate Change." *Earth's Future* 7, no. 9: 1088–1101. <https://doi.org/10.1029/2019EF001178>.
- Chacón-Maldonado, A. M., M. A. Molina-Cabanillas, A. Troncoso, F. Martínez-Álvarez, and G. Asencio-Cortés. 2022. "Olive Phenology Forecasting Using Information Fusion-Based Imbalanced Preprocessing and Automated Deep Learning." In *Hybrid Artificial Intelligent Systems. HAIS 2022. Lecture Notes in Computer Science*, edited by P. García Bringas et al., vol. 13469. Springer. https://doi.org/10.1007/978-3-031-15471-3_24.
- Charalampopoulos, I., I. Polychroni, E. Psomiadis, and P. Nastos. 2021. "Spatiotemporal Estimation of the Olive and Vine Cultivations' Growing Degree Days in the Balkans Region." *Atmosphere* 12: 148. <https://doi.org/10.3390/atmos12020148>.
- Di Paola, A., E. Di Giuseppe, A. P. Gutierrez, L. Ponti, and M. Pasqui. 2023. "Climate Stressors Modulate Interannual Olive Yield at Province Level in Italy: A Composite Index Approach to Support Crop Management." *Journal of Agronomy and Crop Science* 209: 475–488. <https://doi.org/10.1111/jac.12636>.
- Didevarasl, A., J. M. Costa Saura, D. Spano, et al. 2023. "Modeling Phenological Phases Across Olive Cultivars in the Mediterranean." *Plants* 12, no. 18: 3181. <https://doi.org/10.3390/plants12183181>.
- Didevarasl, A., J. M. Costa Saura, D. Spano, et al. 2025. "The Phenological Phases of Early and Mid-Late Budbreak Olive Cultivars in a Changing Future Climate Over the Euro-Mediterranean Region." *European Journal of Agronomy* 168: 127658. <https://doi.org/10.1016/j.eja.2025.127658>.
- Essert, S., I. Koncani-Uhač, M. Uhač, and R. Šoštarić. 2018. "Plant Remains and Amphorae From the Roman Harbour Under Flacius Street in Pula (Istria, Croatia)." *Archaeological and Anthropological Sciences* 10: 955–971. <https://doi.org/10.1007/s12520-016-0410-4>.
- Fornaciari, M., F. Orlandi, and E. Tedeschini. 2025. "Long-Term Analysis on Olive Flowering and Climatic Relationships in Central Italy." *European Journal of Agronomy* 162: 127435. <https://doi.org/10.1016/j.eja.2025.127435>.
- Fraga, H., M. Moriondo, L. Leolini, and J. A. Santos. 2020. "Mediterranean Olive Orchards Under Climate Change: A Review of Future Impacts and Adaptation Strategies." *Agronomy* 11: 56. <https://doi.org/10.3390/agronomy11010056>.
- Fraga, H., J. G. Pinto, and J. A. Santos. 2019. "Climate Change Projections for Chilling and Heat Forcing Conditions in European Vineyards and Olive Orchards: A Multi-Model Assessment." *Climatic Change* 152: 179–193. <https://doi.org/10.1007/s10584-018-2337-5>.
- Fraga, H., J. G. Pinto, F. Viola, and J. A. Santos. 2020. "Climate Change Projections for Olive Yields in the Mediterranean Basin." *International Journal of Climatology* 40: 769–781. <https://doi.org/10.1002/joc.6237>.
- Galán, C., H. García-Mozo, P. Cariñanos, P. Alcázar, and E. Domínguez-Vilches. 2001. "The Role of Temperature in the Onset of the *Olea europaea* L. Pollen Season in Southwestern Spain." *International Journal of Biometeorology* 45, no. 1: 8–12. <https://doi.org/10.1007/s004840000081>.

