EMI R&D PROJECT PROGRESS REPORT

All the following mandatory information needs to be provided. The length should *reflect the complexity and duration* of the project.

Reporting year	…………………2026…………………………..……
Project Title:	Improve representation of hydrological processes for the next generation of Earth system models ……..……
Computer Project Account:	………… spitales ………..…….
Principal Investigator(s):	………Andrea Alessandri…………………..…… Vincenzo Senigalliesi (UNIBO, ISAC-CNR), Annalisa Cherchi (ISAC-CNR), Emanuele Di Carlo (ISAC-CNR), Marco Possega (ISAC-CNR), Simone Gelsinari (ISAC-CNR), Franco Catalano (ENEA)
Affiliation:	…… Institute of Atmospheric Sciences and Climate, National Research Council of Italy (ISAC-CNR)……
Name of ECMWF scientist(s) collaborating to the project (if applicable)	… Gianpaolo Balsamo, Gabriele Arduini, Souhail Boussetta …
Start date of the project:	…………2025……………………………..……
Expected end date:	…………2027…………………………………

Computer resources allocated/used for the current year and the previous one

(if applicable)

Please answer for all project resources

		Previous year		Current year	
		Allocated	Used	Allocated	Used
High Performance Computing Facility	(units)	7500000	6374619	23000000	1122151
Data storage capacity	(Gbytes)	54350	17700	73000	24900

Summary of project objectives (10 lines max)

In this special project we will develop a more realistic representation of hydrology/groundwater in EC-Earth by including a global scale water table depth to replace free drainage bottom boundary conditions and achieve a more realistic representation of hydrological processes. To enable climate feedback driven by groundwater dynamics, we will attempt to include a simple interactive groundwater model. The effects of an improved representation of hydrological processes and the couplings with vegetation will be tested and assessed first in offline land-only simulations. The results of the sensitivities and developments conducted off-line will further drive coupled simulations of EC-Earth conducted with AMIP-type and CMIP7 configurations, including historical and future scenario simulations.

Summary of problems encountered (10 lines max)

The main difficulty encountered was the delayed availability and preparation of CMIP7 forcing data, including their adaptation for use within the EC-Earth consortium workflow. As a result, the planned AMIP-type simulations with CMIP7 forcing could not be completed during 2025. To avoid delaying model development, we carried out preparatory AMIP test simulations with the new EC-Earth4 configuration using CMIP6-compatible forcing. These tests allowed us to check the technical readiness of the workflow, evaluate model behavior in the updated configuration, and prepare for the launch of CMIP7-forced experiments as soon as the required forcing datasets become available.

Summary of plans for the continuation of the project (10 lines max)

The continuation of the project will focus on assessing the land-atmosphere feedbacks enabled by the dynamic groundwater representation, including interactions with vegetation and related hydro-biophysical couplings. Building on the offline results, we will evaluate how groundwater-mediated changes in root-zone moisture availability affect evapotranspiration, surface energy partitioning, atmospheric response, and climate variability over water-limited and transitional regions. These effects will first be assessed in AMIP-type atmosphere-land simulations and subsequently in fully coupled EC-Earth configurations, where ocean-atmosphere-land feedbacks and climate-change signals can also be evaluated. The timing and design of the coupled experiments will follow the availability of CMIP7 forcing data and the readiness of the EC-Earth consortium workflow, with the aim of contributing to CMIP7/AR7 coordinated simulations where feasible.

List of publications/reports from the project with complete references

Senigalliesi, V., Alessandri, A., Cherchi, A., Gelsinari, S. (in press). “Drivers of water resource changes over the Mediterranean Climate Regions of the Northern Hemisphere”. Earth's Future.

Senigalliesi, V., Alessandri, A., Kollet, S., and Gelsinari, S.: Introducing Groundwater Dynamics into the ECLand Land Surface Model: Implementation and Effects, EGU General Assembly 2026, Vienna, Austria, 3–8 May 2026, EGU26-19214, https://doi.org/10.5194/egusphere-egu26-19214, 2026.

Senigalliesi, V., Alessandri, A., Kollet, S., Gelsinari, S., Cherchi, A., and Di Carlo, E., 2026: Developing a groundwater model for ECLand - In preparation.

