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Evaluation of daily crop reference evapotranspiration and sensitivity analysis of FAO Penman-Monteith equation using ERA5-Land reanalysis database in Sicily, Italy

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ABSTRACT

Crop evapotranspiration (ET) is one of the most important components in many hydrological processes. The crop reference evapotranspiration (ETo) represents the atmospheric water demand in each crop type, development stage, and management practices. The Penman-Monteith equation in the version suggested by the Food and Agriculture Organization (FAO56-PM), is one of the most used methods to estimate ETo. In several regions of the world, meteorological observations are not always available. The most recent reanalysis database ERA5-Land, released in 2019, can be useful to overcome this limit. The database provides, with a spatial grid of 0.1° latitude and 0.1° longitude, several hourly climate data such as air temperature, dew point temperature, solar radiation, and wind speed components all at 2.0 m above the soil surface, except wind speed components at 10 m, useful to apply the FAO56-PM equation. The objective of this research is to assess the quality of ERA5-Land climate variables data to estimate daily ETo in Sicily, Italy. The effect of the weather station's elevation associated with the statistical indicators was also evaluated to verify how the morphology affects the measurements. Finally, the sensitivity analysis of the FAO56-PM equation was carried out to identify which climate variables have the most influence on the ETo estimation. For the period 2006–2015, the comparison between air temperature, global solar radiation, wind speed, and relative air humidity, measured from 39 ground weather stations in Sicily, and ERA5-Land was carried out and then, through FAO56-PM equation daily ETo values were estimated using both databases. The statistical indicators Root Mean Square Error (RMSE) and Mean Bias Error (MBE) confirm the possibility of considering the ERA5-Land a suitable solution to estimate ETo. The sensitivity analysis showed that good ETo estimation depends mainly on the accuracy of the relative air humidity and air temperature data.

1. Introduction

The knowledge of crop evapotranspiration ET represents a key factor in many disciplines with agricultural and ecological implications and, specifically in irrigated areas, for irrigation water management and to simulate crop growth and yield.

The concept of reference crop evapotranspiration ETo was introduced to estimate the atmospheric evaporative demand regardless of crop type, development stage, and management practices. ETo is defined as the potential evapotranspiration of a hypothetical green grass (reference crop) with uniform height (8–15 cm), covering the ground, and growing in the absence of water shortage and diseases. Therefore, the value of ETo depends only on climate parameters, so the different computation models, in terms of input data requirement, need only meteorological variables (Doorenbos and Pruitt, 1977). The limited availability of recorded meteorological data in several regions of the world has driven the development of approaches based on simpler equations, such as those only requiring air temperature (temperature-based methods) or air temperature and incoming solar radiation (radiation-based methods). However, among the available methods, the Penman-Monteith equation (FAO56-PM), based on air temperature, global solar radiation, wind speed, and relative air humidity, is

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considered one of the most accurate and therefore is recommended as a reference to calibrate other more simplified procedures, which are normally site-specific (Allen et al., 1998; Minacapilli et al., 2016). Although weather stations can provide accurate data in the measurement sites, spatial interpolation is necessary where information is missing; conversely satellite and reanalysis products of climate data can provide complete spatial coverage, despite the potential inaccuracy (Mendelsohn et al., 2007).

To estimate and map, at the global scale, crop reference evapotranspiration reliable, quasi-continuous over-time and spatially-distributed meteorological informations are needed. For this reason, several gridded of climate data, with different spatial and temporal resolutions, have been developed and are freely available by research agencies, for example, National Aeronautics and Space Administration (NASA) and European Centre for Medium-Range Weather Forecasts (ECMWF). Global datasets of atmospheric and land surface variables, represented in 'maps without gaps', are created coupling weather forecast models and data assimilation systems, periodically 'reanalysed' by past observations. Reanalysis data, based on data assimilation, are among the most used to study climate dynamics (Parker, 2016). The reanalysis method combines model data based on past observations across the world for monitoring and forecasting climate change, for research, education, and commercial applications. The ERA5-Land (*ERA5-L*) product was released in 2019, provided by the ECMWF, as the evolution of the *ERA5* dataset, aimed at enhancing the resolution of the spatial grid of 0.1° latitude and 0.1° longitude. Specifically, in the *ERA5-L* the simulated land fields are controlled by a process of atmospheric forcing using air temperature, air humidity, and air pressure, a detailed description of the model used for the production of *ERA5-L* is available in IFS Documentation CY45R1 (IFS Documentation CY45R1, ECMWF, 2018).

In a recent review presented by Muñoz-Sabater et al. (2021), it is possible to notice the state-of-the-art associated with the use of *ERA5-L* for land and environmental applications.

The suitability of the *ERA5-L* databases related to different climate variables has been recently investigated by several authors (Pelosi et al., 2020; Pelosi and Chirico, 2021; Araújo et al., 2022; Vanella et al., 2022). Pelosi et al. (2020) used air temperature, wind speed, vapor pressure deficit, and solar radiation acquired from 18 ground weather stations in Campania region, afterwards Pelosi and Chirico (2021) investigated data retrieved from 38 weather stations and using FAO56-PM equation found that the reanalysis database can represent a suitable resource to replace missing climate data. Araújo et al. (2022) considered air temperature acquired from 12 automatic weather stations in the Pernambuco state, Brazil, and highlighted that the values retrieved from *ERA5-L* can represent a good surrogate of the corresponding measurements where ground data are not available. Vanella et al. (2022), assessed the performances of the *ERA5-L* reanalysis climate data over 66 weather stations distributed among 7 irrigation districts placed from north to south Italy. The application of bias correction procedure on reanalysis climate variable is surely a relevant issue. Several studies have assessed the quality of bias correction procedure in reanalysis climate variables (Fang et al., 2015; Hwang et al., 2014; Maraun, 2013; Srivastava et al., 2015). Paredes et al. (2018) focused on evaluating the accuracy of the reanalysis database (ERA-Interim) to estimate ETo; the authors found that the highest performances are obtained when on ETo is computed from reanalysis climate data corrected with a bias correction procedure. Although, previous studies have already demonstrated that the bias correction procedures are necessary to improve the quality of ETo predictions, recently, Vanella et al. (2022) and Gourgouletis et al. (2023) obtained reliable and encouraging ETo estimations without implementing bias correction procedure. Moreover, although Pelosi and Chirico (2021) applied the bias correction procedure, they verified that after the application of bias correction to the solar radiation, the performance of ETo estimation does not significantly improve. Therefore, the issue regarding the application of bias correction procedure on climatic reanalysis data can be considered an open research question that requires further investigation.

In literature, many authors have demonstrated that generally (o globally) the reanalysis climate data are a good surrogate of the data recorded by the climatic stations (De Caro et al., 2023; Negm et al., 2017; Pelosi, 2023; Sheffield et al., 2004), probably this is truer for some variables than for others, therefore could be useful to combine the study of the reanalysis climate data quality, with the FAO56-PM equation sensitivity analysis, not investigated yet in Sicily since sensitivity analysis allows to determine which variables have a greater influence on the ETo estimation (Irmak et al., 2006). In general, several applications of sensitivity analysis have been carried out for various models, different reanalysis databases, theoretical approaches, weather conditions as hydrological studies (Anderton et al., 2002) or sediment transport models (Newham et al., 2003), as well as evapotranspiration estimations (Gong et al., 2006; Koudahe et al., 2018; Liang et al., 2008). The purpose of sensitivity analysis is to identify the main variables affecting the process and to evaluate the associated sensitivity coefficient. When referring to a generic variable, v_i, the sensitivity coefficient, S_{vi}, shows how big is the variation of the model output caused by a fixed variation of the variable, v_i. Despite different authors have already investigated the sensitivity of the climate variables required by the FAO56-PM equation (Gong et al., 2006; Liang et al., 2008), possibly the result could be strongly conditioned by the climate of the site for which the analysis is conducted. Considering the heterogeneous Sicilian topography and the diffuse presence of the sea, that could affect the climate variables, to carry on a sensitivity analysis of the FAO56-PM equation in Sicily is appropriate.

The most recent literature focused on the assessment of ETo using climate variables from reanalysis database (Pelosi and Chirico, 2021; Vanella et al., 2022; Pelosi, 2023) have in common with this research the study area and the ground climate data source, but the novelty of this research lies in the using the raw reanalysis *ERA5-L* climate variables databases, in other words without modifying in any way the data provided by *ERA5-L*. Moreover, in this study the sensitive analysis of the FAO56-PM equation was carried out to identify which climate variables have the most influence on the ETo estimations in a region like Sicily which represents the typical Mediterranean environment. Therefore, the main objective of this study is to assess the performance of the FAO56-PM equation using the *ERA5-L* climate dataset in Sicily, Italy and for this purpose, the ground data acquired from 39 weather stations in Sicily managed by the "Servizio Informativo Agrometeorologico Siciliano" (SIAS) have been used: after analysing the differences between each climatic variable, retrieved from the *ERA5-L* dataset and the corresponding measured on the ground at a daily time-step, the accuracy of daily FAO56-PM ETo estimations was evaluated. Finally, a sensitivity analysis was carried out to identify the variables that mostly influence the estimation of ETo and the associated errors were calculated.

