

SEASONAL FORECASTS FOR DECISION-MAKING IN MEDITERRANEAN AGRICULTURE

PRÉVISIONS SAISONNIÈRES POUR LA PRISE DE DÉCISION DANS L'AGRICULTURE MÉDITERRANÉENNE

Daniel Garcia¹, João Rolim¹, João Santos², and Paula Paredes¹

ABSTRACT

Water scarcity is a growing challenge for Mediterranean agriculture, as climate change and variability intensify the imbalance between water availability and irrigation demand, making crop and water management increasingly complex. Uninformed or delayed decisions often lead to economic and environmental losses, highlighting the need for tools that support early decision-making. This study assesses the performance of ECMWF SEAS5 seasonal weather forecasts (SF) and their potential to estimate crop cycles and irrigation requirements in the Mediterranean region. Daily ensemble forecasts with a seven-month lead time (April-October) were analysed for Coruche, Central Portugal, using 1987-2016 as baseline and 2017-2024 for evaluation. The AgERA5 reanalysis dataset, bias-corrected with observational data, served as reference.

Forecasts were evaluated for accumulated precipitation and reference evapotranspiration (ET_0), with indirect validation through maize cycle duration, estimated with the growing degree days approach, and crop water needs using a simplified water balance. Results showed that precipitation exhibited a modest probabilistic skill (CRPSS = 0.13), with no systematic bias but high ensemble spread (CV = 34%), reflecting its inherently low seasonal predictability in the Mediterranean region. ET_0 and crop-related forecasts exhibited higher anomaly correlations (ACC = 0.69-0.83) but may have suffered from a systematic cold bias, driving consistent underestimation of ET_0 and crop water needs (~8%), maize cycle overestimation (~11 days), and probabilistic skill equal or below the climatological reference. Overall, this study demonstrates that SF integration into crop and water balance models can improve early-season predictions of crop development and water needs. The primary limitation identified was not an absence of dynamic predictability but likely the systematic cold biases, suggesting that SF corrections could substantially improve operational usability. Further research should address these biases and extend assessments across broader Mediterranean agricultural contexts.

Keywords: Climate variability; Crop development; Irrigation requirements; Portugal; Maize.

RÉSUMÉ

La rareté de l'eau constitue un défi croissant pour l'agriculture méditerranéenne, car le changement et la variabilité climatiques accentuent le déséquilibre entre la disponibilité en eau et la demande d'irrigation, rendant la gestion des cultures et de l'eau de plus en plus complexe. Des décisions insuffisamment éclairées ou tardives entraînent souvent des pertes économiques et environnementales, ce qui souligne la nécessité d'outils favorisant une prise de décision précoce. Cette étude évalue les performances des prévisions météorologiques saisonnières ECMWF SEAS5 (SF) et leur capacité à estimer les cycles culturaux et les besoins d'irrigation dans la région

¹ LEAF - Linking Landscape, Environment, Agriculture and Food Research Center, Associate Laboratory TERRA, Instituto Superior de Agronomia, ISA, Universidade de Lisboa, Tapada da Ajuda, 1349-017 Lisboa, Portugal, dgarcia@isa.ulisboa.pt, joaorolim@isa.utl.pt, pparedes@isa.ulisboa.pt

² CITAB - Centre for the Research and Technology of Agro-Environmental and Biological Sciences, Inov4Agro - Institute for Innovation, Capacity Building, and Sustainability of Agri-Food Production, Universidade de Trás-os-Montes e Alto Douro, UTAD, P.O. Box 1013, 5000-801 Vila Real, Portugal, jsantos@utad.pt

