



1 **The regional Earth system model ENEA-REG (version 3.0): development and**
2 **validation for the Med-CORDEX region**

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16
17 **Abstract**

18 Regional Earth system models are essential tools for representing climate processes and
19 interactions among Earth system components at spatial scales relevant to impact studies, thereby
20 providing the scientific basis for reliable impact assessments and effective adaptation strategies.
21 This paper presents the third version of the ENEA-REG regional Earth system model,
22 specifically designed to simulate past and present climate variability and to produce centennial-
23 scale climate projections over the Euro-Mediterranean region. Compared with the previous
24 model version (i.e. ENEA-REG2), ENEA-REG3 introduces an enhanced representation of river
25 discharge and floodplain processes and a substantially revised coupler implementing a time-
26 averaged explicit atmosphere–ocean coupling strategy that improves the temporal consistency of
27 the exchanged fluxes.



28 Model performances are assessed using a hindcast simulation driven by the ERA5 and ORAS5
29 reanalyses, together with two historical downscaling simulations driven by the CMIP6 models
30 EC-Earth3 and MPI-ESM1-2-HR. Compared to ENEA-REG2, the results indicate a substantial
31 improvement in simulated river discharge and reduced biases in the ocean component,
32 particularly in regions strongly influenced by freshwater inputs, such as the Adriatic Sea and
33 several coastal areas of the eastern Mediterranean, where the excessive salinization simulated by
34 ENEA-REG2 is markedly reduced. The results also show close agreement among the hindcast
35 and historical simulations, suggesting that model performance is largely governed by the
36 regional coupled system and its parameterizations rather than by the driving global climate
37 models. This consistency strengthens confidence in the robustness of future climate projections.

38

39 **1. Introduction**

40 In the past decades, the Mediterranean basin has been identified as one of the most prominent
41 climate change hotspots worldwide (Giorgi, 2006; Tuel and Eltahir, 2020; Urdiales-Flores et al.,
42 2023). In addition to increasing temperatures and heatwave frequency (Fischer and Schär, 2010;
43 Lionello and Scarascia, 2018; Schär et al., 2004; Vautard et al., 2014; Darmaraki et al., 2019;
44 Marullo et al., 2023), climate projections indicate a reduction in mean precipitation and an
45 intensification of heavy rainfall associated with intense cyclones (Chericoni et al., 2025a). While
46 changes in the frequency and magnitude of heatwaves and cold spells are expected to exacerbate
47 temperature-related mortality (Martínez-Solanas et al., 2021; Masselot et al., 2025), changes in
48 precipitation regimes lead both to more frequent drought events (Forzieri et al., 2014) and to a
49 heightened risk of damaging flooding (Blöschl et al., 2019; Hamitouche et al., 2026a), resulting
50 in severe socio-economic impacts (Dottori et al., 2023; Vousdoukas et al., 2018) and fatalities,
51 such as during the recent flood event in Valencia in 2024 (Piccolroaz, 2024).

52 For these reasons, several coordinated modelling initiatives have been developed to improve
53 understanding of past, present, and future regional climate, with the aim of better evaluating the
54 impacts of climate change on natural ecosystems, human activities and infrastructure and, in
55 turn, supporting the development of adaptation and mitigation strategies from the national to the
56 local level (Giorgi et al., 2009). Among these initiatives, the Coordinated Regional Climate
57 Downscaling Experiment (CORDEX) provides a standardized framework for producing and
58 evaluating regional climate simulations over multiple domains worldwide, enabling consistent



59 inter-comparison of regional climate models and downscaling strategies (Giorgi and Gutowski
60 Jr, 2015; Giorgi et al., 2009). Within this framework, the Med-CORDEX initiative focuses
61 specifically on the Euro-Mediterranean region, promoting coupled regional climate system
62 simulations that account for atmosphere–ocean–land interactions and their role in regional
63 climate variability and change (Ruti et al., 2016). These coordinated initiatives have substantially
64 advanced the development of fully coupled regional models for the Mediterranean region and
65 provided a common framework for their systematic inter-comparison and evaluation (Darmaraki
66 et al., 2019; De Rovere et al., 2026; Parras-Berrocal et al., 2025; Parras-Berrocal et al., 2024;
67 Soto-Navarro et al., 2020).

68 This paper describes the new version of the ENEA-REG regional Earth system model,
69 specifically designed to simulate the Euro-Mediterranean climate, and evaluates its atmospheric
70 (ATM), ocean (OCN), and river-routing (RTM) components. The first version of ENEA-REG
71 (Anav et al., 2021), based on two interchangeable atmospheric components, WRF (Powers et al.,
72 2017) and RegCM (Giorgi et al., 2012), showed substantial biases across all atmospheric
73 configurations. In particular, WRF exhibited a pronounced cold bias during winter over the
74 north-eastern part of the domain and a strong warm bias during summer, while RegCM
75 overestimated wind speed over the Mediterranean Sea. Similarly, the ocean component was able
76 to reproduce the observed large-scale surface ocean characteristics, despite the presence of non-
77 negligible biases in sea surface temperature and salinity. Since then, a second version has been
78 developed based solely on WRF as the atmospheric component. The evaluation demonstrated
79 that the regional model reliably reproduced the mean state and the spatial and temporal
80 variability of essential atmospheric and ocean variables (Anav et al., 2024). In particular, the
81 model was able to simulate the climatology of extreme Mediterranean cyclones and the
82 associated atmospheric fields (Chericoni et al., 2025b), as well as the Mediterranean Sea surface
83 circulation (Parras-Berrocal et al., 2024). In addition, it has been also used to assess future sea
84 level rise (Parras-Berrocal et al., 2025) and quantify projected changes in precipitation associated
85 with intense cyclones (Chericoni et al., 2025a). Despite these improvements, a substantial bias
86 remains in the simulated river discharge (Hamitouche et al., 2026b). For this reason, the river
87 routing component has been replaced, and the aim of this paper is to present the new ENEA-
88 REG version, its main improvements, and an evaluation of the performance of its individual
89 components.



90 2. Model description and experimental design

91 2.1 Model components

92 Compared to ENEA-REG2 (Anav et al., 2024), the atmospheric and ocean components, namely
 93 WRF (v4.2.2) and MITgcm (z67), together with their parameterizations, remain unchanged. In
 94 contrast, based on the performance of different river routing schemes in reproducing the major
 95 rivers flowing into the Mediterranean Sea (Hamitouche et al., 2026b), the main change
 96 introduced in ENEA-REG3 is the replacement of the HD (Hydrological Discharge) model
 97 (Hagemann and Dümenil, 1997) with the CaMa-Flood (Catchment-based Macro-scale
 98 Floodplain) model (Yamazaki et al., 2013; Yamazaki et al., 2011) (**Figure 1**).

99 CaMa-Flood (v4.23) is a global-scale distributed hydrodynamic model designed to simulate river
 100 discharge and floodplain inundation by routing surface and subsurface runoff from land surface
 101 schemes through a prescribed river network at fixed resolution. It discretizes river basins as a
 102 collection of unit catchments connected through a hybrid grid–vector river network, enabling an
 103 efficient description of flow propagation over large spatial domains. Within each unit catchment,
 104 subgrid river and floodplain topographic parameters are used to represent floodplain inundation
 105 as a subgrid-scale process (Yamazaki et al., 2014).

106 River routing accounts for the backwater effect and is solved using the local inertial formulation
 107 of the shallow-water equations, which retains the pressure gradient and friction terms while
 108 neglecting the advection term, thereby providing a compromise between computational
 109 efficiency and physical realism (Bates et al., 2010; Yamazaki et al., 2013). Water storage in each
 110 catchment is updated through mass conservation by accounting for upstream inflows,
 111 downstream outflows, and local runoff contributions. River discharge between adjacent
 112 catchments, as well as water levels and inundated areas, are then diagnosed from the simulated
 113 storage (Yamazaki et al., 2011). The model also incorporates bifurcation channels that allow
 114 water exchanges between neighboring floodplains and distributary branches, improving the
 115 representation of complex hydrodynamics in lowland and deltaic regions (Yamazaki et al.,
 116 2014). Channel flow calculations employ a Manning roughness coefficient of 0.03 for the main
 117 river channels, while the routing time step is dynamically adjusted to satisfy the Courant–
 118 Friedrichs–Lewy stability criterion (Bates et al., 2010; Yamazaki et al., 2013).

119 The river network and associated subgrid topographic parameters are derived using the FLOW
 120 upscaling algorithm (Yamazaki et al., 2009) applied to high-resolution elevation and



hydrography datasets, including MERIT DEM and MERIT Hydro products (Yamazaki et al., 2019), which provide improved consistency of river connectivity and terrain representation. The overall ENEA-REG3 structure is depicted in **Figure 1**. In contrast to previous versions, the ocean–atmosphere coupling frequency is set to 1 hour in accordance with the Med-CORDEX protocol (<https://zenodo.org/records/11659642>). Accordingly, at each hourly coupling step, the atmospheric component receives sea surface temperature (SST) from the ocean model and provides surface pressure, wind components, freshwater fluxes (evaporation–precipitation), and heat fluxes to the ocean. At a daily time step, the hydrological model uses surface and subsurface runoff provided by WRF to compute river discharge, which is then exchanged with the ocean component (**Figure 1**). Heat and water fluxes are remapped between model components using first-order conservative regridding, whereas SST, surface pressure, and wind components are regridded using bilinear interpolation. Unlike previous versions based on the HD model, in which only the discharge from the 15 major rivers was provided to the ocean component, the new version includes all rivers flowing into the Mediterranean Sea with a discharge greater than 5 m³/s. River discharge is remapped onto the ocean grid using nearest-neighbor interpolation.

2.2 The new ENEA-REG coupler and coupling strategies

The coupler, designed to facilitate connections, synchronization, and data exchange between the model components (**Figure 1**), has undergone substantial changes compared to its original version (Turuncoglu, 2019). It is still based on the Earth System Modeling Framework (ESMF) library (Theurich et al., 2016) and the National United Operational Prediction Capability (NUOPC) layer, but now it includes modifications to ensure compatibility with version 8.x of the ESMF library and the updated NUOPC interfaces. This allows the coupler to exploit the new capabilities of the library, which include, among others, improvements and bug fixes in conservative regridding.

Another major improvement of the coupler concerns the definition of the run sequence, which controls the interaction order among the model components during the simulation. While in the first version the run sequence was hard-coded, it can now be easily modified through the coupler namelist. This modification facilitates the switch from sequential to concurrent run mode without compiling the coupler every time. In a sequential execution, all modeling components are defined on the same set of processors; thus, at each component iteration, only one model can



152 advance, and the other components wait for its termination before starting their iterations. This
 153 mode is preferred in cases of limited computing resources. Conversely, in concurrent run mode,
 154 the components execute on mutually exclusive sets of processors; thus, each component can
 155 begin its computation and proceed until it reaches the coupling interval. This mode is preferred
 156 when a substantial amount of computational resources is available; however, assigning
 157 appropriate resources to individual model components is not straightforward and requires
 158 extensive benchmarking to achieve optimal performance (Turuncoglu, 2019).