- Galán, C., H. García-Mozo, L. Vázquez, L. Ruiz-Valenzuela, C. Díaz de la Guardia, and M. Trigo-Pérez. 2005. "Heat Requirement for the Onset of the *Olea europaea* L. Pollen Season in Several Places of Andalusia Region and the Effect of the Expected Future Climate Change." *International Journal of Biometeorology* 49, no. 3: 184–188. <https://doi.org/10.1007/s00484-004-0223-5>.
- Galán, C., L. Vázquez, H. García-Mozo, and E. Domínguez. 2004. "Forecasting Olive (*Olea europaea*) Crop Yield Based on Pollen Emission." *Field Crops Research* 86, no. 1: 43–51. <https://doi.org/10.1016/j.fcr.2003.10.009>.
- García de Cortázar-Atauri, I., N. Brisson, and J. P. Gaudillere. 2009. "Performance of Several Models for Predicting Budburst Date of Grapevine (*Vitis vinifera* L.)." *International Journal of Biometeorology* 53, no. 4: 317–326. <https://doi.org/10.1007/s00484-009-0217-4>.
- García-Mozo, H., F. Orlandi, C. Galán, et al. 2009. "Olive Flowering Phenology Variation Between Different Cultivars in Spain and Italy: Modeling Analysis." *Theoretical and Applied Climatology* 95: 385–395. <https://doi.org/10.1007/s00704-008-0016-6>.
- Garrido, A., M. Fernández-González, S. Álvarez-López, E. González-Fernández, and F. J. Rodríguez-Rajo First. 2020. "First Phenological and Aerobiological Assessment of Olive Orchards at the Northern Limit of the Mediterranean Bioclimatic Area." *Aerobiologia* 36: 641–656. <https://doi.org/10.1007/s10453-020-09659-3>.
- Giorgi, F. 2006. "Climate Change Hot-Spots." *Geophysical Research Letters* 33: L08707. <https://doi.org/10.1029/2006GL025734>.
- Haworth, M., G. Marino, C. Brunetti, D. Killi, A. De Carlo, and M. Centritto. 2018. "The Impact of Heat Stress and Water Deficit on the Photosynthetic and Stomatal Physiology of Olive (*Olea europaea* L.)—A Case Study of the 2017 Heat Wave." *Plants (Basel)* 7, no. 4: 76. <https://doi.org/10.3390/plants7040076>.
- IPCC. 2022. *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by H. O. Pörtner, D. C. Roberts, M. Tignor, et al. 3056. Cambridge University Press. <https://doi.org/10.1017/9781009325844>.
- Jacob, D., J. Petersen, B. Eggert, et al. 2014. "EURO-CORDEX: New High-Resolution Climate Change Projections for European Impact Research." *Regional Environmental Change* 14: 563–578. <https://doi.org/10.1007/s10113-013-0499-2>.
- Jelović, D. 2015. *Vremenska dinamika cvatnje I dozrijevanja plodova masline u maslinicima hrvatskog mediteranskog podneblja*, 25. Završni rad, Agronomski fakultet, Sveučilište u Zagrebu.
- Knežević, M., L. Životić, V. Perović, A. Topalović, and M. Todorović. 2017. "Impact of Climate Change on Olive Growth Suitability, Water Requirements and Yield in Montenegro." *Italian Journal of Agrometeorology* 2: 39–52. <https://doi.org/10.19199/2017.2.2038-5625.039>.
- Krapac, M., and B. Sladonja. 2010. "Fenofaze masline." *Glasnik Zaštite Bilja* 33, no. 5: 56–66. <https://hrcak.srce.hr/163343>.
- Li, J. H., D. X. Jia, Z. Y. Zhou, J. C. Du, Q. G. Xiao, and M. R. Cao. 2025. "Stability Analysis and Multi-Trait Selection of Flowering Phenology Parameters in Olive Cultivars Under Multi-Environment Trials." *Plants* 14: 1906. <https://doi.org/10.3390/plants14131906>.
- Miličević, M., K. Zubrinčić, I. Grbavac, and I. Obradović. 2020. "Application of Deep Learning Architectures for Accurate Detection of Olive Tree Flowering Phenophase." *Remote Sensing* 12, no. 13: 2120. <https://doi.org/10.3390/rs12132120>.
- Moriondo, M., and M. Bindi. 2007. "Impact of Climate Change on the Phenology of Typical Mediterranean Crops." *Italian Journal of Agrometeorology* 3: 5–12.
- Mycking, T. 1997. "Dormancy, Budburst and Impacts of Climate Warming in Coastal-Inland and Altitudinal *Betula pendula* and *B. pubescens* Ecotypes." In *Phenology and Seasonal Climates I*, 51–66. Backhuys Publishers.
