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Impact of Climate Change on the Development of Viticulture in Central Poland: Autoregression Modeling SAT Indicator

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Abstract: Ongoing climate change is having a profound impact on agriculture, which is attracting attention from the scientific community. One of its effects is an increase in average temperature, which is a key factor in grape cultivation. This may increase the popularity of viticulture in central Europe. The aim of this study was to assess the potential for the development of viticulture in central Poland based on SAT changes from 1975 to 2021, in addition to changes in evapotranspiration, occurrence of late spring and early autumn frosts and frosty days in selected years from this period as an important factors relating to climate change. The research utilized data obtained from the Institute of Meteorology and Water Management—National Research Institute. The Bai–Perron test was used to determine the direction of temperature changes. An AR(1) autoregression model was used to predict SAT changes in central Poland for the years 2022–2026, based on the results of the Bai–Perron test. As part of the in-depth research on the SAT index, reference evapotranspiration calculations were also made as a second factor that is considered an important indicator of climate change. The Sum of Active Temperatures from 1975 to 2021 in the provinces of central Poland showed an increasing trend of 0.07% per year. The average SAT in central Poland in 2022–2026 is expected to range from 2700 °C to 2760 °C. Considering the current thermal conditions in central Poland and the forecasts for the coming years, it can be expected that vineyard cultivation will develop in this region. However, the research shows that the observed increasing trend in evapotranspiration, both in total in individual years and in the period of the greatest vegetation, i.e., in the months from May to the end of August, will result in an increasing need in central Poland to ensure adequate irrigation in developing vineyards.

Keywords: climate changes; viticulture; sum of active temperature; evapotranspiration

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1. Introduction

Adverse climate change is one of the most significant environmental, social, and economic threats worldwide. It affects many sectors of the economy, including agriculture, horticulture, forestry, as well as human health and quality of life [1–4]. The interest in this issue has led to numerous studies over the past decade focusing on climate change and its impact on agricultural and horticultural crops [5–7]. The major effects of these changes include increased frequency of extreme weather events such as intense storms, precipitation, and droughts [8,9]. According to the report by Houghton [10], the earth's climate has warmed by 0.3 °C to 0.6 °C over the last 100 years. Jones [11] already noted a significant warming trend, especially from 1925 to 1997. The Intergovernmental Panel on

Climate Change (2014)—a scientific and intergovernmental advisory body at the request of UN members, set up by two United Nations organizations, the World Meteorological Organization and the United Nations Environment Program—reported that each of the three decades from 1980 to 2010 was warmer than the previous one, with the last decade being the warmest. According to the Annual Climate Report by NOAA [12], the combined land and ocean temperature has been increasing at an average rate of 0.08 °C per decade since 1880, but the rate of increase has doubled to 0.18 °C per decade since 1981. Over the next 25 years, it is expected that winter temperatures (December–February) will rise by 1.7–4.6 °C in southern Europe and the Mediterranean Basin, while in northern Europe, the increase may reach 2.6–8.2 °C depending on model projections [13]. For example, research by Rojo [14] highlighted the most noticeable climate change in Bavaria, Germany, as an increase in temperature, especially in spring. Summers and other months throughout the year were warmer, while increased temperature variability indicated a shift towards a more continental climate in the region. On the other hand, Mate [15] noted that the Netherlands stands out with a low climate change risk due to geothermal and hydroelectric energy, abundant agricultural land, and low population density.

Grapes are one of the oldest and most widely cultivated plants in the world. As a result, climate change significantly affects viticulture. Climate is also a major factor influencing wine production [16]. Among environmental factors, it has the greatest impact on grapevine development and fruit composition compared to soil and grape variety [17]. Air temperature is considered the most important factor driving the growth and development of grapevines, in cases where the water, radiation, and nutritional requirements of the plant are met [18,19]. The influence of air temperature on berry composition is interesting from a biological perspective and has practical implications for wine properties [20]. During the growing season, grapevines undergo continuous changes in morphology and physiology [21]. The phenological phases of grapevines, such as bud break, flowering, or onset of ripening, depend primarily on temperature. The relationship is so strong that grapevine phenology can be predicted using models based solely on temperature [22]. During fruit ripening, the sugar and phenolic content are supported by the occurrence of sunny days [23]. Air temperature rise affects grape yield and composition, and consequently, the sensory properties of wine [24–26]. Higher temperatures increase the plant's metabolic rate and influence the accumulation of metabolites, thus affecting progress in key phenological phases [27]. Based on observations of the relationship between climate and phenological requirements for high-quality wine production in benchmark regions worldwide, the 'Syrah' variety may not be adapted to average growing season temperatures above 19 °C (±0.6 °C) [28]. Average monthly temperatures above 22 °C may be detrimental to taste and pigment in dry red wines [19], while daily maximums above 35 °C increase the risk of berry sunburn and photosynthesis inhibition [29].

According to research by Maciejewska et al. [30], vine cultivation in Poland is becoming increasingly popular and characterized by dynamic development. Viticulture is expanding not only in the southern provinces of Poland but also in the central regions. As noted by Lisek [31], one of the primary reasons for the growing interest in vine cultivation in central Poland is observed climate change, manifesting in milder winters and, most importantly, rising average temperatures during the growing season. Regarding viticulture, one of the essential indicators determining the suitability of vine cultivation in a particular area is the SAT index [32]. It is defined as the sum of daily average temperatures during the growing season equal to or exceeding 10 °C, recorded from April 1st to October 31st [11]. Currently, as in the past, climate is clearly a ubiquitous factor for the success of all crops, determining the type and quality of crops in a given region, and driving sustainable economic development [33]. At the same time, global warming in the case of grape cultivation may result in the shifting of known production regions beyond the areas currently designated for grape cultivation and processing [34–37]. Research conducted by Droulia et al. [37] has shown that many wine-producing regions worldwide are currently at or near the ideal climate for the respective grape varieties. According to Maciejczak et al. [38], it is important to understand how weather and climate changes can impact the development of the grape cultivation sector in the Polish context. Statistically, Polish winters are becoming warmer, arriving late and ending quickly, while the growing season is lengthening [39]. Lisek [31] pointed out that the average annual temperature in Poland has shown an increasing trend in recent decades (approximately 0.5 °C per decade), transitional periods have shortened, warm periods have lengthened, and winter has become milder, enabling the cultivation of many grape varieties. Over the next 100 years, average annual temperatures in Poland could increase by as much as 2–4 °C [40]. Warmer seasons are becoming longer, starting earlier. The period of thermal winter is shortening, starting earlier and characterized by milder conditions [41]. Winter temperatures exceeding 0 °C will result in a lack of snow cover, and temperature and precipitation changes will pose challenges for agriculture in maintaining agricultural crops [42]. Additionally, according to Koźmiński et al. [43], a dynamic increase in air temperatures over the area of Poland has been observed, especially after 1987. Climate change also has a complex impact on the cultivation of agricultural and fruit crops in Europe, by changing the dynamics and frequency of spring and autumn frosts. Frosts cause damage to buds and young shoots, thus disturbing the phenological processes taking place in plants. In the case of vines, research on the Pinot Noir variety has shown that spring frosts can damage buds and young shoots, stimulating the growth of the so-called water shoots. This primarily results in a reduction in the number of fruits and a delay in growth stages [44]. Warmer winters accelerate the awakening of vines from dormancy, which leads to earlier bud swelling. However, this earlier awakening increases the susceptibility of grapevine crops to later spring frosts, potentially causing significant damage to production. Analyses forecasting climate change for southwest England show that, despite the expected benefits of higher temperatures during the growing season, the risk of unfavorable weather conditions such as spring frosts may increase. If bud swelling occurs earlier, it makes the vines more vulnerable to low temperatures [45].

