National Recovery and Resilience Plan (Greece 2.0)

Hellenic Foundation for Research and Innovation

Action: Basic Research Financing (Horizontal support for all Sciences),

Sub-action 2: Funding Projects in Leading-Edge Sectors

Thematic Area 3: Agricultural Sciences – Food Science & Technology

Thematic Field 3.7: Climate change: impact on primary production and supply chain (farm to fork) - cyclical economy development of sustainable systems for food adequacy and safety

Project Title:

**Crop and livestock stress under climate change scenarios**

Project Acronym: **AGRO FUTURE CLIMATE STRESS**

Project No: **15743**

# Deliverable D8:

# Technical report on model's application and on simulated datasets

This project is carried out within the framework of the National Recovery and Resilience Plan Greece 2.0, funded by the European Union – NextGenerationEU (Implementation body: HFRI)

## Beneficiaries:

Aristotle University of Thessaloniki (Deliverable Leader)

University of Thessaly

Academy of Athens

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# Summary

This report presents the application of the Weather Research and Forecasting (WRF) high-resolution regional climate model to simulate the present (2005–2014) and near-future (2046–2055) climate over Greece, in the framework of the Work Package 3. The main objective was to provide detailed climatic parameters for the whole country of Greece, which will be used for the agricultural impact assessments of the Work Package 4. Model evaluation against the ERA5-Land dataset demonstrates that WRF simulates present-day temperature with high accuracy across most of Greece, while performance for relative humidity is also satisfactory but shows greater discrepancies, particularly in mountainous and coastal regions. The most notable deviations occur in areas with complex terrain, such as the Pindos mountain range and small islands, where spatial resolution limitations are most evident. Future projections under two applied emission scenarios (SSP2-4.5 and SSP5-8.5) show a robust warming signal throughout the country, with slightly higher warming under the worst-case scenario SSP5-8.5. Relative humidity is projected to decrease in most regions, but with a slightly weaker decline under the high-end SSP5-8.5 scenario—likely due to enhanced moisture evaporation and advection, as well as orographic effects, compensating for the thermodynamic drying. These simulations provide a reliable basis for understanding future climate stress on agricultural productivity in Greece.

# Περίληψη

Η παρούσα έκθεση παρουσιάζει την εφαρμογή του περιοχικού κλιματικού μοντέλου υψηλής ανάλυσης WRF για την προσομοίωση του παρόντος (2005–2014) και του εγγύς μέλλοντος (2046–2055) κλίματος στην Ελλάδα, στο πλαίσιο του Πακέτου Εργασίας 3. Κύριος στόχος ήταν η παραγωγή λεπτομερών κλιματικών παραμέτρων για το σύνολο της ελληνικής επικράτειας, οι οποίες θα χρησιμοποιηθούν για εκτιμήσεις αγροκτηνοτροφικών επιπτώσεων στο Πακέτο Εργασίας 4. Η αξιολόγηση του μοντέλου σε σύγκριση με το σετ δεδομένων ERA5-Land δείχνει ότι το WRF προσομοιώνει τη θερμοκρασία με υψηλή ακρίβεια στο μεγαλύτερο μέρος της χώρας, ενώ η απόδοσή του στη σχετική υγρασία είναι επίσης ικανοποιητική, παρουσιάζοντας όμως μεγαλύτερες αποκλίσεις, ιδιαίτερα σε ορεινές και παράκτιες περιοχές. Οι σημαντικότερες αποκλίσεις εμφανίζονται σε περιοχές με πολύπλοκη τοπογραφία, όπως η οροσειρά της Πίνδου και τα μικρά νησιά, όπου οι περιορισμοί χωρικής ανάλυσης είναι περισσότερο εμφανείς. Οι μελλοντικές προβλέψεις υπό τα δύο σενάρια εκπομπών που εφαρμόστηκαν (SSP2-4.5 και SSP5-8.5) δείχνουν έντονη θέρμανση σε όλη τη χώρα, με ελαφρώς υψηλότερες θερμοκρασίες υπό το δυσμενέστερο σενάριο SSP5-8.5. Η σχετική υγρασία προβλέπεται να μειωθεί στις περισσότερες περιοχές, αλλά με ελαφρώς μικρότερη μείωση στο σενάριο SSP5-8.5—πιθανώς λόγω ενισχυμένης εξάτμισης και μεταφοράς υγρασίας, καθώς και ορογραφικών επιδράσεων, που αντισταθμίζουν τη θερμοδυναμική ξήρανση. Οι προσομοιώσεις αυτές προσφέρουν μια αξιόπιστη βάση για την κατανόηση των μελλοντικών κλιματικών επιπτώσεων στην αγροκτηνοτροφική παραγωγικότητα της Ελλάδας.

