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Mitigating effect of the sea on temperatures along Mediterranean coastal areas: the case of the vine territory of the Matera DOP - Basilicata (Italy)

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Abstract: The temperature variations caused by the climate changes taking place in the Basilicata region, southern Italy - Ionian Seaside of the Gulf of Taranto - on the territory of the DOP Matera vineyard, were studied by means of an analysis of temperature trends considering both the period of the vegetative-productive season of the vineyards and the whole year. Two datasets were analyzed for this study: data from ERA5-Land of the C3S Climate Data Store -relative to the 1981-2022 window- and data from 5 weather stations belonging to the agrometeorological network of the Lucanian Agency for Development and Innovation in Agriculture (SAL-ALSIA), relative to the 2000-2023 window. From the results of this study, it can be deduced that, for the historical period analyzed, the Matera DOP area showed a clear and worrying trend of increasing temperatures and, in particular, minimum temperatures. This increase, moreover, is more evident at higher elevations than at lower elevations close to the sea. At lower altitudes, in fact, temperatures are strongly "buffered" by the thermoregulatory activity of the bordering Ionian Sea. It follows that the DOP Matera viticultural areas, and in particular the areas furthest from the coastal strip, will already have to adapt to severe climatic conditions that will undoubtedly affect the quality and typicality of the wines

Keywords: Climate change; Viticulture; Italy-Basilicata region; Bioclimatic indices; Altitude; Temperature; Mediterranean sea.

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1. Introduction

In recent years, various research conducted in different areas of the world have been concerned with assessing the impact of ongoing climate change on viticulture and winemaking [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11].

With its millennial history and its current 408 DOP (Protected Designation of Origin) and 118 IGP (Protected Geographical Indication) [12], Italy continues to be one of the leading countries in the wine sector [13]. However, particularly on the territories of some DOP facing the coastal areas of the Italian Mediterranean, more or less severe effects of the ongoing global climate change are occurring with continuity [14]. On several of these viticultural areas, the effects of climate change, and in particular temperatures, are severely affecting the resilience of crop quality and sustainability [15] to the point that, some of these areas, in the medium term, will be destined to become marginal for quality wine production [16, 17, 14]. After all, the impact of temperatures on phenological stages also affects and determines the quantity of production [17, 18]. Therefore, it is important to study the temperature trends of viticultural zones (DOP) in order to predict the evolution of potential changes that these zones might undergo in the near future. In fact, there is evidence that temperature plays a predominant role in crop development [19, 20] especially with significant trends, as it affects in a general shortening of the length of phenological stages [21, 22, 23]. Consequently, rising temperatures are undermining the viticultural suitability of many historical areas (DOP) as a result of the emergence of technical issues in vineyard management [24, 25].

In this paper, an analysis of temperatures over the territory of one of the 4 DOP areas in Basilicata is carried out (Figure 1), "Matera DOP", already considered by several studies to be the most at risk as a result of the severe effects of climate change in the Mediterranean context [26, 27]. Piccarreta, Lazzari and Pasini [28] have evidenced an increasing temperature trend involving the entire Basilicata region in the 1981–2010-time window. In addition, Panagiotopoulos [29] identified, for this area, a drastic decrease in the Siberian High index between 1978 and 2000, an index that influences atmospheric circulation and temperature patterns in the entire Northern Hemisphere.

In relation to the warming trend observed at the global level [30, 31] and in order to evaluate these effects at the territorial scale of the Matera DOP, the objectives of this study were, first, to define the trend of air temperatures (1981-2022) in the production area and, second, to evaluate significant changes with regard to the agrometeorological indices most commonly used in viticulture.

The first approach aimed at this analysis was to take into consideration the changes in temperatures according to elevation bands (Figure 1S); assuming that at the higher elevations of the DOP area the rise in temperatures over the given period was less than at the lower elevations. However, this assumption was later refuted by the results from the analysis of ERA5-Land data.

In fact, the overall climate analysis of the study area was carried out using the ERA5-Land dataset from the C3S Climate Data Store - Copernicus Climate Change Service [32]. That is, a re-analysis combining climate model data with observations taken on the ground via meteorological stations. This approach permits to create a globally complete and consistent dataset, and useful in providing an accurate description of the climate of the period analyzed.

In particular, an analysis of temperature trends was carried out considering both the interval related to the vine growing season, which in this context runs from March 15 to October 15, and the entire annual period. The period of analysis was limited to the 1981-2022 time series because there is evidence that, in the Northern Hemisphere, the breaking point in temperature regimes occurred in the early 1980s [33].

In addition, for the purpose of a more circumscribed investigation of the climate evolution of the last twenty years in the study area, the daily temperature series from 2000 to 2023 of five active meteorological stations in the area where the "Matera DOP" wine farms are concentrated were considered.

2. Materials and Methods

2.1. Study Area

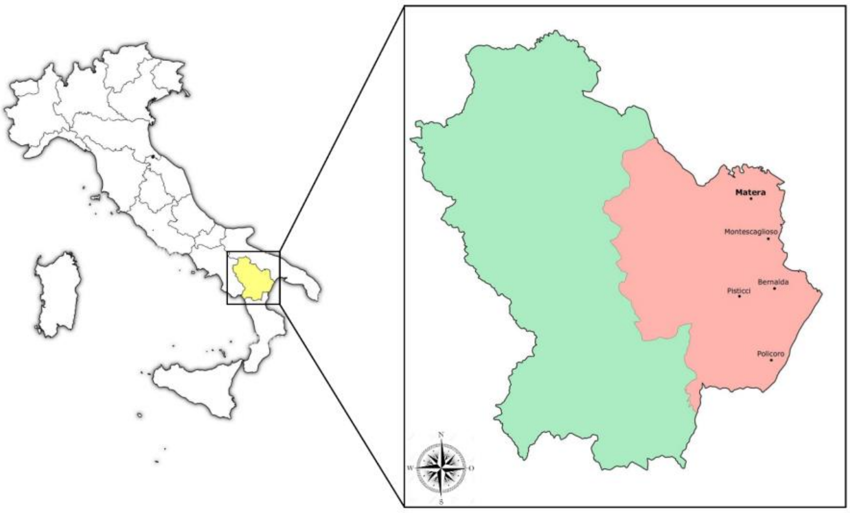


Figure 1. Basilicata Region in Southern Italy (yellow) include the Matera DOP (in red) winegrape-growing area.