The main objective of this study was to assess the potential for the development of viticulture in central Poland based on SAT changes from 1975 to 2021. An additional objective was to study changes in evapotranspiration, as well as the frequency of frost days and temperatures during their occurrence in the late spring and early autumn months, as important factors relating to climate change. The research was carried out for the same area and period.

2. Materials and Methods

2.1. Research Area

According to the Polish NUTS macro-regions classification until 2016, the central part of Poland included the Mazovian and Łódź voivodeships. However, after the classification change in 2017, the Świętokrzyskie Voivodeship was included in the central region, while the Mazovian macro-region was identified as a separate region [46]. Therefore, to analyze the period from 1975 to 2021, the central part of Poland, in this case, consists of three voivodeships: Świętokrzyskie, Mazovian, and Łódź.

According to Council Regulation (EC) No 2165/2005 of 20 December 2005, amending Council Regulation (EC) No 1493/1999 on the common organization of the market in wine (Official Journal of the European Union L 345, 28 December 2005), the aforementioned voivodeships of central Poland are part of Region II, where commercial grape cultivation for wine production is permitted. The Mazovian Voivodeship is not only the largest among the three analyzed regions but also the largest in all of Poland in terms of both area and population [47]. It is located in the central-eastern part of Poland, characterized predominantly by lowland landscapes. The most characteristic feature of the terrain is river valleys, including the Vistula, Narew, Bug, and Pilica rivers [48]. The climate in the Mazovian Voivodeship is classified as warm temperate, transitioning between humid and continental [49]. The average annual temperature in the region is around 7.5 °C. Average precipitation ranges from 450 to 600 mm, with most areas receiving less than 550 mm [50].

The Łódź Voivodeship is also located in the central part of Poland [51]. The region belongs to a transitional zone between the highlands of southern Poland and the central Polish lowlands [52]. The climate in the voivodeship is transitional, influenced by a combination of continental and oceanic climate zones, as well as the Baltic Sea, mountains, and uplands. It is characterized by temporal variability of meteorological elements and low spatial differentiation. The exception is precipitation, with annual sums ranging from 500 mm in the north-eastern part to 650 mm in the region of the Łódź Hills. This is influenced by the topography and the proximity of the city of Łódź, which acts as a source of water vapor condensation nuclei. Average temperatures range from 7.6 to 8.0 °C [53].

The Świętokrzyskie Voivodeship, on the other hand, is located in the central-eastern part of Poland. The climate in the region is quite diverse and exhibits characteristics of a temperate climate [54]. The mountainous part of the region has a cool climate with average annual temperatures below 7 °C, while the southern part is warmer, with average annual temperatures around 8 °C. Precipitation reaches up to 800 mm in the Świętokrzyskie Mountains, while in the south, it is significantly lower, around 550 mm [55].

2.2. Collection and Preparation of Data and Analytical Methods Used

The analyses in this study were conducted based on data obtained from the Institute of Meteorology and Water Management (IMiGW)—the State Research Institute. The data were obtained from the archives available on the website of the Institute of Meteorology and Water Management. The Institute was established in 1919 and conducts observations, measurements, research, development, and implementation works throughout Poland. A total of 94.4 thousand meteorological data points were obtained, from which 392 data points were selected for calculating the SAT and reference evapotranspiration from 1975 to 2021. The data points were collected from three meteorological stations located in the respective voivodeships of central Poland. The station Łódź-Lublinek represented the Łódź Voivodeship, the station Warszawa-Ochota represented the Mazovian Voivodeship, and the station Sandomierz represented the Świętokrzyskie Voivodeship (Figure 1). The selected time range was determined based on the availability of complete time series from all stations. The authors are aware that individual meteorological stations may not be representative due to local anthropogenic impacts, especially the effects of urbanization, which could have played an important role in the increasing temperature trend throughout the voivodeship. However, it should be emphasized that the aim of the research was not to determine the SAT value in detail, but rather to demonstrate the general level and direction of changes in this indicator. Similar assumptions apply to analyses regarding evapotranspiration.

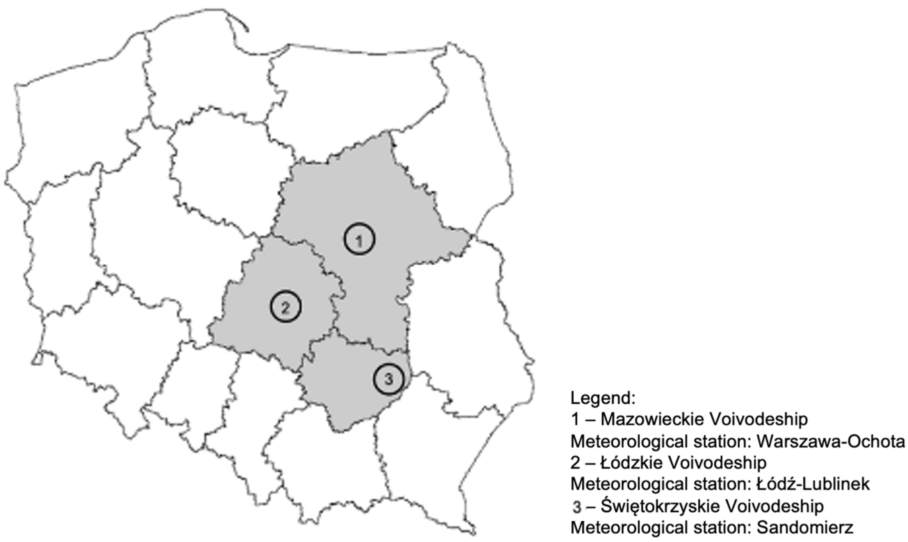

Figure 1. Distribution of meteorological stations in central Poland.

