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RESEARCH

Sensitivity of climate analogues to problem-specific adjustments: a case study

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Abstract
Climate analogues, which identify present-day locations resembling projected future climates are widely considered to offer a powerful tool to support adaptation in climate-sensitive sectors. However, many existing applications rely on coarse climate model outputs and raw variables, often overlooking microclimatic variation and sector-specific climate metrics. In this study, we refine the climate analogue approach by proposing problem-specific adjustments, consisting in incorporating bioclimatic indices tailored to vine growth and pathogens development, sub-grid topographic temperature corrections, and a Principal Component Analysis (PCA) to reduce redundancy among variables. Using European vineyards as a case study, we conduct a sensitivity analysis to assess the impact of each refinement on analogue identification. Each enhancement contributes significantly to the spatial distribution of selected analogues, with analogues shifting at the continental scale in some cases. Our results show the importance of using problem-specific indices, handling variable interdependence, and accounting for fine-scale climatic variability in climate analogue analyses. These three refinements expand the range of climate analogues for the 21,076 considered European vineyards (11,881 vs. 7,573 analogues) allowing a finer pairing. Though developed for viticulture, the methodology and insights are broadly applicable to other climate-sensitive systems, from agriculture to urban planning.

1 Introduction

As climate change reshapes environmental and human systems, the need for adaptation is increasingly urgent (Masson-Delmotte et al. 2021). Because climate impacts vary widely across regions, effective responses must be location- and context-specific and therefore rely on fine-scale information. Climate analogues (or climate twins) identify present-day locations resembling projected future climates (Ungar et al. 2011; Rohat et al. 2017). It has been proposed as a tangible framework for understanding and communicating complex climate projections. By mapping future conditions onto present-day climates, analogues aim at making climate change impacts more rela le and actionable for stakeholders across sectors such as urban planning, agriculture, and ecosystem management (Webb et al. 2013; Esperon-Rodriguez et al. 2022).

However, despite their versatility, many climate analogue applications still rely on coarse, unadjusted climate model outputs–averaging gridded physical parameters without incorporating local factors such as topography or sector-specific climatic thresholds (e.g. Hallegatte et al. 2007; Rohat et al. 2017; Webb et al. 2013). This simplification overlooks important sub-grid microclimatic variability; for instance, locations within the same grid cell may experience significantly different conditions due to local topographic and environmental factors, potentially resulting in inaccurate analogue identification. Additionally, several analogue studies only consider monthly, seasonal or annual temperature and precipitation (e.g. Hallegatte et al. 2007; Veloz et al. 2012; Rohat et al. 2017; Fitzpatrick and Dunn 2019). Analogues based solely on these raw parameters

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may overlook biologically or physiologically meaningful metrics that directly affect agricultural, ecological, and social outcomes (Bos et al. 2015). Furthermore, considering correlations between climate variables, the choice of variables and the method used to aggregate them when identifying climate analogues can significantly influence the results (Bulut et al. 2025). Yet, there is limited research on systematic approaches to variable selection and aggregation when defining climate analogue (Mahony et al. 2017; Yegorova et al. 2025).

In a previous study, a climate-matching method specifically designed for the climatic and topographic characteristics of European vineyards was introduced (Allaman et al. 2026). This method incorporates several bioclimatic indices selected to reflect key factors influencing both grapevine development and the spread of vineyard diseases and pathogens. By using indices tailored to viticultural needs, it ensures that the analogue selection process is based on variables that meaningfully characterize the climate conditions relevant to the study. To better represent the actual conditions experienced by vineyards, sub-grid temperature corrections based on slope, orientation, and elevation are applied. These corrections address the mismatch between the coarse resolution of climate models and the finer-scale topographic variability that strongly affects local climate in vineyard regions. Additionally, redundancy among the indices is reduced by performing a Principal Component Analysis (PCA). The resulting components are weighted according to the variance they explain, and used to compute a weighted Euclidean distance between the location of interest and its potential analogue.

Recently, Chaudhary et al. (2023) showed that climate analogues developed specifically for crops, using agroclimatic variables, differed substantially from generic analogues based solely on temperature and precipitation. These findings raise the question of how sensitive climate analogues are to the various methodological choices outlined above. Here, we perform a sensitivity study and evaluate how much these methodological refinements affect the selection of analogues, compared to a more basic approach relying solely on raw climate model outputs. The comparison is conducted at three levels: the individual vineyard scale, the overall distribution of analogues, and the wine-growing region scale. A single climate model and scenario are considered because the objective of this sensitivity study is to assess the effects of methodological refinements on analogue identification, rather than to quantify climate-projection uncertainty. Our results show that each of these three refinements- sub-grid topographic corrections, bioclimatic indices, and PCA-based weighting- contributes significantly to the identification of climate analogues. Together, they enhance the relevance of the matches obtained.

2 Methods

The data sources and processing methods used in this study are described in detail in Allaman et al. (2026). Here, we provide a brief summary for completeness.

2.1 Data sources

European vineyard locations are derived from the 2018 CORINE Land Cover (CLC) database (Copernicus Land Monitoring Service 2018), and the centroid is extracted for each plot. Topographic data–elevation, slope, and aspect–are extracted from the European Digital Elevation Model (EU-DEM) (Copernicus Land Monitoring Service 2013).

Climate data are taken from the CORDEX EUR-11 domain (Jacob et al. 2014), an international climate downscaling initiative that aims to provide high-resolution climate simulations for Europe using a number of regional climate models (RCMs). We used daily projections from the HIRHAM5 RCM under the RCP8.5 scenario, at 12 km resolution (Christensen et al. 2007). HIRHAM5 provides regional climate simulations at a spatial resolution suitable for investigating climate variability at the scale considered in this study, and has proven to produce reliable climate simulation over Europe (Christensen et al. 2007; Kotlarski et al. 2014). The RCP8.5 simulation was selected for this methodological case study because its relatively strong climate forcing provides a pronounced climate-change signal, facilitating the assessment of differences arising from the methodological refinements in analogue selection. A single climate model and scenario are considered because this sensitivity study focuses on the post-processing of climate-model outputs and the effects of methodological refinements on analogue identification, rather than on quantifying climate-projection uncertainty. We consider near-surface air temperature (average, maximum, and minimum), precipitation, near-surface relative humidity, and downwelling shortwave radiation as the basis variables that will be used to compute bioclimatic indices.

All climate analogue of vines discussed in this work are identified between 2020 and 2080. For each considered year, climate conditions are calculated over a 30-year period centred on that year. The climate corresponding to 2020 is represented by the average climate over 2006–2035, while the climate corresponding to 2080 is represented by the average over 2066–2095.

2.2 Analogues computation

The computation of climate analogues requires to define the similarity between the sets of climate at two locations and/or times. A common method used to in the field of

climate analogues is the standardised Euclidean distance (SED) (Rohat et al. 2017; Bulut et al. 2025). The SED between a vineyard j in the future and a grid point i in the present based on a set of N climate variables is computed as:

$$SED_{ij}^2 = \sum_{k=1}^{N} \frac{(p_{ik} - f_{jk})^2}{s_j^2}, \tag{2.1}$$

where p_{ik} is the value of the climate variable k at the grid point i in the current climate, f_{jk} is the value of the variable k at the vineyard location in the future climate, and s_j is the spatial standard deviation of the variable among the vineyards. The sum is performed over all N variables considered. Normalising by the temporal standard deviation, as done for example in Bulut et al. (2025), would be less adapted in our case since some of the indices used have a temporal standard deviation of zero at some vineyard locations, namely the number of frost and extreme heat days, leading to numerical issues.