159 **Figure 3** shows the computational performance of ENEA-REG3 in both sequential and
 160 concurrent run modes, demonstrating the benefits of the concurrent execution strategy in terms
 161 of reduced wall-clock time. At low processor counts, concurrent mode is less efficient because a
 162 fixed number of processors (i.e., 90) is permanently allocated to the ocean component, reducing
 163 the computational resources available to the atmospheric component, which dominates the
 164 overall computational cost. As the total number of processors increases, the benefits of
 165 concurrent execution progressively compensate for this initial load imbalance, leading to
 166 improved scalability and lower wall-clock times. In particular, the two configurations have
 167 similar performances with 152 ATM cores, then the concurrent mode reaches a wall-clock time
 168 approximately 35% lower than that of the sequential mode when using 512 dedicated ATM
 169 processors. In sequential mode, performance improvements become negligible beyond 360 cores
 170 because of communication bottlenecks. A similar behavior is observed in concurrent mode,
 171 although with overall better scalability, with performance degradation becoming evident beyond
 172 360 dedicated ATM processors. The allocation of 90 processors to the OCN component in
 173 concurrent mode was determined through dedicated profiling experiments using different domain
 174 decompositions, ranging from 8 to 418 dedicated cores. These tests showed only marginal
 175 performance gains beyond 90 processors.

176 Finally, the last significant improvement compared to the previous version is the modification of
 177 the coupling strategy, which determines the sequence of data exchange among the model
 178 components. In previous versions, the coupling was fully explicit, meaning that the ocean and
 179 atmospheric components exchanged instantaneous fields at the same model time (**Figure 2a**). In
 180 ENEA-REG3, the ocean–atmosphere coupling remains explicit, while the transfer of
 181 atmospheric fields to the ocean is now performed using a time-averaged explicit coupling
 182 scheme. In other words, the atmospheric component exports time-averaged fields computed over



the coupling interval rather than instantaneous values (**Figure 2b**). This modification improves the temporal consistency of the exchanged variables: for instance, considering precipitation, in an explicit coupling mode, information about a rainfall event simulated by the atmospheric component cannot be transferred to the ocean component if the event does not occur at the exact coupling time. Similarly, the development and evolution of a convective cloud system have no impact on the radiative fluxes reaching the ocean surface when cloud formation occurs outside the coupling interval. In any case, the shorter the coupling interval, the more similar the fully explicit and the time-averaged configurations become, reaching identical behavior when the coupling interval matches the model component's physical time step.

Considering the river routing component, it runs on a daily time step (slow) and exchanges information with the other components, while, as already discussed in the previous section, the ocean and atmospheric models interact at an hourly frequency (fast), although **Figure 2** reports a 6-hour interval for clarity.

2.3 The experimental setup

In this section, we describe the set-up of present-climate simulations performed with ENEA-REG3. The model domains are shown in **Figure 4a**: the atmospheric component, with a resolution of 12 km, covers all of continental Europe, as does the river routing component, which has a resolution of 3 minutes (i.e., 0.05° , approximately 5.55 km). The ocean model has a horizontal resolution of $1/12^\circ$ (approximately 9 km) and covers the entire Mediterranean Sea, with an open boundary in the Atlantic Ocean west of the Strait of Gibraltar. Freshwater inputs from the Nile River and the Black Sea are prescribed as monthly climatological means.

We performed several downscaling experiments fully compliant with the Med-CORDEX protocol (<https://zenodo.org/records/11659642>): in the hindcast (or control simulation) the ERA5 reanalysis (Hersbach et al., 2020) is used as atmospheric initial and boundary conditions, while ORAS5 (Zuo et al., 2019) is used as forcing for the ocean. In addition, two historical simulations from Phase 6 of the Coupled Model Intercomparison Project (CMIP6) (Eyring et al., 2016) were downscaled selecting the MPI-ESM1-2-HR (Gutjahr et al., 2019) and EC-Earth3 (Döscher et al., 2021) as driving models. Both the hindcast and historical simulations cover the period 1st August 1960–31st December 2014.



213 The ocean initial conditions were derived from a long standalone spin-up of the ocean model. To
 214 this end, WRF was first run independently over the 1960–1969 period, and the resulting
 215 atmospheric fields were used to force MITgcm. In particular, a 400-year ocean spin-up was
 216 performed by repeatedly cycling 1-year simulations, with atmospheric forcing randomly selected
 217 from the 1960–1969 period, until the Mediterranean thermohaline state reached a quasi-
 218 stationary regime, as indicated by the absence of systematic long-term drifts in basin-averaged
 219 temperature and salinity, particularly in the intermediate and deep layers. The random selection
 220 of the forcing prevents the introduction of artificial decadal variability into the ocean
 221 simulations. Finally, the initial conditions were then obtained by averaging the ocean fields over
 222 a 30-year period following the achievement of the quasi-stationary state.

223 Ocean model validation is performed against the Mediterranean regional reanalysis at 1/24°
 224 resolution (hereafter MEDREA24) (Escudier et al., 2021), provided by the Copernicus Marine
 225 Service for the period from 1987 to the present. Model performance is evaluated over three sub-
 226 domains covering different regions of the Mediterranean Sea (**Figure 4**), characterized by
 227 distinct thermohaline properties. To ensure consistency with the ocean analysis, the atmospheric
 228 component is validated against the ERA5 reanalysis over the same temporal period (i.e., 1987–
 229 2014). In this case, model outputs are spatially aggregated over the PRUDENCE sub-domains
 230 (Christensen and Christensen, 2007) (**Figure 4**), which are widely used for regional climate
 231 model evaluation.

232 The river component is evaluated at the basin scale using observed river discharge from Global
 233 Runoff Data Centre (GRDC) gauging stations located at the outlets of eight Mediterranean
 234 exorheic river basins. The selected basins, ordered from the smallest to the largest, are: Köprü,
 235 Arno, Göksu, Ceyhan, Maritsa, Po, Ebro, and Rhône (**Figure 4c**). Model performance was
 236 assessed using a set of statistical metrics: Pearson correlation, relative standard deviation, mean
 237 bias, the root mean squared error and the Kling–Gupta Efficiency (KGE) (Gupta et al., 2009)
 238 (Gupta et al., 2009), which is a comprehensive measure of model performance, combining
 239 correlation, bias, and variability. KGE values can be classified to indicate the quality of
 240 performance: values ≤ -0.41 are unacceptable, $-0.41 < \text{KGE} \leq 0.00$ are very poor, $0.00 < \text{KGE} \leq$
 241 0.30 are poor, $0.30 < \text{KGE} \leq 0.65$ are intermediate, and $0.65 < \text{KGE} \leq 1.00$ are good
 242 (Hamitouche et al., 2026b).

243



244 3. Results

245 3.1 Changes in model performance relative to the previous version

246 Since the main difference relative to ENEA-REG2 is the replacement of the river-routing
 247 component, the largest changes are expected in simulated freshwater discharge and,
 248 consequently, in ocean salinity near river mouths. **Figure 5** shows the daily cycle of observed
 249 and simulated discharge at the outlet locations of the eight selected rivers. The results
 250 demonstrate systematically better performance in ENEA-REG3 relative to ENEA-REG2 across
 251 all eight basins. The most pronounced improvement is observed in the KGE metric: ENEA-
 252 REG2 produced negative values in seven out of eight basins (mean = -0.20), whereas ENEA-
 253 REG3 achieves positive values in all basins, with a mean KGE of 0.38 and a maximum of 0.60
 254 for the Göksu River. The improvement is driven largely by a much better reproduction of
 255 observed variability: the relative standard deviation (rSD) in ENEA-REG2 was severely
 256 underestimated across all basins (mean rSD = 0.18, meaning the model captured less than one-
 257 fifth of the observed variability), while ENEA-REG3 brings rSD considerably closer to unity
 258 (mean = 0.85), with near-perfect variability reproduction at Göksu (1.04) and Rhone (0.98).
 259 Pearson correlation follows the same pattern, increasing from a mean of 0.30 in ENEA-REG2 to
 260 0.61 in ENEA-REG3, with improvements observed across all eight basins. RMSE decreases in
 261 seven out of eight basins, with the Ebro River representing the only exception, where it increases
 262 slightly from 260 to 317 m³/s; overall, the mean reduction is approximately 11%.

263 In terms of water balance, both versions exhibit a predominant dry bias, indicating a systematic
 264 underestimation of observed streamflow. In ENEA-REG2, seven out of eight basins show
 265 negative bias, with severe underestimation at Kopru (-96%), Goeksu (-90%), and Ceyhan
 266 (-75%), and a mean bias of -44% . ENEA-REG3 reduces the magnitude of this dry bias in five
 267 out of eight basins, bringing the mean to -25% , with the most notable improvement at Goeksu
 268 (from -90% to -24%) and Ceyhan (from -75% to -42%). However, the dry bias persists and
 269 remains substantial in several basins, particularly Kopru (-66%) and Arno (-40%). The one
 270 exception is Ebro, which shifts from near-zero bias in ENEA-REG2 (-0.3%) to a prominent
 271 positive bias in ENEA-REG3 ($+41\%$). Maritsa also moves from slightly positive ($+1.5\%$) to
 272 negative (-25%) bias.

273 As changes in freshwater discharge primarily affect ocean salinity, **Figure 6** presents the
 274 seasonal spatial distribution of sea surface salinity (SSS) from the MEDREA24 reanalysis,



275 together with the corresponding biases simulated by ENEA-REG2 and ENEA-REG3. Overall,
276 both model versions reproduce the large-scale Mediterranean salinity gradient reasonably well,
277 characterized by lower salinity values in the western basin and progressively saltier waters
278 toward the eastern Mediterranean. The main regional features associated with freshwater inputs
279 and circulation patterns are also captured, including the relatively fresh waters in the Adriatic
280 Sea and near major river mouths. However, ENEA-REG2 exhibits widespread positive salinity
281 biases across most of the basin throughout all seasons, particularly in the Adriatic Sea, where the
282 bias exceeds 1 psu around the Po river. This salty bias is primarily attributed to deficiencies in
283 the routing component in representing freshwater inputs from river discharge, as highlighted in
284 **Figure 5**, with the largest values generally observed during summer and autumn, when
285 evaporation dominates the surface freshwater budget and the effects of river runoff become
286 particularly important in coastal regions. ENEA-REG3 shows a substantial reduction in SSS
287 biases across most of the Mediterranean basin and in all seasons. The improvement is especially
288 evident in regions strongly influenced by river discharge, such as the Adriatic Sea and several
289 coastal areas of the eastern Mediterranean, where the excessive salinization simulated by ENEA-
290 REG2 is considerably mitigated. This outcome reflects the combined effects of the enhanced
291 representation of freshwater inputs provided by CaMa-Flood and the greater temporal
292 consistency of atmosphere–ocean flux exchanges achieved through the time-averaged explicit
293 coupling strategy, leading to a more realistic sea surface salinity distribution.

