SPECIAL 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	…………………2025……………………….……
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)	… 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)	-	-	18000000	4012377
Data storage capacity	(Gbytes)	-	-	54350	8600

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)

Problems were encountered with the use of the ECLand tools for creating initial conditions and forcings to run the off-line model. In the 2D case, all variables for the initial conditions were not created correctly when retrieving from CDS. For the forcings, the script must be run several times when retrieving from CDS (only option for non-ecmwf users) due to crashes during execution making the process painful (~one week for one year of forcing data retrieved) and with a significant SBU consumption from the allocated budget. The problem has been addressed to ECMWF colleagues but still not solved at the time of writing this report.

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

The effects of prescribing a water table depth — as obtained from existing estimates — to replace the free drainage bottom boundary conditions in EC-Earth will be assessed in off-line land-only simulations. To further enable climate feedback driven by groundwater dynamics, we will attempt to include a simple interactive groundwater model. After the testing and developments conducted off-line, the effects of an improved representation of hydrological processes and the couplings with vegetation will be assessed in i) coupled configuration with Atmosphere (AMIP-type) and ii) fully coupled mode. Taking advantage of the earlier delivery of the CMIP7 forcing data (expected already during second half of 2025), we'll take the opportunity of contributing to CMIP AR7 by running during 2026 the new historical and ScenarioMIP instead of the post-CMIP6. To this aim an amendment request is being submitted to postpone to 2026 the SBU resources that was previously allocated for post-CMIP6 in 2025.

List of publications/reports from the project with complete references

Senigalliesi, V., Alessandri, A., Kollet, S., Gelsinari, S., Cherchi, A., and Di Carlo, E.: Enhancing Hydrological Processes in Earth System Models: Implementing Groundwater Dynamics for Improved Climate Representations, EGU General Assembly 2025, Vienna, Austria, 27 Apr–2 May 2025, EGU25-18989, https://doi.org/10.5194/egusphere-egu25-18989, 2025.

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 current version of the land surface model included in EC-Earth (ECLand-LPJGuess; Balsamo, 2009; Alessandri et al., 2017; Boussetta et al., 2021; Doescher et al., 2023) still assumes a free drainage condition at the bottom of the unsaturated soil column, implying that groundwater is placed at an unrealistic infinite distance below the surface. To address this limitation, we have implemented a Dirichlet boundary condition at the bottom of the unsaturated soil, enabling a fully implicit numerical scheme to be used for coupling with groundwater. We prescribed the water table depth (WTD) directly using estimates from Fan and Miguez-Macho (2013) — hereafter referred to as the STATIC configuration — to enable the computation of realistic water fluxes between the unsaturated zone and the saturated groundwater-layer beneath. Furthermore, we assumed zero hydraulic conductivity when the prescribed water table depth was shallower than that of the soil model. Figure 1 illustrates the comparison of soil moisture content in the deepest modelled soil layer (level 4: 100–289 cm) in two selected stations across (blue) the STATIC configuration and (orange) a control simulation using the default configuration with a representation of groundwater at an infinite distance from the surface (hereafter referred to as CTRL). The two considered stations are the Neu (right panel; Austria: Lat: 47.1167, Longitude: 11.3175; time period 2002–2012) and Gebesee (left panel; Germany - Latitude: 51.0997, Lon: 10.9146; time period 2001–2014). The left panel of Figure 1 shows that prescribing a realistic WTD of 3.8 m in STATIC at the Gebesee station consistently leads to higher soil moisture values compared to CTRL, even though both experiments exhibit similar variability associated with precipitation or other recharge events. This indicates that the presence of a water table close to the unsaturated soil considerably enhances the soil moisture retention at this depth. In the righthand panel of Figure 1, it is shown an even higher effect on the soil moisture at the Neu station where the prescribed WTD in STATIC is shallower (0.5 m) and therefore maintaining a sustained moisture supply from the groundwater to the bottom soil layer that becomes saturated by water during the whole considered period.

Overall, these preliminary results highlight the importance of incorporating groundwater processes into land surface models. As expected, the CTRL simulation, lacking any groundwater influence, produces lower soil moisture values in all the stations considered, especially during dry periods, emphasising the critical role of groundwater in sustaining deep soil moisture. The Neu station displays the greatest impact on soil moisture in STATIC compared to CTRL due to the intensive influence of the prescribed shallower water table in this case.