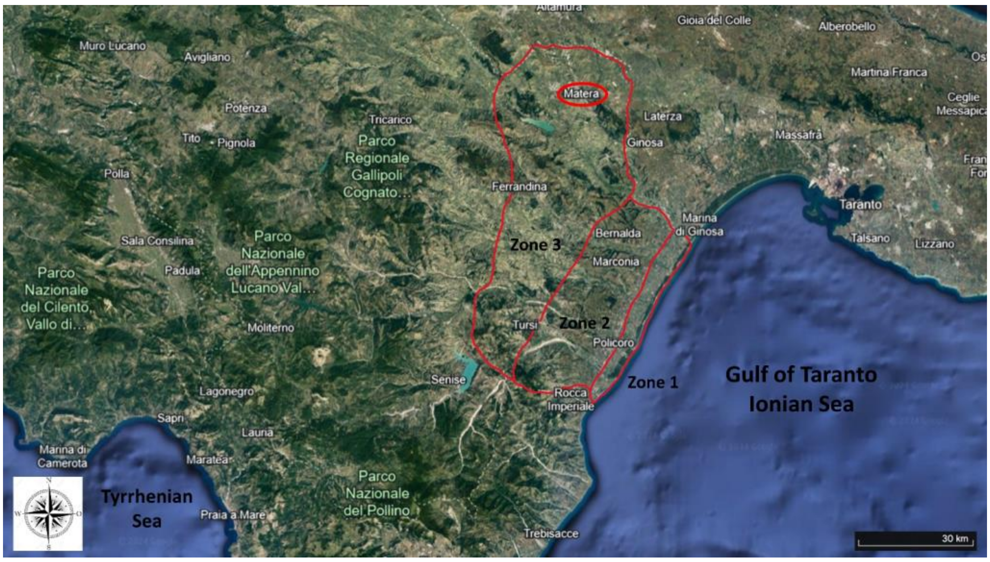


Figure 2. Subdivision of the study area (part of the Matera DOP) into 3 zones: 1) Coastal Plain, 2) Terrazzi Marini, 3) Inner Matera Hills; surrounded in red highlights the city of Matera.

The study area is located in the southeastern part of the Basilicata Region, south-Italy, (Figure 1) and overlooks the Gulf of Taranto (Figure 2). It encompasses part of the territory marked as the province of Matera and, in particular, part of the inland plateaus and the entire marine coastal strip. Starting from the coast, then, and proceeding inland, the territory can be divided, from a geomorphological point of view, into 3 different environments (Figure 2):

- Coastal plain environment (Zone 1) represented by the surfaces of sedimentary origin, with flat morphologies and on which younger soils have evolved (Inceptisols and Entisols).

- Environment of marine terraces (Zone 2) overlying the coastal plain and subdivided into several orders that branch out connecting with the Plio-Pleistocene hills above. These geological formations have a sub-flat morphology, with the presence of evolved, deep, well-drained soils with high iron content.

- Finally, the environments of the innermost surfaces (Zone 3) and at higher elevation, the Plio-Pleistocene hills (Fossa Bradanica), represent most of the territory of the Matera hills. They are characterized by surfaces with morphology varying from sub-flat to undulating; with the presence of soils that give rise to moderately coarse textures; calcareous and very permeable.

For the climatic characterization of the study area, 13 of the 31 municipal territories of the entire province of Matera were identified as they constitute the territories directly affected by the presence of vineyards belonging to the Matera DOP (Figure 3); whose distribution of the municipal area by elevation bands was calculated using the methodology of Raster analysis using GIS algorithms (Figure 1S) and is shown in Table 1.

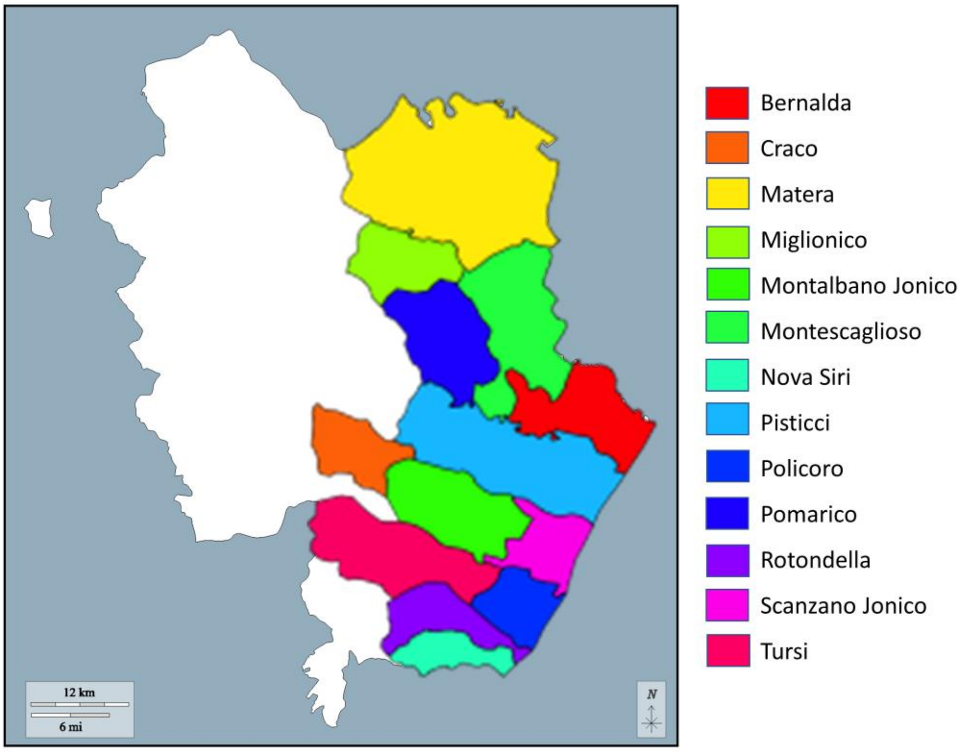


Figure 3. Total area of the province of Matera with the 13 municipalities considered in this study.