To quantify the robustness of the match between a vineyard j and its climate analogue i, a similarity index is defined:

$$SI_{ij} = \frac{1}{1 + SED_{ij}^2} \tag{2.2}$$

This index ranges from 0 to 1, with 1 indicating a perfect match between climate conditions.

Beyond analogues of individual vineyards, we also consider analogues at the scale of wine-growing regions. We adopt the same wine-growing regions as in Allaman et al. (2026). A systematic mapping of a region in the future climate with another climatic region in the present, consistent with the bulk of the individual vine matching, is performed by counting the number of analogues from a given region in each possible analogue region. For a future region A of interest, each present region B is assigned a score $S_{A,B}$:

$$S_{A,B} = \frac{n_{A,B}}{\sqrt{\mathcal{A}_B}}, \tag{2.3}$$

where $n_{A,B}$ is the number of analogues of the future region A present in the analogue region B and $\mathcal{A}_B$ its area. We normalise with the square root of the region area in order to mitigate biases related to the region size and avoid favouring either the largest or the smallest regions. Regions with the highest scores are then considered the best matches for the region A of interest.

Note that the Mahalanobis distance has been proposed to aggregate variables in climate analogues computations (Mahony et al. 2017; Bulut et al. 2025). However, its application in the present framework is not straightforward and would require further methodological investigation (see supplementary material, Section S1.1). We also assessed the relevance of the Wasserstein distance as an alternative to the region-matching score defined in Eq. 2.3. As detailed in the supplementary material (Section S1.2), discrepancies in climate variability between regions make application difficult in our case and would deserve further investigation. Additionally, a thorough comparison of the Euclidean, Mahalanobis and Wasserstein distances is beyond the scope of this study and is therefore not presented here.

2.3 Comparison of climate analogue methodologies

Climate analogues are typically computed using raw variables extracted directly from climate model outputs; hereafter, referred to as the generic method. Allaman et al. (2026) proposed three methodological refinements: subgrid temperature corrections accounting for slope, aspect, and elevation, the use of bioclimatic indices instead of raw climate variables, and a PCA-based weighting accounting for redundancies among variables. Each of these three refinements can be incorporated independently into the analogue computation. When all three refinements are applied together, we refer to the resulting approach as the problem-specific method.

In the present sensitivity analysis, we compare the problem-specific methodology to the generic approach incorporating none of of the three refinements. We also evaluate the contribution of each refinement by ignoring each of them individually while keeping the other two. The five resulting configurations are summarised in Table 1.

To determine how each methodological refinement influences climate analogue selection, the analogue sets obtained using the different methodological configurations are compared at three complementary levels: individual vineyards, the continental distribution of individual vineyard analogues, and wine-growing regions as defined in Allaman et al. (2026).

Table 1 Summary table of the five climate analogue methodology variants evaluated in this study

Label	Method	Temperature corrections	Input variables	PCA
(i)	Problem-specific (PS)	✓	Bioclimatic indices	✓
(ii)	Generic	×	Raw climate variables	×
(iii)	PS; No temperature corrections	×	Bioclimatic indices	✓
(iv)	PS; No bioclimatic indices	✓	Raw climate variables	✓
(v)	PS; No PCA	✓	Bioclimatic indices	×

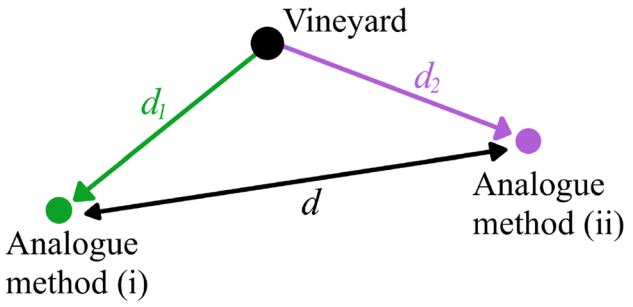


Fig. 1 Schematic representation of the geographical distances used to compare analogue locations identified using two different methods, here methods (i) and (ii)

At the individual scale, analogue patterns are examined for five representative vineyards. At the continental scale, the overall distribution of analogues across Europe is analysed, as well as the mean geographical distance between analogue sets obtained using different methods. This geographical distance d is schematised in Fig. 1. The relative distance between the two analogues is also computed as:

$$d_{\text{rel}} = \frac{2d}{\bar{d}_1 + \bar{d}_2}, \tag{2.4}$$

where $\bar{d}_1$ and $\bar{d}_2$ are the mean distances between the original vineyards and their five best analogues obtained using the two methods, respectively. This relative distance provides a proxy of the magnitude of the methodological refinement effect compared with the overall analogue displacement. Finally, at the regional scale, the number of wine-growing regions whose best analogue region differs between two methodological configurations is quantified. Together, these metrics characterise the extent to which the different methodological refinements influence climate analogue selection. In the next subsections, we detail the methodology of each of these three refinements.

2.4 Temperature corrections

To better represent vineyard-level climate conditions, we apply a temperature correction that accounts for sub-grid topographic features–namely, elevation, slope, and aspect–unresolved by the RCM. The detailed methodology for these corrections is given in Allaman et al. (2026), and their explicit formulations are provided in the supplementary material, Section S2, for completeness.

The correction due to the slope and aspect of the terrain depends on the time-dependent direct solar radiation on a flat surface $R_{\text{dir}}^{\text{flat}}(t)$. While only the direct component is affected by terrain orientation, the climate model provides only the total shortwave solar radiation, which comprises direct, Rayleigh-scattered, and Mie-scattered components. We make the simplifying assumption that the Rayleigh-scattered component can be treated as direct radiation and therefore contributes to the terrain-related temperature correction (Duffie and Beckman 2013). The direct and Rayleigh-scattered components, hereafter called $R_{\text{dir}}^{\text{flat}}(t)$, are then estimated from the daily solar radiation as:

$$R_{\text{dir}}^{\text{flat}}(t) = \frac{\bar{R}}{\bar{R}_{\text{cs}}} R_{\text{cs}}^{\text{flat}}(t), \tag{2.5}$$

with $\bar{R}$ the daily average solar radiation obtained from the RCM given the cloud cover, $R_{\text{cs}}^{\text{flat}}(t)$ the clear sky solar radiation on a flat surface, given by geometry, and $\bar{R}_{\text{cs}}$ the clear sky solar radiation on a flat surface averaged over 24 hours.