2. Materials and methods

2.1. FAO56-Penman-Moteith equation

The FAO56-PM equation was used to estimate daily crop reference evapotranspiration, ETo [mm d^{-1}] (Allen et al., 1998):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{(T+273)} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

where Δ [kPa °C^{-1}] is the slope of the vapour pressure curve, R_n [MJ m^{-2} d^{-1}] is the net radiation at the crop surface, G [MJ m^{-2} d^{-1}] is the soil heat flux density, γ [kPa °C^{-1}] is the air psychrometric constant, T [°C] is the mean daily air temperature, u_2 [m s^{-1}] is the wind speed at 2.0 m height above the ground and, finally, e_s and e_a [kPa] are the saturation and actual vapour pressure. At the daily time step, the value of G can be assumed negligible as its magnitude, compared to the other terms of Eq. (1), is relatively small (Allen et al., 1998).

2.2. Database description and data sources

The carried analysis considered the on-ground climate variables acquired by a network of 39 spatially distributed weather stations, chosen in order to consider the different environmental conditions and morphological characteristics of Sicily Island, belonging to the largest monitoring network of 96 stations operated by the SIAS (www.sias.regione.sicilia.it/). In the decade from January 1st, 2006, to December 31st, 2015, the data from these stations and the corresponding data available in the *ERA5-L* dataset were analysed. Fig. 1 shows the location of the SIAS weather stations and the grid of the *ERA5-L* dataset.

2.2.1. SIAS ground climate variables

The SIAS database contains all the climate variables required for the application of the FAO56-PM equation measured at 2 m above the ground, and, specifically, daily values of maximum and minimum air temperature, T_{min}, T_{max}, [°C], maximum and minimum relative air humidity, RH_{min}, RH_{max}, [%], global solar radiation, R_s, [MJ $m^{-2}d^{-1}$], and wind speed, u_2, [m s^{-1}]. For the analysis that will be described below, the values of the wind speed measured at 10 m above the ground, u_{10} [m s^{-1}], will also be used, provided by 27 out of the 39 weather stations. The screening of the database was first carried out to check the temporal coverage of the climate variables, verifying, for all the SIAS weather stations, the number of days in which all the variables were recorded. Since all the 39 weather stations selected have an acceptable percentage of days in which all the variables are recorded, all were considered in this research. Table 1 reports the station's identification code (ID), the name of the stations, as indicated in the original database, their geographic coordinates, elevation, and percentage of days with complete records.

2.2.2. ERA5-Land reanalysis climate variables

The *ERA5-L* dataset includes all the above-mentioned climate variables, except for wind speed at 2 m height and relative air humidity.

Hourly data of air temperature, global solar radiation, dew-point air temperature, T_{dew} [°C], and the horizontal, U_H [m s^{-1}], and vertical, U_v [m s^{-1}], components of wind speed at 10 m height, were downloaded from the climate data store (CDS3) under the Copernicus C3S/CAMS license agreement (Muñoz-Sabater, 2019) and then a Matlab™ script was developed to identify the grid cells containing the 39 SIAS weather stations.

The hourly relative air humidity, not directly downloadable from the reanalysis database, was calculated as the ratio between actual, $e_a(T_{dew})$ [kPa], and saturated, $e_s(T)$ [kPa], vapour pressure calculated in function of T_{dew}, and T, respectively. Following the formulas suggested by Allen et al. (1998):

$$RH = 100\frac{e_a(T_{dew})}{e_s(T)} \tag{2}$$

Wind speed at 10 m above the soil, u_{10} [m s^{-1}], was calculated using the two components U_H and U_v, according to the methodology proposed by Allen et al. (1998).

Since all the variables, for both databases, are evaluated at 2 m above the ground, it would be necessary retrieve the values of wind speed measured at 2 m from the ground through the ones at 10 m, provided by *ERA5-L*, assuming a logarithmic profile. Therefore, to make the two

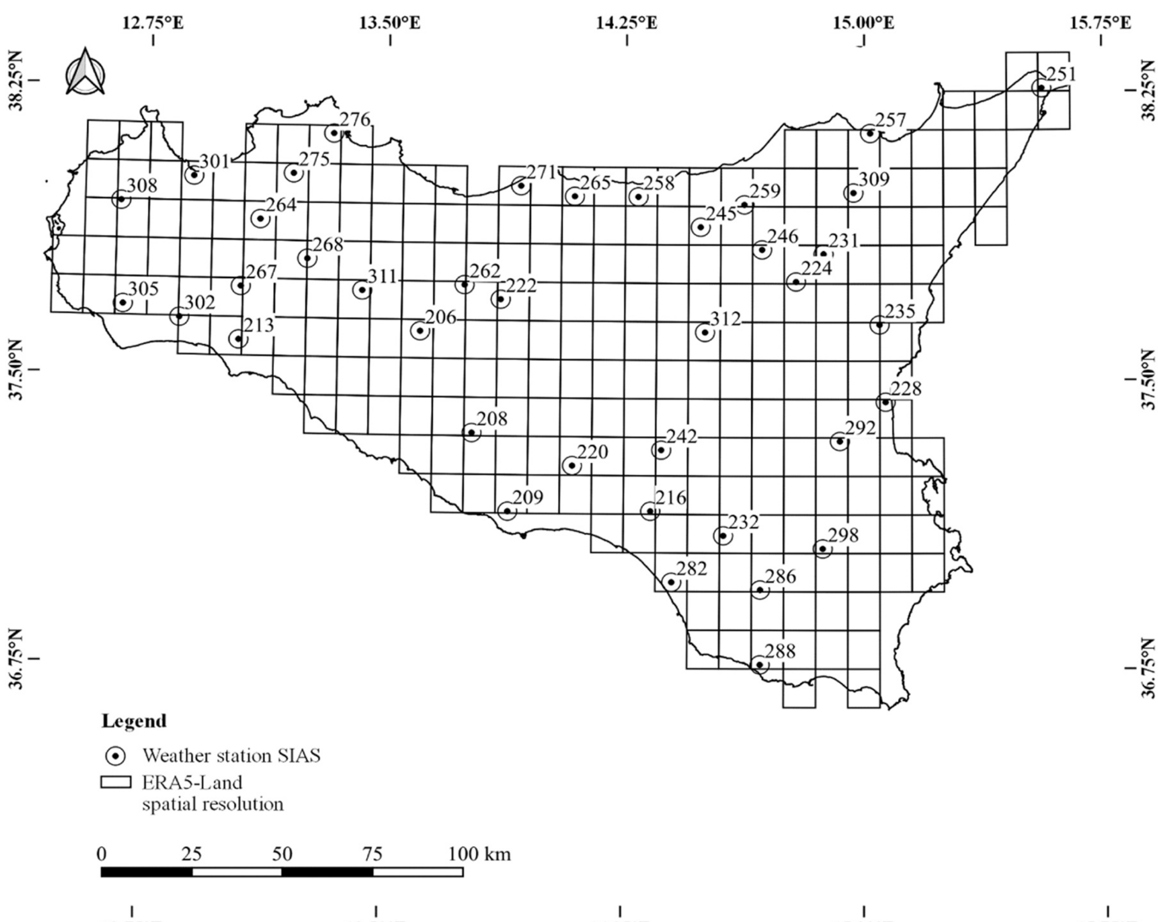

Fig. 1. Sicily map with the position of SIAS weather stations and the grid of ERA5-Land dataset.

Table 1
Identification code (ID), name of SIAS weather station, geographic coordinates, and number of available records in the period 2006–2015.

ID	Weather station	Latitude (°N)	Longitude (°E)	Elevation (m a.s.l.)	Available records (%)
206	Cammarata	37.6205	13.6085	350	96.7
208	Canicatti	37.3580	13.7740	475	95.5
209	Licata	37.1550	13.8888	80	96.9
213	Sciacca	37.5913	13.0398	90	98.6
216	Gela	37.1580	14.3340	70	84.7
220	Riesi	37.2750	14.0890	300	94.5
222	Sclafani_Bagni (*)	37.7050	13.8600	497	97.3
224	Bronte (*)	37.7550	14.7870	424	95.4
228	Catania	37.4430	15.0680	10	95.8
231	Maletto	37.8271	14.8732	1040	95.7
232	Mazzarrone	37.0954	14.5617	300	92.9
235	Pedara (*)	37.6436	15.0492	810	74.2
242	Piazza Armerina	37.3170	14.3670	540	93.7
245	Caronia Pomiere (*)	37.8961	14.4866	1470	78.4
246	Cesarò Vignazza	37.8380	14.6800	820	99.6
251	Messina (*)	38.2581	15.5611	421	92.1
257	Patti	38.1405	15.0195	70	97.6
258	Pettineo	37.9740	14.2900	210	99.7
259	San Fratello (*)	37.9547	14.6239	1040	94.2
262	Alia Porcheria	37.7418	13.7460	560	92.6
264	Camporeale Azzolina (*)	37.9046	13.1010	460	96.9
265	Castelbuono (*)	37.9741	14.0897	430	95.3
267	Contessa Entellina (*)	37.7299	13.0436	200	94.1
268	Corleone	37.8040	13.2510	450	97.9
271	Lascari Lentina	38.0001	13.9201	55	98.7
275	Monreale Vigna	38.0249	13.2031	630	97.5
276	Palermo	38.1300	13.3280	50	92.9
282	Acate	36.9740	14.4010	60	94.6
286	Ragusa	36.9550	14.6770	650	93.0
288	Scicili Palmentella	36.7606	14.6768	30	99.1
292	Lentini	37.3410	14.9250	50	98.2
298	Palazzolo Acreide	37.0620	14.8720	640	94.3
301	Castellammare del Golfo (*)	38.0139	12.8896	90	95.0
302	Castelvetrano	37.6470	12.8530	120	96.7
305	Mazara del Vallo	37.6791	12.6750	30	97.4
308	Trapani	37.9470	12.6620	180	95.2
309	Montalbano Elicona (*)	37.9860	14.9670	1250	95.2
311	Prizzi (*)	37.7240	13.4250	990	79.1
312	Agira	37.6230	14.5020	467	92.3

(*) climate station without the measurement of wind speed at 10 m height.

databases consistent and to avoid possible uncertainty due to the assumption of a logarithmic wind profile (Newman and Klein, 2014), daily ETo values were retrieved combining all climate variables at 2 m height and only wind speed at 10 m height. Negm et al. (2017) demonstrated that this combination could cause an overestimation of 5% in the ETo estimated values.