Summary of results

If submitted **during the first project year**, please summarise the results achieved during the period from the project start to June of the current year. A few paragraphs might be sufficient. If submitted **during the second project year**, this summary should be more detailed and cover the period from the project start. The length, at most 8 pages, should reflect the complexity of the project. Alternatively, it could be replaced by a short summary plus an existing scientific report on the project attached to this document. If submitted **during the third project year**, please summarise the results achieved during the period from July of the previous year to June of the current year. A few paragraphs might be sufficient.

The free-drainage boundary condition at the bottom of the unsaturated soil column — previously assumed in the EC-Earth land surface model (ECLand-LPJGuess; Balsamo, 2009; Alessandri et al., 2017; Boussetta et al., 2021; Doescher et al., 2023) and effectively placing groundwater at an unrealistic infinite distance below the surface — has been replaced by a Dirichlet boundary condition. This enables the use of a fully implicit numerical scheme for coupling the unsaturated soil column with groundwater. The explicit dynamic groundwater parameterization was then implemented by introducing the water stored in an unconfined aquifer, W_a, which evolves according to groundwater recharge (Q) and discharge (R):

$$\frac{dW_a}{dt} = Q - R$$

Recharge Q is defined as positive when water enters the aquifer and is computed as the sum of a conductive component Q_γ (gravitational drainage) and a diffusive component Q_λ (representing upward flux from the groundwater). Groundwater discharge R is formulated as an exponential function of the water table depth (Z_{WT}), such that it decays as the water table deepens:

$$R = R_{max} \cdot e^{-f \cdot Z_{WT}}$$

where $R_{max} = 4.5 \times 10^{-4}\ mm/s$ is a constant and f is a decay factor.

We evaluated how the implementation of an explicit dynamic groundwater parameterization in ECLand-LPJGuess affects the simulation of surface energy fluxes and subsurface hydrology. The scheme replaces the standard free-drainage lower boundary condition with a prognostic water-table-depth (WTD) formulation coupled to the unsaturated soil column, thereby allowing bidirectional water exchange between the saturated and unsaturated zones. We then evaluated its impacts using offline simulations at both flux-tower-site and global scales. The DYN experiment uses the newly implemented dynamic groundwater scheme, whereas the control experiment (CTRL) retains the original free-drainage configuration. At the site scale, model performance was evaluated against flux-tower observations from the PLUMBER2 network (Ukkola et al., 2020). At the global scale, simulated latent heat fluxes were evaluated against the GLEAM reference dataset (Miralles et al., 2025).

1. Off-line land-only simulations forced by PLUMBER2 Station Data

Figure 1 shows the site-by-site $\Delta rmse$ and Δr for latent heat flux (Qle) at the PLUMBER2 flux-tower stations, ordered by increasing DPCI. The DPCI is defined as:

$$DPCI = z(I_{rmse}) + z(I_r)$$

Where $rmse$ is the Root Mean Square Error and r is the Pearson Correlation Coefficient, $I_{rmse} = -\Delta rmse$, $I_r = \Delta r$, $z(x) = \frac{x - median(x)}{\beta \cdot MAD(x)}$, $MAD(x) = median(|x - median(x)|)$ and β is a scaling constant.

The introduction of dynamic groundwater yields mixed results at the station scale: panel a) shows a positive mean change in temporal correlation (Δr = +0.001), and Panel b) shows a reduction in RMSE of −0.05 mm month^{-1}. Statistically significant improvements are concentrated at a subset of stations, while many locations show differences indistinguishable from zero. Nevertheless, the overall tendency across the network is toward an improved representation of the water flux when groundwater dynamics are included, particularly at sites where the water table is shallow enough to support capillary rise into the root zone. This is notably evident at sites such as ***ES1*** (3 m), ***Rig*** (8 m), ***Geb*** (9 m), ***Lon*** (9 m), and ***Sam*** (10 m).