We assessed the parametrisation of Eqs. 2.5 and S2.5 by comparing its output across the year 2006 over the vineyards against the results of the Collares-Pereira and Rabl (CPR) model (Collares-Pereira and Rabl 1979). It is an empirical model for estimating the hourly distribution of global solar radiation from daily irradiation data. The model relates the hourly-to-daily radiation ratio to the solar hour angle and sunset hour angle, accounting for the diurnal and seasonal variation in solar radiation. The results of the CPR model are highly correlated with the hourly solar radiation R_h obtained from the parametrisation given by Eq. 2.5 (Fig. 2, $R^2 = 0.97$). Furthermore, the linear fit between the two models ($R_{\text{CPR}} = 0.87 \cdot R_h + 21.65$) is close to the average of those of the CPR model against on-site measurements over Europe, namely $R_{\text{CPR}} = 0.89 \cdot R_{\text{observed}} + 27.66$ (Kambezidis 2025). As sub-grid observations are unavailable to directly evaluate our model, we do so indirectly by combining these two fits, getting $R_{\text{h}} = 1.02 \cdot R_{\text{observed}} + 6.91$. The

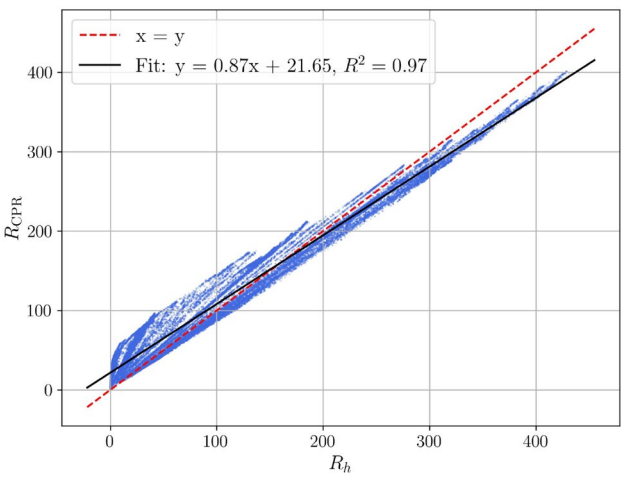


Fig. 2 Scatter plot of the hourly mean estimate $R_h(t)$ of a sample of vineyards computed using the CPR model compared to Eq. 2.5

slope closer to 1 suggests that the model of Eqs. 2.5 and S2.5 performs slightly better than CPR over the vineyards.

2.5 Bioclimatic indices

Six bioclimatic indices are taken into account in this work: the Huglin index, the frost and extreme heat days, a flavescence dorée index and the downy and powdery mildew risk days (Allaman et al. 2026). Their expressions are provided in the supplementary material, Section S3. They are computed from 2006 to 2095, and averaged over each 30-year period of interest. Each 30-year period is labelled by its central year; for instance, 2020 corresponds to the period 2006–2035.

2.6 Principal Component Analysis

To address redundancy between the indices, a Principal Component Analysis (PCA) can be applied (Vidal et al. 2012). It transforms the original indices into a new set of uncorrelated variables called principal components (PC), providing an efficient representation of the dominant modes. After transforming the data into this new coordinate system, we recalculate the Euclidean distance between points, with weights corresponding to the fraction of the variance explained by each principal component. The three main principal components derived from all index values at vineyard locations over the period 2006 to 2095, with temperature correction applied, are presented in Fig. 3. The principal components are provided in the supplementary material (Table S4.1).

The climatic homogeneity of each wine-growing regions appears in Fig. 3, as regions form clusters of similarly coloured points. This homogeneity results in consistent analogue locations of individual vineyards within each region.

3 Results

3.1 Similarity index

This section aims to evaluate the robustness of the analogues obtained from the different configurations described Table 1. All analogues discussed in this section and those that follow are computed between 2020 and 2080.

The distribution of the similarity index (Eq. 2.2) for the 20 best analogues of all European vineyards is found in Fig. 4. For the problem-specific method (method (i), Fig. 4a), the distribution tends to decay with the analogue rank very progressively and remains acceptably high for several analogues ($SI \geq 0.9$ for 92% of the 20 best analogues of all the European vineyards). Therefore, computing only the best matching analogue would reduce the robustness of the method. However, considering the 5 or the 20 best analogues for each vineyard yields similar results: when using 20 analogues per vineyard instead of 5, only 8 regions shift to a different analogue (see Fig. S6.2 for the corresponding analogues of wine-growing regions). From them, 4 new analogue regions are located within 500 km from the one obtained using 5 analogues. Notably, 7 of these 8 regions show a dispersed pattern of analogues across several regions, regardless of the number of analogues considered. Therefore, this cut-off is not critical to the results, validating an arbitrary limit of five analogues per vineyard.

Regarding the similarity index of the best analogue of all European vineyards, the vast majority of the analogues have a very high *SI* (92% above 0.9 for the 20 best analogues of all the European vineyards), but some outliers exhibit similarity indices as low as 0.2. However, 6% out of the 8% of *SI* below 0.9 are in the regions of Bordeaux, South-West of France, and Northern Anatolia, in Turkey (see Fig. S4.1 for details). These regions are projected to experience an increase in the

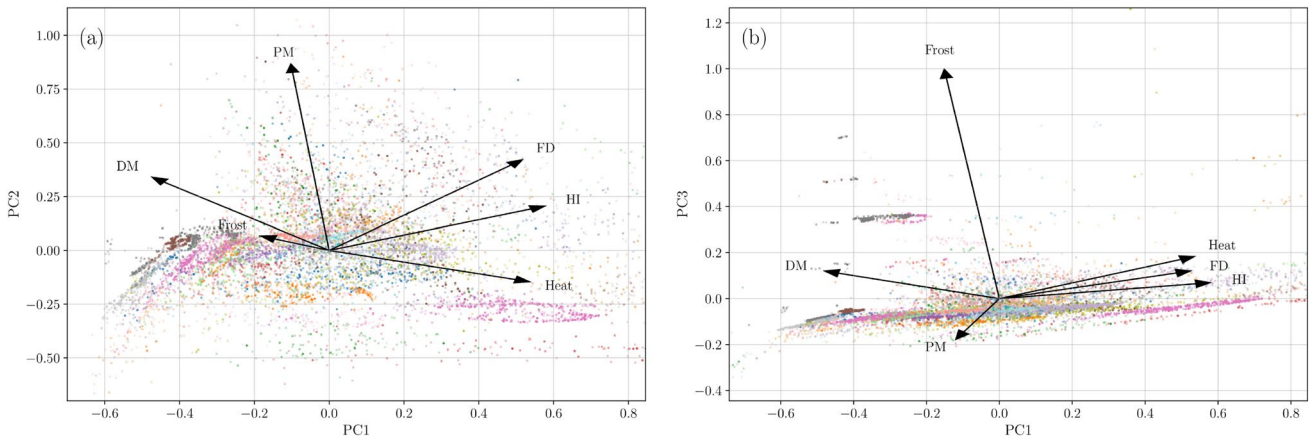


Fig. 3 Scatter plot of (**a**) PC1 vs PC2 and (**b**) PC1 vs PC3 computed from the six bioclimatic indices, showing the contribution of each index (HI: Huglin index, FD: flavescence dorée index, Frost: frost days index, Heat: heat days index, DM: downy mildew index, PM: powdery mildew index). Each colour corresponds to a different wine region