2.3. Sum of Active Temperatures

As indicated above, the SAT index is one of the most important indicators determining the potential for wine production in a given area. Therefore, based on the collected meteorological data from all three meteorological stations, the average daily temperatures during the growing season equal to or higher than 10 °C were extracted and summed. The growing season period considered for calculation was from 1 April to 31 October, according to the following formula:

$$SAT = \sum_{1.04}^{31.10} \frac{T_{max} + T_{min}}{2} \quad \text{for} \quad \frac{T_{max} + T_{min}}{2} \geq 10\ ^{\circ}C$$

where:

SAT—Sum of Active Temperatures
T_{max}—Maximum temperature during the growing season.
T_{min}—Minimum temperature during the growing season.

The value of the SAT is also an important criterion in the selection of grapevine varieties in a specific location. Each variety has specific climatic requirements, which are expressed through this indicator, necessary for achieving full grape maturity [56]. There are other bioclimatic indices used to assess the cultivation possibilities of specific grapevine varieties in a given location, such as SAT. However, in Poland, grapevine varieties are most commonly characterized in terms of their required SAT and the potential for cultivation and obtaining high-quality fruits. For very early and early varieties, this indicator ranges from 2000 °C to 2500 °C, for mid-early varieties from 2500 °C to 2700 °C, for mid-late varieties from 2700 °C to 2900 °C, and for late varieties above 2900 °C [57]. The most commonly cultivated varieties in central Poland are ‘Seyval Blanc’, ‘Solaris’, and ‘Riesling’. The share of the ‘Seyval Blanc’ variety in all grapevine plantings ranged from 12.2% in the Świętokrzyskie Voivodeship to 28.9% in the Łódź Voivodeship (see Table 1). Meanwhile, for the ‘Solaris’ variety, it ranged from 11.3% in the Świętokrzyskie Voivodeship to 15.6% in the Mazowieckie Voivodeship. These are interspecific hybrids mainly of German origin, adapted to the cultivation conditions of central Europe, which have a low Sum of Active Temperatures (SAT) [58,59].

Table 1. The most popular grapevine varieties cultivated in central Poland in the agricultural year 2022 [58,59].

Variety	SAT (°C)	Percentage Share in Vineyards in the Voivodeship		
		Łódzkie	Mazowieckie	Świętokrzyskie
‘Seyval Blanc’	2550–2650	28.9	7.6	12.2
‘Solaris’	2200–2350	12.9	15.6	11.3
‘Riesling’	2869	-	6.9	6.7
‘Cabernet Cortis’	2600	-	7.2	-
‘Johanniter’	2650	-	6.8	-
‘Chardonnay’	2700–2800	-	-	7.4
‘Muscaris’	2650–2700	-	-	7.1
‘Regent’	2400–2500	8.8	-	-
‘Leon Millot’	2440	7.2	-	-
Other varieties	-	36.1	56.0	55.3

2.4. Bai–Perron Multiple Structural Break Analysis and Autoregressive Model

A long-term preliminary analysis of the SAT showed an increasing trend in Poland from 1975 to 2021. It is worth noting that the levels of the SAT were much lower in the earlier years of the analyzed period compared to the later years. Therefore, forecasting the SAT for the coming years, which was also the aim of the study, may have some degree of uncertainty. It was decided to statistically examine whether distinct periods can be identified and to determine breakpoints characterized by higher SAT levels that could be used to forecast future years. These periods were selected based on trends in the annual SAT, using the Bai–Perron multiple structural break analysis [60]. As indicated by Borkowski et al. [60], the Bai–Perron test aims to jointly estimate unknown regression coefficients and turning points. This formula is based on the following multiple linear regression model with k breakpoints estimated using the least squares method [60]:

$$y_t = \acute{x}_t\beta + \acute{z}_t\delta_j + u_t t = T_{j-1} + 1, \ldots, T_j$$

where y_t is the observed dependent variable; both x_t and z_t are covariate vectors with dimensions of $p \times 1$ and $q \times 1$, respectively; β and δ_j are coefficient vectors; $T_1, \ldots, T_k$ are unknown breakpoints; and it is the error term [60].

It is worth noting that the aforementioned Bai–Perron test is rarely applied in research, and although it is advanced, it is valuable to use it for time series analysis, even in areas such as horticultural production and its development. Based on the aforementioned test, one breakpoint was determined, and a subperiod was identified, which served as the basis for making forecasts regarding the changes in the SAT in central Poland for the years 2022–2026. An autoregressive model AR(1) was applied in the analysis. Models of this type stem from a broader class of regression models and find wide application in modeling economic processes, as many phenomena depend on their past states. In an autoregressive model, the current value of the variable is expressed by a finite combination of its previous values [61].

$$y_t = c + \theta y_{t-1} + \varepsilon_t$$

where:

y_t—the forecasted variable for the period.
c—time constant.
θy_{t-1}—time varying/number of observations.
ε_t—residue process.

The following formula was used to calculate the expectations and variances of the process:

$$E(y)_t = E(c) + \theta E(y_{t-1}) + E(\varepsilon_t)$$

$$\mathrm{var}(y_t) = E(y_{t^2}) - u^2 = \frac{\sigma_\varepsilon^2}{1-\theta^2}$$

where:

According to the AR(1) model, the variable y at time t was equal to a constant c plus the variable at time t-1 multiplied by the coefficient, plus an error term.

2.5. Reference Evapotranspiration—Optimized Hargreaves Formula

As part of the in-depth research on the SAT index, reference evapotranspiration was also calculated as a second factor, considered an important indicator of climate change. Reference evapotranspiration (Eto) refers to the amount of water evaporated from plant species grown at low altitudes when sufficient absorbent water is available [62]. This indicator is considered a climatic parameter and can be estimated based on weather data [62]. The optimized Hargreaves formula for Poland was used for calculations [63]. This formula has been shown to be adapted to local climatic conditions [64]:

$$ET_0 = 0.408 \cdot 0.001 \cdot (T_a + 17.0)(T_{max} - T_{min})^{0.724} \cdot R_a$$

where:

T_a—average daily temperature.
T_{max}—maximum daily temperature.
T_{min}—minimum daily temperature.
R_a—radiation at the upper limit of the atmosphere (determined by date).

For calculations according to the optimized Hargreaves formula for Poland, the Ra index was calculated according to the following formula [64]:

$$R_a = \frac{1440}{\pi} G_{sc} d_r [\omega_s \sin(\varphi) \sin(\delta) + \cos(\varphi) \cos(\delta) \sin(\omega_s)]$$

where:

G_{sc}—solar constant = 0.0820 [MJ $m^{-2}min^{-1}$].
d_r—inverse of the relative Earth-Sun distance.
ω_s—sunset hour angle.
ϕ—latitude [rad].
δ—solar declination.

The inverse of the relative Earth–Sun distance

$$d_r = 1 + 0.033 \cos\left(\frac{2\pi}{365} J\right)$$

where:

J—it is the number of the day between 1 (1 January) and 365 or 366 (31 December).