- Omazić, B., M. Telišman Prtenjak, M. Bubola, J. Meštrić, M. Karoglan, and I. Prša. 2023. "Application of Statistical Models in the Detection of Grapevine Phenology Changes." *Agricultural and Forest Meteorology* 341: 109682. <https://doi.org/10.1016/j.agrformet.2023.109682>.
- Omazić, B., M. Telišman Prtenjak, I. Prša, et al. 2020. "Climate Change Impacts on Viticulture in Croatia: Viticultural Zoning and Future Potential." *International Journal of Climatology* 40, no. 13: 5634–5655. <https://doi.org/10.1002/joc.6541>.
- Orlandi, F., E. Avolio, T. Bonofiglio, S. Federico, B. Romano, and M. Fornaciari. 2013. "Potential Shifts in Olive Flowering According to Climate Variations in Southern Italy." *Meteorological Applications* 20: 497–503. <https://doi.org/10.1002/met.1318>.
- Orlandi, F., H. Garcia-Mozo, A. B. Dhiab, C. Galán, M. Msallem, and M. Fornaciari. 2014. "Olive Tree Phenology and Climate Variations in the Mediterranean Area Over the Last Two Decades." *Theoretical and Applied Climatology* 115: 207–218. <https://doi.org/10.1007/s00704-013-0892-2>.
- Orlandi, F., C. Sgromo, T. Bonofiglio, L. Ruga, B. Romano, and M. Fornaciari. 2009. "A Comparison Among Olive Flowering Trends in Different Mediterranean Areas (South-Central Italy) in Relation to Meteorological Variations." *Theoretical and Applied Climatology* 97, no. 3–4: 339–347. <https://doi.org/10.1007/s00704-008-0079-4>.
- Orlandi, F., L. M. Vazquez, L. Ruga, et al. 2005. "Bioclimatic Requirements for Olive Flowering in Two Mediterranean Regions Located at the Same Latitude (Andalusia, Spain and Sicily, Italy)." *Annals of Agricultural and Environmental Medicine* 12, no. 1: 47–52.
- Osborne, C. P., I. Chuine, D. Viner, and F. I. Woodward. 2000. "Olive Phenology as a Sensitive Indicator of Future Climatic Warming in the Mediterranean." *Plant, Cell & Environment* 23: 701–710. <https://doi.org/10.1046/j.1365-3040.2000.00584.x>.
- Oses, N., I. Azpiroz, M. Quartulli, I. Olairola, S. March, and D. Guidotti. 2020. "Machine Learning for Olive Phenology Prediction and Base Temperature Optimisation." *Global Internet of Things Summit (GIoTS), Dublin, Ireland 2020*: 1–6. <https://doi.org/10.1109/GIOTS49054.2020.9119611>.
- Paparrizos, S., and A. Matzarakis. 2017. "Present and Future Responses of Growing Degree Days for Crete Island in Greece." *Advances in Science and Research* 14: 1–5. <https://doi.org/10.5194/asr-14-1-2017>.
- Patarčić, M., M. Gajić-Čapka, K. Cindrić, and Č. Branković. 2014. "Recent and Near-Future Changes in Precipitation Extreme Indices Over the Croatian Adriatic Coast." *Climate Research* 61: 157–176. <https://doi.org/10.3354/cr01250>.
- Pérez-López, D., F. Ribas, A. Moriana, H. Rapoport, and A. Juan. 2008. "Influence of Temperature on the Growth and Development of Olive (*Olea europaea* L.) Trees." *Journal of Horticultural Science and Biotechnology* 83: 171–176. <https://doi.org/10.1080/14620316.2008.11512366>.
- Radilović, S., D. Koračin, C. Denamiel, D. Belušić, I. Güttler, and I. Vilibić. 2020. "Simulated and Observed Air Temperature Trends in the Eastern Adriatic." *Atmospheric Science Letters* 21: e951. <https://doi.org/10.1002/asl.951>.
- Ruti, P., S. Somot, F. Giorgi, et al. 2016. "Med-CORDEX Initiative for Mediterranean Climate Studies." *Bulletin of the American Meteorological Society* 97: 1187–1208. <https://doi.org/10.1175/BAMS-D-14-00176.1>.
- Silveira, C., A. Almeida, and A. C. Ribeiro. 2023. "How Can a Changing Climate Influence the Productivity of Traditional Olive Orchards? Regression Analysis Applied to a Local Case Study in Portugal." *Climate* 11: 123. <https://doi.org/10.3390/cli11060123>.
- Šimunić, I., T. Likso, S. Husnjak, and M. Bubalo Kovačić. 2021. "Analysis of Climate Elements in Central and Western Istria for the