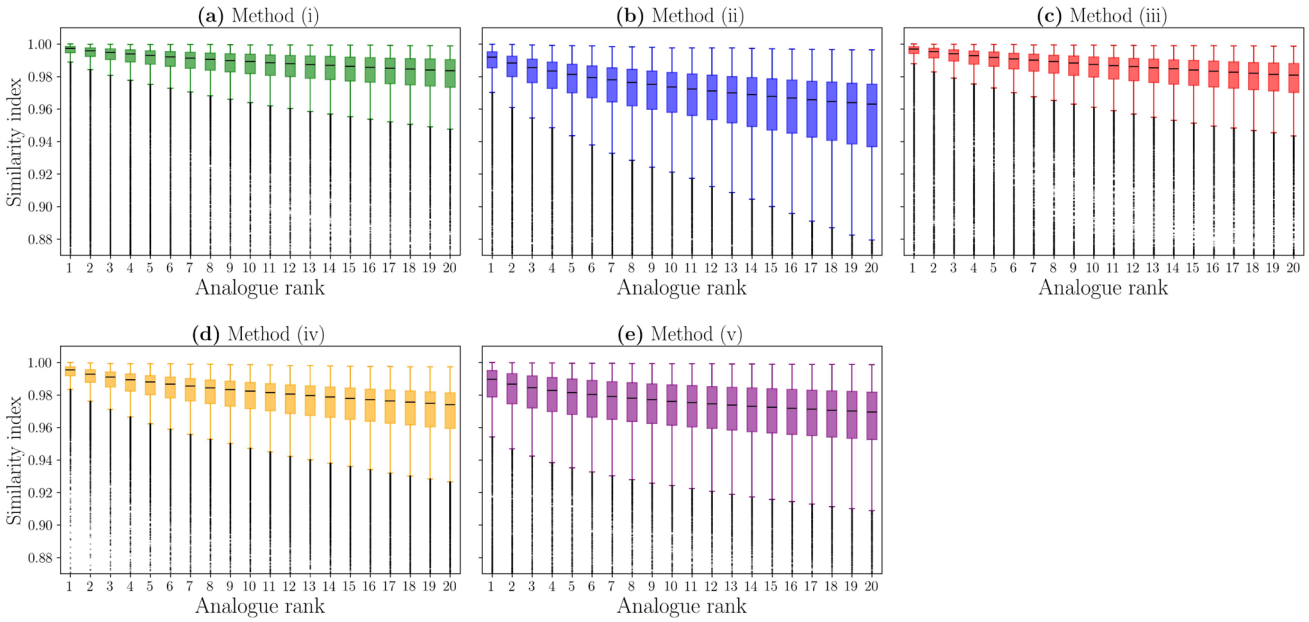


Fig. 4 Statistical distribution of the similarity index for the 20 best analogues of all vineyards. Each panel corresponds to one of the methods (see Table 1 for details). The coloured box spans the 25th to 75th percentiles, the whiskers span the 5th to 95th percentiles, and outliers are shown as black dots. Some outliers exhibiting similarity indices down to 0.2 have been truncated for clarity, see discussion in the main text for details on these outliers

number of frost days, due to earlier bud break (Allaman et al. 2026). The asymmetric distribution of the frost index, which is strongly skewed towards zero, implies that high values are rare and disproportionately influence the selection of analogues. All other regions within the study area successfully find analogue locations with climate conditions similar to those predicted in the future.

3.2 Added value of the problem-specific method

As detailed in Section 2, our approach provides a problem-specific framework for identifying climate analogues. We investigate the extent to which these methodological refinements affect the selection of climate analogues for European vineyards, in comparison to a more generic approach based solely on raw climate model output parameters.

Figure 5 shows the locations of the five best analogues of European vineyards, computed using different analogue configurations. Figure 5a illustrates typical analogue behaviours for five individual representative vineyards obtained using method (i) and method (ii). The Oberderdingen vineyard (Germany) shows little sensitivity to the analogue selection method. This vineyard is located on a flat terrain, with no pronounced topographic features in the surrounding area. Therefore, the slope temperature correction was negligible, and the elevation temperature correction is only 0.1° C. The effects of bioclimatic indices and PCA weighting are more statistical and are therefore difficult to interpret based on individual vineyards alone.

The analogues of the four other vineyards differ markedly depending on the method. In Noicattaro (Italy), the problem-specific method identifies five analogues across the Mediterranean, whereas the generic method clusters them mainly in Tunisia. In Tállya (Hungary), the problem-specific method produces more geographically consistent analogues. Figure 5b shows the locations of the five best analogues for all vineyards, again using methods (i) and (ii). The analogues computed from the generic method spread across 7,573 grid points, mostly concentrated along Mediterranean and Atlantic coastal regions. In contrast, the problem-specific method yields 11,881 grid points, with analogues distributed more broadly across the continent. The average distance between vineyards and their five best analogues is only marginally affected by the method used: it is 1196 ± 528 km with the generic method, compared to 1190 ± 582 km using the problem-specific method.

Figure 6a shows the mean distance between the analogues selected by methods (i) and (ii). In addition to the absolute distance in kilometres (distance d, see Fig. 1), a second scale shows the relative distance between the two analogue sets (distance d_{rel}, see Eq. 2.4). This relative distance is normalised by the mean distance between the original vineyards and their five best analogues and provides an indication of the magnitude of the methodological refinement effect compared with the overall analogue displacement. The mean distance between the analogues is 552 ± 479 km, reaching up to 3000 km in extreme cases, which represents up to 2.5 times the mean distance between a vineyard

and its best analogues. This indicates that analogue selection is highly dependent on the method applied. Regarding the similarity index (Fig. 4b), $SI < 0.9$ for 29.2% of the five best analogues of each vineyard when the generic method is applied, compared to only 5.8% with the problem-specific method. Although both methods yield high similarity indices, the problem-specific method consistently produces even higher values (median ≥ 0.99 for the problem-specific method, against 0.98 for the generic method), indicating a more robust analogue pairing.

At the region level, using the problem-specific method, 44 out of 57 regions shift to a different analogue region than the one obtained using the generic method (see Fig. S6.3 for the corresponding analogues). Of these, 9 shifts are within 500 km of the previous analogue, while 35 exceed 500 km, again illustrating the relevance of the problem-specific method.

3.3 Impact of temperature correction on the analogues selection

To distinguish between the individual contribution of the three features of our problem-specific approach (temperature corrections, bioclimatic indices and PCA) to the selection of the analogue, we investigate in the next subsections the effect of each of them, starting with the local temperature correction for topography on the bioclimatic indices, and on the selection of the vineyards analogues.

Corrections can exceed +10°C for some vineyards in Alpine regions, mainly due to elevation corrections for vineyards located in deep valleys. Moreover, temperature corrections on the order of ±1°C or more are widespread across the domain, emphasizing the importance of incorporating such adjustments to accurately capture microclimatic effects at vineyard locations. The correction to the daily mean temperature on May 15, 2006 at each vine location is presented in the supplementary material (Fig. S5.1).