Hourly sunset angle

$$\omega_s = \arccos[-\tan(\varphi)\tan(\delta)]$$

where:

ϕ—latitude [rad].
δ—solar declination.

$$\delta = 0.409 \sin\left(\frac{2\pi}{365} J - 1.39\right)$$

where:

J—it is the number of the day between 1 (1 January) and 365 or 366 (31 December).

2.6. Occurrence of Frosty Days and Frosts in Late Spring and Early Autumn

The research methodology for analyzing the scale of occurrence of frost days and frosty days in central Poland in the years 1975–2021 was based on temperature data obtained from the database of the Institute of Meteorology and Water Management (IMIGW). Frost days were defined under the IMIGW methodology as days in which the minimum temperature was below 0 °C at a height of 5 cm above the ground surface (tmin < 0 °C), while at a height of 2 m the minimum temperature was above 0 °C (tmin > 0 °C). Frosty days were defined as days in which the maximum temperature at a height of 2 m above ground level was lower than or equal to 0 °C and higher or equal to −10 °C (−10 °C ≤ tmax ≤ 0 °C). For each station and each year, the total number of days with ground frost and frosty days was calculated separately for April, May, September, and October. These are the months when, in Poland, frosts and frosty days can cause the most damage to vineyards. It is generally assumed that in this moderate climatic zone, frosts and frosty days should not occur in the months from June to the end of August. Linear regression was used to analyze trends.

3. Results

As mentioned earlier, when analyzing the possibilities of grape cultivation in central Poland, climate change, specifically the SAT over a long-term period, needs to be taken into account. From the perspective of predicting changes in this indicator in the coming years, including its levels from several decades ago may negatively impact the assessment of grape cultivation possibilities. The analysis conducted revealed that the average SAT in the central Polish voivodeships in 2021 was 2702 °C, and despite the long research period, it differed only slightly from 1975, being lower by 4.89%. However, this was due to the relatively high values of this indicator recorded in 1975, which significantly decreased in subsequent years. Overall, there was an increasing trend observed between 1975 and 2021, supported by an average growth rate of 0.07% per year. However, it is worth noting that there was significant variability in the analyzed indicator throughout the entire period. It is worth mentioning that since the second half of the 1990s, SAT values started to stabilize at a higher level than in previous years. On the other hand, the forecasted values based on the original data suggest that using the entire analyzed period for SAT predictions in the coming years would result in lower forecasted values. The predicted autoregressive function values calculated for the years 2022–2032, based on the data from 1975–2021, are practically lower than those in the decade of 2010–2020, which may lead to inaccurate estimations (Figure 2). For example, the SAT in the years 2022–2026 could range from 2666.7 °C to 2693.25 °C, whereas in the years 2010–2020, it ranged from 2702.4 °C to 3226.4 °C. Therefore, it is necessary to determine a shorter sub-period that could serve as a basis for further forecasts. The analysis conducted on the indicator of the SAT showed an increasing trend in central Poland from 1975 to 2021, which is a positive phenomenon indicating the potential for grapevine cultivation in regions not commonly associated with this crop, such as central Poland.

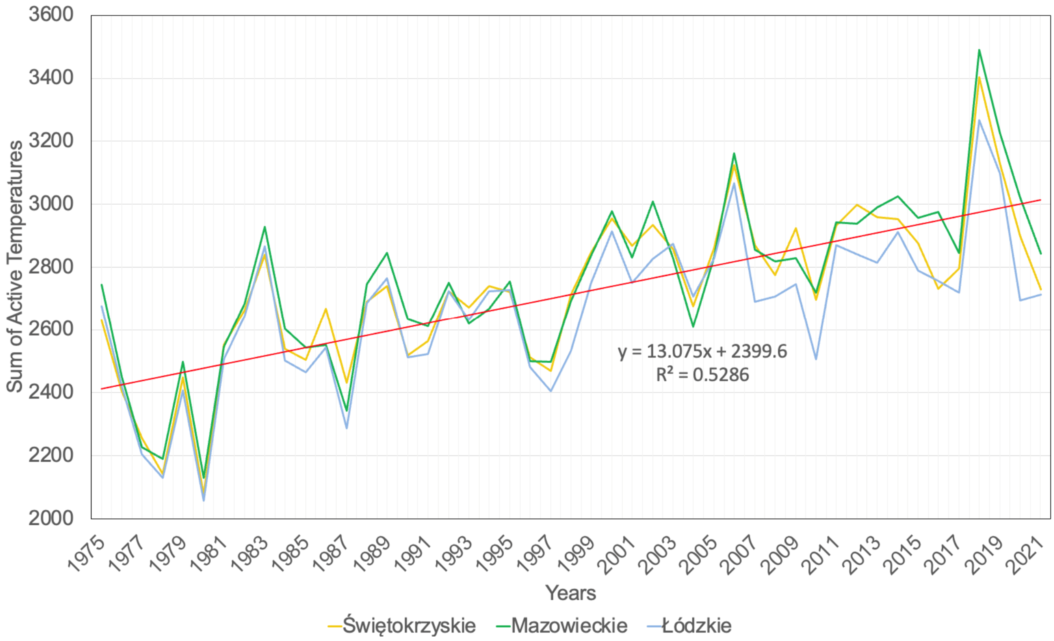

Figure 2. The Sum of Active Temperatures in central Poland from 1975 to 2021.

Therefore, the Bai–Perron test was conducted to determine the breakpoints at which the levels of SAT significantly differed from each other from 1975 to 2021. The Bai–Perron test allowed the identification of one breakpoint for the exogenous variable—SAT. Consequently, the period was divided into two subperiods, namely, 1975–1997 and 1998–2021 (Figure 3). The analysis conducted using the Bai–Perron test revealed significant temperature variations between the examined subperiods. The first subperiod from 1975 to 1997 was characterized by a low Sum of Active Temperatures and significant variability in the SAT. The second subperiod from 1998 to 2021 showed an increase in temperatures with no drastic changes in SAT.

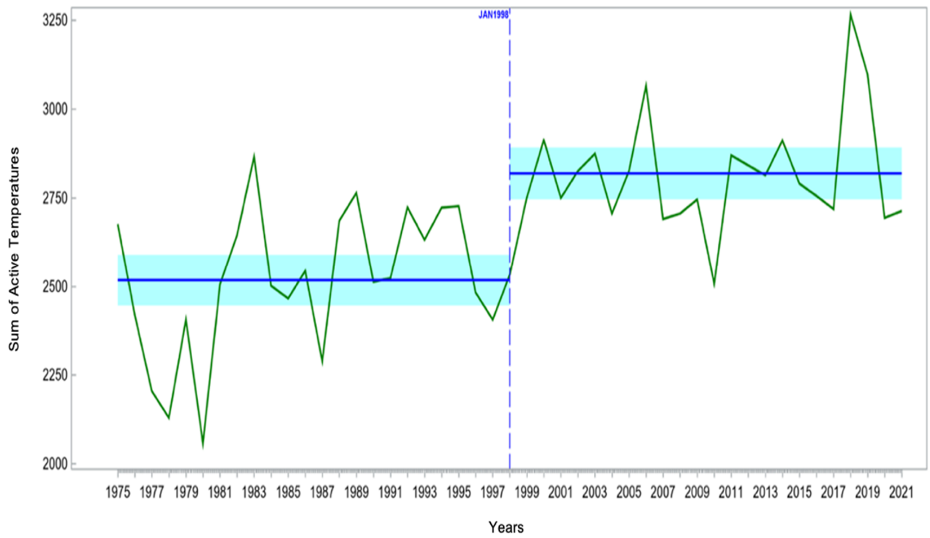

Figure 3. Autoregressive model for SAT in central Poland in the years 1975–2021 based on the Bai–Perron test.