Finally, all mentioned climate variables were aggregated at daily time-step. The complete daily reanalysis database, for the period 2006–2015, contains 3652 records for each variable.

2.3. Statistical indicators

For each daily climate variable, *vi*, the comparison between SIAS values and *ERA5-L* values was carried out considering the slope of the regression line, forced to the origin, b_{vi}, whose target is one, and coefficient of determination, R^2, whose unitary target indicates that the variance of the observed values is totally explained by the model (Eisenhauer, 2003). The slope of the regression line b_{vi} was used as a measure of accuracy, while the coefficient of determination R^2 was considered as a measure of precision (Sentelhas et al., 2010).

The quality of the *ERA5-L* dataset was also evaluated, regarding the best fitting line (1:1 line), in terms of Root Mean Square Error (RMSE), representing the mean error associated with the *ERA5-L* variable, and Mean Bias Error (MBE), which provides information about possible over- (positive value) or under- (negative value) estimations, calculated as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(y_{ERA5,i} - y_{SIAS,i}\right)^2}{N}} \tag{3}$$

$$MBE = \frac{\sum_{i=1}^{N}\left(y_{ERA5,i} - y_{SIAS,i}\right)}{N} \tag{4}$$

where $y_{ERA5,i}$ is the generic climate variable retrieved at the day "i" from the *ERA5-L* dataset, $y_{SIAS,i}$ is the corresponding measured by SIAS, and N is the number of available records. The statistical indicators, RMSE and MBE allows evaluating the errors with the same unit of the examined variable.

2.4. Sensitivity analysis method

The sensitivity analysis was carried out to evaluate the influence of

Table 2
Physical explanation of sensitivity coefficient.

S_{vi}	Increase/Decrease v_i	Increase/Decrease ETo
0.20	+ 10%	+ 2%
	- 10%	- 2%
-0.20	+ 10%	- 2%
	- 10%	+ 2%

the climate variables, T_{min}, T_{max}, RH_{min}, RH_{max}, R_s and u_{10}, on the estimation of ETo (Irmak et al., 2006). The daily sensitivity coefficient, S_{vi}, associated with each generic variable, *vi*, was calculated based on the partial derivative of ETo with respect to *vi*, $\frac{\partial ET_0}{\partial vi}$, transformed into a non-dimensional form (Beven, 1979; McCuen, 1974), as:

$$S_{vi} = \frac{\partial ET_0}{\partial vi} \quad \frac{vi}{ET_0} \tag{5}$$

where ∂ETo is the variation of reference evapotranspiration caused by the change ∂vi associated with the variable *vi*. To evaluate the daily S_{vi}, the partial derivatives were calculated using the symbolic calculation tool of Matlab™. The analytical expressions of S_{vi} for each variable are reported in the supplementary data provided by Gong et al. (2006).

A positive (negative) S_{vi} indicates, in percentage, the increase (decrease) of the reference evapotranspiration caused by an over-estimation (underestimation) of the variable *vi*. For instance, a sensitivity coefficient equal to 0.2 for a certain variable, would mean that a 10% increase in that variable, $\frac{\partial vi}{vi} = 0.1$, may increase ETo by 2%, while all other variables are held constant (Liang et al., 2008) (Table 2). Obviously, a high absolute value of the sensitivity coefficient for a variable *vi*, means that an error on *vi* value has, as consequence, a great error on ETo estimation.

At first, sensitivity coefficients, for each variable, were calculated monthly as average of the 27 weather stations, for each of the ten years analysed (2006–2015). Then, a single value of sensitivity coefficient was calculated considering the average value for each station referred to the analysis period (2006–2015). Based on the single values of sensitivity coefficient, for each climate variable and weather station, a spatial interpolation, using the Inverse Distance Weighting (IDW) interpolation method, was carried out to obtain sensitivity coefficient maps. The *p* parameter, which is the inverse distance power, was set equal to 2 (Mitas, L and Mitasova, H, 2005); this choice is the most popular and the resulting method is called Invers Distance Squared (IDS).

Finally, the sensitivity coefficients have been used to retrieve the total error $\sum E$ on ETo for each station, obtained as the sum of the individual errors, E_{vi}, associated with each examined *ERA5-L* variable.

The individual error, which consider the deviation of the regression slope as well as dispersion from the best fitting line (1:1 line), was evaluated according to the follow equation:

$$E_{vi} = \left[\left(1 - R^2\right) \cdot S_{vi} \right] \cdot 100 \tag{6}$$

If the value of R^2 is equal to one, which means that there are no differences between SIAS and *ERA5-L* variables, therefore E_{vi} is zero; on the other hand, greater S_{vi}, greater is the error E_{vi}, and conversely.

3. Results

3.1. Climate variable-by-variable comparisons

In the period 2006–2015, the percentage of days containing all the climate variables required to apply Eq. (1) resulted generally higher than 85%, (Table 1) except for the three weather stations (ID 235, 245, and 311), in which it resulted equal to 74.2%, 78.4%, and 79.1%, respectively. However, the short periods with the occurrence of missing data were randomly distributed in different seasons and years, and therefore it was assumed that the lack of data does not affect the statistical analysis, so all the 39 SIAS stations were considered.

Initially, a comparison between ground and reanalysis data was conducted on all the 39 stations. Then, the analysis of ETo estimates from the two different sources was carried out to verify the possibility of retrieving this variable from reanalysis data when ground measurements are not available. For this comparison only the 27 stations with the wind speed values have been used.

In terms of statistical indicators, Table 3 shows the values of b, R^2, RMSE and MBE associated with all the examined climate variables, as well as the minimum, maximum, average, and standard deviation values referred to the entire database. On average, most climate variables assume a positive MBE value suggesting that the *ERA5-L* database in general shows overestimations, except for T_{max} and u_{10}. In terms of average RMSE associated with T_{min}, T_{max}, RH_{min}, RH_{max}, R_s, and u_{10} the values were equal to 2.13 °C, 2.52°C, 14.14%, 9.94%, 2.95 MJ m^{-2} d^{-1} and 1.27 m s^{-1}, respectively.

Fig. 2 shows two examples of the scatterplots obtained for the weather stations installed in Canicattì (ID 208) and Lentini (ID 292) of T_{min}, T_{max}, RH_{min}, RH_{max}, R_s, u_{10}, retrieved from measurements on the ground *versus* the corresponding *ERA5-L* dataset. These two stations were chosen as examples of the one of the best and the one of the worst cases in terms of statistical indicators, according to the values reported in Table 3. As can be observed, not all the variables were dispersed around the 1:1 line (line black), resulting in certain over- or under- estimations of the *ERA5-L* records when compared with the ground climate data. In particular, the trends of air temperature T_{min}, T_{max} from the reanalysis dataset follow those of the corresponding measured and the data resulted generally bit disperse around the 1:1 (line black); on the other hand, when comparing relative air humidity, RH_{min} and RH_{max}, global solar radiation R_s, and wind speed u_{10}, consistent deviations from the 1:1 (line black) were observed. Similar results were observed for the other considered weather stations. Overall, daily air temperature T_{min}, T_{max} were predicted with satisfactory accuracy by the *ERA5-L*, whereas for the other variables (RH_{min}, RH_{max}, R_s, u_{10}) evident differences from the ground climate data were observed.

Since Negm et al. (2017) have been retrieved a threshold of 600 (m a. s.l.) after that is possible to notice an increase of the statistical indicators, for all the weather stations, analysis between the values of RMSE and MBE as a function of the ground elevation z (m a.s.l.) were done, but no significant correlation resulted, so the scatterplots are not reported here.

3.2. Crop reference evapotranspiration comparison

As mentioned before, the suitability of the *ERA5-L* database to estimate ETo by FAO56-PM equation, was assessed for 27 out 39 weather stations, in which wind speed data at 10 m were available.

Fig. 3 **a,b** show the scatterplots between ETo estimated from the *ERA5-L* database and ground measurement for the Canicatti (ID 208) and Lentini (ID 292) weather stations, respectively, characterized by the best and the worst result, respectively. In Canicatti (ID 208) the slope of the regression line b_{vi} is equal to 0.99; in Lentini (ID 292) scatterplot the slope b_{vi} is equal to 0.77. The values of RMSE and MBE for these two stations are reported in Table 4 and are respectively equal to 0.42 mm d^{-1} (the lowest value) and 0.00 mm d^{-1} for Canicatti (ID 208) and 1.26 mm d^{-1} and −1.03 mm d^{-1} for Lentini (ID 292).

For all the weather stations, Table 4 summarizes the values of the statistical indicators associated with ETo. Generally, the estimates of ETo from the *ERA5-L* database are in good agreement with the corresponding values obtained from the SIAS weather stations. The slope *b* ranged between 0.77 and 1.00 with an average of 0.90, denoting a maximum average underestimation of 23% in the *ERA5-L* database. The dispersions of the ETo values around the best fitting line, passing through the origin, were expressed in terms of the determination coefficient R^2. The values range between 0.86 and 0.96 with an average value equal to 0.92, indicating a good result. Daily ETo values result characterized by a fairly good accuracy, with average RMSE and MBE equal to 0.73 mm d^{-1} and −0.36 mm d^{-1}, respectively.