Figure 7 shows the distribution of temperature corrections due to slope and elevation across the 21,076 vineyards on May 15, 2006. The corrections fall within the range of $[-0.05, 0.05]$°C (central bin) for 16,106 vineyards for the daily mean temperature slope correction ($\Delta T_{\text{slope,daily}}$), and 13,223 vineyards for the daily maximum temperature slope correction ($\Delta T_{\text{slope,max}}$). The elevation correction (ΔT_{el}) dominates the overall corrections. It ranges from −5.2°C to 11.3°C with an average value of $+0.19 \pm 0.76$°C across all vineyards. It is mostly positive because vineyards are typically located on sloped terrain, such as mountain slopes, but not at high elevations to optimise temperature. As a result, in mountainous regions, the average elevation of the RCM grid tends to be higher than the actual elevation of the vineyards, leading to a positive temperature correction. Furthermore, 26% of vineyards have an elevation correction exceeding ±1°C, which is significant for grape development as it corresponds to a correction over 180 degree-days over the season. While the slope correction to the daily mean temperature remains relatively small overall, with only 9% of vineyards experiencing a correction greater than ±0.1°C, this proportion rises to 44% when considering values of the slope correction to the daily maximum temperature. The impact of the temperature correction on the bioclimatic indices and on the Principal Components is discussed in the supplementary material, Section S5.

Beyond the values of the local temperature correction, we investigate its effect on the analogues of European vineyards. Analogues are computed using method (iii) from Table 1. Fig. 5c illustrates different typical behaviours for the same five specific vineyards as in Fig. 5a with and without temperature corrections. In Villamanrique de la Condesa (Spain) and Tállya (Hungary), analogues are dispersed without corrections but align consistently in Southern France and Croatia, respectively, when corrections are applied. For Alektora (Cyprus), the analogues are split into distinct regions with temperature corrections. Noicattaro (Italy) shows analogues spread across the entire coast of the Mediterranean Sea both with and without temperature corrections. Finally, analogues of Oberderdingen (Germany) shows minimal influence on the corrections. Analogues obtained without temperature corrections represent an intermediate result between generic and problem-specific methods (Fig. 5a). However, these corrections alone do not account for the full difference between the two approaches, indicating that the incorporation of bioclimatic indices and PCA-weighting also have a significant impact, as will be discussed in Sections 3.4 and 3.5.

The first five analogues of each of the 21,076 European vineyards are distributed across 8,318 distinct points of the RCM computational grid without temperature corrections, and 11,881 with temperature correction (Fig. 5d). This indicates that temperature correction widens the geographic area where climate analogues are distributed by better considering the local features. Indeed, the correction increases the contrast between two vineyards that are located close to each other, especially within the same grid cell. Furthermore, several analogues located in northern regions, such as England, Czech Republic, Austria, and Ukraine, appear only when temperature corrections are not applied. In contrast, warmer regions, such as the northern African coastal areas, are more represented when temperature corrections are taken into account. This trend is driven by the overall positive temperature correction, which results in warmer climatic conditions at vineyard locations. Temperature corrections also allow analogues to be located at higher elevations on mountain slopes, whereas they remain

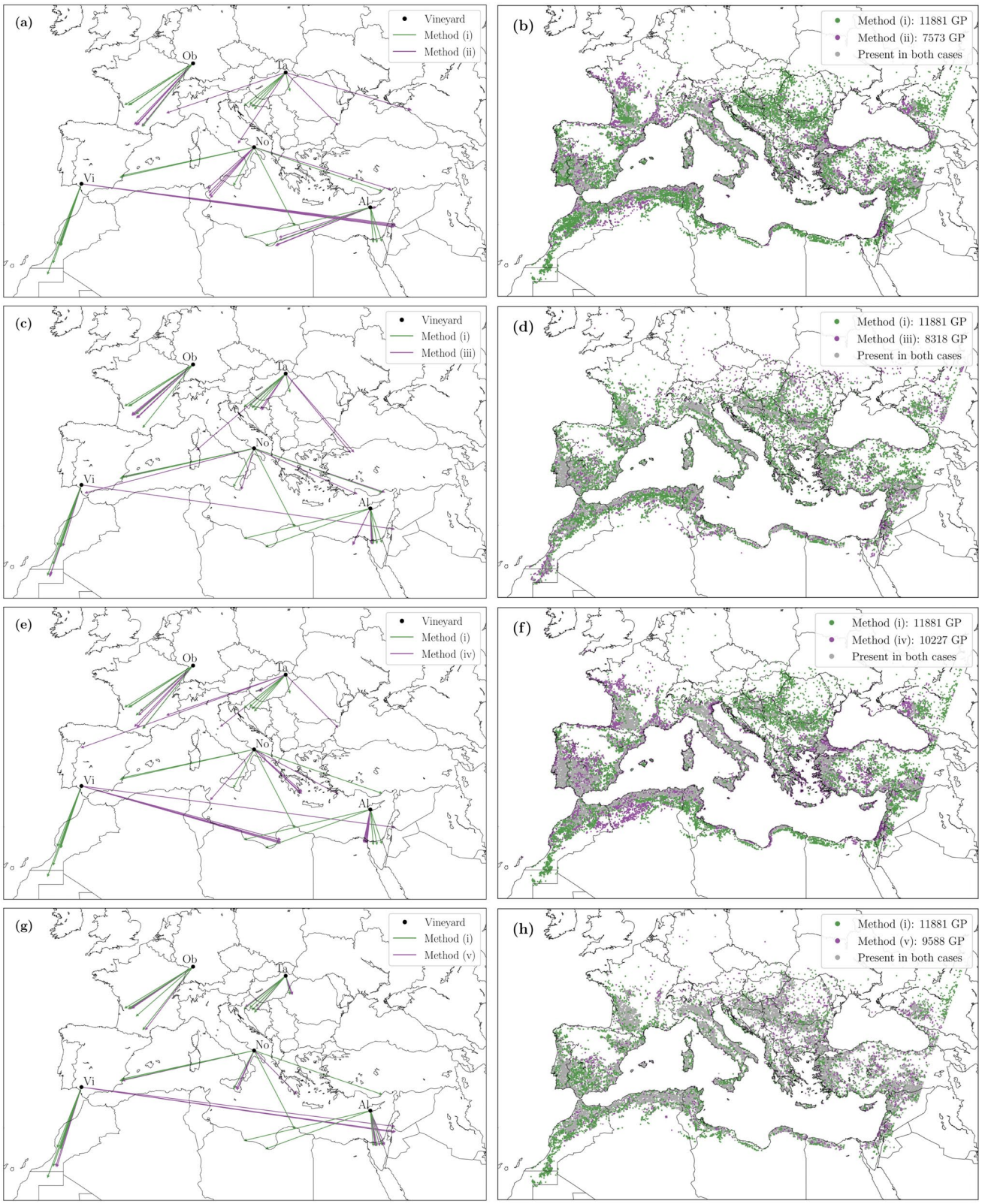

(a)
Vineyard
Method (i)
Method (ii)
Ob
Ta
No
Vi
Al
(b)
Method (i): 11881 GP
Method (ii): 7573 GP
Present in both cases
(c)
Vineyard
Method (i)
Method (iii)
(d)
Method (i): 11881 GP
Method (iii): 8318 GP
Present in both cases
(e)
Vineyard
Method (i)
Method (iv)
(f)
Method (i): 11881 GP
Method (iv): 10227 GP
Present in both cases
(g)
Vineyard
Method (i)
Method (v)
(h)
Method (i): 11881 GP
Method (v): 9588 GP
Present in both cases