Figure 4 presents the predicted autoregressive model (AR1) of the SAT from 1998 to 2026. The years 1998–2021 were treated as a subset for making predictions using the autoregressive model (AR1) of the SAT for the period 2022–2026. Significant fluctuations in the analyzed indicator were also observed during this subperiod. In 2010, the lowest value in the entire analyzed period was recorded, amounting to 2510 °C. In the following year, this indicator reached 2880 °C. Additionally, there were peaks in 2016 and 2020, followed by a decrease in subsequent years. According to the predictions, the average level of the SAT in central Poland from 2022 to 2026 should range from 2700 °C to 2760 °C.

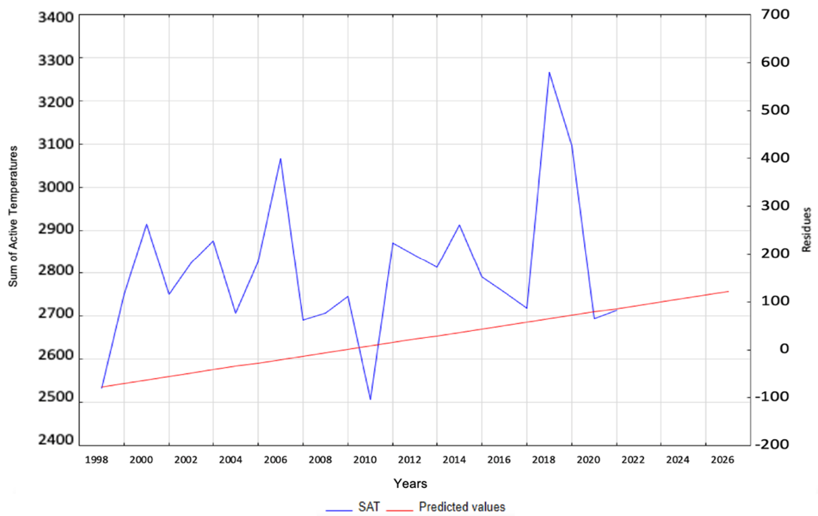

Figure 4. Prediction of SAT based on data from 1998–2021.

The above research results were supported by analyses of reference evapotranspiration, which, as mentioned earlier, is considered an important indicator of climate change. The analyses performed showed a very high similarity between the SAT index and changes occurring in reference evapotranspiration from 1975 to 2021. The chart below (Figure 5) illustrates the sum of annual evapotranspiration in the three voivodeships comprising central Poland. A clear upward trend was observed in all voivodeships, despite numerous fluctuations in reference evapotranspiration in individual years. It should be noted that the average annual growth rate of this indicator in individual voivodeships ranged from 0.09 to 0.05%.

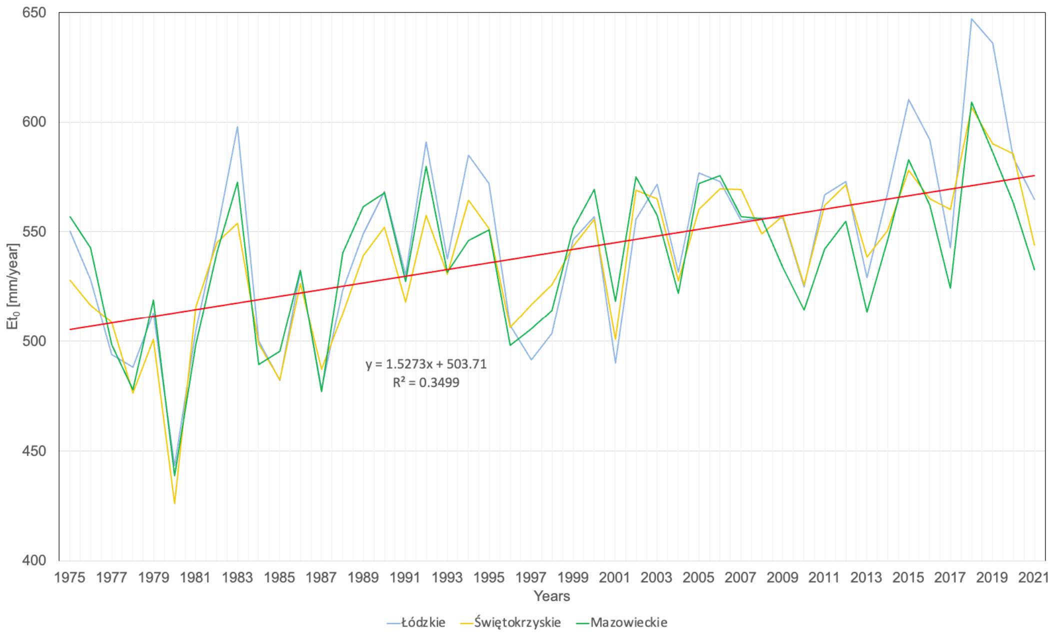

Figure 5. Sum of evapotranspiration from 1975 to 2021.

Taking into account the detailed monthly distribution of evapotranspiration in individual voivodeships, to synthetically illustrate the discussed changes, the results are presented for selected years within the period 1975–2021. Figure 6 depicts that in the province of Łódź, in most of the years studied, there was an increasing number of days where daily ET_0 values exceeded 4 [mm/day] from May to the end of August. For instance, in 1975, there were only 13 days, in 1995, 30 days, and in 2015, as many as 38 days were recorded. A similar trend was observed in the Świętokrzyskie Voivodeship (Figure 7). In 1975, only 6 days with evapotranspiration exceeding 4 mm per day were recorded in this voivodeship, while in 1995, it was 21 days, and in 2015, as many as 26. Similarly, in the third analyzed voivodeship, Masovia (Figure 8), ET_0 values exceeding 4 [mm/day] occurred for 13 days in 1975, 24 days in 1995, and 29 days in 2015.