3.3. Sensitivity analysis

For the analysis period (2006–2015), annual patterns of average monthly sensitivity coefficients are presented in Fig. 4. Global solar radiation and relative air humidity sensitivity coefficients had the largest variations along the year. The sensitivity of ETo to global solar

Table 3
Slope of the regression line, forced to the origin, b, coefficient of determination, R^2, Root Mean Square Error, RMSE, and, Mean Bias Error, MBE, values associated with the climate variables calculated for all the weather stations.

	T_{min}				T_{max}				RH_{min}				RH_{max}				Rs				u_{10}			
ID	*b*	R^2	*RMSE*	*MBE*	*b*	R^2	*RMSE*	*MBE*	*b*	R^2	*RMSE*	*MBE*	*b*	R^2	*RMSE*	*MBE*	*b*	R^2	*RMSE*	*MBE*	*b*	R^2	*RMSE*	*MBE*
	[-]		[°C]		[-]		[°C]		[-]		[%]		[-]		[%]		[-]		[MJ $m^{-2}d^{-1}$]		[-]		[m s^{-1}]	
206	1.05	0.92	1.80	0.61	0.90	0.98	2.73	-2.48	1.12	0.67	10.67	7.33	0.98	0.53	6.99	-2.09	1.04	0.91	2.51	1.01	0.60	0.60	0.59	-0.16
208	1.00	0.94	1.50	-0.07	0.96	0.98	1.49	-0.95	1.01	0.75	8.08	2.10	0.99	0.46	6.83	-0.46	1.04	0.91	2.47	1.11	0.60	0.60	0.63	-0.02
209	0.86	0.90	2.77	-2.23	0.95	0.96	1.96	-1.48	1.15	0.59	11.18	7.84	1.03	-0.52	10.22	3.44	1.00	0.90	2.45	0.21	0.63	0.63	1.02	-0.54
213	1.07	0.92	1.83	1.26	0.86	0.97	3.70	-3.38	1.37	-1.11	22.43	20.13	1.00	-0.16	9.15	0.81	0.97	0.90	2.48	-0.24	0.41	0.41	1.74	1.20
216	1.02	0.88	1.94	0.73	0.89	0.96	3.07	-2.83	1.15	0.60	11.20	8.55	0.99	-0.03	8.04	-0.61	1.02	0.91	2.36	0.55	0.42	0.42	0.95	-0.36
220	0.91	0.94	1.83	-1.23	0.95	0.97	1.73	-1.24	1.06	0.73	8.77	4.63	1.00	0.16	7.75	0.84	1.05	0.90	2.57	0.98	0.53	0.53	0.69	0.16
222	1.11	0.92	2.04	1.13	0.91	0.98	2.47	-2.13	1.13	0.60	12.02	8.26	1.01	0.42	8.15	1.31	1.03	0.89	2.67	1.02				
224	0.96	0.89	2.07	-0.59	0.78	0.94	5.79	-5.60	1.42	0.49	19.85	17.82	1.04	-0.43	10.83	4.28	1.04	0.87	2.86	1.09				
228	1.05	0.93	1.78	0.86	0.96	0.93	2.18	-1.31	1.20	0.47	13.21	10.09	1.03	-0.58	8.35	3.53	1.00	0.88	2.56	0.24	0.58	0.58	0.75	0.04
231	0.86	0.94	2.15	-1.61	0.89	0.97	2.42	-2.02	1.12	0.23	15.77	9.55	1.05	-0.55	12.93	6.26	1.00	0.81	3.27	0.60	0.27	0.27	1.47	-1.13
232	1.05	0.92	1.80	0.79	0.93	0.97	1.98	-1.63	1.21	0.48	14.14	11.17	0.99	0.41	7.63	-0.27	1.00	0.90	2.42	0.37	0.53	0.53	0.89	-0.14
235	1.11	0.91	2.21	1.40	1.02	0.97	1.39	0.50	1.09	0.30	13.79	6.78	1.05	-0.70	10.91	5.32	1.06	0.82	3.33	1.65				
242	0.95	0.93	1.67	-0.47	0.96	0.97	1.66	-0.81	1.05	0.61	10.16	5.12	1.00	-0.07	9.31	1.27	1.01	0.88	2.60	0.65	0.65	0.65	0.80	-0.36
245	1.23	0.70	3.76	3.36	1.18	0.82	4.05	3.57	0.90	-0.69	19.48	1.51	0.97	-0.56	10.52	-1.64	1.03	0.61	4.75	1.99				
246	0.99	0.95	1.41	-0.15	0.97	0.97	1.46	-0.55	1.09	0.41	13.44	7.67	1.08	-1.46	14.37	8.45	1.03	0.83	3.20	1.02	0.20	0.20	0.93	-0.57
251	1.10	0.86	2.46	1.74	1.04	0.92	1.82	1.01	1.05	-0.95	13.70	5.88	0.91	-0.12	10.97	-7.86	0.98	0.85	2.96	0.25				
257	0.99	0.93	1.55	-0.33	0.88	0.91	3.63	-3.20	1.23	0.07	17.17	12.39	1.00	-1.03	9.18	0.45	1.03	0.85	3.00	1.45	0.04	0.04	1.18	0.85
258	1.03	0.94	1.41	0.46	0.88	0.97	2.88	-2.66	1.35	-0.09	19.71	17.85	1.03	-0.78	10.71	4.01	1.03	0.85	3.00	1.25	0.40	0.40	1.35	0.51
259	1.29	0.79	3.91	3.50	1.01	0.95	1.53	0.54	1.01	-0.68	16.43	5.92	0.97	-1.41	10.80	-2.11	1.09	0.60	5.02	3.04				
262	0.95	0.94	1.62	-0.84	0.94	0.98	1.76	-1.26	1.10	0.64	10.87	6.49	1.03	0.35	8.53	3.14	1.03	0.88	2.74	1.00	0.80	0.80	1.29	-1.08
264	1.01	0.90	1.82	0.06	1.04	0.97	1.67	0.98	1.05	0.69	9.57	3.65	1.00	-0.09	9.85	1.35	1.03	0.86	2.92	1.41				
265	1.05	0.94	1.59	0.87	0.90	0.95	2.55	-2.06	1.34	-0.78	21.16	18.54	0.97	-1.29	12.79	-1.19	1.01	0.84	3.07	0.86				
267	1.07	0.94	1.65	1.08	0.87	0.98	3.47	-3.20	1.20	0.27	14.79	11.78	0.98	0.38	7.67	-1.35	1.01	0.90	2.44	0.62				
268	0.91	0.93	1.99	-1.35	0.91	0.98	2.45	-2.20	1.09	0.74	10.19	5.64	1.03	0.25	9.60	3.93	1.02	0.88	2.77	0.90	0.64	0.64	0.91	-0.53
271	1.05	0.94	1.54	0.80	0.85	0.95	3.93	-3.71	1.32	-0.23	19.05	16.70	0.98	0.00	8.30	-0.92	1.03	0.86	2.91	1.19	0.54	0.54	1.54	0.91
275	1.09	0.90	2.11	1.12	1.00	0.97	1.30	0.09	1.04	0.33	12.73	4.45	1.01	-0.28	9.98	1.48	1.04	0.82	3.38	1.69	0.39	0.39	1.45	-0.80
276	0.90	0.95	1.99	-1.63	0.87	0.92	3.78	-3.48	1.33	0.34	17.59	15.10	1.09	-0.78	12.66	8.56	1.06	0.87	2.96	1.46	0.53	0.53	1.46	1.13
282	1.15	0.82	3.07	2.62	0.92	0.93	2.55	-2.06	1.17	-0.12	14.24	11.05	0.93	0.33	9.22	-6.22	1.00	0.88	2.54	0.23	0.62	0.62	1.93	1.43
286	1.02	0.91	1.76	0.52	1.06	0.96	1.88	1.33	0.96	0.48	11.40	0.64	0.98	0.12	10.22	-0.69	0.98	0.83	3.12	0.14	0.78	0.78	2.27	-1.91
288	1.04	0.93	1.51	0.78	0.89	0.95	2.97	-2.74	1.16	-0.21	13.80	10.37	0.95	-0.07	9.42	-4.25	1.01	0.87	2.67	0.38	0.79	0.79	1.67	1.16
292	0.98	0.94	1.60	-0.33	0.92	0.95	2.72	-2.29	1.25	0.56	15.00	12.18	1.01	0.09	9.10	1.81	0.99	0.87	2.73	0.02	0.64	0.64	1.34	-1.10
298	0.98	0.92	1.74	-0.27	0.97	0.97	1.45	-0.53	1.06	0.66	10.15	4.79	1.02	0.18	9.90	3.22	1.01	0.84	3.00	0.53	0.76	0.76	1.25	-1.01
301	0.95	0.91	1.90	-0.70	1.00	0.90	2.48	-0.25	0.97	0.32	13.75	-0.28	0.99	0.27	7.90	-0.44	1.10	0.86	3.41	2.35				
302	1.20	0.78	3.57	3.16	0.87	0.95	3.29	-2.77	1.40	-1.85	24.15	21.69	0.94	-0.16	10.36	-4.70	1.00	0.91	2.34	0.33	0.59	0.59	1.99	1.51
305	1.22	0.75	3.86	3.36	0.90	0.97	2.71	-2.45	1.14	0.11	13.22	9.97	0.90	0.33	11.54	-9.19	1.03	0.88	2.69	0.77	0.66	0.66	1.31	1.00
308	0.96	0.94	1.50	-0.64	0.98	0.97	1.37	-0.65	1.06	0.71	8.81	4.18	1.04	-0.14	10.08	4.12	1.03	0.87	2.81	1.07	0.80	0.80	1.76	-1.38
309	1.24	0.81	3.49	3.09	1.16	0.88	3.70	3.30	0.98	-0.02	15.67	4.04	1.00	-0.80	10.30	1.19	1.06	0.75	3.92	1.91				
311	1.00	0.84	2.40	0.43	1.06	0.91	2.59	1.66	1.00	0.27	14.34	4.18	1.02	-0.28	11.84	3.44	1.06	0.82	3.50	1.61				
312	0.87	0.93	2.42	-1.90	0.95	0.98	1.54	-0.98	1.10	0.72	9.70	6.26	1.10	-0.87	14.58	9.81	1.01	0.88	2.65	0.44	0.43	0.43	1.18	-0.82
min	0.86	0.70	1.41	-2.23	0.78	0.82	1.30	-5.60	0.90	-1.85	8.08	-0.28	0.90	-1.46	6.83	-9.19	0.97	0.60	2.34	-0.24	0.04	0.04	0.59	-1.91
max	1.29	0.95	3.91	3.50	1.18	0.98	5.79	3.57	1.42	0.75	24.15	21.69	1.10	0.53	14.58	9.81	1.10	0.91	5.02	3.04	0.80	0.80	2.27	1.51
average	1.03	0.90	2.13	0.50	0.95	0.95	2.52	-1.28	1.14	0.18	14.14	8.77	1.00	-0.23	9.94	0.98	1.03	0.85	2.95	0.95	0.55	0.55	1.27	-0.07