Municipalities	Areas (% of total municipal area)								
	0-100	100-200	200-300	300-400	400-500	500-600	600-700	700-800	800-900
Craco	11%	58%	28%	2%	0%	0%	0%	0%	0%
Bernalda	86%	14%	1%	0%	0%	0%	0%	0%	0%

Policoro	99%	1%	0%	0%	0%	0%	0%	0%	0%
Scanzano Jonico	99%	1%	0%	0%	0%	0%	0%	0%	0%
Pisticci	71%	22%	6%	1%	0%	0%	0%	0%	0%
Montalbano Jonico	30%	60%	9%	0%	0%	0%	0%	0%	0%
Pomarico	18%	29%	28%	17%	8%	0%	0%	0%	0%
Rotondella	38%	32%	13%	8%	5%	3%	1%	0%	0%
Nova Siri	31%	24%	20%	13%	7%	3%	1%	1%	0%
Miglionico	9%	49%	21%	15%	7%	0%	0%	0%	0%
Tursi	26%	36%	14%	10%	8%	5%	0%	0%	0%
Matera	4%	25%	23%	36%	12%	1%	0%	0%	0%
Montescaglioso	40%	43%	16%	1%	0%	0%	0%	0%	0%

Table 1. Percentage distribution by elevation bands of the areas of the 13 municipalities.

2.2. Climate characterization and data used

The ERA5-Land dataset from the C3S Climate Data Store - Copernicus Climate Change Service 2019 [32] was used to characterize the climate of the study area, and in particular, the trends of the main climate variables. It is worth noting that spatialized data of the type of ERA5 Land can be used to study the trend over time of the climate variables included in the dataset as well as to make comparative analyses in space; however, the levels of the variables do not fully match the values found with spatial data. For this reason, point data from 5 weather stations were also used, which are more suitable for the calculation of some bioclimatic indices of interest to grapevine.

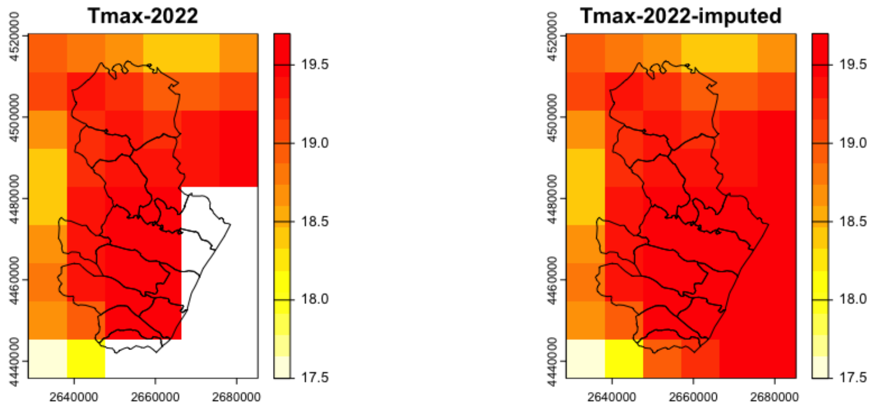
For the purpose of the study, the entire annual and vine growing season, from March 15 to October 15, were considered as periods of interest. So, from the ERA5 Land data, the following variables were studied: daily maximum temperature (Tmax), daily average temperature (Tavg), daily minimum temperature (Tmin).The same variables were also analyzed using territorial data from the 5 meteorological stations.

2.2.1 Spatialized data

ERA5 is the fifth generation of spatialized dataset produced by the "European Centre for Medium-Range Weather Forecasts" (ECMWF) globally, constructed on the basis of data derived from climate models corrected with locally available point values. The dataset used in this study, i.e., ERA5-Land is based on the same climate model through which the better-known ERA5 dataset is generated, with the addition of some equations describing the physical aspects related to the land. This addition allows for a global resolution of 9 km compared to ERA5's 31 km and describes the evolution of water and energy cycles on land in a consistent manner [34]. ERA5-Land climate data are released as hourly data in a regular grid, where the spatial resolution of each grid cell is 0.1°x 0.1° and the coordinate reference system (CRS) is WGS84. The time series produced range from 1950 to the present.

Hourly temperature data were unit transformed from Kelvin to Celsius by applying the equation T(°C)=T(°K)-242.15, then aggregated to a daily resolution. Next, the daily data were aggregated considering both the interval related to the growing season-March 15 to October 15-and the entire annuality, according to the following scheme: average daily temperatures, maximum (Tmax), mean (Tavg) and minimum (Tmin), of 214 days (growing season) and 365/366 days (annuality). The result is a time series of 42 data points from Jan-Jan 1981 to Dec 2022 for the following variables: Tmax, Tavg, Tmin-growing season and Tmax, Tavg, Tmin-annual. The time series of Tmax, Tavg and Tmin-journal were analyzed in R through the "terra" library [35].

Once the time series for growing season and annuality were constructed, the CRS (Coordinate Reference System) was transformed from WGS84 to Monte Mario/Italy zone 2 (EPSG:3004) to align the climate data with the geography of the administrative boundaries. Therefore, only grid cells within the administrative boundary of the Matera DOC area were selected.



(**a**) (**b**)

Figura 4. (A) Example of the Tmax for 2022 where 12 cells in the study area are not covered by ERA5 Land climate data; **(B)** reconstruction of the complete time series for each missing cell using, for each year, the average of the data from the 5 nearest cells.

The selection resulted in the identification of 42 regular cells, each containing a 42-year historical series. However, as can be seen from the example of Tmax for 2022 shown in Figure 4A, some areas are not covered by the ERA5 Land climate data, specifically these are 12 cells. Therefore, we reconstructed the complete historical series for each missing cell by averaging the data from the 5 nearest cells for each year (Figure 4B).

2.2.2 Timely data

The characteristics of the five active meteorological stations in the area where the farms producing Matera DOP wine are concentrated, belonging to the agrometeorological monitoring network of the Lucanian Agrometeorological Service of the Lucanian Agency for Development and Innovation in Agriculture (SAL-ALSIA), an instrumental body of the Basilicata Region, are shown in Table 2 and Figure 5.

For each of the five stations, the daily series of minimum and maximum temperatures, from 2000 to 2023, were acquired and on which checks were made for data absent due to non-measurement. Accordingly, a search was also performed on the individual quantities to highlight suspicious data and provide for the elimination of outliers.