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# 1 Introduction

The objective of Work Package (WP) 3 is the application of the WRF high-resolution regional climate model to produce climate simulations covering the present climate and the near future climate, and thus provide the necessary meteorological and climate parameters required by WP4 for the estimation of the agricultural indices and their future changes. The scope of this report is a thorough analysis of the simulation results produced in the context of WP3. The simulation period representing the present climate was chosen to be 2005–2014, as historical CMIP6 runs extend only up to 2015, after which the SSP-based scenario simulations begin. The year 2004 was used as a spin-up year preceding the present-climate simulation. Similarly, the near-future decade was chosen to be 2046–2055 and year 2045 was used as a spin-up year. These spin-up periods are essential for allowing soil temperature and moisture fields to stabilize across WRF's four-layer soil representation. Initial conditions from the global forcing data typically provide soil state variables for only a single layer, which must be interpolated across all soil levels in WRF. Without sufficient spin-up time, this interpolation can lead to imbalances or unrealistic vertical gradients in the land surface state, potentially compromising the accuracy of the early simulation years. For a more detailed description of the model setup, please refer to the deliverable D7 entitled "Technical report on model's setup". This report focuses on two main components of the analysis of the simulation results: (a) the evaluation of the model's performance in simulating the present climate using multiple statistical metrics, and (b) the analysis of future projections and the projected changes in key climate parameters—namely temperature and relative humidity—relative to the present climate.

# 2 Model Evaluation Framework

To evaluate the model's performance in reproducing the current climate, mean monthly values of air temperature (T, ˚C) and relative humidity (RH, %) at 2 m height above ground were evaluated against the corresponding monthly values from the ERA5-Land dataset (Munoz-Sabater et al., 2021) for the reference period 2005–2014. This dataset is produced as a replay of the land-surface model component of the ERA5 reanalysis, and outputs results in an enhanced ~9 km resolution, forced by meteorological fields from ERA5 (~31 km resolution). Consequently, it should be noted that variables such as wind speed and shortwave radiation are not directly computed at 9 km by the land-surface model, as in the case for T and RH, but are linearly interpolated from the original 31 km ERA5 fields. Therefore, a direct comparison of our results with ERA5-Land data for those variables was not performed.

Multiple commonly used evaluation metrics have been employed to create a complete and conclusive picture of the model's performance. To examine the models ability to simulate mean climatic values, the Mean Bias (MB) and Mean Absolute Error (MAE) were used. For the model's performance in simulating climate variability, the Pearson's $R$ coefficient ($R$) has been employed. To complement the evaluation of climate variability reproduction, the % Normalized Mean Bias of the Standard Deviation (NMB%STD) of the monthly values was also used. The formulas for the calculation of the abovementioned evaluation metrics are shown below (Eqs. 1, 2, 3 and 4, respectively):

$$MB = \frac{1}{N}\sum_{i=1}^{N}(M_i - O_i) \quad (1)$$

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$$MAE = \frac{1}{N}\sum_{i=1}^{N}|M_i - O_i| \quad (2)$$

$$R = \frac{\sum_{i=1}^{N}(M_i-\overline{M})(O_i-\overline{O})}{\sqrt{\sum_{i=1}^{N}(M_i-\overline{M})^2 \sum_{i=1}^{N}(O_i-\overline{O})^2}} \quad (3)$$

$$NMB\%STD = \frac{STD_{WRF}-STD_{ERA}}{STD_{ERA}} \cdot 100\% \quad (4)$$

where $M_i$ and $O_i$ represent the mean monthly WRF and ERA5-Land values, respectively, and $STD_{WRF}$ and $STD_{ERA}$ represent the standard deviation of the WRF and ERA5-Land mean monthly values, respectively.