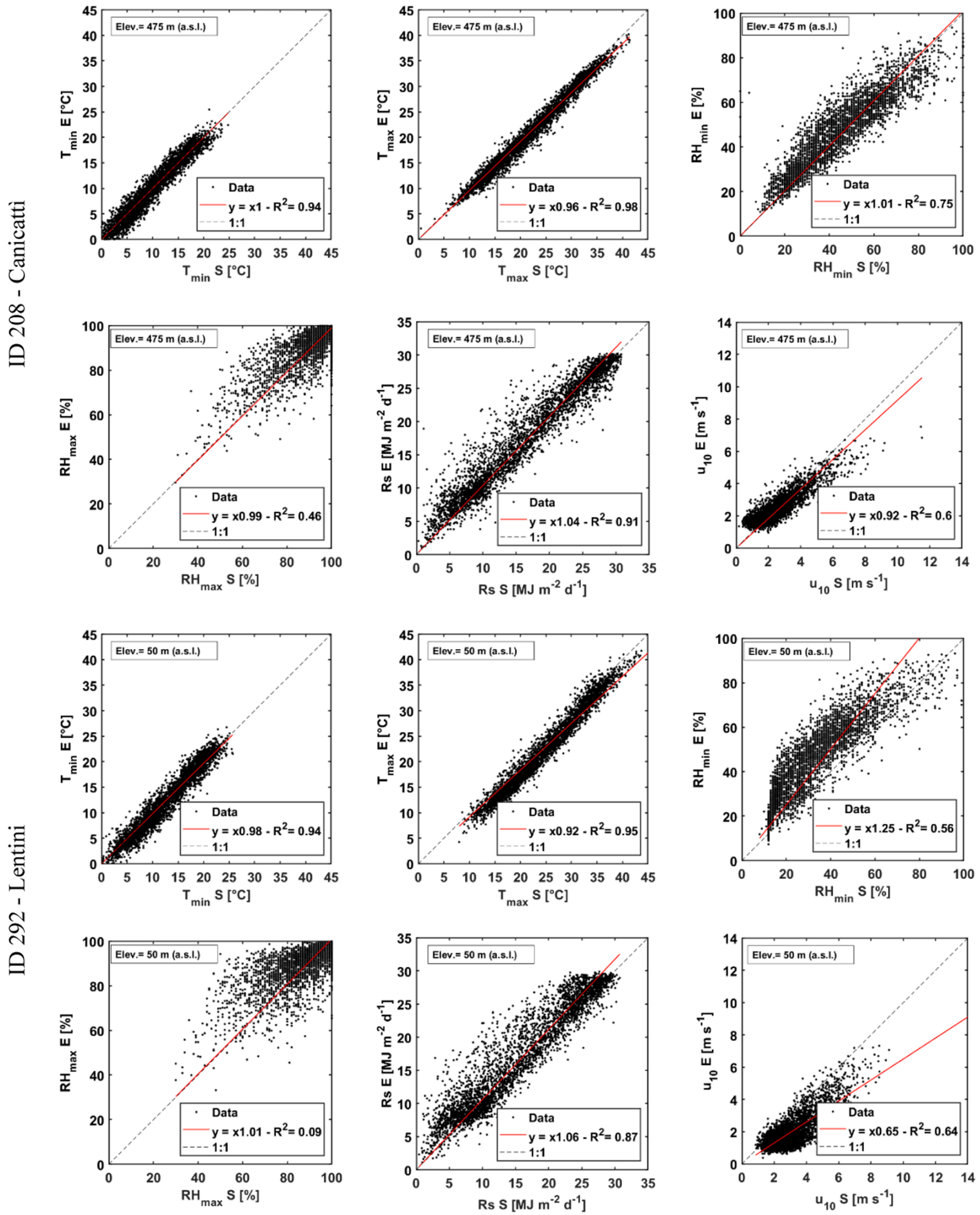

Fig. 2. Scatterplots of daily climate variables (T_{min}, T_{max}, R_s, RH_{min}, RH_{max}, U_{10}) measured on the ground by two SIAS weather stations (S, x-axis) (Canicatti, ID 208 and Lentini, ID 292) and retrieved from ERA5-L dataset (E, y-axis).

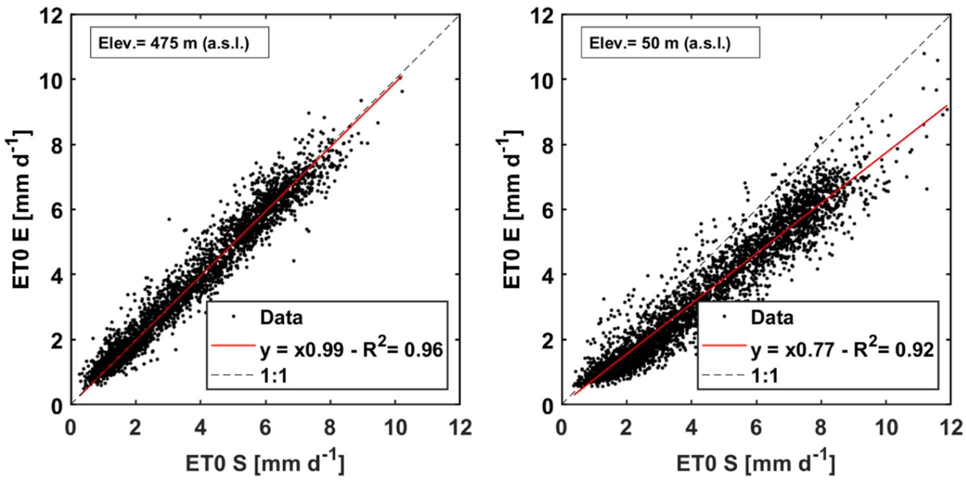

Fig. 3. Scatterplots between Crop Reference Evapotranspiration ETo estimated using climate variables retrieved from ground measurement by two SIAS weather stations (S, x-axis) (Canicatti, ID 208 and Lentini, ID 292) and using ERA5-Land database (E, y-axis).

Table 4
Statistical indices associated with Crop Reference Evapotranspiration ETo values estimated with SIAS and ERA5-Land database.

ID	*b [-]*	R^2 *[-]*	*RMSE [mm d⁻¹]*	*MBE [mm d⁻¹]*
206	0.90	0.96	0.58	-0.34
208	0.99	0.96	0.42	0.00
209	0.86	0.91	0.92	-0.63
213	0.81	0.90	1.07	-0.65
216	0.85	0.94	0.87	-0.68
220	0.96	0.95	0.48	-0.12
228	0.93	0.92	0.62	-0.31
231	0.82	0.93	0.84	-0.59
232	0.88	0.93	0.73	-0.45
242	0.92	0.93	0.59	-0.22
246	0.89	0.93	0.65	-0.33
257	1.00	0.90	0.56	-0.04
258	0.88	0.94	0.62	-0.39
262	0.86	0.95	0.74	-0.53
268	0.88	0.94	0.73	-0.45
271	0.91	0.88	0.66	-0.30
275	0.92	0.86	0.80	-0.20
276	0.97	0.92	0.52	-0.11
282	1.00	0.90	0.54	0.04
286	0.88	0.88	0.83	-0.26
288	0.95	0.90	0.57	-0.16
292	0.77	0.92	1.26	-1.03
298	0.87	0.92	0.79	-0.44
302	0.87	0.90	0.81	-0.41
305	0.98	0.93	0.51	0.03
308	0.86	0.93	0.88	-0.56
312	0.81	0.91	1.05	-0.67

radiation and relative air humidity was lower during the wet season and higher in the irrigation season (April-September). Temperature sensitivity coefficients are almost constant during the entire year. Different seasonal pattern is it possible to note for the wind speed sensitivity coefficients in which the values decreased from January to April and then increase until to December.