Code	Station name	Istitution	Coordinates		
			Lat	Lon	Masl
MTP 21	Matera – C. da Matinelle	SAL-ALSIA	40,69393	16,51744	224
PAN 39	Metaponto 1 (Bernalda) – AASD Pantanello	SAL-ALSIA	40,389966	16,786328	9
MO4 10	Montalbano J. – (MT) Cozzo del Fico	SAL-ALSIA	40,281331	16,614422	151

MTS 26	Montescaglioso (MT) – Fiumicello Cozzo del Presepe	SAL-ALSIA	40,480373	16,720097	32
NS3 16	Nova Siri Sc. (MT) – Agriturism "La Collinetta"	SAL-ALSIA	40,147778	16,589166	136

Table 2. List of stations of the Lucanian Agrometeorological Service of the Lucanian Agency for Development and Innovation in Agriculture (SAL-ALSIA).

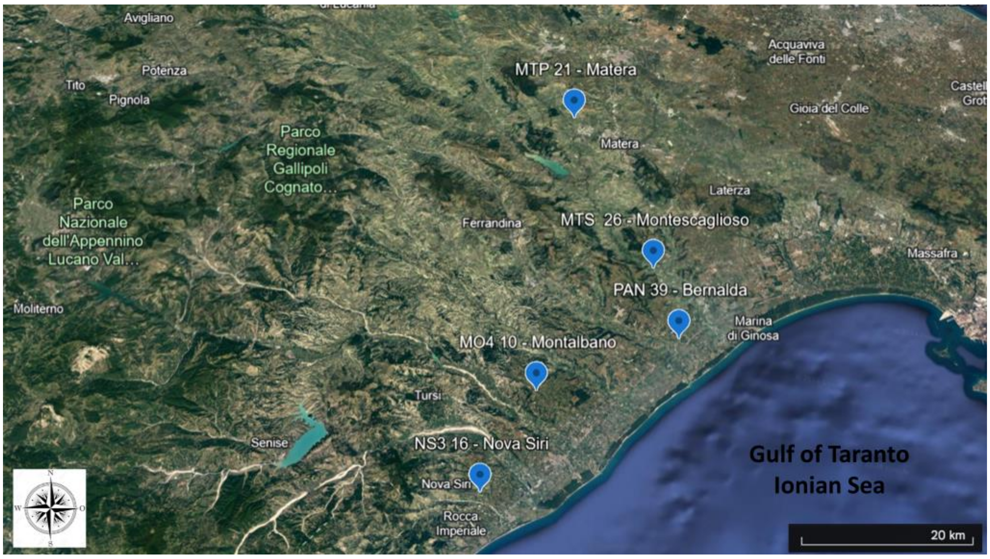


Figure 5. Location of the five agrometeorological stations falling within the production area of the Matera DOC.

On the daily minimum and maximum temperature series and also on the bioclimatic indicators of the five stations, trend analysis was carried out. Agrometeorological indices are often used to assess the suitability and variability of climate in different areas for viticulture, but, at the same time, they can provide a fairly complete picture of changes in current climatic conditions. Table 3 and 4 show the climate variables and bioclimatic indices used in this study with their respective formulas and classes for viticulture. Specifically, Winkler's thermal index (WI), also known as Growing Degree Day (GDD), refers to the thermal accumulation during the growing season, (April 1 to October 31), and takes into account the base temperature of 10 °C, below which vines hardly grow. Huglin's heliothermal index (HI) represents the thermal accumulation also calculated during the growing season that uses the average temperature and the daily maximum temperature, giving more weight to the latter than to the GDD and also takes into account a correction factor related to the increase in daylight duration toward higher latitudes. The Cool Night Index (CI) is based on the average minimum air temperature obtained during the grape ripening month (September 1-30). The number of days with frost during the year (ND with Tmin <= 0 °C). The number of days with excessive heat during (ND with Tmax > 35 °C), the temperature above which there is a stasis of vine vegetative activity.

Variable	Description	References
Tmin	Annual minimum air temperature (Annual minimum air temperature)	
Tmin 4-10	Growing season minimum air temperature April 1-October 31 (Growing season minimum air temperature)	[36]

Tmax	Maximum air temperature (Annual maximum air temperature)	
Tmax 4-10	Growing season maximum air temperature April 1-October 31 (Growing season maximum air temperature)	[36]
WI	Winkler index (Growing Degree Day or Winkler Thermal Index),	[37]
HI	Huglin index (Heliothermal Index or Huglin Index 1 April–30 September)	[38]
CNI	Cool night index (Cool Night Index (average of minimum temperatures 1–30 September)	[39]
ND ≤ 0 °C	Number of days with frost (Number of days with air minimum temperature ≤ 0 °C)	
ND > 35 °C	Number of hot days with Tmax > 35 °C (Number of days with air maximum temperature > 35 °)	[40]

Table 3. List of climate parameters and bioclimatic indices used in this study.

Bioclimatic index	Class/Region of viticultural climate	Acronym	Interval
[a] Winkler index	Too cold		≤ 850
	Region I		> 851 < 1390
	Region II		≥ 1390 < 1668
	Region III		≥ 1668 < 1945
	Region IV		≥ 1945 < 2223
	Region V		≥ 2223 < 2700
	Too hot		≥ 2701
[b] Huglin index	Very cool	HI-3	≤ 1500
	Cool	HI-2	> 1500 ≤ 1800
	Temperate	HI-1	> 1800 ≤ 2100
	Temperate warm	HI+1	> 2100 ≤ 2400
	Warm	HI+2	> 2400 ≤ 3000
	Very warm	HI+3	> 3000
[b] Cool night index	Very cool nights	CI+2	≤ 12
	Cool nights	CI+1	> 12 ≤ 14
	Temperate nights	CI-1	> 14 ≤ 18
	Warm nights	CI-2	> 18

Table 4. Classification system of Winkler's Index (WI), Heliothermic or Huglin's Index (HI) and Fresh Nights Index (CI) with their calculation formulas; [a] [41]; [b][42].