294 Despite the overall improvement, some residual positive biases remain, particularly in localized
295 coastal regions and in the eastern basin during summer and autumn. Interestingly, although the
296 HD model underestimates the high flow of the Ebro River in ENEA-REG2, the SSS exhibits a
297 marked negative bias, which is further amplified in ENEA-REG3 due to the larger amount of
298 freshwater input simulated by CaMa-Flood (**Figure 5**). Considering ENEA-REG2, the validation
299 of the river-routing component does not reveal any substantial overestimation of Ebro River
300 discharge (**Figure 5**) and no evident deficiencies were identified in the simulated branching of
301 the Algerian Current around the Balearic Sea (Anav et al., 2024). Assuming that neither the river
302 discharge used by MEDREA24 nor the SSS represented by the reanalysis is affected by
303 substantial systematic errors, the remaining SSS bias simulated by ENEA-REG2 may be related
304 to deficiencies in the ocean component’s representation of local mixing processes or coastal
305 circulation dynamics. These features are more effectively constrained in MEDREA24 through



306 data assimilation, whereas they are entirely determined by the model dynamics and
307 parameterizations in the free-running ENEA-REG simulations. In ENEA-REG3, this bias is
308 further amplified by the larger freshwater flux discharged by the Ebro River, which enhances
309 surface freshening without a corresponding increase in the vertical and lateral dispersion of
310 freshwater.

311 Finally, to assess the combined effects of the updated river-routing component, the modified
312 coupling strategy, and the longer ocean spin-up, **Figure 7** presents potential temperature–salinity
313 (T–S) diagrams comparing the seasonal thermohaline characteristics simulated by ENEA-REG2
314 and ENEA-REG3 over the three selected Mediterranean sub-domains (**Figure 4c**) against the
315 MEDREA24 reanalysis. Consistent with the spatial SSS analysis, both ENEA-REG2 and ENEA-
316 REG3 generally exhibit a positive salinity bias relative to MEDREA24 across all sub-domains
317 and seasons extending from the surface to the bottom. However, ENEA-REG3 systematically
318 reduces this bias compared to ENEA-REG2, particularly in the Levantine and Ionian basins,
319 where the simulated T–S curves shift closer to the reanalysis and the potential density at the
320 maximum mixing depth shows substantially better agreement with the reanalysis. The
321 improvement is especially evident during summer and autumn, when the excessive salinization
322 simulated by ENEA-REG2 is substantially mitigated. A similar result was already discussed by
323 (Storto et al., 2023), who found a substantial reduction in salinity biases down to the halocline
324 when improved river-runoff freshwater inputs were employed.

325 The reduction in salinity biases is also associated with a partial improvement in the
326 representation of upper-ocean thermal stratification. In particular, ENEA-REG3 better
327 reproduces the shape and position of the seasonal thermocline in several regions, especially in
328 the Ionian basin during summer and autumn, while the North-Western Mediterranean shows
329 comparatively smaller differences between ENEA-REG2 and ENEA-REG3, suggesting that
330 river runoff plays a more limited role in controlling the regional thermohaline structure which is
331 mostly controlled by deep convection. Despite improvements in ENEA-REG3, biases remain
332 evident, particularly in the Levantine basin, where the simulated surface waters are colder and
333 saltier than in the reanalysis during summer.

334

335 **3.2 Evaluation of atmospheric component**

336



Looking at the performances of the atmospheric component, **Figure 8** displays the seasonal distribution of near-surface air temperature over the PRUDENCE sub-domains for the ERA5 reanalysis, the ENEA-REG3 hindcast, the historical simulations driven by EC-Earth3 and MPI-ESM1-2-HR, and an ensemble of 25 CMIP6 models. Overall, results suggest that WRF is able to reproduce the observed spatial and seasonal variability of temperature across all regions, although some large biases are found in some domains and seasons. Similarly, the violin plots indicate that the CMIP6 multi-model ensemble average outperforms the individual models (Knutti et al., 2010) reproducing the seasonal variability and distribution of temperatures reasonably well despite some discrepancies are found in regions characterized by complex topography, such as the Alps (AL) and Iberian Peninsula (IP), where the large distributional spreads from ERA5 likely reflect the limited ability of the global models to capture elevation-dependent processes and the high spatial heterogeneity of local temperature regimes.

The hindcast simulation generally shows good agreement with ERA5, with only limited systematic error. The most pronounced deviation occurs during DJF over Eastern Europe, where the model underestimates surface air temperature by 2.3 °C. This cold bias is consistent with previously documented limitations of WRF in snow-covered and forested regions (García-Díez et al., 2015; Katragkou et al., 2015; Mooney et al., 2013), and has been attributed to an overestimation of snow depth caused by excessive snowfall and insufficient snowmelt (Varga and Breuer, 2020). Other relevant biases are found in winter in ME (-1.3 °C) and in summer in EA (2.1 °C) and over the Alps (1.4 °C), while in the other domains and seasons the bias is well below 1 °C.

The historical simulations also fairly reproduce the main regional temperature patterns, although systematic differences relative to ERA5 emerge in several regions and seasons, reflecting a combination of biases inherited from the driving global models and known model deficiencies in forested and snow-covered areas (Varga and Breuer, 2020). During DJF, both the EC-Earth3 and MPI-ESM1-2-HR downscalings exhibit substantial cold biases over Eastern Europe (-1.8 °C and -2.1 °C, respectively) and Mid-Europe (-1.0 °C and -1.3 °C), consistent in both sign and magnitude with the hindcast simulation. In MAM, simulated temperatures are broadly consistent with ERA5, although a residual cold bias persists across several domains. In JJA, temperatures across most sub-regions closely match the reanalysis, particularly over southern Europe, the Mediterranean basin, and the British Isles. Interestingly, in this season over some domains (FR,



ME, AL, EA) the historical simulations outperform the hindcast. Nevertheless, both the hindcast and the two historical simulations exhibit a persistent warm bias in Eastern Europe, suggesting a systematic model deficiency in reproducing summer surface air temperatures over this region, that is largely independent of the driving models. Finally, no substantial biases are detected during SON.

An interesting feature is the capability of the ENEA-REG3 model to correct the bias of the driving global model. This is particularly evident for the historical simulation driven by EC-Earth3 in JJA and SON for most of the Prudence regions and DJF over FR, AL and MD, where EC-Earth3 display a cold bias.

Figure 9 presents the seasonal distribution of mean daily precipitation across the PRUDENCE sub-domains for ERA5, the ENEA-REG3 hindcast, the EC-Earth3 and MPI-ESM1-2-HR historical downscalings, and 25 CMIP6 models. Results indicate that WRF reproduces the main spatial and seasonal precipitation gradients across Europe reasonably well, capturing the wetter conditions characteristic of mountainous and Atlantic-influenced regions, as well as the drier climate of the Mediterranean and Iberian regions, particularly during summer. The violin plots reveal that the CMIP6 ensemble spread in precipitation is considerably wider than for temperature, particularly during JJA over the Alpine and Mid-Europe sub-regions, reflecting the well-known challenge of simulating orographic and convective precipitation in global models (Chen et al., 2021; Dai, 2006).

Examining the ENEA-REG3 performance in more detail, the hindcast exhibits a slight dry bias during DJF across most sub-regions, with the largest discrepancies (-0.2 mm/day) occurring over the British Isles (BI) and Mid-Europe (ME). A similar pattern is found in MAM, although the bias increases substantially over the Alps, reaching -0.39 mm/day. The most pronounced discrepancies occur during JJA, followed by SON, when a widespread dry bias is evident across all domains, consistent with the well-documented difficulties of parameterized convection schemes in reproducing summer precipitation over Europe (Kendon et al., 2012; Prein et al., 2015). During JJA, the largest biases are found over AL (-1.31 mm/day) and EA (-0.84 mm/day), where ENEA-REG3 is degrading the signal of the forcing, while in SON the strongest bias remains over the Alps, although with a smaller magnitude (-0.61 mm/day).

Considering the historical experiments, the observed precipitation climatology is generally well reproduced, although regional biases and clear differences between the two downscalings are



399 evident. In particular, the MPI-ESM1-2-HR-driven simulation consistently produces higher
 400 precipitation amounts than the downscaling driven by EC-Earth3 across most sub-regions
 401 throughout the year and is characterized by the largest discrepancies relative to ERA5. During
 402 DJF, these are most pronounced over the AL (0.84 mm/day¹) and France (FR, 0.76 mm/day),
 403 while in MAM model performance improves over most domains, with precipitation amounts
 404 remaining close to ERA5 and biases below 0.5 mm/day in absolute value for both the historical
 405 experiments. During JJA, the simulations successfully reproduce the strong seasonal drying over
 406 the IP region and the Mediterranean basin. However, consistent with the hindcast experiment,
 407 precipitation tends to be underestimated over most regions. During SON, the spatial distribution
 408 and magnitude of precipitation are generally well reproduced, with the EC-Earth3-driven
 409 simulation showing the largest dry biases over AL (-0.79 mm/day), and MD (-0.45 mm/day).
 410 Interestingly, across all seasons, the hindcast and historical simulations display similar behavior
 411 (with the exception of FR, ME, and AL regions), suggesting that the precipitation biases
 412 primarily originate from the regional model formulation and internal physical parameterizations
 413 rather than from the large-scale forcing provided by the driving general circulation models
 414 (GCMs).

415

416 **3.3 Evaluation of ocean component**

417

418 The seasonal spatial distribution of SST derived from the MEDREA24 reanalysis together with
 419 the corresponding SST biases simulated by the hindcast and the two historical simulations is
 420 shown in **Figure 10**. In general, all the simulations reproduce the large-scale seasonal SST
 421 variability across the Mediterranean basin, including the colder conditions during winter, the
 422 progressive warming in spring, the summer maximum, and the subsequent cooling during fall.