méditerranéenne. Des prévisions journalières d'ensemble, avec une échéance de sept mois (avril-octobre), ont été analysées pour Coruche, dans le centre du Portugal, en utilisant la période 1987-2016 comme référence et la période 2017-2024 pour l'évaluation. Le jeu de données de réanalyse AgERA5, corrigé des biais à l'aide de données d'observation, a servi de référence. Les prévisions ont été évaluées pour les précipitations cumulées et l'évapotranspiration de référence (ET_0), avec une validation indirecte au moyen de la durée du cycle du maïs, estimée par l'approche des degrés-jours de croissance, et des besoins en eau de la culture, calculés à l'aide d'un bilan hydrique simplifié. Les résultats ont montré que les précipitations présentaient une compétence probabiliste modeste ($CRPSS = 0,13$), sans biais systématique mais avec une forte dispersion de l'ensemble ($CV = 34\%$), ce qui reflète leur faible prévisibilité saisonnière intrinsèque dans la région méditerranéenne. Les prévisions de l' ET_0 et celles liées aux cultures présentaient des corrélations d'anomalies plus élevées ($ACC = 0,69-0,83$), mais elles pourraient avoir été affectées par un biais froid systématique, entraînant une sous-estimation constante de l' ET_0 et des besoins en eau des cultures (environ 8%), une surestimation de la durée du cycle du maïs (environ 11 jours) et une compétence probabiliste égale ou inférieure à celle de la référence climatologique. Dans l'ensemble, cette étude montre que l'intégration des SF dans les modèles de culture et de bilan hydrique peut améliorer les prévisions, en début de saison, du développement des cultures et de leurs besoins en eau. La principale limite mise en évidence ne résidait pas dans une absence de prévisibilité dynamique, mais vraisemblablement dans les biais froids systématiques, ce qui laisse penser que la correction des SF pourrait améliorer sensiblement leur utilité opérationnelle. Des recherches complémentaires devraient corriger ces biais et étendre les évaluations à des contextes agricoles méditerranéens plus vastes.

Mots-clés : Variabilité climatique; Développement des cultures; Besoins en irrigation; Portugal; Maïs.

1. INTRODUCTION

The Mediterranean region is a recognised climate change hotspot, where rising temperatures, higher climatic demand, shifting precipitation patterns, and increasing frequency and severity of extreme droughts and heatwaves are becoming more pronounced (Ali et al., 2022). These changes directly impact crop development and productivity, while intensifying the imbalance between water availability and irrigation demand (Pereira, 2017; Rezaei et al., 2023). Climate variability adds substantial irregularity and uncertainty, making crop and irrigation water management increasingly complex (Thorton et al., 2014; Ray et al., 2015). These challenges highlight the need for accessible and innovative tools to support timely decision-making in Mediterranean agriculture.

Crop growth and water requirements are strongly driven by climatic conditions, particularly temperature and precipitation. Temperature regulates crop development rates, influencing the length of crop cycles as well as yield quantity and quality (Jagadish et al., 2016; Zhao et al., 2017). Under non-stress conditions, development is often assumed to be linearly related with temperature, forming the basis of the Growing Degree Days (GDD) approach (Paredes et al., 2025a), providing a simple method to estimate crop phenology and cycle duration. The combined influence of temperature and precipitation determines crop water requirements and irrigation needs (Pereira et al., 2025). In the Mediterranean region, hot and dry conditions create persistent water deficits during the growing season, making irrigation essential for sustaining productivity (Bodner et al., 2015; Yang et al., 2020). The balance expressed as the difference between crop evapotranspiration (ET_c) and precipitation is a simple indicator of crop water deficit and irrigation requirements. When driven by weather forecast data, these two agroclimatic indicators (GDD and $ET_c - \text{Precipitation}$) provide a practical approach to support early decision-making in crop and water management.

Seasonal Forecasts (SF) provide probabilistic information on weather conditions over the coming months (Johnson et al., 2019). Advances in numerical modelling and computation have significantly improved forecast reliability, establishing them as valuable decision-support tools in several sectors, including agriculture (Gualdi et al., 2026). Some studies have explored SF to estimate crop cycle timing (Yang et al., 2023), predict early-season yields (Bento et al., 2022), and support water management (Villani et al., 2021). These works report benefits over historical averages, which fail to represent climate variability and become outdated under climate change. In theory, SF provide

valuable information for dynamic agricultural decision-making by enabling earlier planning and more efficient resource allocation. However, their operational use in the Mediterranean region remains limited due to uncertainties in the accuracy of numerical model forecasts over this area and the complexity of their application. Forecast skill also varies according to the target variable, season, and region, which further constrains their practical uptake (Crespi et al., 2021). As a result, the integration of SF into crop and irrigation management tools is underdeveloped, highlighting the need for further studies to assess their usability in this context.