Winkler index

$$IW = \sum_{1\ April}^{31\ October} \left(\frac{Tmin+Tmax}{2} - 10°C \right) \quad (1)$$

Tmin= Minimum daily temperature (°C)
Tmax= Maximum daily temperature (°C)

Huglin index

$$IH = \sum_{1\ April}^{30\ September} \left(\frac{(Tmean-10°C)+(Tmax-10°C)}{2} * K \right) \quad (2)$$

Tavg= Mean daily temperature (°C)
Tmax= Maximum daily temperature (°C)
K= 1.02

Cool night index

$$CNI = 1/\mathrm{N} \sum_{1.9}^{30.9} Tmin \quad (3)$$

Tmin= Minimum daily temperature (°C)
N=Number of days

2.3. Trend test

To test for the presence of a trend in a time series, a parametric statistical test, for example, the classical linear model, or a nonparametric test can be used. In this study, the Mann-Kendall test on trend was used, which belongs to the family of nonparametric tests, that is, it is not based on a theoretical model from which the observed data are generated, but only on how the observed data are distributed. In addition, the β-Sen methodology was used to calculate the magnitude of the trend [43]. In practice, the magnitude of the trend is calculated as the median of the slopes obtained from all possible combinations of two points taken along the time series. For this purpose, the R package "zyp" was used. [44].

Before being applied, the Mann-Kendall trend test was corrected for autocorrelation. In fact, due to multi-year cycles, annual temperature time series can be affected by autocorrelation. When there is positive autocorrelation in the time series, the test tends to report a significant trend more often than it should [45, 46]. To account for autocorrelation, the approach proposed by Zhang [47] was applied. This iterative method considers a first estimate of autocorrelation based on the data, which is used to obtain a de-correlated series by the autoregressive (AR) method of order 1. On the de-correlated series, a first estimate of β-Sen is calculated, which in turn is used to de-trend the historical series. On the de-trended series, the autocorrelation coefficient is re-estimated and proceeded according to the previous scheme until the differences in the estimated parameters between two successive runs is almost zero.

The statistical test was applied on the entire historical series spanning from 1981 to 2022 of Tmax, Tavg and Tmin at both the growing season and annual levels, relative to each ERA5 Land cell. The trend is considered significant when the P-value associated with the results of the statistical test is less than 0.05. When this is the case, the graphs and tables show the corresponding value and sign of the trend calculated by the β-Sen procedure described above.

Equivalently, the same statistical test was applied on the bioclimatic indices. In addition, for comparison with the results obtained through ERA5 Land data, a trend analysis was also performed on the time series of Tmin and Tmax obtained from the 5 meteorological stations.

3. Results

3.1. Results derived from ERA5 data

The following figures show the variation of climate variables over 42 years (1981 - 2022). It should be noted that the trend value assigned to each cell is always significant at the 0.05 level of the statistical test, except when labeled with "no trend." So, the observed changes over the period 1981-2022 are associated with colors ranging from yellow to red according to the classes shown in the legend.

3.1.1 Maximum temperature (Tmax), minimum temperature (Tmin) and average temperature (Tavg)

Regarding the trend of Tmax, the results of the Mann-Kendall test and the calculation of variances by the β-Sen method shown in Figure 6A and 6D show a clear signal of growth over time that also reaches variances between +2 and +2.2°C, particularly during the growing season of grapevine. In fact, the variations over time are more pronounced during the growing season than during the annual season. In addition, the growth signal also shows a spatial trend from southeast to northwest, which, in the case of the Matera study area also corresponds with a move away from the sea toward hilly elevations. A more specific trend analysis by elevation bands is given in Table 5.

Regarding the Tmin trend, the results of the statistical test show a much more spatially spread variation over time than Tmax and with higher average growth values (Figure 6B and 6E). In fact, relative to the growing season, for more than half of the study area there is evidence of variations occurring between 1981 and 2022 greater than +1.9 °C.

Finally, with regard to Tavg, the results of the statistical test show variations over time with intermediate values from the results of Tmax and Tmin (Figure 6C and 6F)

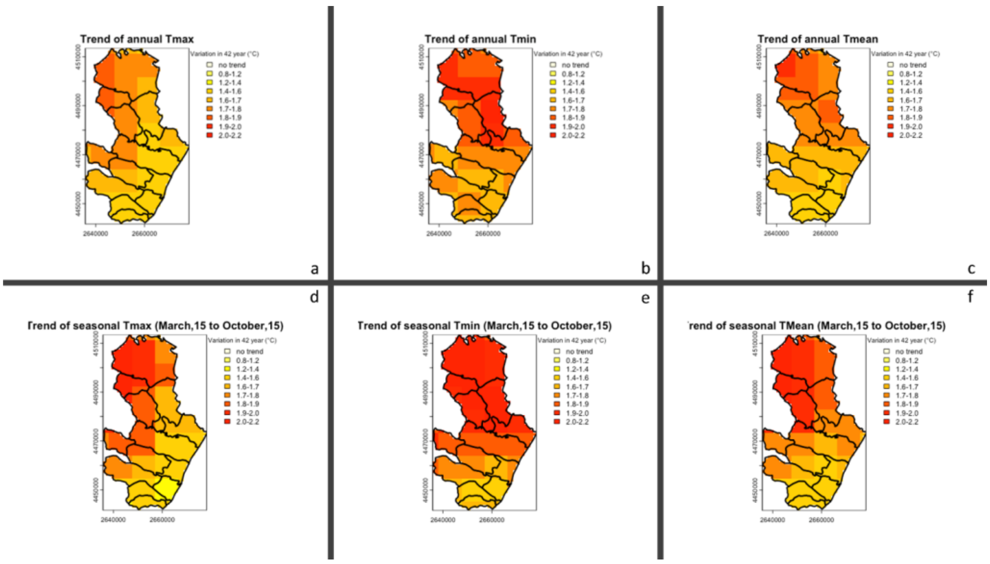


Figura 6. Trend of temperatures calculated by β-Sen method on ERA5 Land data; **(A)** maximum temperature for the whole year; **(B)** minimum temperature for the whole year; **(C)** average temperature for the whole year; **(D)** maximum temperature for the vine growing season; **(E)** minimal temperature for the vine growing season; **(F)** average temperature for the vine growing season.

3.1.2 Trend of aggregate temperature by elevation classes

In order to characterize climate change by elevation, ERA5 Land data were aggregated according to the 4 elevation bands: 0-100, 100-300, 300-500 and 500-800 meters. By first averaging the clipped data for each band, the statistical test was then applied to identify the trend relative to the vine season.