423 The west-to-east SST gradient and the main regional thermal structures are also generally well
 424 captured. The spatial correlations indicate near-perfect agreement between the reanalysis and
 425 both the hindcast and the two historical simulations, with correlation coefficients greater than
 426 0.99 in all seasons. This overall agreement is further supported by relatively low RMSE values
 427 throughout the year, ranging from 0.32 to 1.41 °C across all simulations. The smallest RMSE are
 428 found in spring (0.32–0.39 °C), whereas the largest occur during summer (0.88–1.41 °C). The
 429 hindcast simulation exhibits the lowest RMSE during summer and autumn, whereas the EC-



430 EARTH3-driven downscaling produces the largest errors, with RMSE values of 1.41 °C in JJA
431 and 1.02 °C in SON.

432 Despite the overall consistency between the hindcast and historical simulations in terms of their
433 systematic biases, some notable spatial and temporal differences emerge. In particular, while
434 during DJF all ENEA-REG3 simulations exhibit a marked east–west bias, characterized by warm
435 anomalies in the western Mediterranean and cold anomalies in the eastern basin, during MAM
436 the hindcast retains a warm bias across much of the domain, whereas this feature largely
437 disappears in the historical simulations. In contrast, during summer and autumn, all simulations
438 tend to underestimate SST over most of the Mediterranean Sea, with the strongest cold biases
439 occurring during JJA (up to 2 °C in some areas) in the EC-EARTH3-driven downscaling.

440 These results indicate that the coupled model reproduces the annual SST cycle reasonably well in
441 all configurations, although the seasonal amplitude is generally underestimated. Notably, this
442 behavior was already identified in ENEA-REG2 (Anav et al., 2024). Hence, despite the
443 transition from explicit to time-averaged explicit coupling and the improved representation of
444 freshwater inputs, the seasonal SST bias patterns remain largely unchanged in ENEA-REG3.

445 This suggests that the dominant sources of SST error are neither directly related to the coupling
446 strategy nor to the representation of river runoff, nor are they inherited from the driving GCMs.
447 Instead, they are more likely associated with deficiencies in the simulation of air–sea heat
448 exchanges, upper-ocean mixing, or regional circulation processes. These processes will be
449 investigated in future work through targeted sensitivity experiments and a detailed analysis of the
450 surface energy budget and upper-ocean dynamics, with the aim of reducing these biases in the
451 next release of the model.

452 The performance of ENEA-REG3 in reproducing observed sea surface salinity is consistently
453 good across all simulations (**Figure 11**), with spatial correlation coefficients exceeding 0.99
454 relative to the MEDREA24 reanalysis in all seasons. In particular, the inflow of Atlantic Water
455 through the Strait of Gibraltar and its subsequent eastward propagation toward the Sicily
456 Channel are realistically represented by all simulations, indicating a good reproduction of the
457 large-scale Mediterranean circulation, as already described by (Parras-Berrocal et al., 2024) for
458 ENEA-REG2. Nevertheless, the results also highlight a slight but systematic positive salinity
459 bias affecting this water mass in all experiments and seasons, particularly during winter and
460 spring. This bias gradually weakens during summer and autumn but remains evident throughout



461 the year. Conversely, negative salinity anomalies are found along portions of the western
462 Mediterranean coast and in localized regions of the Aegean Sea, possibly reflecting either an
463 overestimation of the prescribed freshwater inputs from the Black Sea or deficiencies in the
464 representation of local mixing processes. Despite these regional biases, basin-scale RMSE values
465 remain low, ranging from 0.19 to 0.38 psu across all simulations and seasons. The largest RMSE
466 occur during spring (0.37–0.38 psu), whereas the smallest are found in autumn (0.19–0.25 psu),
467 with only minor differences among the three simulations.

468 Error! Reference source not found. compares the thermohaline characteristics simulated by the
469 ENEA-REG3 hindcast and historical simulations against the MEDREA24 reanalysis for the
470 Levantine, Ionian, and Northwestern Mediterranean sub-domains. Notably, the hindcast results
471 are identical to those already shown in **Figure 7** and are reproduced here solely to facilitate
472 comparison with the historical simulations. The Levantine sub-basin exhibits the highest
473 salinities among the three regions, consistent with its role as the saltiest basin of the
474 Mediterranean and the source region of Levantine Intermediate Water (LIW). MEDREA24
475 exhibits the characteristic S-shaped T–S structure in all seasons, reflecting the vertical
476 stratification associated with relatively fresh Atlantic Water (AW) in the upper layers and the
477 saltier LIW at intermediate depths. The hindcast closely follows the MEDREA24 T–S structure
478 throughout the water column, although a systematic salt bias of approximately 0.1–0.2 psu is
479 present in all seasons. Both GCM-driven simulations exhibit systematic cool and salt biases
480 relative to MEDREA24. The discrepancies are particularly evident during JJA and SON, when
481 surface temperatures reach 23–24 °C in the reanalysis but are underestimated by both historical
482 simulations, consistent with **Figure 10**. Differences between the two driving GCMs are generally
483 modest, although the EC-Earth3-driven simulation tends to exhibit slightly larger temperature
484 biases in the upper layers. A similar behavior is found in the Ionian Sea, where all simulations
485 reproduce the seasonal thermocline structure, characterized by AW influence in the upper layers
486 and LIW advection at depth. The three downscaling experiments show similar skill in
487 reproducing the observed T–S structure, with no configuration consistently providing a better
488 agreement with MEDREA24 across seasons and depth ranges. It should be also noted that in JJA
489 and SON results show a convergence of all simulations at deeper levels, suggesting that model
490 spread is primarily driven by surface and intermediate-layer processes rather than deep-water
491 properties. The NWM is characterized by the lowest salinities and temperatures of the three sub-



basins, reflecting strong AW influence and intense winter deep convection that leads to the dense water formation (Western Mediterranean Deep Water, WMDW). MEDREA24 shows a well-defined near-vertical T–S profile in winter (DJF), indicative of deep mixing, which is only partially reproduced by the hindcast and even less by the GCM-driven runs. Despite some discrepancies, in general the three ENEA-REG3 configurations produce remarkably similar T–S structures, particularly when compared with the much larger differences relative to MEDREA24. This indicates that the simulated thermohaline characteristics of the Mediterranean Sea are primarily controlled by the regional coupled model configuration, including the ocean model physics and the atmospheric parameterizations, rather than by the choice of large-scale forcing.

502

503 **4. Summary, discussion, and future developments**

504

In this study, we presented the third generation of the regional Earth system model ENEA-REG designed for the simulation of past, present, and future climate over the Euro-Mediterranean region. Compared to ENEA-REG2 (Anav et al., 2024), the new version introduces three major developments: (i) the replacement of the HD river routing model with the CaMa-Flood hydrodynamic model, enabling both inland flood simulation (Hamitouche et al., 2026a) and a more realistic representation of river discharge; (ii) a substantially revised coupler, which now allows a flexible run-sequence configuration that facilitates switching between sequential and concurrent execution modes; and (iii) the adoption of a time-averaged explicit coupling strategy, in which the atmospheric component exports time-averaged fluxes over the coupling interval rather than instantaneous values, thereby improving the temporal consistency of the exchanged fields.

To assess the model performance, a hindcast simulation driven by ERA5 reanalysis and ORAS5 ocean reanalysis, together with two historical downscalings of the CMIP6 models EC-Earth3 and MPI-ESM1-2-HR, were evaluated against ERA5 (atmosphere), MEDREA24 (ocean), and GRDC gauge observations (river discharge). Although CaMa-Flood enables ENEA-REG3 to simulate floodplain inundation processes, flood extent and water-level dynamics are not evaluated in the present study. These capabilities have, however, been investigated in a separate study assessing present and future hydrological extremes across the Euro-Mediterranean region (Hamitouche et al., 2026a).



524 Results demonstrate that replacing the HD model with CaMa-Flood represents a significant
525 advancement in ENEA-REG3, leading to systematic improvements in river discharge
526 simulations across all analyzed basins. In particular, the adoption of CaMa-Flood substantially
527 increases correlation coefficients, yields positive KGE values for all basins, and reduces RMSE
528 in nearly every catchment, indicating a more accurate representation of both streamflow timing
529 and magnitude. Despite these marked improvements, a persistent low-flow bias remains,
530 particularly in the Köprü and Ceyhan basins, highlighting the need for further model refinement
531 in future developments. In fact, a key weakness of the current CaMa-Flood implementation is
532 that it is forced by total runoff, without distinguishing between surface and subsurface
533 contributions (Yamazaki et al., 2011). Consequently, the model does not account for the
534 temporal lag between rapid surface runoff and delayed groundwater drainage to the river
535 network. This simplification may affect the timing of river discharge peaks and reduce the
536 agreement between observed and simulated hydrographs, particularly in basins where
537 groundwater storage plays an important role (Hamitouche et al., 2025). Similar limitations have
538 been identified in previous studies, which showed that separating fast and slow runoff
539 components can improve the simulation of streamflow seasonality and low-flow conditions
540 (Hamitouche et al., 2026b).

541 In addition, the model neglects anthropogenic influences, including irrigation systems, water
542 withdrawals, and other river management practices. Consequently, simulations based solely on
543 natural hydrological processes may not fully reproduce the observed river behavior. This
544 limitation is especially relevant for highly managed basins such as the Ebro, Po, Rhône, and
545 Arno, where human interventions strongly modify the timing and magnitude of streamflow (Grill
546 et al., 2019) (Grill et al., 2019). Furthermore, the relatively coarse spatial resolution of the
547 simulations may also hinder the accurate representation of small catchments and fine-scale
548 hydrological processes. Finally, biases in the climate forcing datasets can propagate through the
549 hydrological modelling chain, affecting runoff generation and subsequently river discharge and
550 flood simulations (Hamitouche et al., 2025).

551 Despite the aforementioned limitations of the river routing component, the improved
552 representation of river discharge, combined with the time-averaged explicit atmosphere–ocean
553 coupling, leads to a more realistic simulation of sea surface salinity. Compared with ENEA-
554 REG2, salinity biases are substantially reduced, particularly in coastal regions strongly



555 influenced by riverine freshwater inputs and in the upper ocean down to the halocline. The
556 Mediterranean salinity distribution, including the Atlantic Water inflow through the Strait of
557 Gibraltar and the basin-scale west-to-east salinity gradient, is generally well reproduced by all
558 ENEA-REG3 configurations. However, residual salinity and temperature biases persist,
559 suggesting that their origin extends beyond the representation of river runoff and is likely related
560 to shortcomings in the representation of key physical processes, including atmospheric
561 parameterizations. This conclusion is further supported by additional coupled simulations
562 employing a different set of atmospheric parameterization schemes (Struglia et al., 2025), which
563 produce distinct bias patterns (not shown) despite being driven by the same large-scale forcing
564 (i.e. ERA5 and ORAS5).