This study evaluates the performance of raw (non-bias-corrected) SF in the Mediterranean region. Ensemble forecasts were analysed, focusing on the maize crop in the Coruche region, Central Portugal, using reanalysis as reference. The specific objectives are: (1) assess the accuracy and skill of SF in predicting ET_0 and precipitation for the spring-summer season; (2) evaluate maize crop cycle length estimation using the GDD approach; (3) assess irrigation requirements estimates using a simplified crop water balance. This provides insight into the practical utility of SF for supporting early agricultural decision-making in Mediterranean systems and represents a step towards identifying both the potential and limitations of integrating SF into accessible crop and water management tools for stakeholders.

2. MATERIAL AND METHODS

2.1. Study area characterization

The Coruche region, located in Central Portugal, has a Mediterranean climate (Csa) characterised by hot, dry summers and mild winters (Figure 1). The mean annual temperature is 16.4°C, while the annual mean precipitation is 556 mm, with only 27% occurring between April and September, highlighting strong seasonality and a pronounced summer water deficit. It is one of the most important agricultural areas in Portugal, supported by the “Vale do Sorraia” Irrigation Scheme Association and a well-developed pressurised irrigation network. Maize is one of the dominant and most representative crops in the region. Given its high relevance to irrigated agriculture and sensitivity to climatic variability, Coruche provides a relevant case study for assessing climate impacts and supporting water management strategies under Mediterranean conditions.

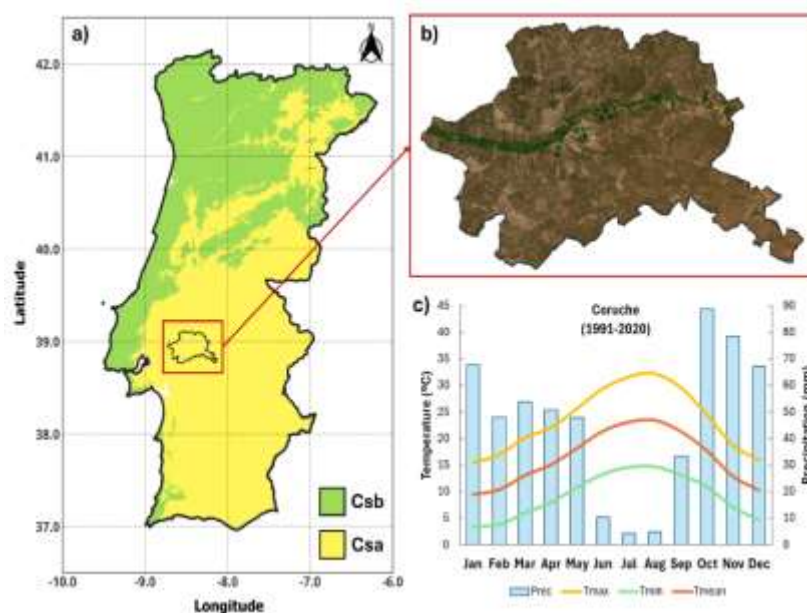


Figure 1. (a) Portugal Köppen-Geiger classification, (b) Coruche region, and (c) Ombrothermic diagram of Coruche (1991-2020).

2.2. Meteorological datasets

2.2.1. Reanalysis

The AgERA5 daily reanalysis dataset (Boogaard et al., 2020), available through the Copernicus Climate Change Service Data Store (C3S CDS), was selected as the reference for SF assessment. AgERA5 provides global coverage at a spatial resolution of 0.1° for agricultural and agroecological applications. For this study, grid cells covering Coruche region were extracted. Daily maximum temperature ($T_{\max}$), minimum temperature ($T_{\min}$), and precipitation data for the period 1987-2024 were collected. The AgERA5 dataset was bias-corrected using ground-based meteorological observations from the National Weather Service network. To account for altitude differences between weather stations and the corresponding reanalysis grid points, a temperature adjustment was applied using a standard environmental lapse rate of 6.5 °C km⁻¹. For temperature, a simplified bias correction was applied by adding a month-specific constant to the uncorrected reanalysis values. An analogous approach was used for precipitation, applying a month-specific multiplicative correction factor. The corrections were derived using the grid cells closest to the stations, and the same correction factors were then applied to all grid cells within the respective station's area of influence.