For all the 27 examined weather stations, Fig. 5 shows the mean and the corresponding standard deviation of the sensitivity coefficients, S_{vi}, associated with the different climate variables. As it can be observed, the sensitivity coefficients associated with T_{max}, R_s and u_{10} are always positive, the values related to T_{min} are positive but very small, probably they are not significantly different by zero. The sensitivity coefficients associated with RH_{max} and RH_{min} are always negative. Therefore, an overestimation of the variables T_{max}, R_s and u_{10} determines the overestimation of ETo, whereas an overestimation of the variables RH_{max} and RH_{min} determines the underestimation of ETo. When considering all

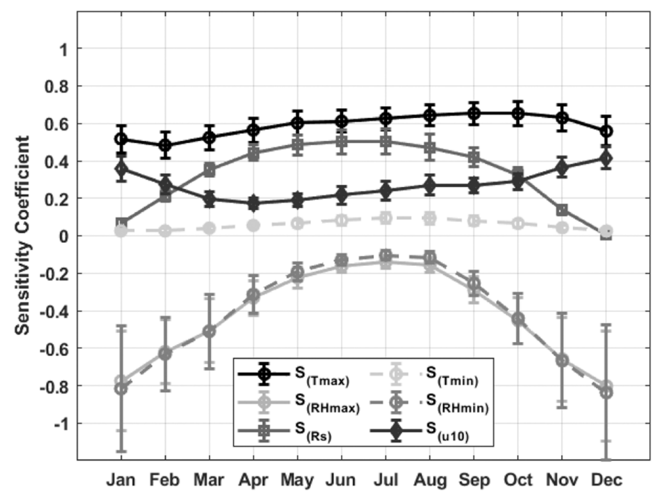

Fig. 4. Annual evolution of monthly averaged sensitivity coefficients.

the weather stations, the average and standard deviation of S_{vi} associated with T_{min}, T_{max}, R_s, and u_{10}, resulted equal to 0.06±0.02, 0.59 ±0.06, 0.33±0.03 and 0.27±0.03, respectively, while the values associated with RH_{min}, RH_{max}, resulted equal to −0.41±0.13, −0.42±0.12, respectively.

Therefore, for a fixed error on the generic climate variable, the values of ETo are mostly affected by T_{max}, RH_{max} and RH_{min}, and in a more limited way by R_s and u_{10}, characterized by relatively lower sensitivity coefficients. The values of standard deviation (Fig. 5) associated to each S_{vi} show that the most dispersed variables are RH_{max} and RH_{min}, with the largest variability range.

In Fig. 6 are reported the regional distribution of the mean sensitivity coefficients for each variable. The sensitivity coefficients associated to the maximum air temperature is higher in southwest (Mazara del Vallo [305]) and in centre east (Licata [209], Gela [216] and, Lentini [292]). In the northern coastal area (Patti [257], Pettineo [258] and, Palermo [276]), the sensitivity coefficients associated to the minimum air temperature are the highest, the lowest in the centre (Cammarata [206]) and medium in the southeast (Scicili Palmentella [288]). The sensitivity coefficients for R_s are higher in the northeast (Patti [257]). For both RH_{max} and RH_{min} sensitivity coefficients, the values are very low in the southeast (Ragusa [286]), higher in the north (Palermo [276] and, Patti [257]) and medium in the centre. Finally, the maximum value of the u_{10}

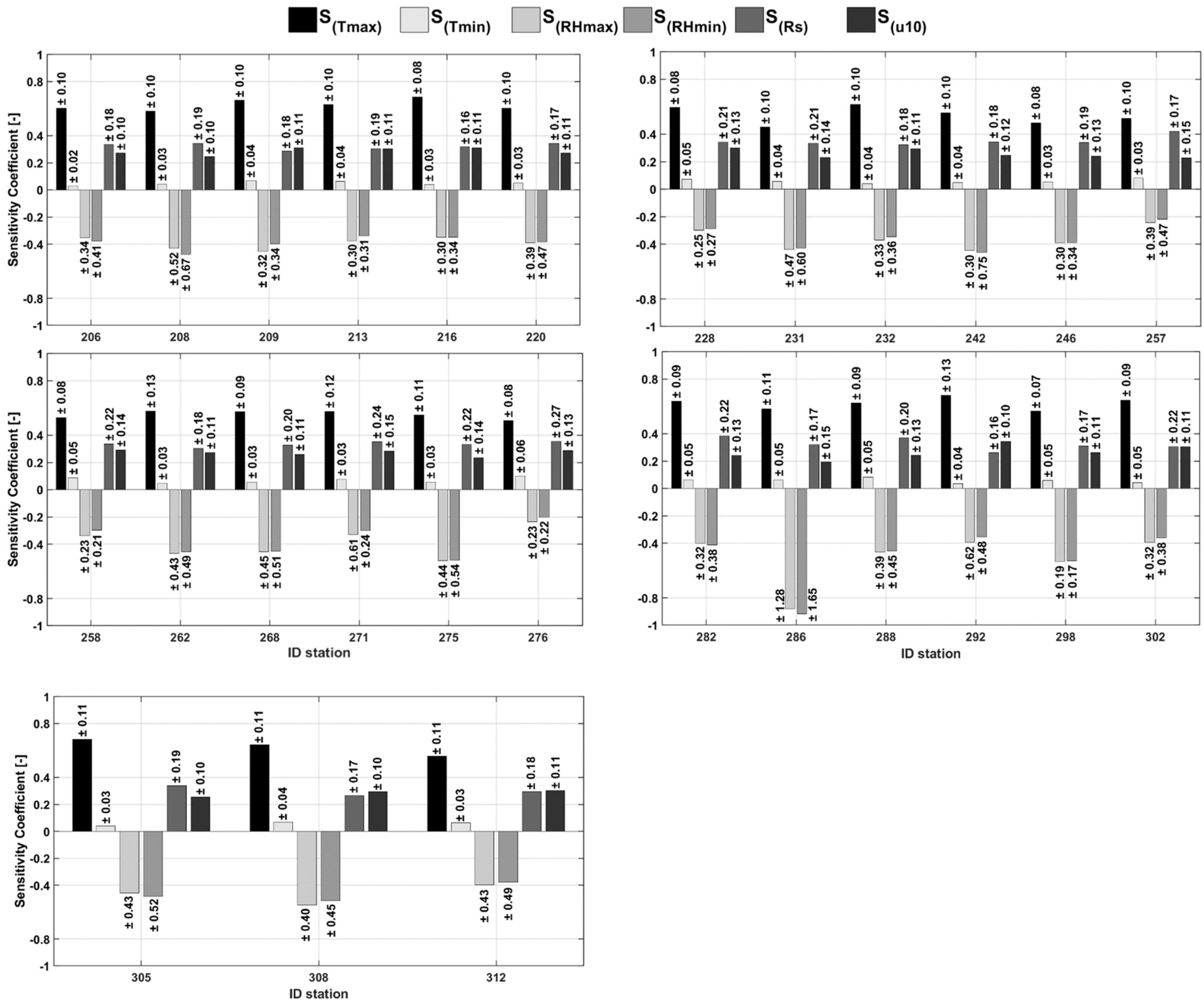

Fig. 5. Mean values of sensitivity coefficient for each variable and for each weather station, for each climate variable the standard deviation referred to the analysis period (2006–2015) is also written up/down the corresponding bar.

sensitivity coefficient is reached in Lentini [292].

After calculating the S_{vi} for all the weather stations, the individual error, E_{vi}, associated with each variable was calculated with Eq. 6 Table 5 summarizes the values of R^2_{vi}, S_{vi} E_{vi}, referred to each variable as well as the total error, E, on the ETo estimation in the last column.

As can be notice in Table 5, the values of the sensitivity coefficients for T_{min}, T_{max}, R_s and, u_{10} suggest that if the climate variables increase (decrease) ETo increase (decrease) too. On the contrary, if RH_{max} or RH_{min} increase (decrease), ETo decrease (increase).

As example, the results of Cammarata (ID 206) and Castelvetrano (ID 302) weather stations, characterized by the best and the worst results in terms of total error are better described.

Regarding the Cammarata weather station (ID 206), the determination coefficient, R^2, associated with the different variables, ranged between 0.53 and 0.98, in particular, T_{min}, T_{max}, and R_s from the *ERA5-L* database resulted well estimated ($R^2 > 0.90$) compared with the corresponding measured, whereas RH_{max}, RH_{min} and u_{10}, were characterized by values of R^2 lower then 0.70. Based on the determination coefficients and the corresponding sign of the sensitivity coefficients, the individual error on ETo associated with each examined climate variable results negative for RH_{min} and RH_{max}, and positive for T_{min}, T_{max}, R_s and u_{10}. The relatively low overall error, E, on ETo obtained for the Cammarata weather station, equal to –13.37%, is the consequent of the compensatory effect of the single errors associated with the different climate variables. On the contrary, for Castelvetrano weather station (ID 302) the overall error on ETo resulted equal to −129.72%, because of the underestimation of T_{max}, RH_{max} and, u_{10} and the contemporary overestimation of T_{min} and RH_{min}.

4. Discussion

Once the comparison between the variables, obtained from the two different databases, as well as that between statistical indicators and station's elevation have been conducted and the ETo total error has been calculated, through sensitivity analysis, it is possible to comment the results.