Fig. 5 Locations of the first five current (2020) analogues of European vineyards in 2080 using method (i) and compared with those obtained using method (**a**, **b**) (ii), (**c, d**) (iii), (**e**, **f**) (iv), and (**g**, **h**) (v). See Table 1 for details of the configurations. Analogues identified using method (i) are displayed in green, while those identified using the alternative methods are displayed in purple. **Left column:** Analogues of five vineyards representative of the observed behaviours: Vi: Villamanrique de la Condesa (Spain); Ob: Oberderdingen (Germany); No: Noicattaro (Italy); Ta: Tállya (Hungary); Al: Alektora (Cyprus). Each arrow points to an analogue of the corresponding vineyard. **Right column:** Grid points (GP) identified as analogues of at least one individual European vineyard using the corresponding method. The number of analogue GP displayed in the legend corresponds to the total number of distinct GB identified as analogues for at least one vineyard using the corresponding method

in lower-lying plains without corrections. Indeed, sloped terrains experience locally higher temperatures due to the corrections, making them more suitable for vine-growing. This effect can be observed in regions such as the south of the Carpathian Mountains in Romania, along the Apennine Mountains in Italy, the Atlas Mountains in Morocco and Algeria, and parts of Turkey. Hence, sub-grid scale corrections are essential for representing reliable climate analogues and capturing the full range of sub-grid phenomena. However, the similarity index is only marginally affected by the temperature correction (Fig. 4c), with 5.6% of of the five best analogues exhibiting a value of $SI < 0.9$, against 5.8% with temperature corrections.

Temperature corrections slightly reduce the mean distance between vineyards and their analogues from 1330 ± 608 km to 1190 ± 582 km. This is because, with corrections, analogues can be found at higher elevations instead of shifting north or south to maintain similar climatic conditions. Furthermore, the distribution of distances between analogues obtained with and without temperature corrections (Fig. 6b) includes many values significantly greater than zero, indicating that the analogue for certain vineyards can differ at the continental scale when these corrections are applied.

Out of the 57 wine-growing regions, 9 have a best analogue region located within 500 km of the one obtained

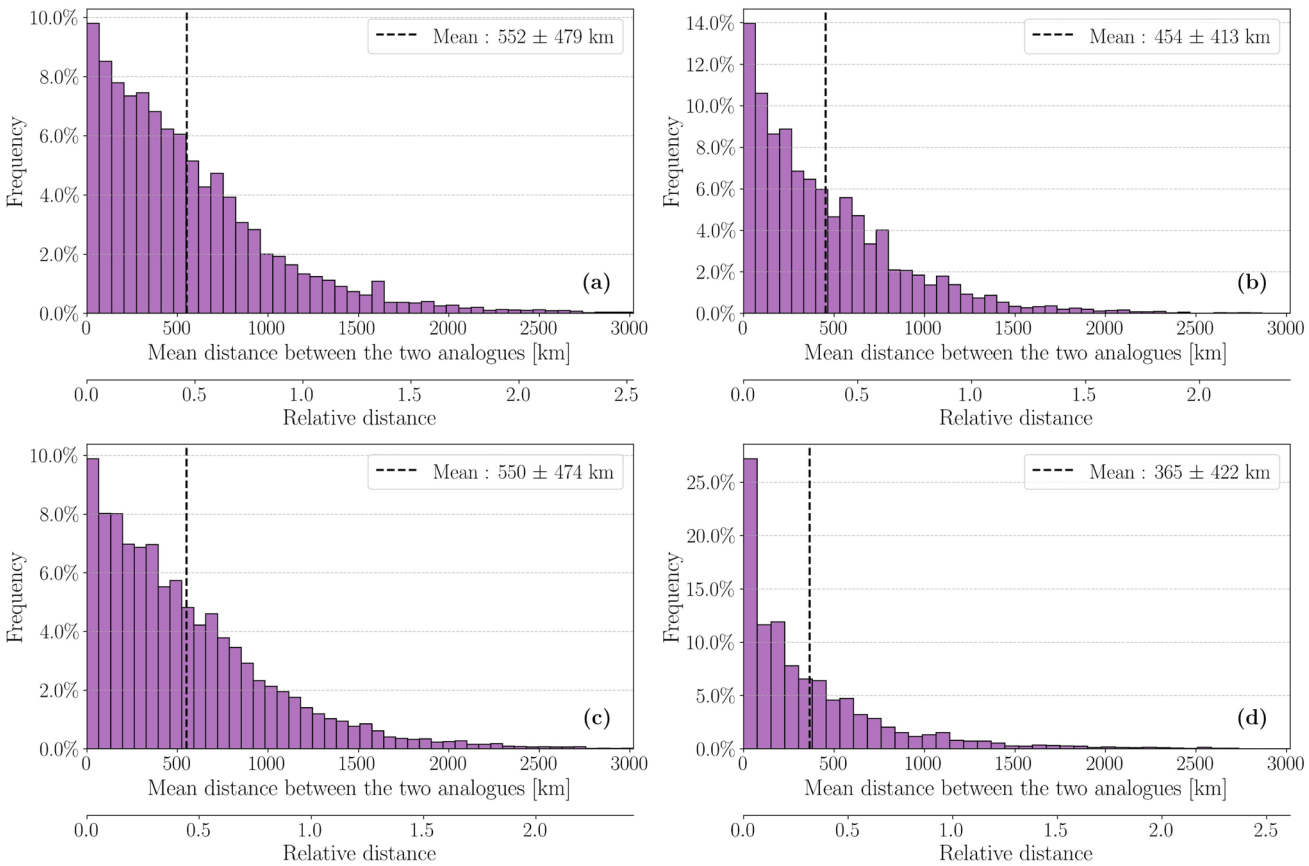


Fig. 6 Distribution of the mean distance between the five best analogues obtained with method (i) and those obtained with (**a**) method (ii), (**b**) method (iii), (**c**) method (iv), and (**d**) method (v). See Table 1 for details of the methodological configurations. Relative distances represent the distance normalised by the mean distance between a vineyard and its five best analogues, averaged between method (i) and the corresponding alternative method, computed using Eq. 2.4