Purpose of Determining Irrigation Requirements of Agricultural Crops.” *Agriculturae Conspectus Scientificus* 86: 225–233.

Snyder, R. L., D. Spano, C. Cesaraccio, and P. Duce. 1999. “Determining Degree-Day Thresholds From Field Observations.” *International Journal of Biometeorology* 42, no. 4: 177–182. <https://doi.org/10.1007/s004840050102>.

Šoštarić, R., and H. Küster. 2001. “Roman Plant Remains From Veli Brijun (Island of Brioni), Croatia.” *Vegetation History and Archaeobotany* 10: 227–233. <https://doi.org/10.1007/PL00006934>.

Sviličić, P., V. Vučetić, S. Filić, and A. Smolić. 2015. “Soil Temperature Regime and Vulnerability due to Extreme Soil Temperatures in Croatia.” *Theoretical and Applied Climatology* 126: 247–263. <https://doi.org/10.1007/s00704-015-1558-z>.

Tanasijević, L., M. Todorović, L. S. Pereira, C. Pizzigalli, and P. Lionello. 2014. “Impacts of Climate Change on Olive Crop Evapotranspiration and Irrigation Requirements in the Mediterranean Region.” *Agricultural Water Management* 144: 54–68. <https://doi.org/10.1016/j.agwat.2014.05.019>.

Tedeschini, E., F. Orlandi, and M. Fornaciari. 2025. “Exploring Reproductive Timing in Olive Tree: Male Meiosis and Anthesis Events.” *Plants* 14: 2522. <https://doi.org/10.3390/plants14162522>.

Tojčić, I., C. Denamiel, and I. Vilibić. 2024. “Kilometer-Scale Trends, Variability, and Extremes of the Adriatic Far-Future Climate (RCP 8.5, 2070–2100).” *Frontiers in Marine Science* 11: 1329020. <https://doi.org/10.3389/fmars.2024.1329020>.

Vučetić, V., and M. Vučetić. 2005. “Variations of Phenological Stages of Olive-Trees Along the Adriatic Coast.” *Periodicum Biologorum* 107: 335–340.

Vuletin Selak, G., S. Goreta Ban, and S. Perica. 2018. “Onset of Flowering in Olive Cultivars in Relation to Temperature.” *Acta Horticulturae* 1229: 127–134. <https://doi.org/10.17660/ActaHortic.2018.1229.20>.

Vuletin Selak, G., S. Goreta Ban, and S. Perica. 2019. “The Effect of Temperature on Olive Pollen Germination.” *Acta Horticulturae* 1231: 49–54. <https://doi.org/10.17660/ActaHortic.2019.1231.9>.

Willmott, C. J., S. M. Robeson, and K. Matsuura. 2012. “A Refined Index of Model Performance.” *International Journal of Climatology* 32: 2088–2094. <https://doi.org/10.1002/joc.2419>.

Zouari, I., A. Mezghani, and F. Labidi. 2017. “Flowering and Heat Requirements of Four Olive Cultivars Grown in the South of Tunisia.” *Acta Horticulturae* 1160: 231–236. <https://doi.org/10.17660/ActaHortic.2017.1160.34>.

Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** Supporting Information.