When considering the initial 39 weather stations the average values of RMSE (Table 3) associated with T_{min}, T_{max}, are equal to 2.13 C° and 2.52 C°, respectively, lower than those found by Negm et al. (2017) in Sicily, using the POWER-NASA database, which resulted, on average, equal to 5.0 C° and 3.6 C°, respectively, probably as a consequence of the better *ERA5-L* dataset spatial resolution. In Campania region, Pelosi

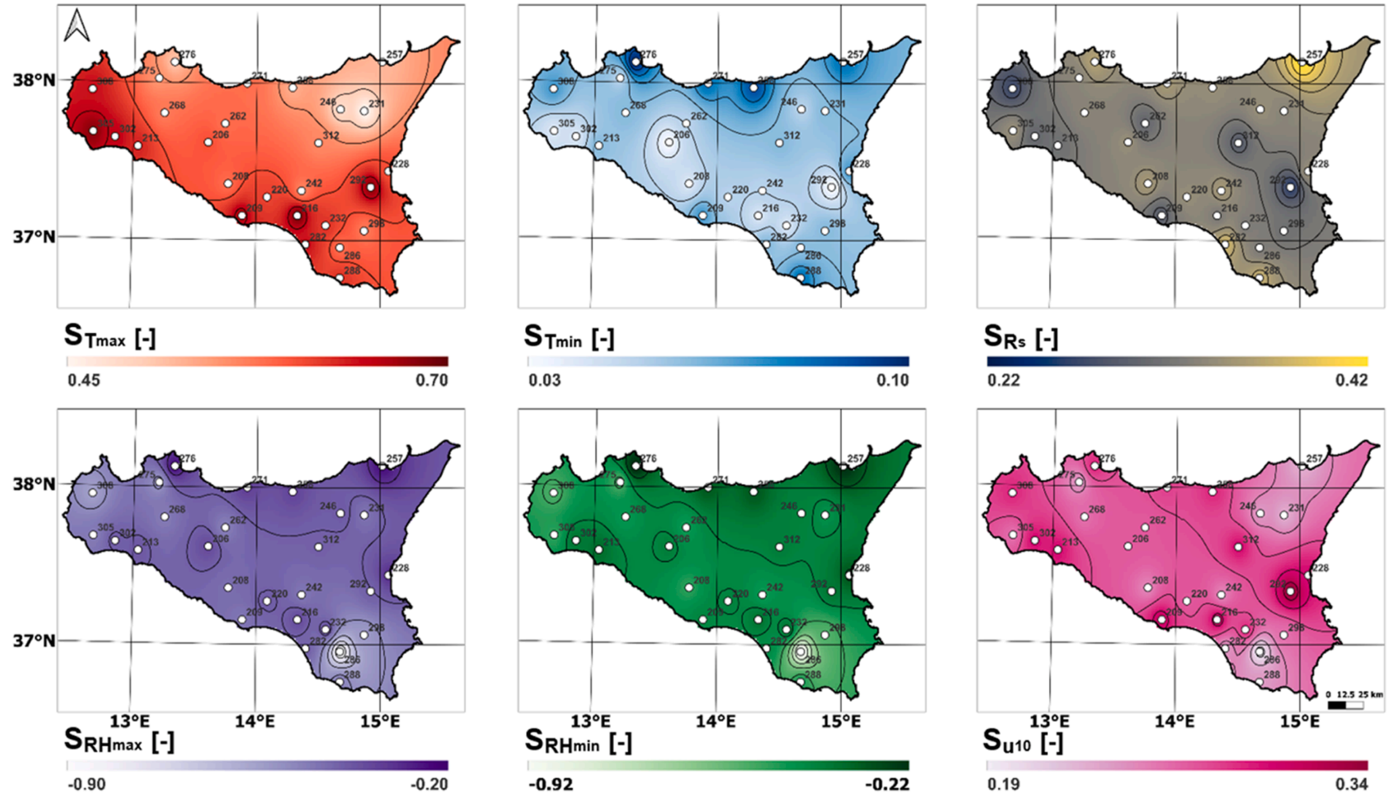

Fig. 6. Spatial distribution of mean sensitivity coefficients for each variable.

et al. (2020) using *ERA5-L* database, found an average RMSE value associated with the daily average air temperature equal to 1.20 C°, slightly lower of the RMSE obtained in this work associated with T_{min} and T_{max}, this effect, presumably is caused by less topographic complexity of the study area (White et al., 2008). The values could be similar because both Italian regions are characterized by a Hot summer Mediterranean climate (Csa) (Kottek et al., 2006), according to the last version of the Köppen climatic classification, with rainfall concentrated in fall and winter and quite hot and dry summer. In general, the low RMSE values associated with the records of air temperature from the *ERA5-L* database, indicate that the reanalysis variable can be considered a suitable surrogate of the ground measurements. This result has a greater impact on the maximum temperature values which turns out to be a variable that significantly influences the ETo estimate.

In terms of R_s, the RMSE value associated with the *ERA5-L* database resulted equal to 2.95 MJ m^{-2} d^{-1}. This value was similar with those obtained by Negm et al. (2017) and Bai et al. (2010), retrieved using both the POWER-NASA database, equal to 2.70 MJ m^{-2} d^{-1} and 3.10 MJ m^{-2} d^{-1}, respectively. Despite the different spatial resolution characterizing both databases (POWER-NASA and *ERA5-L*), the RMSE values associated with the daily solar radiation resulted quite similar. This result is in according with Vanella et al. (2022), who found that the best performance in the estimation of R_s resulted in the regions characterized by hot-summer temperate climate (Csa) condition (Kottek et al., 2006), such as Sicily. These results demonstrates that the R_s values retrieved by *ERA5-L* database are in good agreement with the corresponding ground measurements, even without applying bias correction procedure. These results agree with Pelosi and Chirico (2021), who verified that the bias correction applied to the solar radiation does not significantly improve the estimates. Although other authors tested different satellite-based solar radiation data such as CM-SAF (Pelosi and Chirico, 2021) and LSA-SAF (Paredes et al., 2021), replacing the corresponding *ERA5-L* variable, to retrieve ETo, the obtained performances demonstrate that R_s from *ERA5-L* could be used to implement ETo, that is required for a variety of uses in hydrology and irrigation management.

In this work, the suitability of the *ERA5-L* database to estimate ETo was assessed for 27 weather stations in which wind speed data at 10 m a. s.l. were available. In terms of RMSE (Table 4), the values ranging between 0.42 mm d^{-1} and 1.26 mm d^{-1} with a mean value equal to 0.73 mm d^{-1}. The values of RMSE found by Negm et al. (2017), using POWER-NASA database, were also similar to those found in this study, with a minimum and maximum RMSE equal to 0.68 mm d^{-1} and 1.27 mm d^{-1}, respectively. Instead, similar results, using the *ERA5-L* database, were obtained by Pelosi et al. (2020), who considered 18 weather stations over the Campania region. They found RMSE values ranging between 0.44 mm d^{-1} and 1.04 mm d^{-1} with a mean value equal to 0.67 mm d^{-1}. In terms of R^2, the average value found in this work shows good performance considering all seasons. This result agrees with the study by Pelosi and Chirico (2021), who considered to replace the R_s values from *ERA5-L* with the ones retrieved by the CM-SAF database, only during irrigation seasons. The good performance in terms of RMSE and R^2 obtained in this study highlights the capacity of the *ERA5-L* climate variables to estimate ETo when ground data are not available, also in regions characterized by a complex morphology and along all the seasons.

The annual patterns of average monthly sensitivity coefficients showed values associated to Rs ranged from 0.01 to 0.50, to u10 from 0.17 to 0.42 and, to RH_{max} and RH_{min} from –0.80 to –0.14 and from –0.84 to –0.10, respectively (Fig. 4). These results were in according with those obtained by Estévez et al. (2009) in which the authors assessed the seasonal pattern of each climate variable associated with ETo estimations, the annual evolution of sensitivity coefficients and, their geographical distribution in Andalusia.

In this study, ETo values resulted mainly affected by maximum air temperature and maximum and minimum relative air humidity followed by global solar radiation and wind speed. The standard deviation values for each S_{vi} suggest that the most dispersed, among the analyzed weather stations, were the maximum and minimum relative air humidity (Fig. 5,

Table 5

Average values of coefficient of determination R^2_{vi}, sensitivity coefficient S_{vi}, and individual error E_{vi} for the weather stations in which wind measurements 10 m above the ground are available.