# 3 WRF Model Application, Evaluation and Future Projections

## 3.1 Parameters Simulated by the WRF Model

**Table 1**: Parameters simulated by the WRF Model and supplied to WP4 for the calculation of the agricultural indices.

| Name | Description | Units | Comments |
|---|---|---|---|
| T2 | Temperature at 2m | K | |
| Q2 | Specific Humidity at 2m | kg/kg | |
| PSFC | Surface Pressure | Pa | |
| RH | Relative Humidity at 2m | % | Computed using T2, Q2 and PSFC |
| U10 | X component of Wind at 10m | m/s | |
| V10 | Y component of Wind at 10m | m/s | |
| WS | Wind Speed at 6m | m/s | Computed at 10m using the U10 and V10 components and adjusted to 6m using the logarithmic wind law |
| WS | Wind Speed at 2m | m/s | Computed at 10m using the U10 and V10 components and adjusted to 2m using the logarithmic wind law |
| GRDFLX | Ground Heat Flux | $W/m^2$ | |
| LH | Latent Heat Flux at the Surface | $W/m^2$ | |
| SWDNB | Instantaneous Downwelling Shortwave Flux at Bottom | $W/m^2$ | |

## 3.2 Performance Evaluation of the WRF Model

The results of the model evaluation are presented in this section, highlighting its strengths and limitations in reproducing observed climate patterns over Greece for the period 2005–2014.

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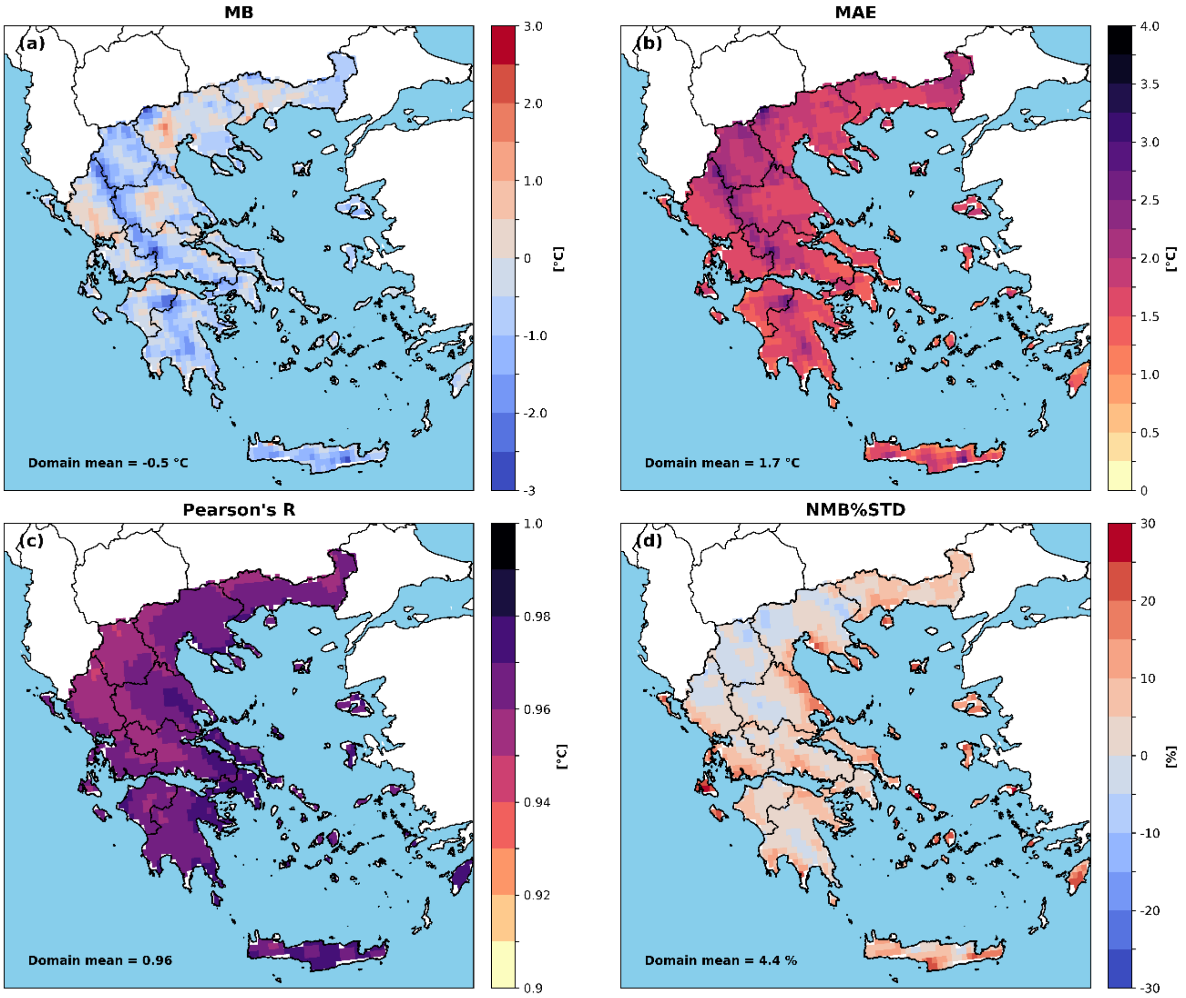