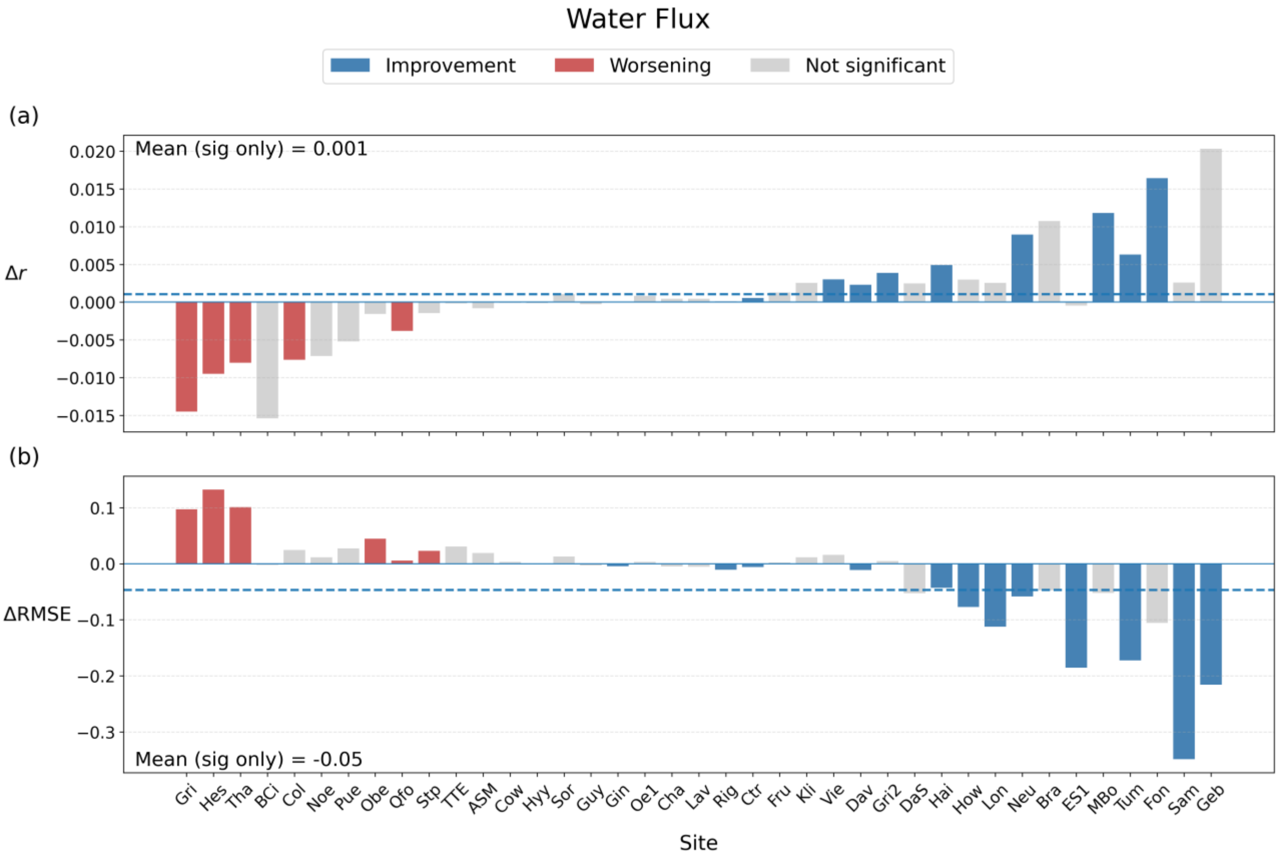

Fig. 1: site-by-site Δrmse and Δr for water flux (latent heat flux; Qle) at the PLUMBER2 flux-tower stations, ordered by increasing DPCI. Panel (a) shows changes in Pearson's r correlation coefficient (Δr) with observation. Panel (b) shows changes in root mean square errors (Δrmse, units: mm/month).

2. Off-line land-only simulations forced by ERA-5

Figure 2 compares the long-term mean water table depth (WTD) simulated in the DYN configuration with the gridded reference estimate from Fan et al. (2013), hereafter referred to as OBS. Panel (a) shows the simulated WTD averaged over 1941–2020, whereas Panel (b) shows the corresponding static reference estimate. The spatial pattern correlation between the two fields is 0.67, indicating that the dynamic groundwater parameterization captures a substantial fraction of the large-scale spatial heterogeneity in water table depth. Shallow water-table areas are generally well reproduced, particularly over North America (including the Great Plains and the Mississippi River basin), inland South America (the Amazon and La Plata basins), eastern Europe, and northern Eurasia.