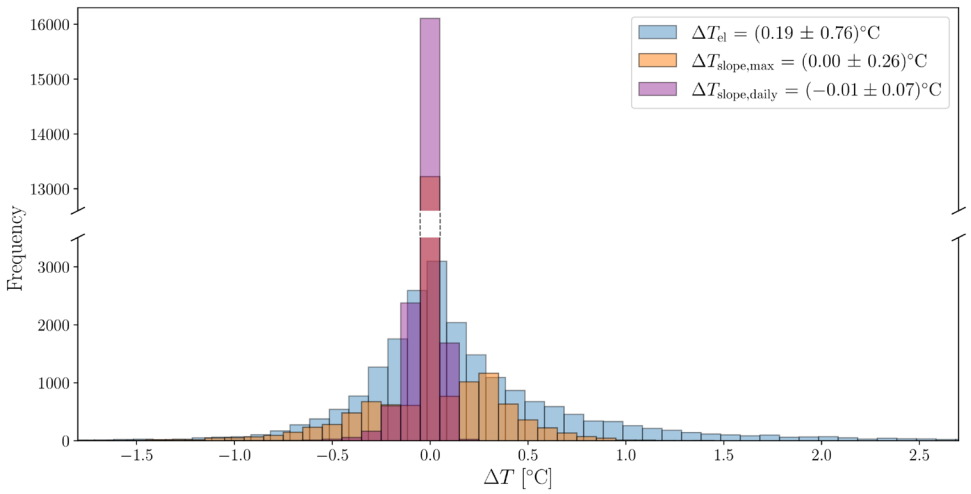


Fig. 7 Distribution of the temperature corrections due to elevation and slope on May 15, 2006. ΔT_{el}: correction to the mean, maximum and minimum temperature due to elevation; $\Delta T_{slope,max}$: correction to the daily maximum temperature due to slope; $\Delta T_{slope,daily}$: correction to the daily mean temperature due to slope

using temperature corrections, while 20 regions shift to a new analogue region located more than 500 km away (see Fig. S6.4 for the corresponding analogues). Hence, sub-grid corrections have a significant impact on the analogue selection of the regions, and cannot be discarded.

Hence, the temperature corrections for sub-grid topography substantially affects the identification of both individual vineyard analogues and vine-growing regions, in some cases at the continental scale. Corrections extend the spread of the area featuring vineyard analogues and reduce the distance between regions and their analogues by allowing more elevation shifts. Therefore, these corrections, particularly the effect of elevation, is essential to get application-relevant analogues. However, it is far from explaining the full difference between the generic and the problem-specific methods.

3.4 Impact of bioclimatic indices on the analogues selection

In this section, we investigate the effect of calculating analogues using bioclimatic indices rather than the raw physical model outputs, namely the daily mean, maximum and minimum temperature, precipitations and humidity. In this section, analogues are computed using method (iv) from Table 1.

Figure 8 compares the principal components derived from bioclimatic indices with those derived directly from the underlying physical variables. In both cases, the first principal component contrasts temperature-related variables (daily mean and maximum temperature, Huglin index, flavescence dorée index, and extreme heat days) with

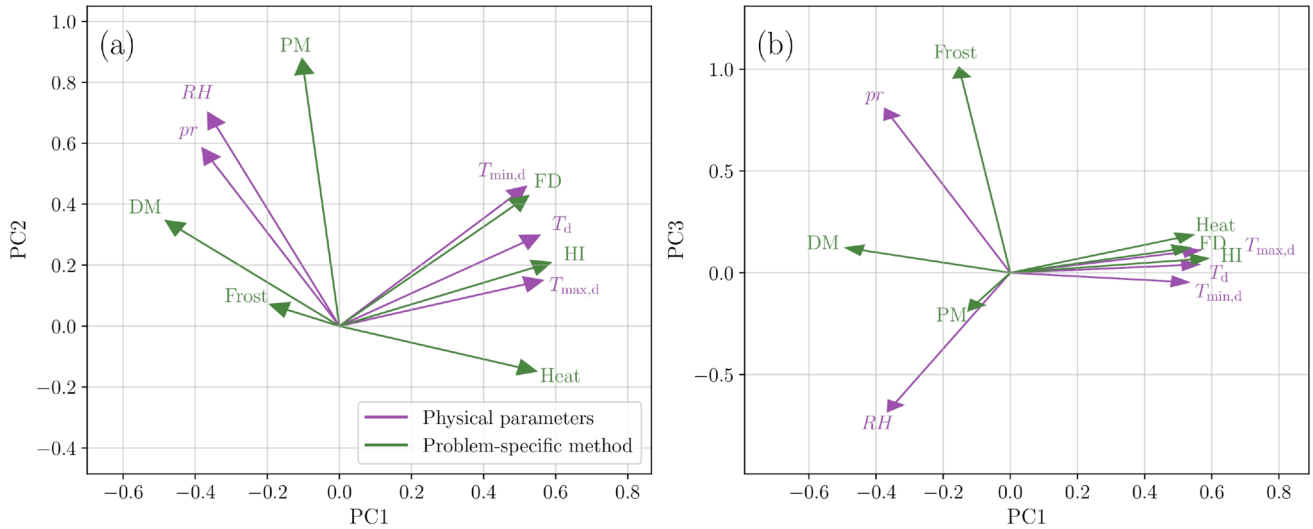


Fig. 8 Contribution of each index to the three first principal components computed from the six bioclimatic indices, and from five physical parameters. (a) PC1 vs PC2 and (b) PC1 vs PC3. HI: Huglin index, FD: flavescence dorée index, Frost: frost days index, Heat: heat days index, DM: downy mildew index, PM: powdery mildew index, T_d: daily mean temperature, $T_{max,d}$: daily maximum temperature, $T_{min,d}$: daily minimum temperature, *pr*: precipitation, *RH*: relative humidity

humidity-related variables (relative humidity, precipitation, and the downy mildew index), consistent with the Clapeyron equation (Wallace and Hobbs 2006). One notable exception is the frost index, which contributes modestly but in the opposite direction as other temperature-related variables. The second principal component is strongly influenced by the powdery mildew index when using bioclimatic indices, whereas it is dominated by relative humidity and precipitation in the case of raw physical variables. In contrast, the third component is led by the frost index–opposed to the powdery mildew index–in the bioclimatic indices PCA, while in the physical variables PCA, it reflects a contrast between precipitation and relative humidity.

Figure 5e and 5f show the locations of the five best analogues of European vineyards, computed using either method (i) or (iv). The typical analogue behaviours for the same five representative vineyards as in the previous subsections are illustrated in Fig. 5e. While Oberderdingen (Germany), shows minimal impact of the bioclimatic indices, all other selected vineyards have significantly different analogues depending on the parameters chosen. This evidences the added value of the bioclimatic indices. However, method (iv) is not equivalent to method (ii) (Fig. 5a), highlighting the importance of temperature corrections and the PCA-weighted SED (see Sections 3.3 and 3.5).

The locations of the five best analogues for all European vineyards (Fig. 5f) are spread across 11,881 points when bioclimatic indices are used, vs. 10,227 points when considering physical parameters. In this latter case, there are significantly fewer analogues in Northern Africa, Turkey, as well as in the Balkans, compared to the distribution observed when using bioclimatic indices. In contrast, analogues tend to be located in coastal regions, such as the Atlantic coast, Israel, and around the Black Sea. This is primarily because coastal regions are typically more humid, and two out of the five physical parameters–precipitation and relative humidity–are directly related to humidity. As a result, even when accounting for correlations between variables using PCA, these two variables have a significant weight in the selection of analogues. The use of physical parameters results in less contrasted similarity index (Fig. 4d), with fewer low values (0.5% below 0.9 for the five best analogues, compared to 5.8% when using bioclimatic indices), but also fewer very high values (57.9% above 0.99, compared to 77.5% with bioclimatic indices).