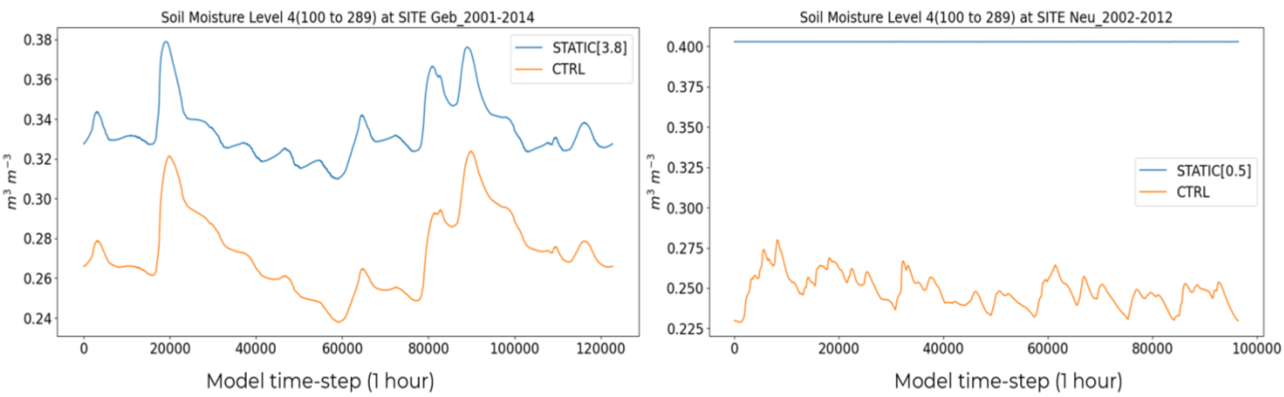

Figure 1: Comparison of soil moisture content at the deepest soil layer (100–289 cm) in the Geb and Neu sites, for the 2001–2014 and 2002-2012 periods, respectively (see text for more details). For each site two configurations are considered: CTRL (no groundwater consideration) and STATIC (prescribed water table depth of 3.8 m at Geb and 0.5 m at Neu according to Fan and Miguez-Macho *[2013] estimates). Shallower depths correspond to wetter conditions and a greater influence of groundwater on deep soil moisture.*

References:

Alessandri, A., F. Catalano, M. De Felice, B. Van Den Hurk, F. Doblas Reyes, S. Boussetta, G. Balsamo, P. Miller, 2017: Multi-scale enhancement of climate prediction over land by increasing the model sensitivity to vegetation variability in EC-Earth, Clim. Dyn., 49, 1215–1237. https://doi.org/10.1007/s00382-016-3372-4

Balsamo, G., Viterbo, P., Beijaars, A., van den Hurk, B., Hirschi, M., Betts, A. K., and Scipal, K.: A revised hydrology for the ECMWF model: Verification from field site to terrestrial water storage and impact in the integrated forecast system, J. Hydrometeorol., 10, 623–643, https://doi.org/10.1175/2008JHM1068.1, 2009.

Boussetta, Souhail, Gianpaolo Balsamo, Gabriele Arduini, Emanuel Dutra, Joe McNorton, Margarita Choulga, Anna Agustí-Panareda, Anton Beljaars, Nils Wedi, Joaquín Munõz-Sabater, and et al. 2021. "ECLand: The ECMWF Land Surface Modelling System" *Atmosphere* 12, no. 6: 723. https://doi.org/10.3390/atmos12060723

Döscher, R., Acosta, M., Alessandri, A., Anthoni, P., Arsouze, T., Bergman, T., Bernardello, and co-authors, 2022: The EC-Earth3 Earth system model for the Coupled Model Intercomparison Project 6, Geosci. Model Dev., 15, 2973–3020, *https://doi.org/10.5194/gmd-15-2973-2022*

Fan, Y., H. Li, G. Miguez-Macho (2013) Global patterns of groundwater table depth, Science, 339 (6122): 940-943, https://doi.org/10.1126/science.1229881