**Figure 1:** (a) MB, (b) MAE, (c) R and (d) NMB%STD for the WRF model's 2 m T compared to ERA5-Land for the reference period 2005–2014.

Overall, the model simulates T satisfactorily, capturing the main spatial patterns across the region of Greece, as well as the temporal mean and variance. The mean T across all model grid cells ranges from 5.5 °C to 19.7 °C, accurately representing the spatial T range, variability and distribution of Greece. The largest discrepancies are observed in the Pindos mountain range, characterized by complex topography with steep hypsometric gradients, as well as in some coastal zones with steep shorelines and small islands, areas that are not explicitly resolved by the model even at a 10 km resolution. MB values range between -2.8 °C and 1.9 °C, with a mean value of -0.5 °C, indicating an overall underestimation of T by the model (Figure 1a). However, this underestimation is largely confined in mountainous areas and particularly the Pindos mountain-range, while the vast majority of the country (>78% of grid cells) presents values between -1 °C and +1 °C, with no obvious overall hot or cold bias. Indicatively, MB values lower than -2 °C are found almost exclusively in the Pindos mountains, accounting for less than 1.5% of the total grid cells. MAE (Figure 1b) shows a similar spatial distribution to the MB, with values lower than 2 °C over the majority of the country (85% of grid cells), reaching up to 2.5–3 °C in the mountainous regions of Pindos. R values exceed 0.95 in all of Greece (Figure 1c), with the eastern part of the country presenting values up to 0.99, while NMB%STD (Figure 1d) ranges between -5% and +5% across nearly the entire country, with the exception of some coastal areas and small islands. These results indicate that the model performs well in simulating present-day T, with the exception of the complex and steep topography area of the Pindos mountain range, where larger discrepancies are observed.