	T_{min}			T_{max}			RH_{min}			RH_{max}			Rs			u_{10}			ETo
	[-]			[-]			[-]			[-]			[-]			[-]			[%]
206	0.92	0.03	0.25	0.98	0.60	1.33	0.67	-0.38	-12.37	0.53	-0.35	-16.62	0.91	0.34	3.15	0.60	0.27	10.89	-13.37
208	0.94	0.04	0.27	0.98	0.58	1.28	0.75	-0.48	-11.90	0.46	-0.43	-23.39	0.91	0.35	3.26	0.60	0.25	9.98	-20.50
209	0.90	0.07	0.68	0.96	0.66	2.85	0.59	-0.40	-16.29	-0.52	-0.45	-69.06	0.90	0.29	2.95	0.63	0.31	11.37	-67.51
213	0.92	0.06	0.53	0.97	0.63	2.08	-1.11	-0.34	-71.39	-0.16	-0.38	-43.51	0.90	0.31	3.03	0.41	0.30	18.02	-91.24
216	0.88	0.04	0.48	0.96	0.69	2.75	0.60	-0.35	-13.93	-0.03	-0.35	-36.05	0.91	0.32	2.98	0.42	0.31	17.98	-25.79
220	0.94	0.05	0.28	0.97	0.61	1.63	0.73	-0.39	-10.37	0.16	-0.39	-32.56	0.90	0.34	3.43	0.53	0.27	12.85	-24.73
228	0.93	0.07	0.51	0.93	0.60	4.30	0.47	-0.29	-15.28	-0.58	-0.30	-47.35	0.88	0.34	3.97	0.58	0.30	12.60	-41.25
231	0.94	0.06	0.34	0.97	0.45	1.27	0.23	-0.43	-32.96	-0.55	-0.44	-67.92	0.81	0.33	6.29	0.27	0.23	16.72	-76.27
232	0.92	0.04	0.33	0.97	0.62	1.60	0.48	-0.35	-18.06	0.41	-0.37	-22.03	0.90	0.32	3.35	0.53	0.29	13.68	-21.13
242	0.93	0.05	0.36	0.97	0.56	1.78	0.61	-0.46	-17.82	-0.07	-0.45	-47.93	0.88	0.35	4.01	0.65	0.25	8.64	-50.96
246	0.95	0.05	0.27	0.97	0.48	1.40	0.41	-0.39	-22.99	-1.46	-0.39	-95.94	0.83	0.34	5.92	0.20	0.24	19.38	-91.96
257	0.93	0.08	0.57	0.91	0.52	4.86	0.07	-0.22	-20.47	-1.03	-0.24	-49.72	0.85	0.42	6.30	0.04	0.23	22.09	-36.37
258	0.94	0.09	0.50	0.97	0.53	1.59	-0.09	-0.30	-32.38	-0.78	-0.34	-60.24	0.85	0.34	5.07	0.40	0.29	17.35	-68.12
262	0.94	0.05	0.29	0.98	0.58	1.39	0.64	-0.46	-16.51	0.35	-0.47	-30.75	0.88	0.30	3.57	0.80	0.27	5.61	-36.40
268	0.93	0.06	0.42	0.98	0.57	1.20	0.74	-0.45	-12.03	0.25	-0.46	-34.04	0.88	0.33	4.05	0.64	0.26	9.38	-31.02
271	0.94	0.08	0.44	0.95	0.58	3.05	-0.23	-0.30	-36.60	0.00	-0.33	-32.75	0.86	0.35	4.90	0.54	0.28	13.17	-47.79
275	0.90	0.05	0.53	0.97	0.55	1.70	0.33	-0.52	-34.77	-0.28	-0.52	-66.56	0.82	0.33	5.96	0.39	0.24	14.47	-78.66
276	0.95	0.10	0.48	0.92	0.51	4.12	0.34	-0.20	-13.32	-0.78	-0.24	-41.86	0.87	0.36	4.55	0.53	0.29	13.65	-32.39
282	0.82	0.06	1.14	0.93	0.64	4.47	-0.12	-0.41	-46.34	0.33	-0.40	-26.82	0.88	0.38	4.50	0.62	0.24	9.12	-53.92
286	0.91	0.06	0.58	0.96	0.58	2.50	0.48	-0.92	-47.79	0.12	-0.88	-77.77	0.83	0.32	5.52	0.78	0.19	4.33	-112.63
288	0.93	0.08	0.57	0.95	0.62	3.25	-0.21	-0.46	-55.33	-0.07	-0.47	-50.01	0.87	0.37	4.78	0.79	0.24	5.08	-91.66
292	0.94	0.03	0.22	0.95	0.68	3.27	0.56	-0.36	-15.56	0.09	-0.40	-35.99	0.87	0.26	3.38	0.64	0.34	12.24	-32.45
298	0.92	0.06	0.45	0.97	0.57	1.70	0.66	-0.53	-18.21	0.18	-0.53	-43.83	0.84	0.31	4.95	0.76	0.26	6.38	-48.56
302	0.78	0.04	0.94	0.95	0.65	3.17	-1.85	-0.36	-103.41	-0.16	-0.39	-45.62	0.91	0.30	2.86	0.59	0.30	12.35	-129.72
305	0.75	0.04	0.98	0.97	0.68	1.85	0.11	-0.48	-43.02	0.33	-0.46	-30.81	0.88	0.34	3.95	0.66	0.26	8.69	-58.36
308	0.94	0.07	0.42	0.97	0.64	1.81	0.71	-0.52	-15.10	-0.14	-0.55	-62.75	0.87	0.27	3.37	0.80	0.29	6.01	-66.25
312	0.93	0.06	0.44	0.98	0.56	1.06	0.72	-0.38	-10.60	-0.87	-0.40	-74.28	0.88	0.29	3.53	0.43	0.30	17.12	-62.72
Min	0.75	0.03	0.22	0.91	0.45	1.06	-1.85	-0.92	-103.41	-1.46	-0.88	-95.94	0.81	0.26	2.86	0.04	0.19	4.33	-129.72
Max	0.95	0.10	1.14	0.98	0.69	4.86	0.75	-0.20	-10.37	0.53	-0.24	-16.62	0.91	0.42	6.30	0.80	0.34	22.09	-13.37
Avg.	0.91	0.06	0.49	0.96	0.59	2.34	0.27	-0.41	-28.32	-0.16	-0.42	-46.89	0.87	0.33	4.21	0.55	0.27	12.19	-55.99
St. Dev.	0.05	0.02	0.23	0.02	0.06	1.12	0.60	0.12	21.79	0.51	0.12	19.36	0.03	0.03	1.09	0.19	0.03	4.71	29.66

Fig. 6, and Table 5). The standard deviation values associated to the S_{RHmin} and S_{RHmax} obtained in this study, are equal, for both the climate variable, to 0.12. The same result was obtained by Estévez et al. (2009) in Spain and Liang et al. (2008) in China, using the Beven (1979) approach to assess the sensitivity coefficients. The latter found that in Tao'er River Basin the sensitivity coefficient referred to relative air humidity has the highest spatial variability, as well as, that the errors in ETo are mainly due to the relative air humidity and air temperature values. On the other hand, Gong et al. (2006) indicated, for the lower region of the Chang Jiang River basin in China, values of the standard deviation associated to the sensitivity coefficients of the minimum and maximum relative air humidity equal to 0.20, higher than that find in this work; whereas, for all the other variables (S_{Tmin}, S_{Tmax}, S_{Rs} and S_{u10}) the authors did not found relevant spatial variations.

In this work, the *ERA5-L* product demonstrate that a reanalysis database for water management applications in a region with a Mediterranean climate is a good product. The results confirmed that reanalysis data represent a valid proxy of ground climate data for assessing ETo, especially when ground weather data cannot be easily gathered due to the malfunctions and/or lack of the climate stations. Recently, Pelosi (2023) tested the performances of CERRA data in Sicily, during twenty irrigation seasons. Although even in this work the results are very good, the computational burden could be more expensive due to the very high horizontal resolution equal to 5.5 km.

5. Conclusion

This study explored the suitability of the *ERA5-L* climate variables to replace ground measurements when these are missing and assess daily crop reference evapotranspiration, ETo, evaluated according to the FAO-56-PM equation in Sicily. The reliability of climate variables from *ERA5-L* database was assessed through the sensitivity analysis of the FAO56-PM equation.

The comparison between reanalysis climate variables and ground measurement evidenced that *ERA5-L* database generally was in good agreement with the measured variables. The most accuracy estimations were observed for T_{min} and T_{max}, followed by R_s and u_{10}. Whereas the worst variables estimated were RH_{min} and RH_{max}. This last result may be due to the dependency of the *ERA5-L* relative air humidity is estimated as function of the dew point and air temperature.

The ETo values estimated based on climate variables from *ERA5-L* were in good agreement with those obtained from ground measurement by 27 weather stations, as demonstrated by low RMSE and MBE average values.

The results obtained in this study demonstrate that *ERA5-L* database is a good alternative to ground measurements, especially in regions characterized by large topographical heterogeneity as the Sicily Island. Moreover, the results provide an approach to assess ETo in areas where climate data are not available and also to replace eventual lack in the ground measurements.

The sensitivity analysis showed that the main contribution to ETo quality estimation derives from the accuracy of T_{max}, RH_{min}, and RH_{max}, measurements. Moreover, the seasonal analysis of the sensitivity coefficient indicates that in a semi-arid region like Sicily obtaining reliable values of ETo is important to measure with high accuracy global solar radiation, relative air humidity and wind speed, whose dynamics vary during the year.

The spatial distribution of the sensitivity coefficients can be an useful tool to guide the user, to a more accurate choice of model to be used for the ETo estimation and to understand in which areas of the Sicily region the FAO56-PM equation is the more appropriate approach.

The sensitivity analysis of the FAO56-PM equation shows that to improve the water management and reduce the errors on the ETo estimation is essential improve the accuracy in air temperature and relative air humidity measurements. For this reason, to guarantee reliable estimation of ETo the accurate measurements of the latter variables are needed. Finally, these results can be used as a theoretical basis for future research.

CRediT authorship contribution statement

Dario De Caro: Conceptualization, Data curation, Methodology, Writing – original draft, Writing – review & editing, Investigation, Formal analysis, Visualization. **Matteo Ippolito:** Conceptualization, Data curation, Methodology, Writing – original draft, Writing – review & editing, Investigation, Formal analysis, Visualization. **Giuseppe Provenzano:** Conceptualization, Methodology, Supervision, Writing – original draft. **Marcella Cannarozzo:** Methodology, Writing – original draft, Writing – review & editing, Supervision. **Giuseppe Ciraolo:** Funding acquisition, Supervision, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The author declares that no conflict of interest exists.

Data Availability

Data will be made available on request.

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All the Authors organized experiments and edited the final version of the manuscript. Experimental setup, data acquisition and processing were handled by MI and DDC. The authors would like to express their profound gratitude to Prof. Giuseppe Provenzano (who sadly passed away in December 2022) for his significant contributions to the initial draft of this article, as well as for fostering extraordinary human and professional relationships.

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