2.2.2. Seasonal forecasts

SF data were obtained from the C3S multi-system seasonal forecast service. The data are publicly available from the CDS under the product "Seasonal forecast daily and sub-daily data on single levels" and are produced by the ECMWF SEAS5 system (v5.1) (C3S, 2018). The dataset consists of a global ensemble of gridded forecasts at a horizontal resolution of 1°, with temporal coverage spanning from 1981. It comprises hindcasts for the period 1981-2016, based on 25 ensemble members, and real-time forecasts from 2017 onwards, based on 51 ensemble members, each extending up to 7 months into the future. For this study, daily $T_{\max}$, $T_{\min}$, and precipitation forecasts, starting on 1 April and covering the spring-summer season (April-October), were retrieved for the Coruche region. The study period spans 1987-2024, with 1987-2016 serving as the 30-year climatological reference baseline and 2017-2024 used as the forecast performance assessment period.

2.3. Seasonal forecasts assessment

The performance of seasonal forecasts was evaluated, focusing on two climatic indicators - accumulated precipitation and ET_o for the April-October period - and two key agronomic indicators - maize cycle duration, estimated using the GDD method, and a simplified crop water balance between ET_c and precipitation, used in this study as an estimate of maize irrigation water requirements. In the present study, CGDD was assumed to represent the cumulative sum of temperatures (T_{mean}) above a baseline threshold (T_{base}) required to reach a given growth stage, while crop development was assumed to cease above an upper temperature threshold (T_{upper}) (Eq. 1).

$$GDD = \begin{cases} 0, & \text{if } T_{\text{mean}} \leq T_{\text{base}} \\ T_{\text{mean}} - T_{\text{base}}, & \text{if } T_{\text{base}} < T_{\text{mean}} < T_{\text{upper}} \\ T_{\text{upper}} - T_{\text{base}}, & \text{if } T_{\text{mean}} \geq T_{\text{upper}} \end{cases} \quad (1)$$

ET_o (mm d⁻¹) was calculated using the temperature-based FAO Penman-Monteith method (Eq. 2), adopting a k_{RS} value of 0.159 °C^{-0.5} for solar radiation estimation (Paredes & Pereira, 2019).

$$ET_o = \frac{0.408 \cdot \Delta \cdot (R_n - G) + \gamma \cdot \frac{900}{T + 273} \cdot u_2 \cdot (e_s - e_a)}{\Delta + \gamma \cdot (1 + 0.34 u_2)} \quad (2)$$

where R_n : net radiation at the crop surface (MJ m⁻² day⁻¹); G : soil heat flux density (MJ m⁻² day⁻¹); T : air temperature at 2 m height (°C); u_2 : wind speed at 2 m height (m s⁻¹); e_s : saturation vapour pressure (kPa); e_a : actual vapour pressure (kPa); Δ : slope vapour pressure curve (kPa °C⁻¹); γ : psychrometric constant (kPa °C⁻¹).

The crop parameters used in this study are summarised in Table 1.

Table 1. Maize parameters used in the GDD and crop water balance calculations.

Parameter	Value	References
Sowing date	15 April	Paredes et al. (2025b)
T _{base} (°C)	10	
T _{upper} (°C)	32	
CGDD for harvest	1955	
K _{c ini}	0.3	Pereira et al. (2025)
K _{c mid}	1.2	
K _{c end}	0.3	

K_{c ini}, K_{c mid}, K_{c end} are the crop coefficients for the initial, mid-season and late stages, respectively.