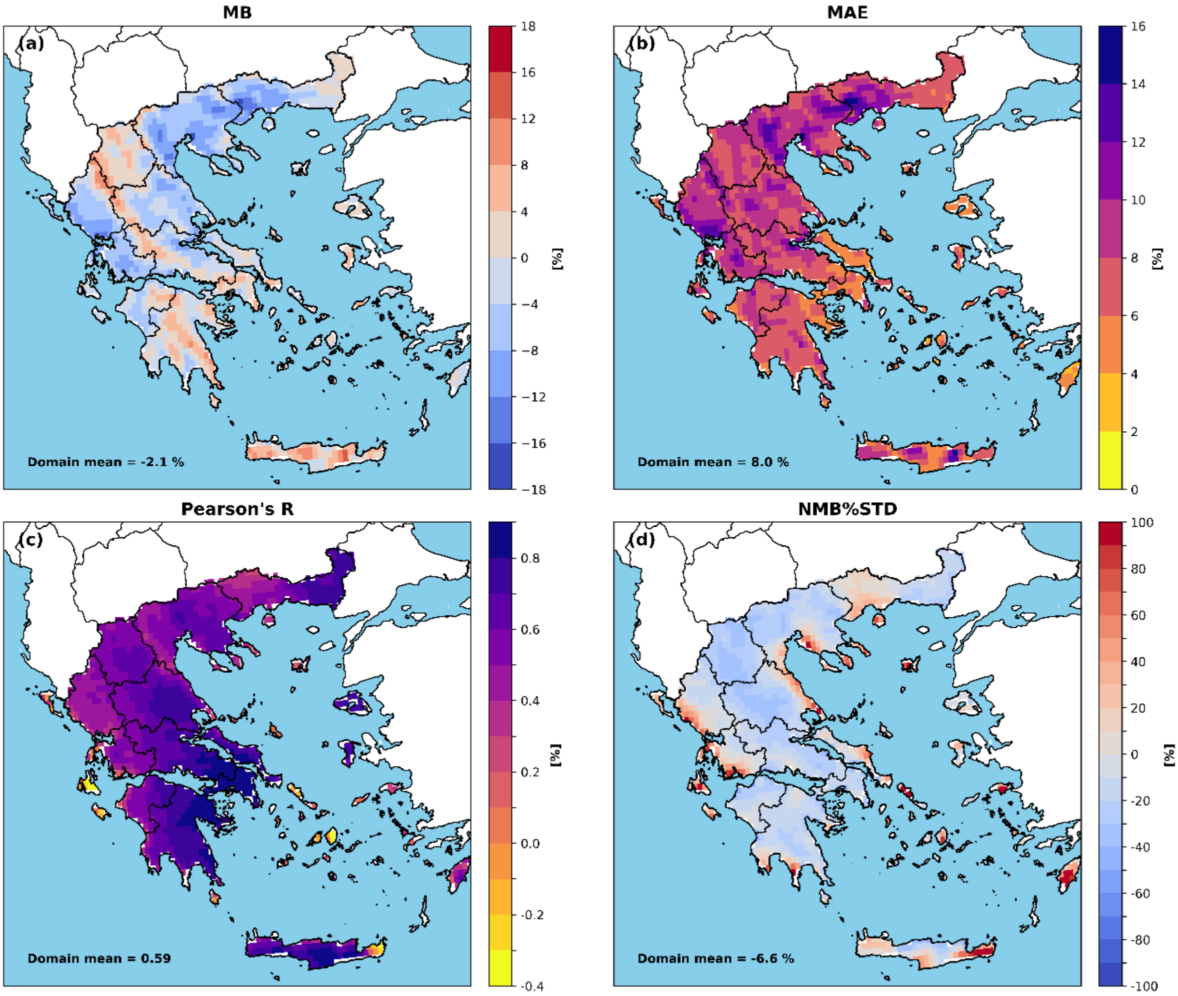


**Figure 2:** (a) MB, (b) MAE, (c) R and (d) NMB%STD for the WRF model's 2 m RH compared to ERA5-Land for the reference period 2005–2014.

With regard to RH, the model's performance is generally adequate and follows a similar pattern to T, although RH is inherently more complex and thus larger discrepancies are found compared to T. This complexity arises because RH is a derived variable that heavily depends on atmospheric dynamics, moisture transport, and interactions with precipitation and wind. Simulated mean annual RH for the reference period ranges between 54.5% and 79.6%. MB values span from -16.5% to +13.9%, with a domain-wide mean of -2.0% (Figure 2a). The majority of the country (>68% of total grid cells) present values between -6% and +6%. Positive RH biases are concentrated in mountainous regions, particularly the Pindos range, likely due to the concurrent underestimation of temperature in the region, leading to reduced air capacity for moisture. Additionally, the Pindos range is the most precipitation-intense area in Greece due to strong orographic lifting of moist westerly air masses (Baltas, 2008; Katsafados et al., 2012; Politi et al., 2023). Thus, discrepancies in modelled wind and precipitation in this region may therefore further contribute to RH biases. MAE presents values between 3.5% and 16.7%, with a mean value of 7.9% (Figure 2b). Most of the country (>86% of grid cells) presents values lower than 10%, with the highest errors occurring in mountainous areas and along steep coastal regions. R varies between 0.5 and 0.9 across the mainland (Figure 2c), with higher values in eastern Greece and lower values in the west—likely due to the disruptive influence of the Pindos mountains on humid westerlies. However, the model performs poorly over the Ionian and certain Aegean islands, where R values can fall below zero. This is a clear indication that the 10 km spatial resolution of the model is not enough to adequately resolve these small islands. Finally, the NMB%STD falls between -20% and +20% for the majority of the country (Figure 2d). However, in certain coastal zones and smaller islands, the model significantly overestimates variability, with standard deviations reaching up to twice those of the ERA5-Land dataset. In total, the model presents satisfactory skills in reproducing the current climatology of RH for most of its mainland regions and large islands, while lower to poor performance is demonstrated in areas with complex and steep topography, steep coastlines and small islands, features that remain unresolved at the model's spatial resolution.