As can be seen from Table 5, the seasonal temperature variation (March,15 - October,15) in 42 years (°C) is very similar in the first 3 elevation bands for Tmax, while Tmin shows a slightly lower trend for the 100-300 class than for the 0-100 class (-0.15 °C) and the 300-500 class (-0.23 °C). In general, for the 500-800 meter class, a variation in the 42 years is shown to be lower than for the other classes, reaching -0.29 °C in the case of Tmax and -0.61 °C in that of Tmin. From Table 1, it can be seen that most of the areas with elevations above 500 meters are included in the municipalities of Tursi, Rotondella and Nova Siri, i.e., in the southwestern part of the study area.

Growing season (March, 15 – October, 15)			
Elevation	Tmax (°C)	Tmin (°C)	Tavg (°C)
[0-100]	1.86	2.02	1.77
(100-300]	1.82	1.87	1.86
(300-500]	1.82	2.10	1.91
(500-800]	1.57	1.49	1.61

Table 5. Temperature change over 42 years calculated by the β-Sen method relative to the period March 15-October 15, for 4 elevation bands.

3.1.3 Trend (trend) of aggregate temperature by municipality.

Similar to what was done for the elevation bands, ERA5 Land data were aggregated for the 13 municipalities in the Matera DOP area (Table 6). These values are obtained as the median of the cell values within the boundary of each municipality. Table 6 shows the annual and seasonal temperature variation (March,15 - October,15) over 42 years (°C). The results at the municipal level show that it is the municipality of Policoro that has the lowest temperature increases during the growing season (+0.72°C Tmax, +1.17°C Tmin), followed by the municipalities of Rotondella (+0.81°C Tmax, +1.17°C Tmin) and Nova Siri (+0.82°C Tmax, +1.18°C Tmin), all 3 located in the southwest part of the study area. In contrast, the municipalities with larger increases are Miglionico (+1.16°C Tmax, +1.64°C Tmin), Matera (+1.07°C Tmax, +1.6°C Tmin), Montescaglioso (+0.88°C Tmax, +1.63°C Tmin) and Pomarico (+1.05°C Tmax, +1.48°C Tmin), all located in the area northwest of the study area and furthest from the sea.

	Annual			Growing season (March, 15 – October, 15)		
Municipalities	Tmax	Tmin	Tavg	Tmax	Tmin	Tavg
Bernalda	1.04	1.45	1.18	0.92	1.53	1.23
Craco	1.22	1.20	1.18	1.05	1.38	1.23
Matera	1.09	1.42	1.30	1.07	1.60	1.29
Miglionico	1.16	1.47	1.30	1.16	1.64	1.41
Montalbano Jonico	1.10	1.23	1.10	0.85	1.29	1.08
Montescaglioso	1.04	1.46	1.27	0.88	1.63	1.26
Nova Siri	1.00	1.22	1.09	0.82	1.19	1.01
Pisticci	1.03	1.35	1.13	0.91	1.42	1.18
Policoro	1.00	1.24	1.06	0.72	1.17	0.95
Pomarico	1.13	1.39	1.21	1.05	1.49	1.34
Rotondella	1.03	1.25	1.11	0.81	1.17	1.05

	Annual			Growing season (March, 15 – October, 15)		
Municipalities	Tmax	Tmin	Tavg	Tmax	Tmin	Tavg
Tursi	1.13	1.28	1.11	0.99	1.33	1.16
Scanzano Jonico	1.04	1.29	1.11	0.88	1.30	1.09

Table 6. Temperature changes over 42 years calculated by the β-Sen method relative to the period March 15-October 15 and annual, for municipalities.

3.2 Risultati derivanti dai dati puntuali

Tab. 7 shows the climatic data calculated over the period 2000-2023 of the five stations falling within the Matera DOP wine production area. At the Matera station, the average annual temperature was the lowest at 16 °C compared to Nova Siri, which recorded 18.1 °C. In all locations, the coldest month was January with an average minimum temperature ranging from 2.2 °C in Montescaglioso, to 6.4 °C in Nova Siri. As for frosts, in 24 years Matera and Montescaglioso recorded more than 500 days with frost, compared with 45 days in Nova Siri. For cool nights, they range from a low of 11 °C in Montalbano to almost 19 °C in Nova Siri. July was the hottest month for all stations with an average temperature of 33-34 °C. In contrast, for hot days the minimum was in Nova Siri with 19 days, and the maximum with 38 days recorded in Montescaglioso.

Station	Tmed (°C)	Coldest month	Tmed coldest month	Total frosts 2000-2023	Average cool nights 2000-2023	Hottest month	Tmed hottest month	Average hot days 2000-2023
Montalbano J.co	16.4	January	3.7	173	11.1	July	33.6	23
Nova Siri	18.1	January	6.4	45	18.9	July	33.1	19
Matera	16.0	January	2.5	576	15.2	July	34.4	35
Montescaglioso	16.6	January	2.2	535	15.3	July	34.9	38
Bernalda	17.1	January	3.8	211	16.7	July	33.7	24

Table 7. Climate values calculated over the 2000-2023 period of the five stations.

Winkler's bioclimatic index, calculated for the 5 weather stations in the study area (Table 1S), yielded the final result that all localities fall within Region V (Typically only suitable for extremely high production, fair quality table wine or table grape varieties destined for early season consumption are grown) [37]. Table 8 shows the Huglin Index value, which for four localities falls in the HI+1 class, i.e., "warm," while only Bernalda falls in the HI+2 class, i.e., "warm temperate," in which the heliothermic requirements for the growth of almost all grape varieties, including late varieties, are still met [42]. Regarding the CI Cool Nights index (Table 9), there are some differences between the values of the five stations: Matera, Montescaglioso and Bernalda are part of the same CI+1 class i.e. "temperate nights"; Montalbano Jonico falls in the "very cool nights" class, which is characterized by rather low night temperatures unlike Nova Siri, which is part of the CI-2 climate class, "warm nights".

Station	Huglin index			
	Value	Class of viticultural climate	Acronym	Class Interval
Montalbano Jonico	2798	Warm	HI + 2	2400<HI≤3000
Nova Siri	2903	Warm	HI + 2	2400<HI≤3000
Matera	2806	Warm	HI + 2	2400<HI≤3000
Montescaglioso	2937	Warm	HI + 2	2400<HI≤3000
Bernalda	2326	Warm temperate	HI + 1	2100<HI≤2400

Table 8. Huglin bioclimatic index calculated over the period 2000-2023 for the five stations.