Statistical metrics were used to quantify the accuracy and skill of the SF for each variable (Table 2). One cell of the reanalysis (39°N, -8.5°E) was selected as representative of the Coruche region and compared with the nearest cell of the SF grid (39°N, -8.0°E). A probabilistic approach using the full forecast ensemble was considered, though some analyses followed a deterministic approach using the ensemble median. Significance tests were conducted to assess the statistical significance of the performance metrics. Pearson's correlation t-test was applied to the ACC to evaluate whether the correlation between reanalysis and forecasted anomalies were statistically significant, while one-sample t-tests were used for MAE and PBIAS to determine whether the mean absolute differences and mean bias, respectively, were significantly different from zero ($\alpha = 0.05$)

Table 2. Performance Metrics for Seasonal Forecast Evaluation (Owens & Hewson, 2018).

Indicator	Equation	Description
Mean Absolute Error (MAE) *	$ F - R $	R: reanalysis; F: forecast. Measures the average magnitude of errors between forecasts and reanalysis, without considering their direction. Lower values indicate better accuracy.
Percentage Bias (PBIAS) *	$100 \cdot \frac{F - R}{R}$	R: reanalysis; F: forecast. Positive values indicate forecast overestimation, while negative values indicate forecast underestimation of the reanalysis.
Coefficient of Variation (CV) **	$\frac{\sigma_F}{\mu_F} \cdot 100$	Standard deviation (σ_F) and mean (μ_F) of the SF ensemble. Expresses the dispersion of the ensemble. Higher values indicate greater SF ensemble spread and higher relative uncertainty.
Standardised Anomaly Index (SAI) **	$\frac{X - X_c}{\sigma}$	X is the value for a given year, X _c and σ are the mean and standard deviation for the 1987-2016 period, respectively. Indicates how many standard deviations the value deviates from the long-term mean.
Anomaly Correlation Coefficient (ACC) *	$\frac{(F - F_c) \cdot (R - R_c)}{\sqrt{(F - F_c)^2 \cdot (R - R_c)^2}}$	R: reanalysis; R _c : 1987-2016 reanalysis mean; F: forecast; F _c : 1987-2016 forecast mean. Measures the correlation between forecast anomalies and observed anomalies. Ranges from -1 to 1, with positive values indicating agreement between forecast and reanalysis anomalies.
Continuous Ranked Probability Skill Score (CRPSS) **	$1 - \frac{CRPS_F}{CRPS_{R_c}}$	CRPS _F and CRPS _R are the continuous ranked probability scores for the forecast and the reanalysis, respectively. Quantifies the skill of the forecast in relation to the reanalysis-based climatology (1987-2016). 1 means a perfect forecast, and negative values indicate worse skill than the historical average.

* Deterministic approach; ** Probabilistic approach

3. RESULTS AND DISCUSSION

Seasonal forecast skill differed markedly between the variables, reflecting their contrasting predictability regimes in Mediterranean climates. Figure 2 and Table 3 show that SF resulted in a statistically significant MAE (46.5 mm) for precipitation, which is consistent with the high interannual variability inherent to this region. The non-significant PBIAS (4.8%), ACC (0.25), and CRPSS (0.13) collectively indicate that, while no systematic bias is present, probabilistic forecasts offer only modest improvement over a climatological reference.

This is a limitation due to the low seasonal predictability of Mediterranean precipitation. The wide ensemble range (CV = 34%) reflects the broad spread of the SF ensemble, underscoring the large uncertainty the forecasting system assigns to precipitation. The picture diverges substantially for ET_o . A highly significant MAE (81.6 mm) and the systematic negative PBIAS (-8.2%) reveal a consistent underestimation of ET_o likely driven by cold biases in the temperature forecasts.

This systematic displacement translates into a strongly negative CRPSS (-0.91), indicating that ET_o probabilistic forecasts are outperformed by the climatological baseline. Nonetheless, as shown in Figure 3b, the SAI agreement and the significant ACC (0.74) demonstrate that SF retain meaningful capacity to reproduce the sign and relative magnitude of interannual anomalies. The narrow ensemble range (CV = 3.5%) indicates that ensemble members converge on very similar outcomes, consistent with the more constrained interannual variability of ET_o .