In general, the WRF model demonstrates satisfactory performance in reproducing the present-day climate over Greece, effectively capturing the spatial and temporal variability of T and RH across most regions. While performance is strong over the mainland, biases are more evident in areas with complex terrain such as the Pindos mountains, as well as in narrow coastal zones and small islands that are not fully resolved at the model's horizontal resolution. RH shows greater discrepancies, reflecting its dependence on multiple atmospheric processes, including T, moisture transport, and precipitation. Furthermore, potential limitations of the ERA5-Land dataset should be considered, as its origin from a land-surface model component may introduce inaccuracies in variables that are sensitive to atmospheric dynamics—especially in areas with strong land–atmosphere interactions or complex terrain. Nonetheless, the multi-metric evaluation suggests that the WRF model captures the key climatological characteristics of the region with reasonable accuracy.

## 3.2 Near-Future Projections Under Climate Change

This section analyses the near future (decade 2046-2055) changes imposed by climate change under the SSP2-4.5 and SSP5-8.5 emission scenarios.

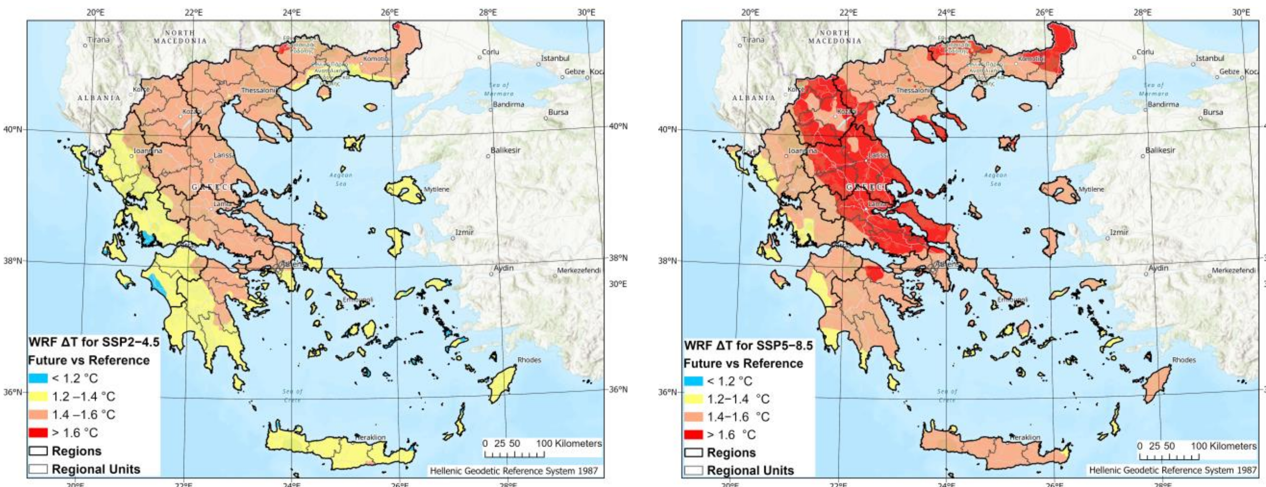


**Figure 3:** Projected difference (future vs reference period) of mean temperature (ΔT) (°C) at 2 m for each model grid cell under the SSP2–4.5 (left map) and SSP5–8.5 (right map) mission scenario across Greece.