Station	Cool Night Index			
	Value	Class of viticultural climate	Acronym	Class Interval
Montalbano Jonico	11,1	Very cool nights	CI+2	Tmin < 12 °C
Nova Siri	18,9	Warm nights	CI-2	Tmin > 18 °C
Matera	15,2	Temperate nights	CI-1	14 °C<Tmin≤18 °C
Montescaglioso	15,3	Temperate nights	CI-1	14 °C<Tmin≤18 °C
Bernalda	16,7	Temperate nights	CI-1	14 °C<Tmin≤18 °C

Table 9. Bioclimatic index Fresh nights calculated over the period 2000-2023 for the five stations.

Meteorological data and bioclimatic indices from the five ALSIA stations were used to identify possible trends over the period 2000-2023 (Table 10). Statistically significant trends for the different magnitudes are shown in bold. Montalbano Jonico was the only location where no statistically significant changes occurred over the 20-year period, unlike Nova Siri, which recorded significant changes in five out of six cases. No significant changes are recorded for the frost variable. Significant trends for maximum temperature are evident at four of the five stations: Nova Siri (+2.17 °C), Matera (+2.74 °C), Montescaglioso (+1.45 °C) and Bernalda (+1.43 °C), which are followed by significance for hot days (Tmax > 35 °C) in Nova Siri (+14 days in 24 years), Matera (+23 days in 24 years) and Montescaglioso (+24 days in 24 years). For bioclimatic indices, changes are recorded for Huglin's Index in Nova Siri, Matera and Bernalda.

Station	p-value					
	Tmin	Tmax	Tmin ≤ 0 °C	Notti fresche	Tmax>35 °C	HI
Montalbano Jonico	0,56122	0,38531	0.50864	0.47194	0.70927	0,86216
Nova Siri	0,00088	0,00004	0.31399	0.00072	0.06944	0,01224
Matera	0,39804	0,00602	0.32831	0.33336	0.0645	0,05614
Montescaglioso	0,7513	0,01746	0.39804	0.18029	0.01746	0,44193
Bernalda	0,13026	0,00106	0.23077	0.05614	0.11156	0,00001

Table 10. Trend of bioclimatic indices calculated over the period 2000-2023 of the five stations falling within the Matera PDO production area; p-value is considered significant if <0.1.

Discussion

The purpose of this work was to assess the impact of ongoing climate change on viticulture in the Matera PDO area, carried out through a temperature trend analysis. The analysis was developed through the use of spatialized data from ERA5 Land for the historical period 1981-2022; and point data from five meteorological stations falling within the Matera PDO production area for the period 2000-2023. The historical period 1981-2022 was chosen because, as recorded in the literature [33], the early 1980s was identified as the period when the ongoing climate change began, which preliminarily resulted in a substantial increase in temperatures and shortening of phenological phases [48].

Considering the results derived from the ERA5 Land data, as far as temperatures are concerned there is a general increase over the period 1981-2022, which is particularly evident in the vine vegetative-productive cycle typical of these areas [49, 50] - March 15/October 15. The maximum temperature shows a clear sign of growth over time, and the maximum increase mainly concerns the municipalities of Matera, Miglionico, Pomarico, Craco and the western areas of the municipalities of Pisticci, Montalbano Jonico and Tursi. Here there are increases ranging from 1.7°C up to 2.2°C (Figure 6A and 6D); while the remaining areas still show variations of no less than 1.2-1.6°C. This distribution of temperature variations also shows a spatial trend running from southeast to northwest, which, in the case of the Matera PDO study area, also corresponds to a distancing from the sea (Figure 2 coastal belt - zone 1) in the direction of the hilly surfaces (Figure 2, marine terraces - zone 2 and Matera hill - zone 3). With regard to the minimum temperature trend, the results of the statistical test show a much more spatially widespread variation than for maximum temperature; and with higher average growth values (Figure 6B and 6E). In fact, relative to the growing season, for the northern half of the study area (zone 3), comprising the territories of the municipalities of Matera, Miglionico, Pomarico, Montescaglioso and the northern area of Bernalda and Pisticci, variations in minima, occurring between 1981 and 2022, are shown to range between 2 and 2.2 °C. The remaining areas, however, show marked variations in minimum temperatures ranging from 1.7 to 1.9 °C for the central area of the Matera DOP (Pisticci, Craco, Montalbano Jonico, Scanzano Jonico and Tursi); and still not falling below 1.2 -1.6 °C for the southern area of the study area (Nova Siri, Rotondella, Policoro). Finally, as for mean temperature, the results of the statistical test confirm the maximum and minimum temperature results, with increases more concentrated in the northwest area (Figure 6C and 6F). In addition, taking into consideration the spatial trend, related to the distribution of growth variations that goes from southeast to northwest; and considering that in the case of the Matera DOP area this spatial trend corresponds to both a move away from the sea (zone 1) and a rise in elevations (zones 2 and 3), it was decided to also carry out a study on the trends of temperatures aggregated by elevation classes. For this purpose, ERA5 Land data were aggregated according to 4 elevation bands: 0-100, 100-300, 300-500 and 500-800 meters. As can be seen from Table 5, the variation of maximum temperature, in relation to the vine production season, over 42 years is very similar in the first 3 high-metric bands (1.82-1.86 °C); on the contrary, as far as minimum temperature is concerned, a slightly lower trend is observed for the 100-300 band (1.87 °C) than for the 0-100 class (2.02 °C). In particular, it can be seen that the 300-500 range (2.10 °C) shows the greatest value of minimum temperature increase. As for the average temperature, it can be seen that the lowest temperature increment values are in the 0-100 and 500-800 ranges; while the largest increments are observed in the 100-300 range and, particularly, in the 300-500 range. These results ultimately indicate a smaller increase in temperature in the 0-100 range (zone 1) than in the 100-300 (zone 2) and 300-500 (zone 3). These trends occur contrary to what is known in the literature, namely that with increasing elevation there is also a decrease in temperatures [51]. This counter-trend phenomenon can be explained by referring to the thermoregulatory action of the (neighboring) sea, which tends to absorb quantities of heat [52] and lower the higher temperatures that would otherwise occur on the coastal belts. This phenomenon of "sequestration" of heat shares, which is linked to the ongoing warming of the Mediterranean Sea, explains why the above spatial trend leading to a greater increase in temperatures as you move away from the sea.