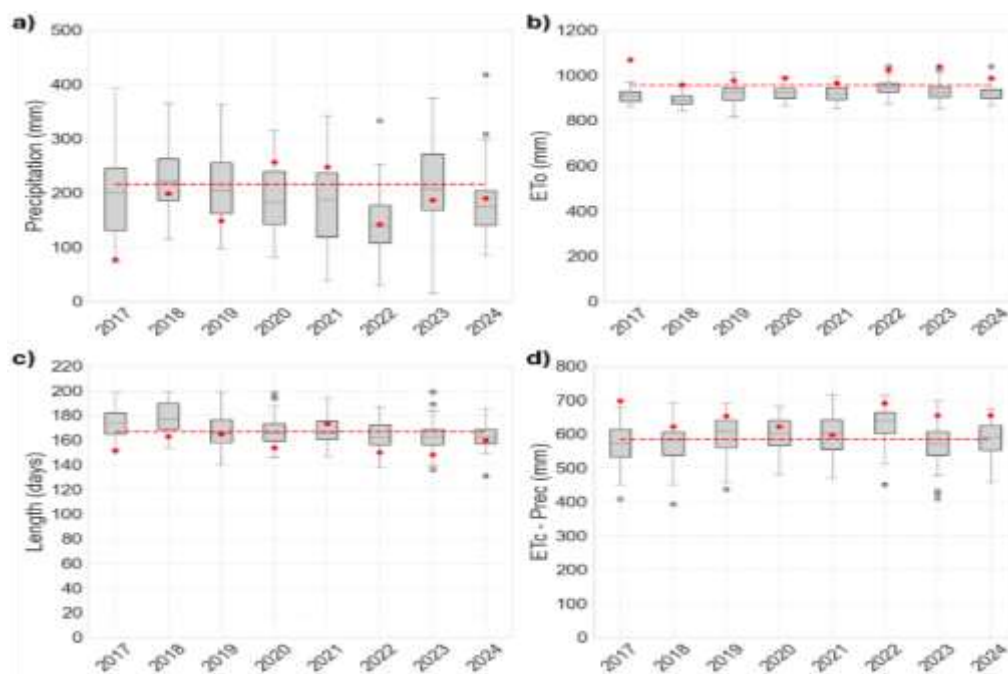


Figure 2. Box and whisker plots of April-October forecasts for accumulated precipitation (a) and ET_o (b), maize cycle duration (c) and crop water balance (d), estimated using the seasonal forecasts and reanalysis (red dots) (2017-2024). The dashed red line represents the reanalysis climatological mean (1987-2016).

For maize cycle duration (Figure. 2c), the propagation of temperature biases into the crop model introduced errors. The systematic cold bias in seasonal temperature forecasts delays thermal accumulation, leading to an average overestimation of cycle length by 11 days (Table 3). This negatively affects probabilistic skill, as indicated by the negative CRPSS (-0.16). Nevertheless, the ACC (0.69) and SAI agreement (Figure 3c) suggest the SF's ability to capture the interannual variability of maize cycle duration in Coruche, highlighting the potential benefits of correcting systematic temperature biases in these forecasts.

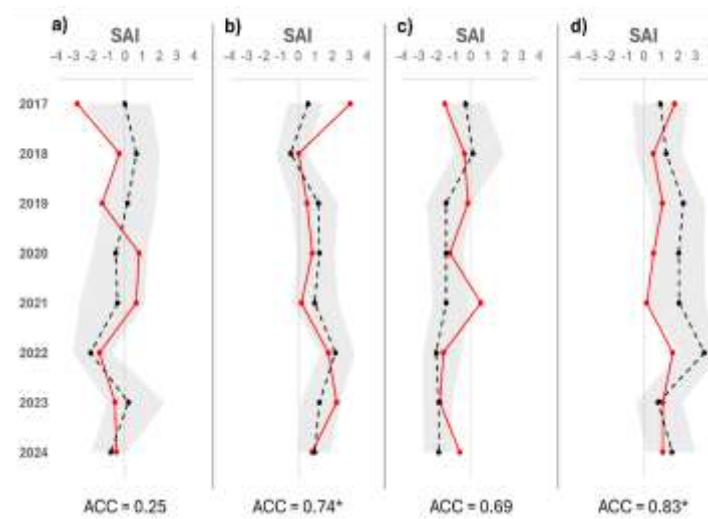


Figure 3. Standardised Anomaly Index (SAI) and Anomaly Correlation Coefficient (ACC) for seasonal forecast (a) precipitation, (b) ET_0 , (c) maize crop cycle duration, and (d) crop water balance (2017-2024). Anomalies are computed relative to the 1987-2016 climatology. Dashed black lines represent SAI estimates with SF median, while the grey shading indicates the interquartile range (25-75 percentiles) of SF ensemble. Red solid lines correspond to reanalysis-based reference data. *ACC statistical significance ($\alpha = 0.05$).