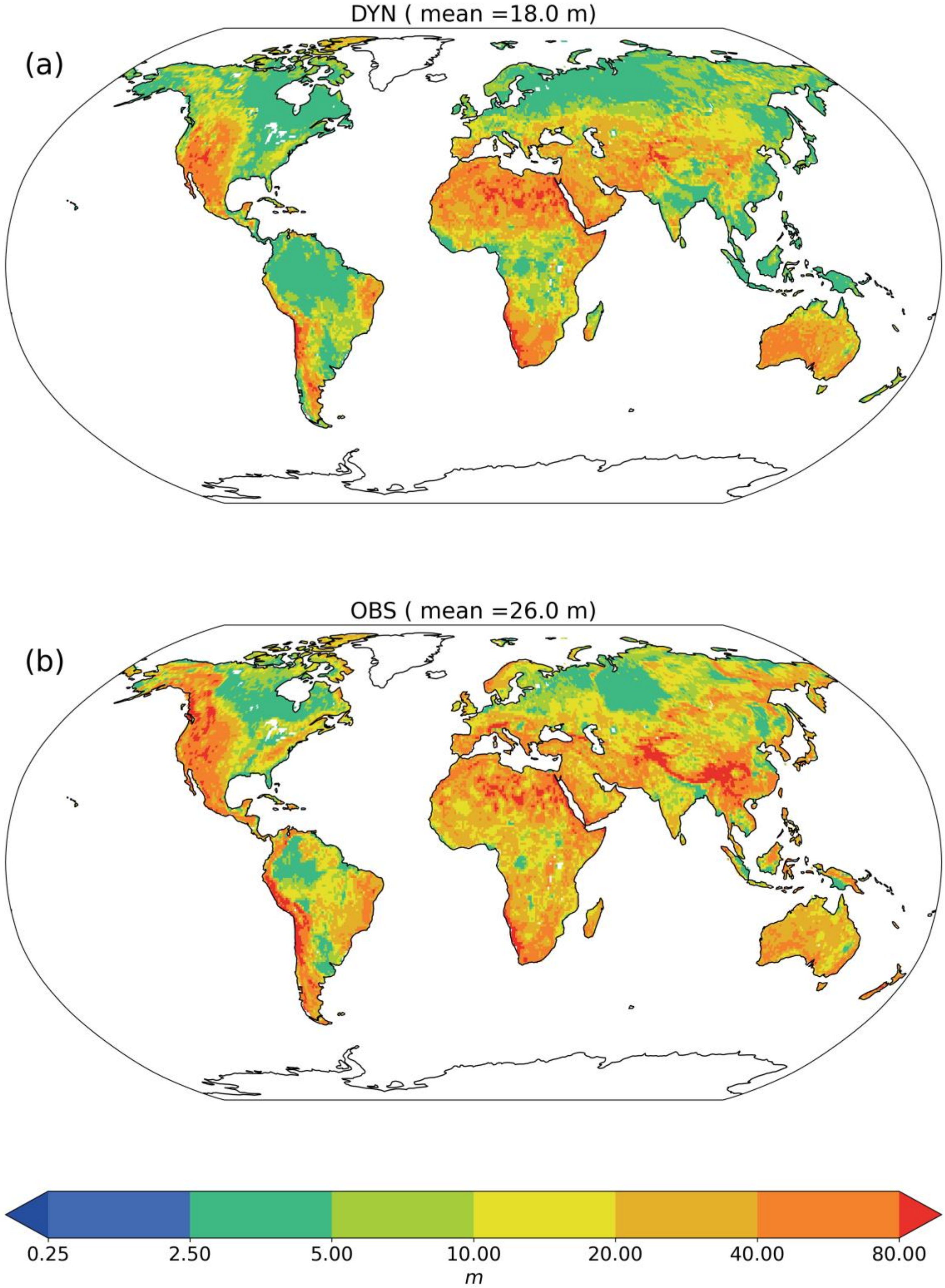

Fig. 2: Mean water table depth (WTD; m). a) ECLand simulation with dynamic groundwater (DYN), averaged over 1941–2020. b) Gridded static reference estimate from Fan et al. (2013) (OBS). Note that OBS is not a temporal mean over 1941–2020 but an independent reference estimate representative of modern broad-scale WTD patterns. Domain-mean values are reported in each panel title.

Figure 3 evaluates the global-scale impact of the DYN configuration on the simulation of latent heat flux (Qle), relative to CTRL and using GLEAM as reference. The inclusion of dynamic groundwater leads to a small but spatially widespread improvement in temporal correlation, with a domain-mean increase of $\Delta r = +0.01$. The largest gains occur mainly over water-limited and transitional regions, including parts of North America, central Eurasia, and South America. Consistent improvements are also found for RMSE, with a domain-mean reduction of −0.09 mm month^{-1} and statistically significant decreases broadly co-located with the areas of enhanced correlation. This spatial pattern suggests that the dynamic groundwater scheme improves the representation of land–atmosphere water exchange particularly where groundwater can contribute to root-zone moisture availability through capillary rise. Overall, the results indicate that the benefits of explicitly representing groundwater dynamics are regionally dependent and closely linked to the simulated water-table depth.