For the intermediate emission scenario (SSP2-4.5), mean T is projected to rise by 1.2 – 1.4 $^{o}$C in the area that covers Western Greece, Crete and the Ionian and Aegean islands, while a higher increase, namely 1.4 – 1.6 $^{o}$C, is projected almost for the rest of the country (Figure 3, left map). These two greater Greek areas correspond to 38% and 58%, respectively, of the country's territory. For the worst-case emission scenario (SSP5-8.5), a clear shift to higher ΔT classes is projected. Mean T increases higher than 1.6 $^{o}$C are projected for central Greece (Figure 3, right map), corresponding to an area that accounts for the 32% of Greek territory. Increases 1.4 – 1.6 $^{o}$C are projected almost for the rest of the country, corresponding to the 61% of the Greek territory.

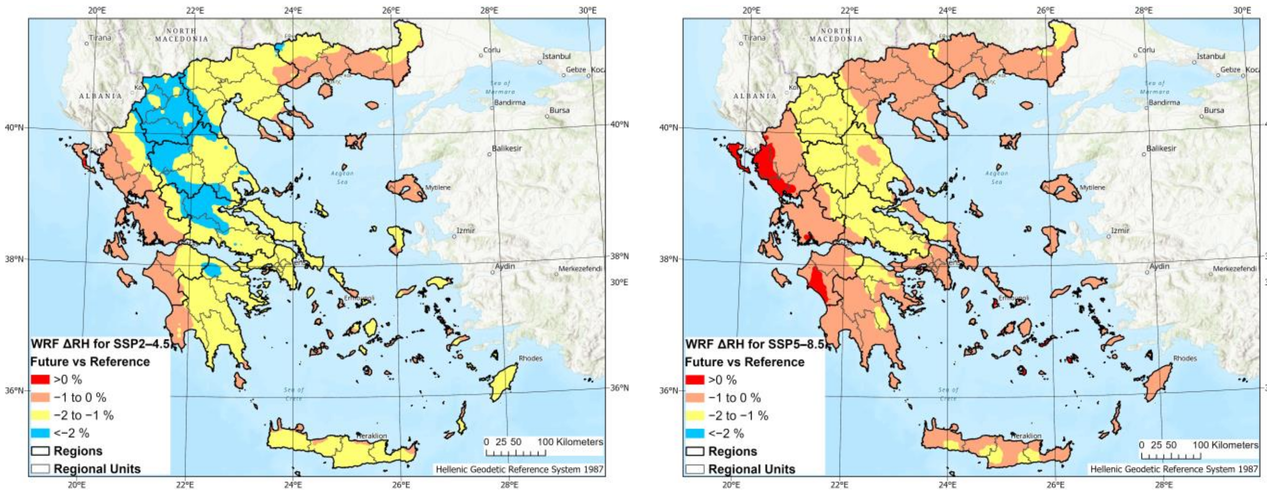


**Figure 4:** Projected difference (future vs reference period) of mean relative humidity (ΔRH) (%) at 2 m for each model grid cell under the SSP2–4.5 (left map) and SSP5–8.5 (right map) emission scenario across Greece.

Mean ΔRH projections are presented in Figure 4. For the intermediate emission scenario (SSP2-4.5), mean RH is projected to decrease up to -1% in the area that covers Western Greece, the greater part of Thrace and Northern Aegean islands, more than -2% in the area that covers Western Macedonia and the mountainous areas of central Greece and by -1% to -2% in the rest of the country (Figure 5, left map). These regions correspond to 27%, 16% and 57%, respectively, of the country's territory. For the worst-case emission scenario (SSP5-8.5), a clear shift to lower ΔRH classes is projected. Mean RH is projected to decrease up to -1% and by -1% to -2% in areas that correspond to 63% and 33%, respectively, of the country's territory, while mean RH is projected to mildly increase in small parts of the west (Figure 4, right map). This result is somewhat counter-intuitive, as the stronger warming under SSP5-8.5 would, in principle, suggest a greater decrease in relative humidity, given that warmer air can hold more moisture—even if the absolute atmospheric water content remains constant. However, this thermodynamic effect may be offset by increased evaporation over the Mediterranean due to elevated temperatures (Skliris et al., 2025). In addition, changes in regional circulation patterns could influence future RH values by affecting moisture transport (Gimeno-Sotelo et al., 2024), as well as orographic convection and percipitation in the west and the Pindos mountain range where the differences between the two scenarios are most pronounced. Hence, these findings reflect the complex interaction between thermodynamic and dynamic processes in determining future relative humidity patterns.