Table 3. Seasonal forecast accuracy and skill assessment for precipitation and ET_0 (April-October), maize cycle duration and crop water balance (2017-2024).

Variable	MAE (mm or days)	PBIAS (%)	CV (%)	CRPSS
Precipitation	46.5 *	4.8	34.0	0.13
ET_0	81.6 *	-8.2 *	3.5	-0.91
Maize cycle length	10.9 *	5.8 *	7.1	-0.16
ET_c - Prec	54.1 *	-8.2 *	9.9	0.00

* MAE and PBIAS statistical significance ($\alpha = 0.05$).

For the crop water balance, the ACC (0.83) is the highest and most significant among all evaluated variables, demonstrating, together with the SAI, that SF reliably captured the direction and relative magnitude of interannual anomalies in crop water deficit (Figure 3d). However, the high MAE and the negative PBIAS reveal a systematic underestimation of the water deficit (-8.2%), inherited directly from the underestimation of ET_0 (Table 3). This bias affects the probabilistic added value of SF, resulting in a near-zero CRPSS, with no improvement over the climatological reference. The moderate forecast ensemble spread, intermediate between the narrow ET_0 ensemble and the wider precipitation ensemble, reflects the combined uncertainty of both driving variables.

These results are consistent with previous studies that report SF temperature underestimation across Southern Europe (Villani et al., 2021), with downstream impacts on crop cycle estimation and evapotranspiration (Lalic et al., 2018; Costa-Saura et al., 2022; Yang et al., 2023). As reported by Cali Quaglia et al. (2021), seasonal forecast systems typically exhibit significant temperature anomaly correlations over the western Mediterranean region. For Portugal, Crespi et al. (2021) and Yang et al. (2023) highlight good seasonal mean temperature performance during summer season using SEAS5 forecast system, although with a tendency toward cooler predictions, which is reflected in a negative ET_0 bias reported for the Iberian Peninsula (Costa-Saura et al., 2022). Precipitation seasonal forecasts remain particularly challenging due to high spatial and temporal variability and dependence on small-

scale atmospheric processes, with generally low skill scores reported across the Mediterranean region (Crespi et al., 2021; Villani et al., 2021).

CONCLUSIONS

This study provided a comprehensive assessment of the performance of SF for agro-meteorological applications in a Mediterranean context, revealing both promising potential and important limitations that must be considered for their operational use in agricultural decision-making. The integration of SF into crop and water balance modeling tools offers an alternative to the use of fixed historical reference averages, which generally fail to represent interannual climate variability and become rapidly outdated under climate change. Overall, SF showed better results for ET_0 , maize cycle duration and crop water balance, where anomaly correlation skill is strongest. The promising ACC values reveal that the interannual anomaly trends of these temperature-driven variables are well captured by the forecast system, whereas the main limitation likely comes from a systematic cold bias rather than an absence of atmospheric predictability. This distinction is relevant for the operational usability of SF, as the primary constraint is not the ability of the forecasting system to capture climate variability, but rather biases in its mean climatological state. Therefore, results suggest that the application of bias correction techniques to raw temperature forecasts could substantially improve both the accuracy and probabilistic skill of SF, making them more suitable for operational crop and water management. Precipitation remains the most challenging variable, where limited predictability at seasonal timescales in the Mediterranean region constrains the overall performance of precipitation forecasts. It should be noted that the conclusions of this study are based on a single location and forecast system, which limits their direct application to other Mediterranean agricultural contexts. Further research should focus on evaluating the added value of bias-corrected SF across a wider range of sites and cropping systems, as well as on developing operational methodologies that translate forecast skill into practical early decision-support tools for agriculture.

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