565 Notwithstanding the reduced bias in the ocean and river routing components, the atmospheric
566 model exhibits a persistent cold bias during winter over Eastern Europe. This is a well-
567 documented limitation of WRF (García-Díez et al., 2015; Katragkou et al., 2015; Kotlarski et al.,
568 2014; Mooney et al., 2013) associated with snow-related land–atmosphere feedbacks (Varga and
569 Breuer, 2020). In spite of this limitation, the atmospheric component reproduces the main
570 climatological features of near-surface temperature and precipitation across Europe, showing
571 strong consistency between hindcast and historical simulations. Furthermore, over most of the
572 seasons and regions, ENEA-REG3 is able to reduce the biases of the driving global forcing in the
573 historical simulations.

574 The close correspondence between the hindcast and historical simulations, found both in the
575 atmospheric and ocean components, allows several conclusions to be drawn. First, model
576 performance, including biases, is mainly associated with intrinsic model deficiencies rather than
577 being solely inherited from the driving GCMs. In addition, the improvements introduced in
578 ENEA-REG3, particularly in the representation of freshwater inputs, are robust across different
579 forcing datasets. Furthermore, this agreement between the hindcast and historical simulations
580 enhances confidence in the robustness of the climate projections, thereby providing more reliable
581 information for regional climate assessments.

582 Nevertheless, the persistent systematic bias in the components requires further investigation.
583 Among other improvements, an updated version of the atmospheric component will be used in a
584 future release of our regional Earth system model, with specific tuning of physical



parameterizations and parameters, particularly those controlling the exchange of sensible and latent heat between soil, vegetation, and atmosphere.

587

588 **Code and data availability**

The source code of ENEA-REG3, including the coupler and the model components, is available at <https://doi.org/10.5281/zenodo.22829764> (Anav, 2026). The ERA5 and ORAS5 reanalysis data are publicly available from the Copernicus Climate Change Service (C3S) Climate Data Store at <https://cds.climate.copernicus.eu/datasets>, while due to their large volume, the other forcing data used in this study, as well as the model outputs and scripts, are available from the authors upon request.

595

596 **Author contributions**

AA improved the code to connect the model components through the coupler and carried out the simulations. MH conducted the CaMa-Flood validation, MF performed the benchmark analysis, while AA led the analysis and wrote the paper with input from all authors.

600

601 **Competing interests**

The authors declare that they have no conflict of interest.

603

604 **Acknowledgements**

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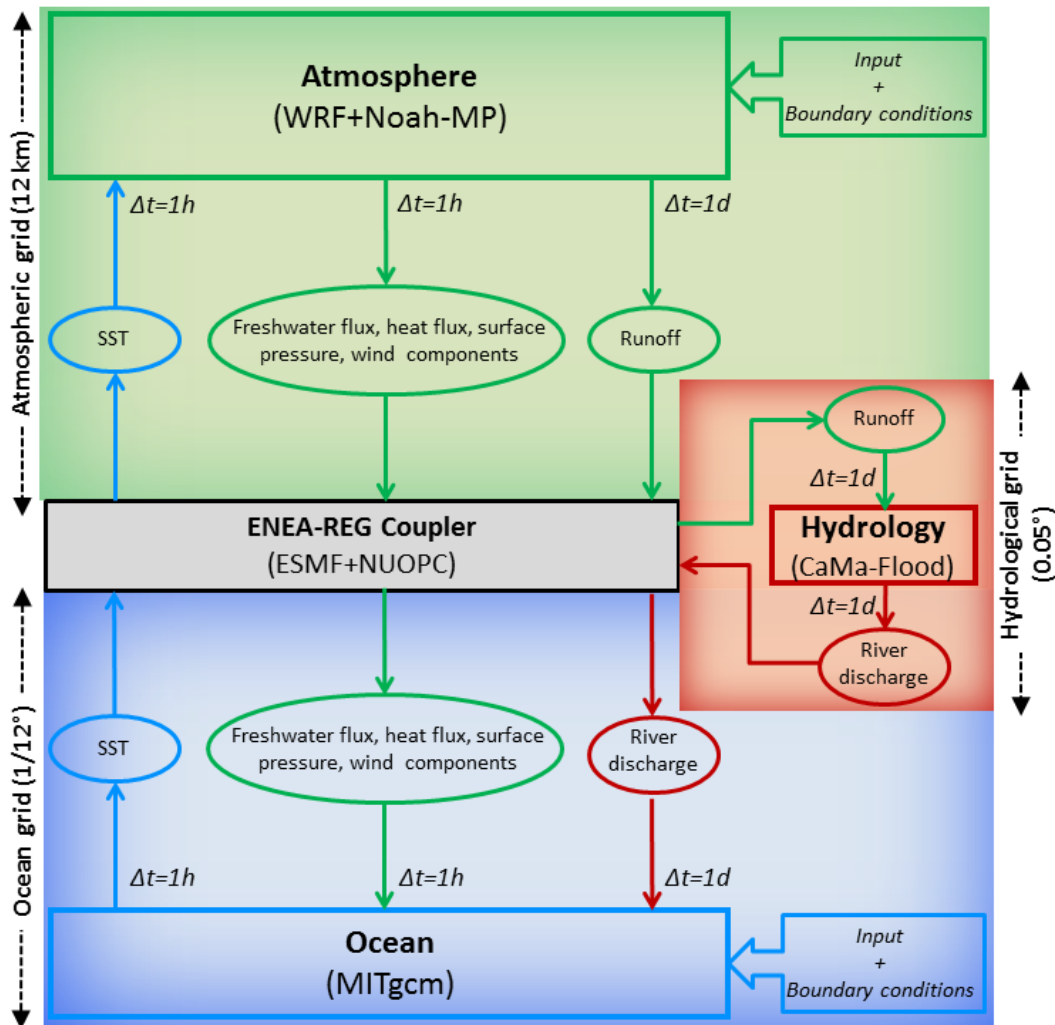
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621



622 **FIGURES**



623

624 **Figure 1.** Schematic representation of the ENEA-REG3 regional Earth system model. The green
625 block represents the atmospheric component (ATM) together with the embedded land surface
626 scheme (i.e., WRF+Noah-MP), the blue block represents the ocean component (i.e., MITgcm,
627 OCN), and the red block represents the river routing component (RTM). The coupler, based on
628 the ESMF/NUOPC libraries, is represented by the grey block and is responsible for collecting,
629 regridding, and exchanging variables among the different system components.

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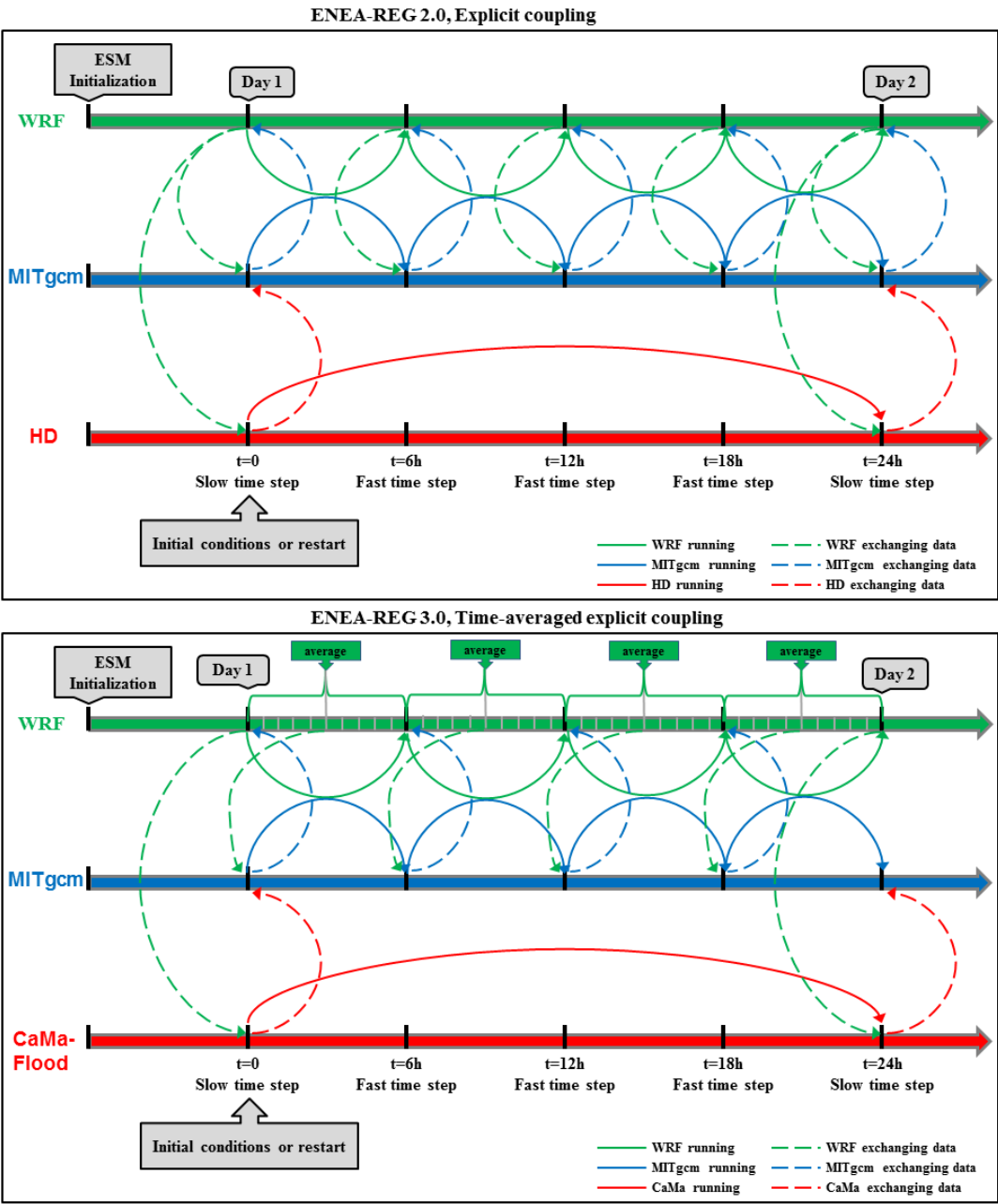
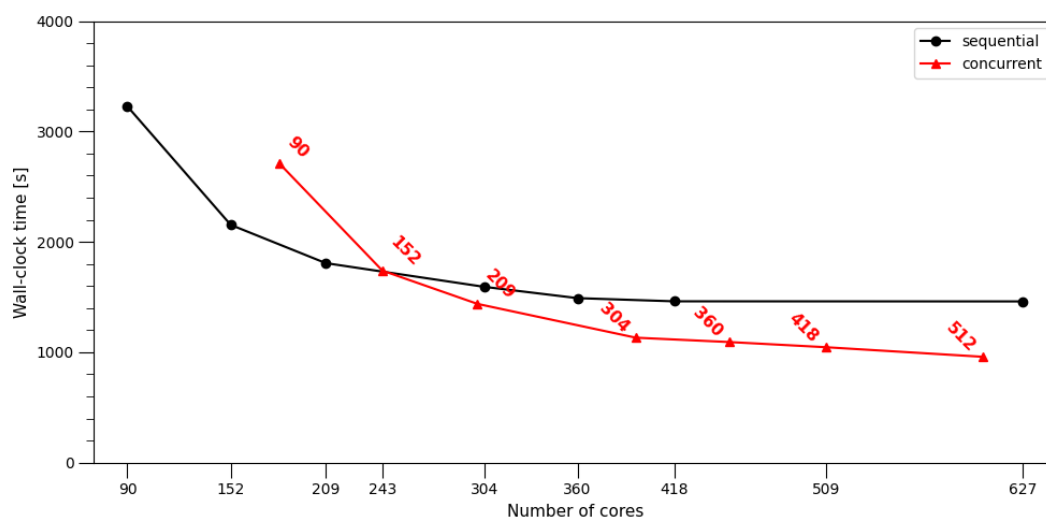