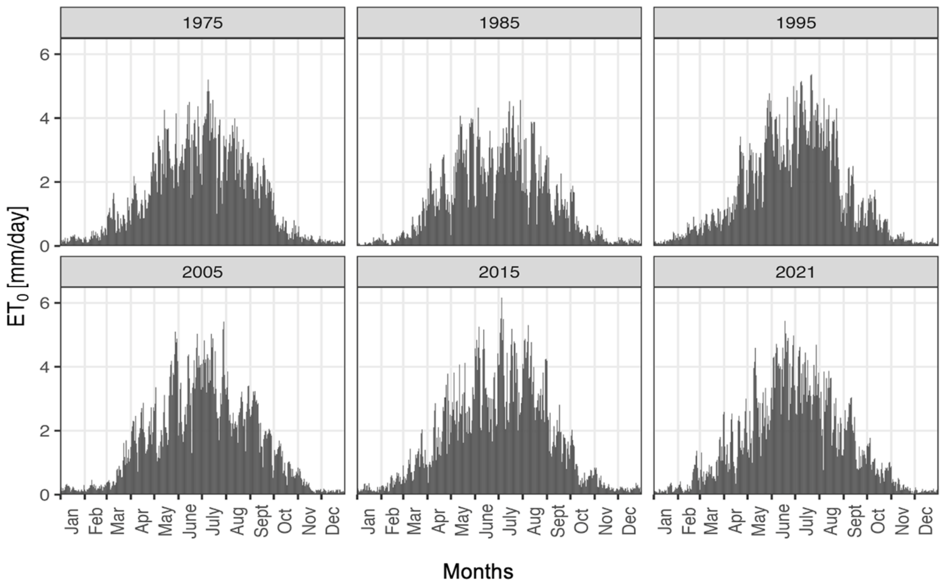

Figure 6. Evapotranspiration in Łódzkie Voivodship in selected years of the period 1975–2021.

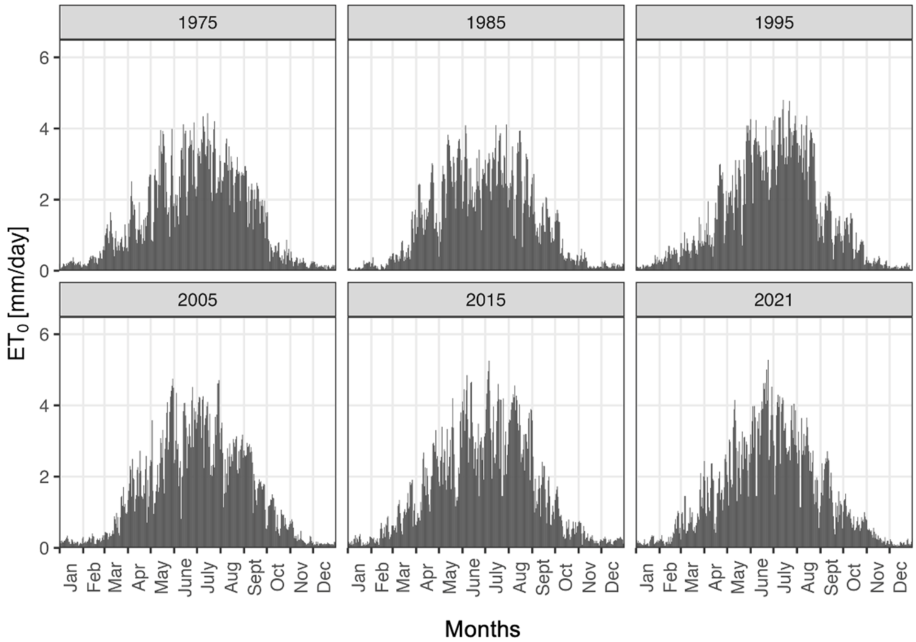

Figure 7. Evapotranspiration in Świętokrzyskie Voivodship in selected years of the period 1975–2021.

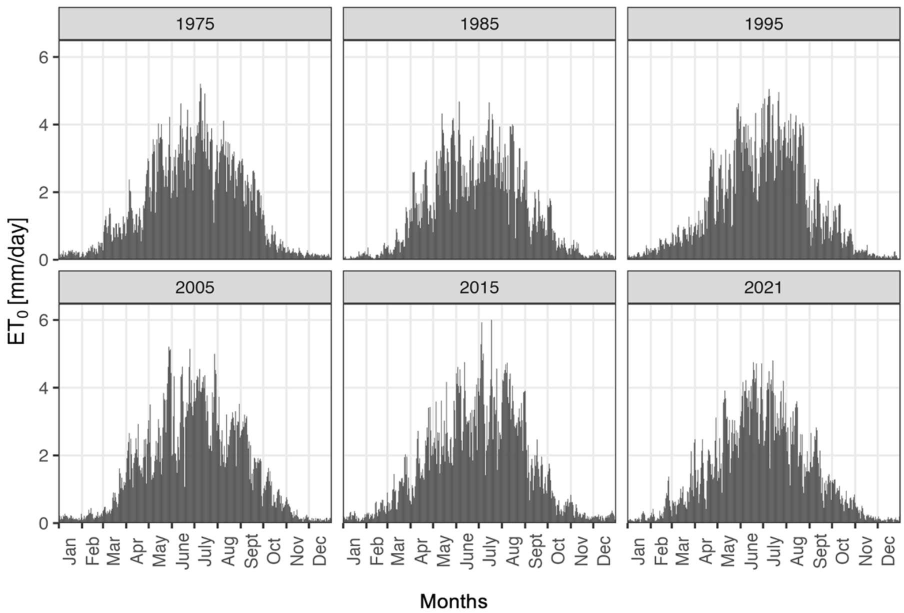

Figure 8. Evapotranspiration in Mazowieckie Voivodship in selected years of the period 1975–2021.

Far fewer days with such high daily evapotranspiration exceeding 4 [mm/day] occurred in the last year examined in all analyzed voivodeships. However, this is a result of the variability and deviations described earlier throughout many years of the analyzed period. Generally, it should be noted that evapotranspiration in central Poland is systematically increasing, especially from May to the end of August.

The analyses carried out showed that in April, similar trends in temperature during frost days were observed in all three voivodeships of central Poland. Generally, attention should be paid to the increasing trend observed in this month consisting of a gradual decrease in the intensity of frosts (Figures 9–11). At the same time, it should be noted that in the Masovian Voivodeship in this month the most frost days were recorded of all three voivodeships. The situation was slightly different in May, with a decreasing trend in temperatures recorded in the Łódź and Świętokrzyskie voivodeships during the examined period. In these voivodeships, the intensity of frosts was higher in the following years. Conversely, in the Masovian Voivodeship, the intensity decreased in subsequent years. Generally, taking into account September, single days with frost were recorded in all three voivodeships throughout the studied period. This observation, especially of September frosts, the intensity of which is decreasing, may be one of the factors indicating the prolongation of the thermal summer, as a result of which many late grape varieties have a chance to ripen in the conditions of central Poland. Significantly more frost days were recorded in October, but their intensity decreased in the Świętokrzyskie and Masovian voivodeships in the examined period, while it increased slightly in the Łódź Voivodeship. Throughout the study period, only isolated frosty days were recorded, occurring solely in April and May.