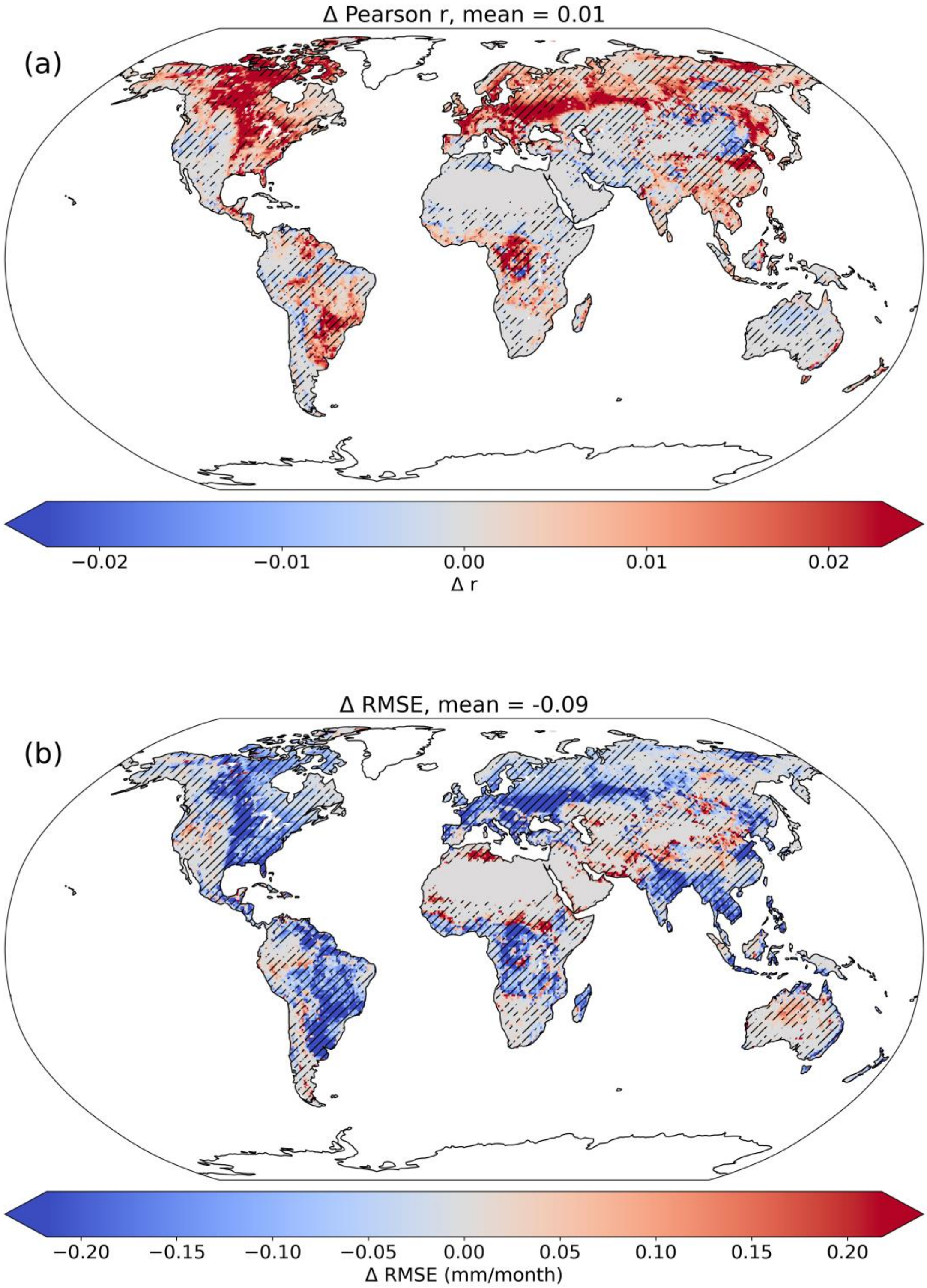

Fig. 3: Global changes in Pearson's r (Δr) and root mean square errors (Δrmse) for latent heat flux (Qle), DYN minus CTRL, evaluated against GLEAM over 1979–2020. (Panel (b) unit: mm/month). Hatched areas denote significant changes (p<0,1).

References:

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