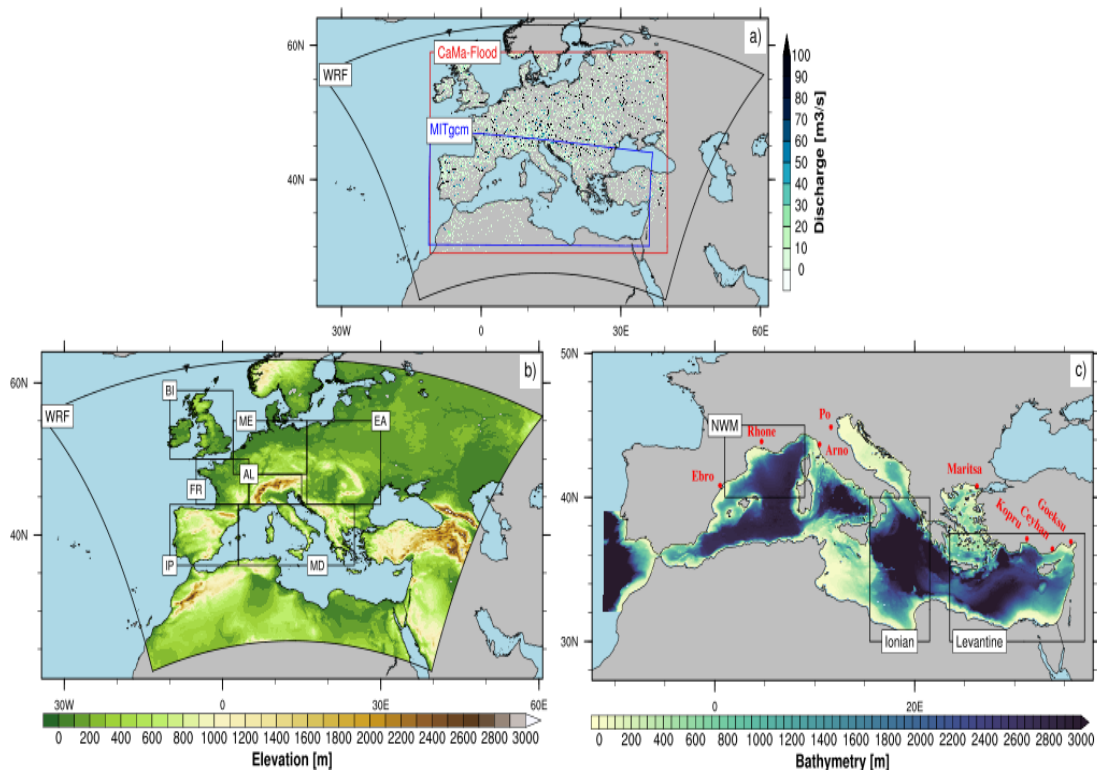
Figure 2. Schematic representation of the run sequence of the model components, together with the explicit coupling adopted in previous model versions (upper panel) and the updated semi-implicit coupling implemented in ENEA-REG3 (lower panel).



638

639 **Figure 3.** Benchmark results of ENEA-REG3 concurrent and sequential run modes performed
 640 on a 2 Intel Xeon Platinum 8592+ with 64 physical cores each and 512GB of RAM,
 641 interconnected with a 200Gb high speed, low latency InfiniBand network. The annotations
 642 indicate the number of processors assigned to the ATM component in each concurrent
 643 simulation.

644



645

646 **Figure 4.** Computational domains used by the ENEA-REG3 model components (upper panel).
647 Panel (b) displays the WRF domain together with the PRUDENCE sub-regions used for validation:
648 the Alps (AL), the British Isles (BI), Eastern Europe (EA), France (FR), the Iberian
649 Peninsula (IP), the Mediterranean (MD), and Mid-Europe (ME). Similarly, panel (c) shows the
650 MITgcm domain and the sub-regions used for ocean validation: the Levantine, Ionian, and
651 North-Western Mediterranean (NWM) regions. In addition, the locations of the gauge stations
652 for the eight analyzed rivers are highlighted by red dots.

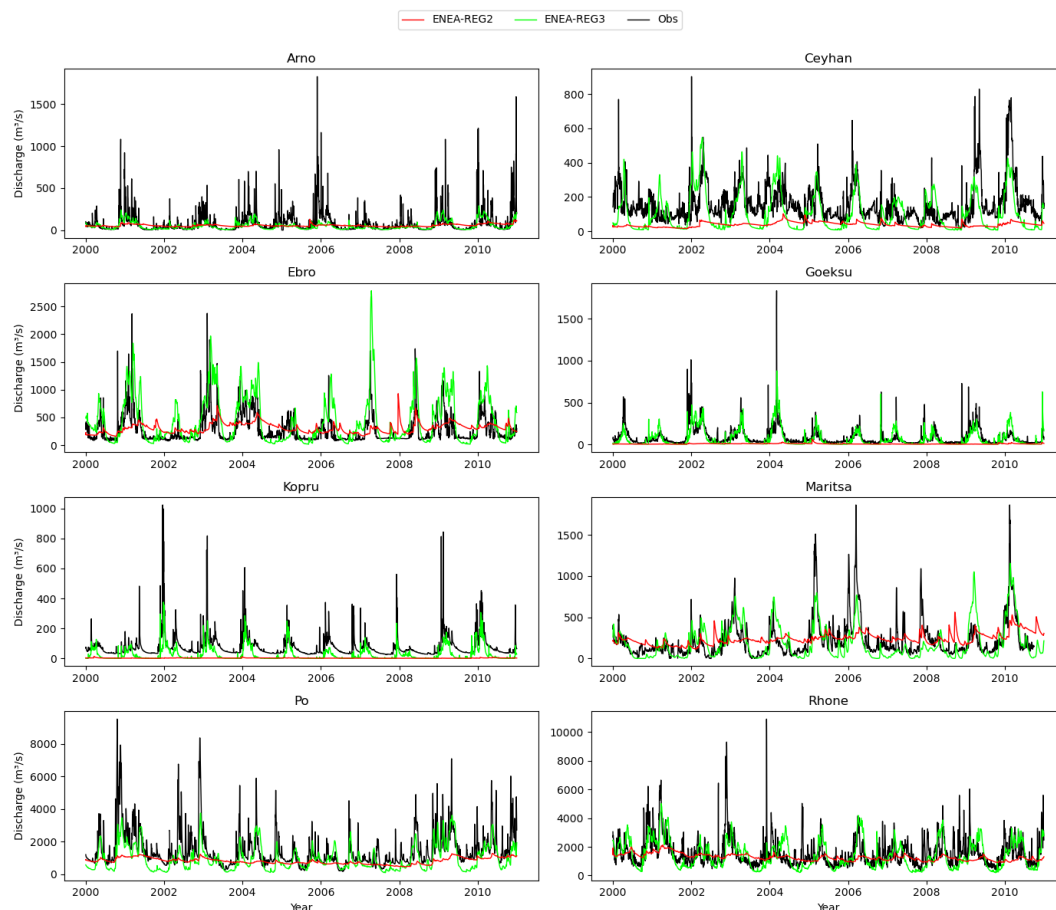


Figure 5. Comparison of daily river discharge simulated by ENEA-REG2 (red lines) and ENEA-REG3 (green lines) against observations (black lines) at gauge stations located near the river mouths of the Arno, Ceyhan, Ebro, Göksu, Köprü, Maritsa, Po, and Rhône rivers over the 2000–2014 period.