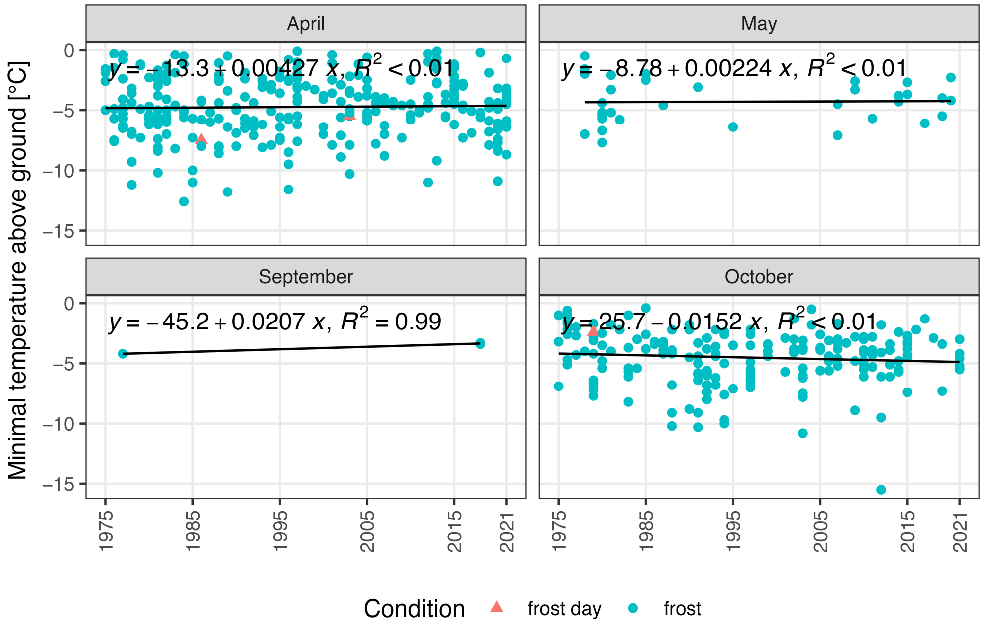

Figure 9. Minimal temperature above ground in Łódzkie voivodship in selected months in the period 1975–2021.

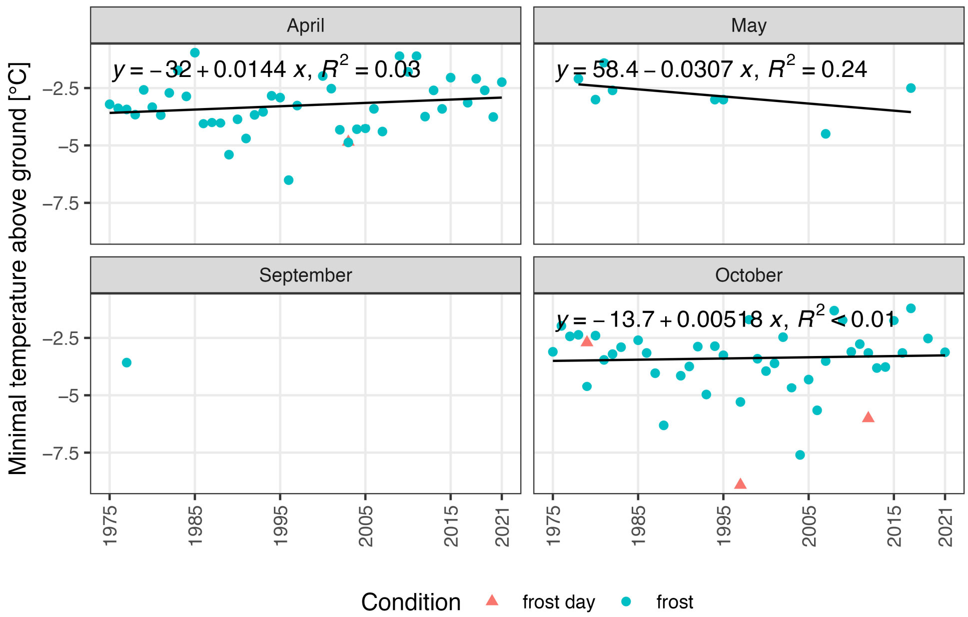

Figure 10. Minimum temperature above ground in Świętokrzyskie voivodship in selected months in the period 1975–2021.

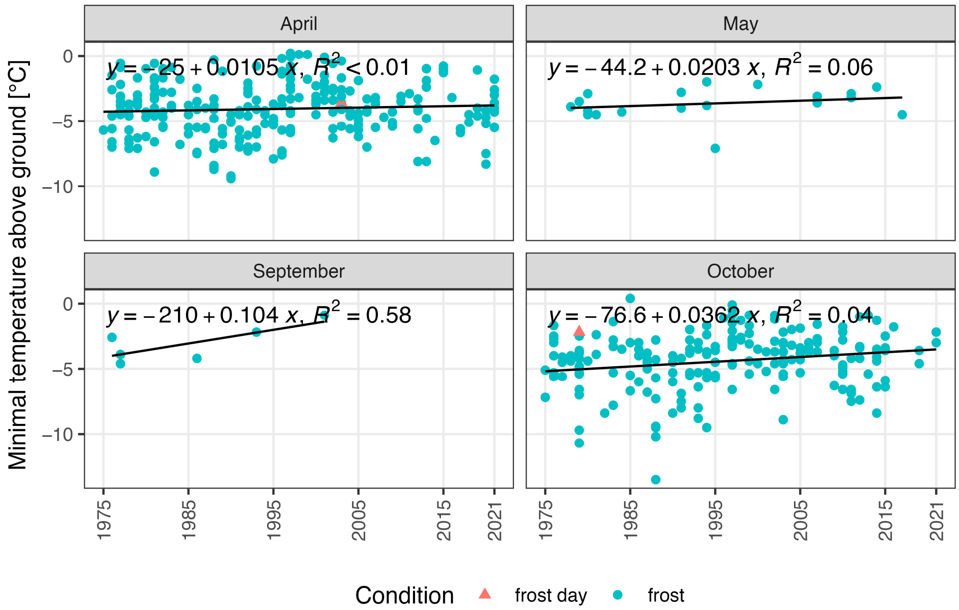

Figure 11. Minimum temperature above ground in Mazowieckie voivodship in selected months in the period 1975–2021.