The mean distance between each vineyard and its five best analogues is slightly greater using method (iv) compared with method (i) ($1,290 \pm 538$ km vs. $1,190 \pm 582$ km). Additionally, 98% of vineyards have a non-zero distance between analogues obtained with and without temperature corrections (Fig. 6c). This again underscores that omitting to consider problem-specific indices can substantially alter the analogue identified for certain vineyards. Only 10 best analogue regions are the same than when considering bioclimatic indices (see FigS6.5 for the corresponding analogues). Southern Turkey and Southeastern Anatolia are mapped to themselves due to their topography, and Bourgogne, Champagne, Alsace, and Western Switzerland all map to Bordeaux and South-West of France. Of the remaining regions, 8 experience a shift in their analogue region of less than 500 km, while 39 undergo a shift exceeding 500 km. Thus, considering the selected bioclimatic indices instead of the raw climate variable significantly changes the analogues obtained, illustrating the added value of using bioclimatic indices tailored to the case under study.

3.5 Impact of the compensation for redundancies between indices on the analogues selection

Finally, we analyse the impact of PCA on the analogue selection. In this section, all analogues have been computed using method (v) from Table 1.

Examples of the same vineyard analogues as in previous sections are presented in Fig. 5g, showcasing the impact of PCA on different patterns of analogue distribution. The distribution of climate analogues varies widely, ranging from tightly clustered matches within a localized area to more dispersed analogues spread across larger geographic regions, both with and without PCA. For some vineyards–such as Oberderdingen or Tállya–the application of PCA has little effect on analogue selection, while other sites exhibit notable differences in analogue locations. Villamanrique de la Condesa has more spread results without PCA. In contrast, Noicattaro and Alektora have more spread analogues with PCA. The analogues are again intermediate results between the problem-specific and the generic methods (Fig. 5a).

We now turn to the overall distribution of analogues across all vineyards. The five best analogues of all European vineyards are spread over 11,881 points when PCA is applied, against 9,588 points without PCA. Although the distribution of analogues does not differ significantly in both cases, more analogues are found in Northern Africa, Southern Spain and Southern Russia when PCA is applied (Fig. 5h). These regions are mountainous and coastal, where the pathogen indices are more important due to the influence of moisture. Reducing the artificial overweighting of the temperature-related indices, especially the highly correlated Huglin and flavescence dorée indices, leaves more space for fungi-related indices to contribute to the results. Furthermore, the robustness of each analogue pairing is significantly influenced by the application of PCA. Figure 4e illustrates the similarity indices for the top 20 analogues of each European vineyard computed without PCA, while those obtained with PCA are shown in Fig. 4a. Without

PCA, 8.5% of the analogues have a similarity index below 0.9, whereas this decreases to 5.8% when PCA is applied. This indicates that the refined methodology yields more reliable and consistent analogue matches.

Figure 6d presents the distribution of the mean distance between analogues identified with methods (i) and (v). The overall mean distance remains similar ($1,121 \pm 686$ without PCA vs. $1,190 \pm 582$ with PCA). The distance between the two sets of analogues is skewed towards zero, indicating that most vineyards are only slightly affected by PCA. Nonetheless, the mean distance of 365 ± 422 km indicates that a notable subset of vineyards displays substantial changes in analogue identification when PCA is applied.

At the region level, among the 57 regions, 39 have the same best analogue, 4 retain a best analogue within 500 km of the one identified with PCA, while 14 shift to a different analogue region more than 500 km away (see Fig. S6.6 for the corresponding analogues).

In summary, the three methodological refinements yield significantly different analogues compared to the generic method, and the three effects are cumulative. Differences arising between analogue sets obtained using different configurations reflect differences in the information provided by the selected input variables, but also their processing. They highlights the added value of considering problem-specific adjustments which have a significant impact on analogue selection and lead to analogues that are more tailored to the specific application. Among the three methodological adjustments examined, the incorporation of bioclimatic indices has the greatest impact on analogue selection, while the effect of PCA is slightly lower. They affect both individual vineyards and broader vine-growing regions, with differences sometimes observed on a continental scale. Bioclimatic indices notably expand the area of potential analogues, reaching more inland regions, whereas physical variables tend to limit analogues to coastal zones. A summary of all the results associated with the five climate analogue methodologies can be found on Table 2.

One should note that study is based on a single RCM simulation (HIRHAM5) and a single emission scenario (RCP8.5). This setup does not represent the full range of uncertainties associated with future climate projections. The results should therefore be interpreted solely as a methodological case study for demonstrating and refining the identification of climate analogues, rather than as predictions of future vineyard conditions or recommendations for vineyard establishment and planning.

Table 2 Summary table of the results associated with the five climate analogue methodologies. See Table 1 for the definitions of the different methodological configurations

Method	Vineyards with $SI < 0.9$	Distance to 5 best analogues [km]	Distance with analogues of (i) [km]	Analogue grid points	Analogue region different from (i)
(i)	5.8%	$1,190 \pm 582$	–	11,881	-
(ii)	29.2%	$1,197 \pm 582$	552 ± 479	7,573	77%
(iii)	5.6%	$1,330 \pm 608$	454 ± 413	8,318	51%
(iv)	0.5%	$1,290 \pm 538$	550 ± 474	10,227	82%
(v)	8.5%	$1,121 \pm 686$	365 ± 442	9,558	32%

4 Conclusion

This study examines how incorporating problem-specific considerations influences the choice of climate analogues for European vineyards. This problem-specific methodology encompasses three dimensions: a sub-grid temperature correction accounting for altitude, slope, and aspect, the use of bioclimatic indices representative of the vine growth and pathogens, and the use of PCA to disentangle redundancies between the considered indices. Each of these refinements to the generic climate analogue approach converges towards a finer pairing of the analogues. The set of obtained analogues covers a wider area when they are considered. Furthermore, while they have only a minimal effect on the distance statistics between the reference points and their analogues, their consideration can shift the analogue of a given vineyard by hundreds to above one thousand kilometres, hence at the continental scale. Furthermore, the magnitude of the impact of the three investigated adjustments on the determined analogues is comparable, so that the three of them have to be considered for obtaining relevant analogues. In contrast, the cut-off in the number of analogues to consider per individual vineyard in the process of determining analogue regions turns out to be arbitrary, as the results are pretty robust against its changes.

Our sensitivity study therefore illustrates the critical need to properly define the indices used in the determination of climate analogues by tailoring them to the problem of interest, of properly handling the typical redundancies between these indices, as well as consider local sub-grid features likely to influence the relevant indices. While our case study focuses on vine, any physiologically-related situation, including other crops, but also human comfort, e.g., in the context of urban planning would benefit of a problem-specific approach in defining climate analogues. Depending on the specific context, the appropriate temporal resolution may need to be adjusted, ranging from daily to yearly scales.

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Author Contributions J.K. and S.G. conceived the study. H.A. defined the methodology, performed the analysis, and drafted the paper. H.A., S.G., P.-H.D. and J.K. analysed the results and reviewed the manuscript.

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Data Availability The locations of European vineyards were obtained from the CORINE Land Cover database. Topographic data were extracted from the European Digital Elevation Model provided by Eurostat. Climate datasets were obtained from the CORDEX data base. The Python code used to process the data is available in the Yareta repository of the University of Geneva (Allaman et al. 2025).

Declarations

Competing Interests The authors have no relevant financial or non-financial interests to disclose.

Ethics approval and consent to participate Not applicable.

Consent for publication All authors consent to the publication of this manuscript.

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