To confirm this hypothesis, we also carried out a study of aggregate temperature trends by municipal areas, also using Table 1 in which the distribution of the territories of the municipalities by altitude band is shown in percentages. Considering the period of vine production, we note that for the maximum temperature, the municipality in which the greatest increase was recorded is Miglionico; followed by Matera, Craco and Pomarico. On the other hand, as far as minimum temperature is concerned, the municipality in which the greatest increase is confirmed to be Miglionico; followed by Matera, Montescaglioso and Bernalda. On average, therefore, the municipal territories on which the greatest increase in temperature was recorded were Miglionico, Matera and Pomarico. On the contrary, the territories of municipalities that recorded the lowest temperature increases are Policoro, Nova Siri and Rotondella. Looking at Table 1, we see that the territories of the municipalities most affected by the increase in temperatures are mainly concentrated in the elevation ranges from 100 to 500 meters (zones 2 and 3); which also represent the 3 municipal territories furthest northwest and furthest from the sea in the entire study area. In contrast, the municipal areas least affected by the increase in temperatures are largely concentrated on the elevation bands closest to sea level (zone 1). In particular, Policoro, which has an area exclusively at sea level, is the municipality least affected by the average temperature increase (<C° increases). This indepth analysis leads us to confirm our hypothesis of thermoregulatory action of the sea.

In addition to the spatialized data study, a climate analysis was performed using point data from the 5 weather stations surveyed for the period 2000-2023. As can be seen in Table 7, despite the fact that the average temperatures of the higher-lying municipalities (Table 2), such as Matera, are on average lower (16 °C) than the municipalities closer to sea level, such as Nova Siri (18.1 °C) and Bernalda (17.1 °C), we can see that the same municipality of Matera has the average number of cool nights among the lowest, and the average number of warm days among the highest. In addition, Matera has one of the highest average temperatures for the month of July (Table 7). Next, with regard to bioclimatic indices, both Huglin's and Winkler's indexes were examined. The latter placed the territories of the 5 analyzed municipalities in Region V (Table 1S), which translates to "Typically only suitable for extremely high production, fair quality table wine or table grape varieties destined for early season consumption are grown," as confirmed in the bibliography [37, 53]. Table 8 shows the value of Huglin's Index: four municipal territories fall into class HI+1, i.e. "warm"; while only Bernalda falls into class HI+2, i.e. "temperate-warm." The HI+2 class still meets the heliothermic requirements for the growth of almost all grape varieties, including late varieties [42]. Regarding the Cool Nights CI index (Table 9), there are some differences between the values of the five municipal areas. Matera, Montescaglioso and Bernalda are part of the same CI+1 class, i.e. "temperate nights"; Montalbano Jonico falls in the "very cool nights" class characterized by rather low night temperatures. Nova Siri, on the other hand, is part of climate class CI-2, "warm nights." Finally, the meteorological data and bioclimatic indices of the five stations were used to identify possible trends over the period 2000-2023 (Table 10). Montalbano Jonico was the only location where no statistically significant changes occurred over the 20-year period. This may be explained by the fact that the Montalbano Jonico station is located at an average high altitude, and at an average distance from the sea compared to the other 4 stations. Nova Siri records significant changes in five out of six cases (Table 10), and significant trends for maximum temperature are shown in four stations (exclusion of Montalbano Jonico) followed by significance for hot days (Tmax > 35 °C) in Nova Siri, Matera and Montescaglioso. For Huglin's bioclimatic index, changes are recorded in Nova Siri, Matera and Bernalda.

5. Conclusions

This study, for the historical period analyzed, shows how the Matera DOP area showed a clear trend of increasing temperatures, and was predominantly classified as "Warm" based on the value of HI. This phenomenon of considerable temperature increase, which was initially assumed to be lower at higher elevations (zone 3) than at lower elevations close to the sea (zones 1 and 2), is strongly "buffered" by the thermoregulatory effect of the bordering Ionian Sea.

In fact, the rise in minimum and average temperatures was mainly observed in the northwest area of the study area (zone 3 of the "Matera Hills"), which is characterized by higher altitudes and also the most distant from the sea. The municipalities of Matera, Miglionico and Pomarico, which are the areas furthest northwest and furthest from the sea, recorded increases of up to 2.0-2.2 °C; on the contrary, the areas closer to the sea and at lower altitudes, for example, the municipalities of Nova Siri, Rotondella and Policoro, were more slightly affected by the increase in temperatures, recording 1.2-1.4 °C. Based on the analyses performed, therefore, the hypothesis on the differences found between the temperature regimes of coastal and inland areas is related to the mitigating function (with respect to temperatures) of the sea, which has a greater influence on coastal areas that are located in its vicinity. That is, the sea [52] acts with thermoregulatory action on neighboring and bordering areas by going to "sequester" part of the heat that accumulates on them. This action is not carried out and does not affect the mitigation of temperatures in the areas of zones 2 and 3 that are more distant and at higher altitudes (municipalities of Matera, Miglionico and Pomarico).

It follows that these viticultural areas (zones 2 and 3), in particular, will already have to adapt to severe climatic conditions that may affect the quality and typicality of Matera DOP wines.

We can draw some general inferences from the results of this study. The first is that moving vine breeding to higher altitudes (as per the trend) is not always sufficient to preserve it and counteract the effects of ongoing climate change. The second is that the sea plays, to date, its "thermoregulating effect" only along coastal areas. Third and final consideration is that we must, in any case, resort, as of now, to a radical rethinking of the positioning of viticulture on a given DOP territory, and the most appropriate adaptation strategies for the purpose of preserving the cultivation and typicality of the different DOPs.

Supplementary Materials: The following supporting information can be downloaded at: www.mdpi.com/xxx/s1, Figure 1S. Distribution by elevation bands of the study area; the source of the DTM (Digital Terrain Model) used is: NASA's Shuttle Radar Topography Mission (SRTM) digital topographic data Version 2. Table 1S. Huglin bioclimatic index calculated over the period 2000-2023 for the five stations.

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