# Conclusions

This report presented the application of the WRF regional climate model for simulating present and near-future climate conditions over Greece, with a focus on air temperature and relative humidity. The simulation results were evaluated against the ERA5-Land dataset. Multiple evaluation metrics have been used for a thorough and complete assessment of model performance in reproducing both mean climatological values and climate variability. The model successfully captured the main spatial and temporal patterns of the present climate, with high accuracy for temperature and satisfactory performance for relative humidity, despite some expected limitations in areas with complex topography and unresolved small-scale features. Future climate projections for the 2046–2055 period under the SSP2-4.5 and SSP5-8.5 scenarios indicate a clear warming trend across the country, with slightly higher temperature increases under the high-end scenario. Relative humidity is projected to decrease in most regions, but the reduction is less pronounced under SSP5-8.5 in areas such as western Greece and the Pindos range. This is likely due to enhanced moisture evaporation and advection, as well as orographic convection procedures. Overall, the WRF model outputs provide a reliable and spatially detailed climate dataset, suitable for the computation of the agricultural indices in WP4.

# Συμπεράσματα

Η παρούσα έκθεση παρουσίασε την εφαρμογή του περιοχικού κλιματικού μοντέλου WRF για την προσομοίωση των κλιματικών συνθηκών του παρόντος και του εγγύς μέλλοντος στην Ελλάδα, με έμφαση στη θερμοκρασία και στη σχετική υγρασία. Τα αποτελέσματα των προσομοιώσεων αξιολογήθηκαν σε σύγκριση με το σετ δεδομένων ERA5-Land. Χρησιμοποιήθηκαν πολλαπλοί δείκτες αξιολόγησης, προκειμένου να επιτευχθεί μια ολοκληρωμένη και λεπτομερής εκτίμηση της απόδοσης του μοντέλου, τόσο ως προς την αναπαραγωγή των μέσων κλιματικών τιμών όσο και της κλιματικής μεταβλητότητας. Το μοντέλο αναπαράγει με επιτυχία τα κύρια χωρικά και χρονικά χαρακτηριστικά του παρόντος κλίματος, με υψηλή ακρίβεια για τη θερμοκρασία και ικανοποιητική απόδοση για τη σχετική υγρασία, παρά ορισμένους αναμενόμενους περιορισμούς σε περιοχές με σύνθετο ανάγλυφο και χαρακτηριστικά μικρής κλίμακας. Οι μελλοντικές προβλέψεις για την περίοδο 2046–2055, βάσει των σεναρίων εκπομπών SSP2-4.5 και SSP5-8.5, δείχνουν σαφή τάση αύξησης της θερμοκρασίας σε όλη τη χώρα, με ελαφρώς μεγαλύτερη αύξηση στο δυσμενέστερο σενάριο. Η σχετική υγρασία προβλέπεται να μειωθεί στις περισσότερες περιοχές, με ηπιότερη μείωση υπό το σενάριο SSP5-8.5 σε περιοχές όπως η δυτική Ελλάδα και η οροσειρά της Πίνδου. Το γεγονός αυτό αποδίδεται πιθανώς σε ενισχυμένη εξάτμιση και μεταφορά υγρασίας, καθώς και σε διαδικασίες ορογραφικής ανύψωσης. Συνολικά, τα αποτελέσματα του μοντέλου WRF παρέχουν ένα αξιόπιστο και χωρικά λεπτομερές κλιματικό σετ δεδομένων, κατάλληλο για τον υπολογισμό των αγροκτηνοτροφικών δεικτών στο Πακέτο Εργασίας 4.



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