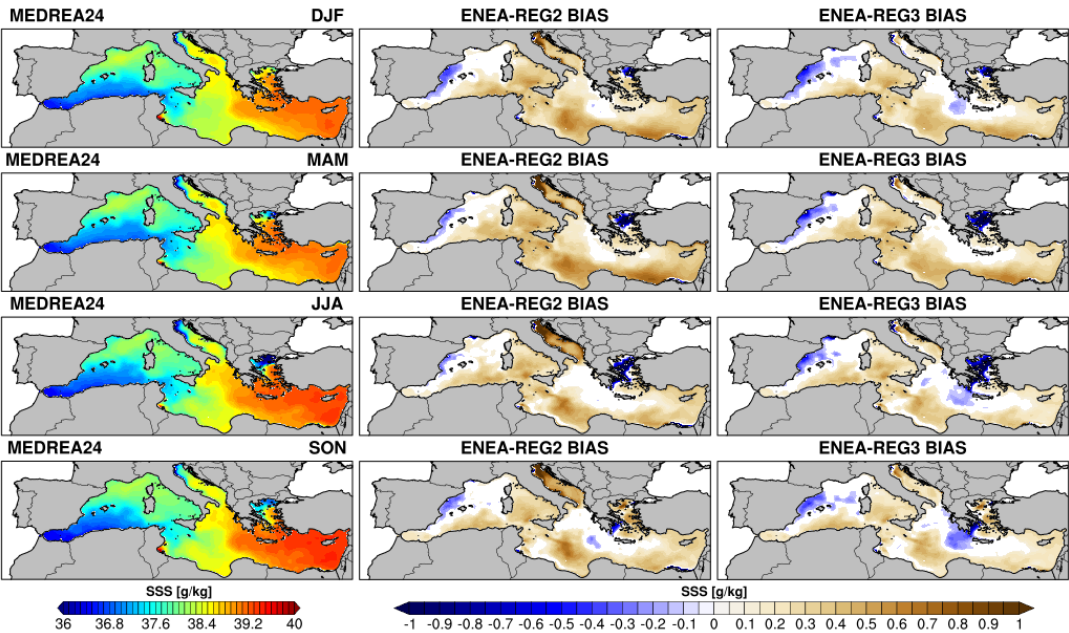
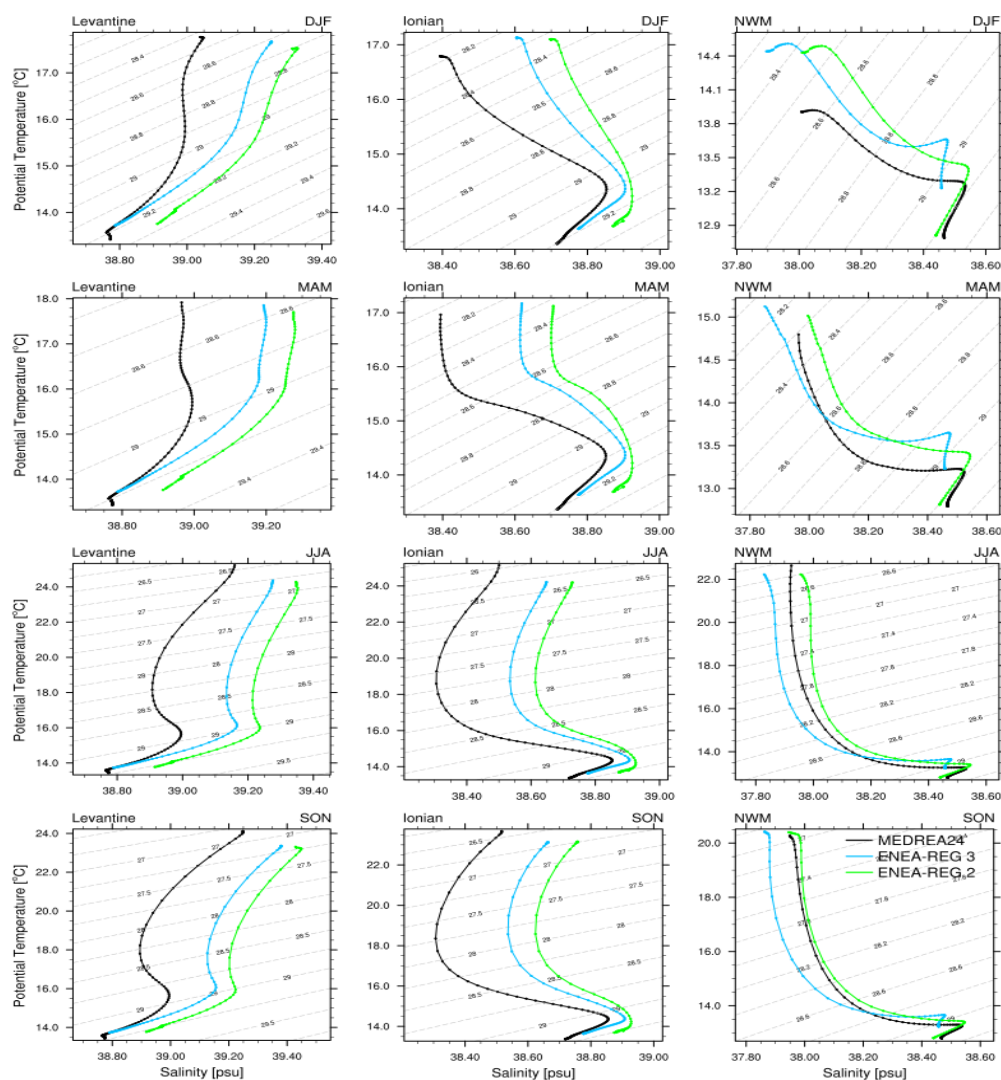


Figure 6. Seasonal spatial patterns of sea surface salinity (SSS) derived from the MEDREA24 reanalysis (Escudier et al., 2021) together with the associated biases (model-reanalysis) in ENEA-REG2 and ENEA-REG3, computed for the period 1987-2014.



668

669 **Figure 7.** Potential temperature–salinity (T–S) diagrams showing the thermohaline
 670 characteristics simulated by ENEA-REG2 and ENEA-REG3 over the three selected sub-domains
 671 in **Figure 4**, together with the corresponding MEDREA24 reanalysis over the period 1987–2014.
 672 Contour lines indicate isopycnals of potential density (kg m^{-3}).

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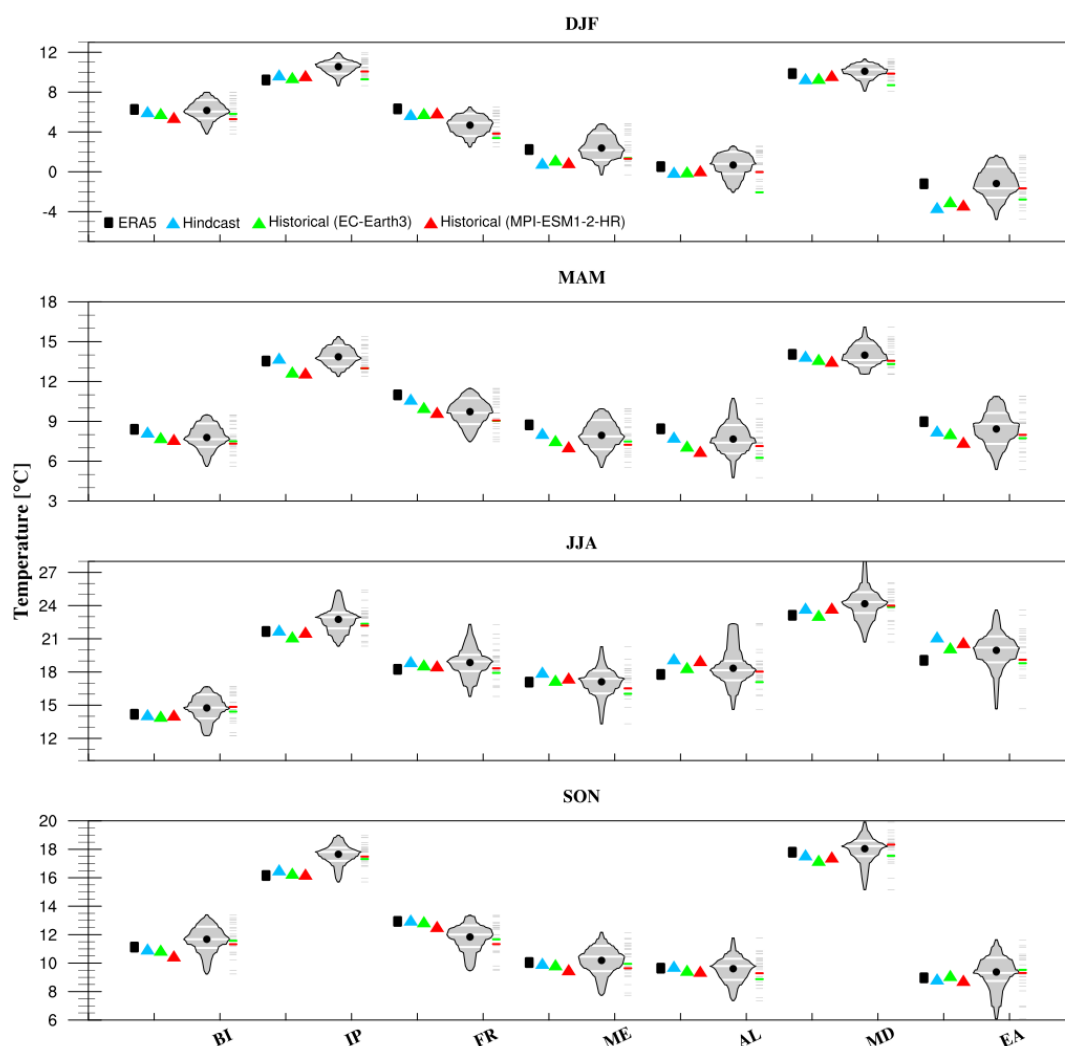
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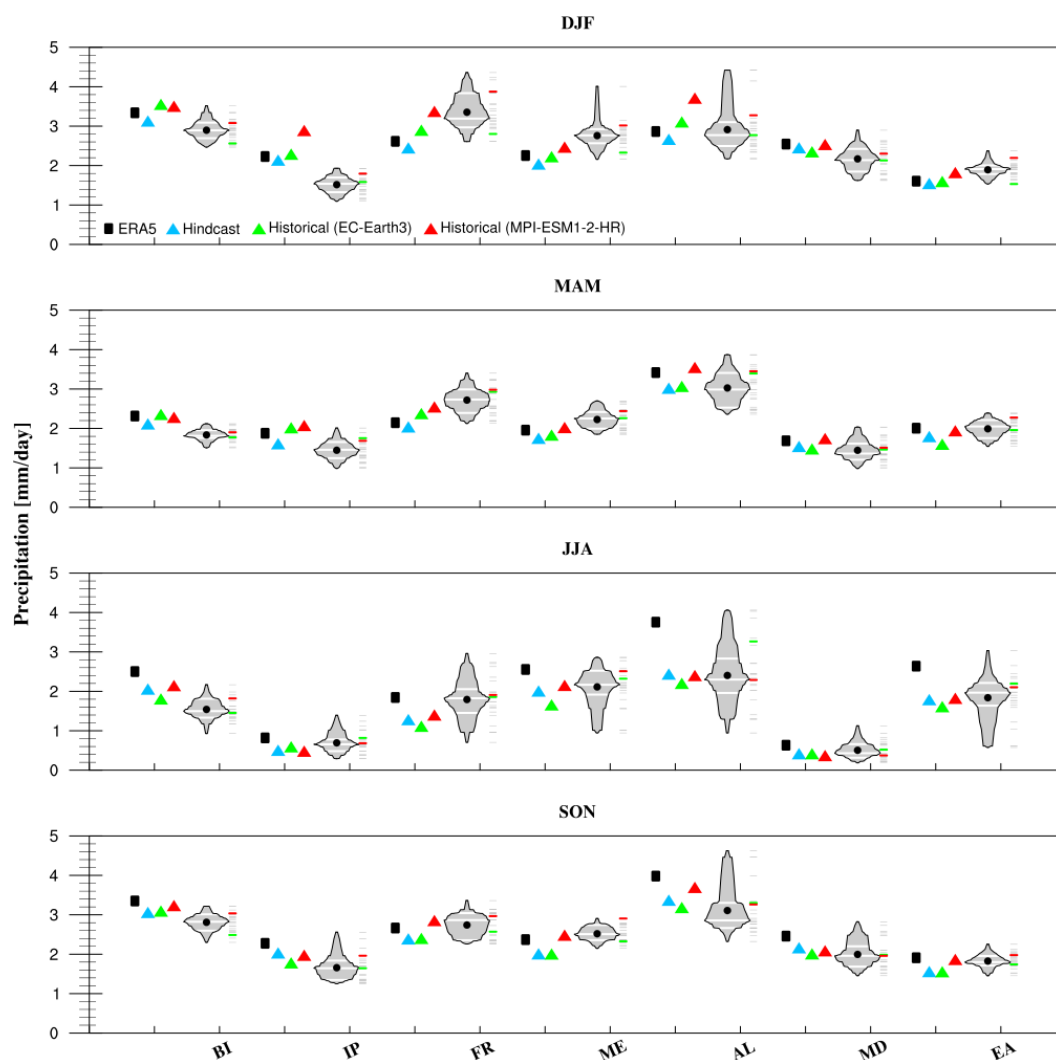


678

679 **Figure 8.** Violin plots showing the mean seasonal surface air temperature (°C) computed over
 680 the PRUDENCE sub-regions (x-axis) over the period 1987–2014. Black squares denote the
 681 reference ERA5 reanalysis, light blue triangles represent the ENEA-REG3 hindcast, green
 682 triangles indicate the ENEA-REG3 downscaling of EC-Earth3, and red triangles correspond to
 683 the ENEA-REG3 downscaling of MPI-ESM1-2-HR. The gray violins represent the distribution
 684 of seasonal mean temperatures from 25 CMIP6 historical simulations over each PRUDENCE
 685 region, with violin width proportional to the probability density of model values and the black
 686 dot indicating the ensemble median. Horizontal ticks alongside each violin identify values from
 687 the individual CMIP6 models, while the green and red ticks highlight EC-Earth3 and MPI-
 688 ESM1-2-HR, respectively.