4. Discussion

Ongoing climate change can have a positive impact on the acclimatization and development of grapevine cultivation in central Poland. According to the study by Lisek [38], the most significant aspect of climate change favoring grapevine cultivation in Poland is the increase in average air temperature during the vegetation period, expressed as the SAT. Between 1975 and 2021, a significant increase in the SAT index was observed in central Poland, which may create new opportunities for grape cultivation in these areas. This climate change potentially enhances the possibilities for vineyards, expanding the boundaries of traditional wine regions and enabling the development of grapevines in locations that were not previously considered favorable for this cultivation. Koźmiński et al. [43] have already pointed out that the ongoing climate warming will lead to a significant northward shift (from 100 km to 150 km) of the current boundary for intensive grapevine cultivation in Poland, which will facilitate the introduction of new varieties with increased thermal requirements. However, as indicated by Kapłan et al. [65], the climate in Poland still exhibits high variability, and therefore, the location of cultivation, optimal variety selection, and protection against pathogens are also important factors to consider.

The change in temperature trends indicated in the analysis conducted using the Bai–Perron test may point to various phases of climate change resulting from changing atmospheric conditions, which is crucial for long-term planning, including production in climate-dependent sectors. Currently, SAT calculations are a crucial parameter for grapevine producers in Poland to select varieties adapted to the thermal conditions of the region and obtain the best fruit quality. It should be noted that the ripening of some older American hybrids, which have low thermal requirements, may have a weak correlation with SAT values, as the ripening of these varieties often occurs in both warmer and cooler years around the same time [66].

Similar studies conducted by Jarvis et al. [67] on another bioclimatic indicator, Growing Degree Days, in Australia, revealed rapid climate warming in the country between 1986 and 2015, which had a negative impact on early fruit ripening. Many grape-growing regions in Australia may become unsuitable for producing varietal wines due to excessively high temperatures [68]. On the other hand, according to Karvonen [69], the global warming trend will improve grapevine cultivation conditions in southern Finland, shifting it further north towards central Finland by the end of this century. In the Baltic Sea region, grape cultivation with suitable varieties is already possible, and with the projected climate warming, the cultivation will be supported by breeding suitable varieties for a cooler climate.

The modeling presented in Maciejczak et al. [38] suggests a significant probability of grapevine cultivation progressing and developing in Poland if appropriate practices are adopted to respond to climate change. The studies by Neumann and Matzarakis [70] indicate that the observed increase in air temperature will continue to exert pressure on grape producers to adapt to the current climatic conditions. The analysis of temperature forecasts until 2026 showed an increase in the SAT indicator for central Poland. The prospective aspect of the conducted research is that the SAT is expected to show a rising trend, which is a positive phenomenon and will undoubtedly contribute to the further development of grapevine cultivation in central Poland and the production of higher-quality fruits.

The expected temperature increase in central Poland will affect the agroclimatic conditions of the Łódź, Mazovia, and Świętokrzyskie voivodeships. According to Żmudzka [71], the increasing temperature contrasts in Poland, resulting from the overall increase in thermal resources, can be utilized to introduce new crop varieties or expand species diversity. Grapevine cultivation offers new opportunities for producers and serves as a good alternative to plant species with declining demand.

In the research by Jurak in 1995 on spatial changes in average annual sums of field evaporation and potential evapotranspiration, the author published, among other findings, annual sums of potential evaporation obtained using the Penman method for five Polish macro-regions, including the macro-region of central Poland (period 1951–1990) [72]. The convergence of long-term changes in evaporation and air temperature in Poland is evident. A change in the average annual air temperature in Poland by 1 °C results in an increase or decrease in evaporation obtained by the Penman method by over 10 km^3 per year. The analysis of reference evapotranspiration and the SAT index in the macro-region of central Poland from 1975 to 2021 confirmed an increase in evaporation and temperature. According to the research of Olechnowicz-Bobrowska, the sum of potential evaporation during the growing season (April–October) was in the range of 650–750 mm in central Poland [73]. The analysis of reference evapotranspiration from 1975 to 2021 corroborated this trend. Throughout individual seasons and years, most of central Poland experienced a significant deficit of water resources [74]. In the future, it is recommended to conduct broader research that also considers the northern regions of Poland regarding temperature changes and forecasting, and focuses on issues related to spring and autumn frosts, which significantly affect the quality and quantity of grapevine yields. An important aspect will also be broader research on changes taking place in evapotranspiration to identify sensitive stages of vine growth in central Poland.

Proper protection against frost and the adaptation of plants to changing climatic conditions are key to ensuring the durability and productivity of fruit crops, including vines, in the face of evolving challenges related to extreme weather conditions. In the context of climate change that may reduce exposure to frost in fruit-growing regions such as California, significant reductions in frost risk are projected for almond, avocado, and orange crops. It is important to consider both the benefits and potential negative effects of such changes, including increased demand for water and pressure from pests [75].

The use of delayed winter pruning is crucial, as it can postpone bud break and potentially reduce the risk of frost damage in early spring, particularly for viticulture [76]. Although higher temperatures during the growing season are expected to benefit viticulture in colder regions of Europe, the risk of spring frosts remains a significant threat due to warmer winters, which may occur after early bud swell [45].

Therefore, an important aspect is the appropriate selection of varieties and the use of suitable rootstocks when grafting plants. These factors can significantly influence both the moment of bud break and the fruit ripening period, delaying the former and accelerating the latter. This approach protects both young spring shoots and ripening fruit against the effects of spring and autumn frosts.

5. Conclusions

Monitoring climate change in the context of rising temperatures is crucial for agricultural production, including high temperature-sensitive crops such as grapes. The present study, through its analysis, includes temperature measurements over a period of more than 45 years, and the analytical methods used provide a scientifically objective representation of temperature trends and predictions. Despite the extended research period, it differed only slightly from the 1975 value, being 4.89% lower. However, a long-term upward trend in the SAT was observed in central Poland between 1975 and 2021, with an average annual growth rate of 0.07%. It should be noted that there was considerable variability in the indicators analyzed throughout the period. Therefore, the use of the Bai–Perron test allowed the identification of breakpoints and the division into shorter subperiods. A notable increase in the SAT indicator occurred in the second half of the 1990s. The SAT values for 1998–2021 are significantly different from those for 1975–1997, as confirmed by the Bai–Perron test. According to the predictions of an autoregressive model (AR1), the average SAT level in central Poland in 2022–2026 is expected to be between 2700 °C and 2760 °C, which should favor grape cultivation. At the same time, it should be expected that the observed increasing trend in evapotranspiration, both in total for individual years and during the period of greatest vegetation, i.e., from May to the end of August (especially the increase in the number of days with evaporation exceeding 4 mm per day), will result in a growing need to ensure adequate irrigation for developing vineyards. The research conducted on the total number of days with ground frost and frosty days separately for April, May, September, and October of the research period 1975–2021 indicates different trends in the number of days and the temperature scale during frost in individual voivodeships of central Poland. Particularly noteworthy, however, is the decreasing number of frost days in September in all provinces, which will allow many grape varieties to ripen. Therefore, this is a factor that requires further in-depth analysis to determine its potential impact on the development of viticulture in central Poland.

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