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690

691 **Figure 9.** As Figure 8 but for mean daily precipitation.

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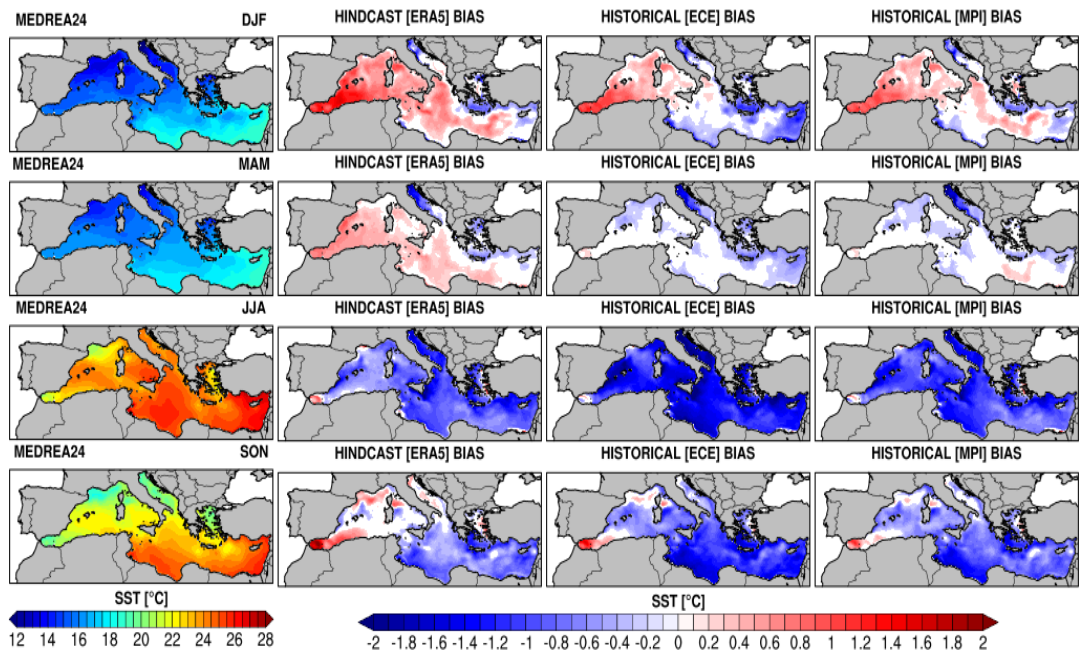


Figure 10. Seasonal spatial patterns of sea surface temperature (SST) derived from the MEDREA24 reanalysis, together with the associated biases (model-reanalysis) of the ENEA-REG3 hindcast and historical simulation, computed over the period 1987–2014.

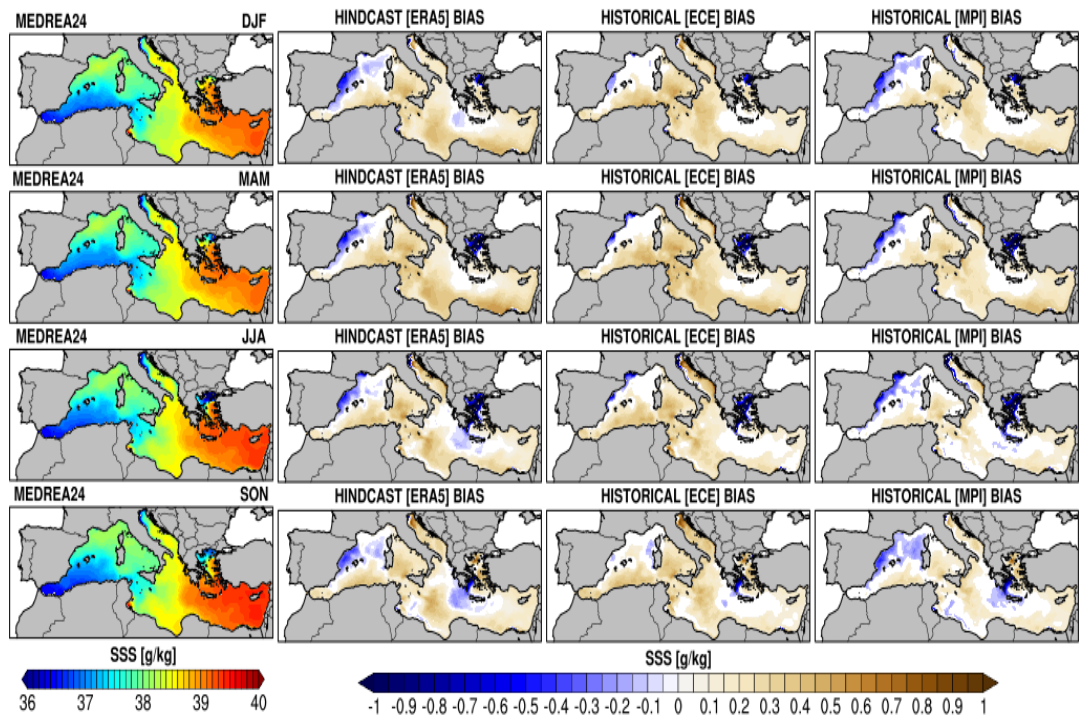


Figure 11. Seasonal spatial patterns of sea surface salinity (SSS) derived from the MEDREA24 reanalysis, together with the associated biases (model-reanalysis) of the ENEA-REG3 hindcast and historical simulation, computed over the period 1987–2014.

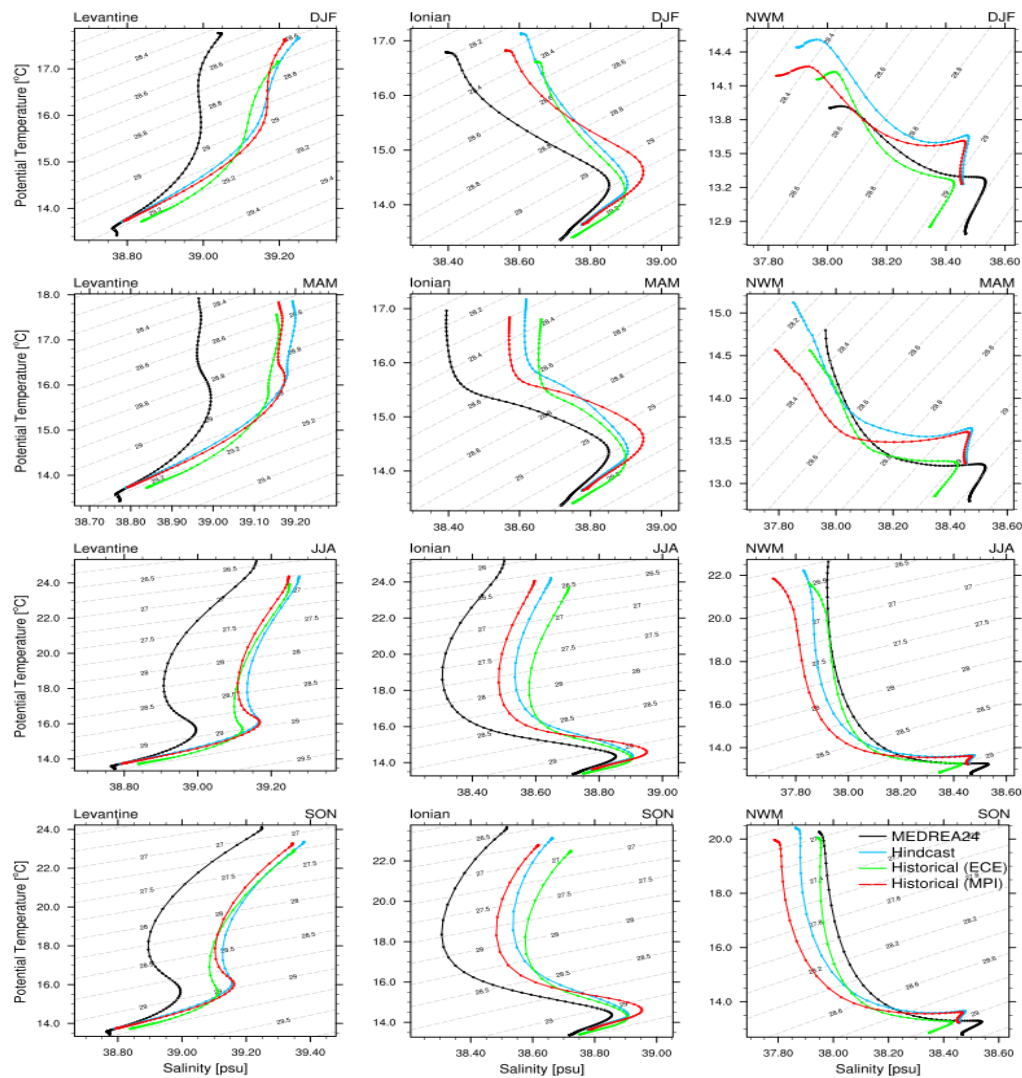


Figure 12. Potential temperature–salinity (T–S) diagrams showing the thermohaline characteristics simulated by the ENEA-REG3 hindcast and historical simulation over the three selected sub-domains in **Figure 4**, together with the corresponding MEDREA24 reanalysis over the period 1987–2014. Contour lines indicate isopycnals of potential density (kg m^{-3}).



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