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Produce, validate, and document a version of ORCHIDEE with specialized features for water resource management

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1. Introduction

This deliverable contributes to WP2.2. Land-atmosphere interactions and land processes. To support climate service activities for water resource managers, our goal is to better describe complex waterscapes in the land surface model ORCHIDEE of the IPSL ESM (e.g. Cheruy et al., 2020), as well as their human controls (including irrigation and its supply by groundwater pumping and artificial reservoirs). To this end, we aimed at combining several recent developments to describe (i) rivers and their discharge at the kilometric scale, (iii) how irrigation can be supplied by withdrawals in rivers and aquifers and artificial reservoirs.

This report describes the advances of this work since the beginning of the PEPR TRACCS on November 2023 (planned at M15, delivered at M29). The people directly involved were:

- 2 permanents researchers : Frédérique Cheruy, Agnès Ducharne
- 2 permanent research engineers : Antoine Bierjon, Yann Meurdesoif
- 2 contractual post-doctoral researchers : Pedro Arboleda-Obando (18 months) and Peng Huang (18 months, including 6 months funded by TRACCS)
- 1 PhD student : Pierre Tiengou (24 months)

These developments are described in three research papers (Arboleda-Obando et al., 2024; Huang et al., 2024; Peylin, Luyssaert et al., in prep) and one PhD thesis (Tiengou, 2025). They led to scientific results published in six research papers (Arboleda-Obando et al., 2025; Yao et al., 2025a,b,c; Tiengou et al., 2026; Sauquet et al., 2026) and one PhD thesis (Tiengou, 2025).

2. Developments on river routing and irrigation

2.1 Routing scheme

The routing scheme is used to transform the surface runoff and drainage produced in each grid cell of ORCHIDEE into river discharge along the river network. In doing so, it provides a simplified description of groundwater storage and dynamics into a linear reservoir in each ORCHIDEE grid-cell (Figure 1).

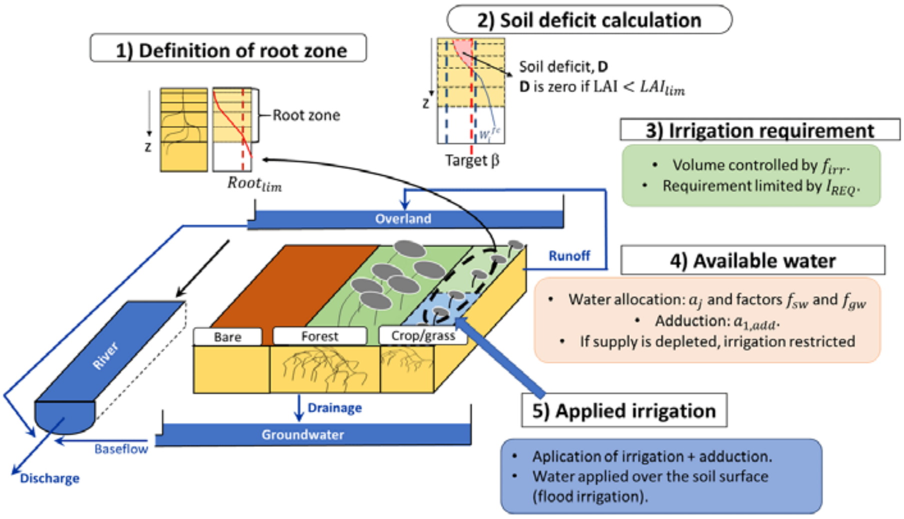


Figure 1 - Links between the routing scheme and irrigation in an ORCHIDEE grid cell. Source: Arboleda-Obando et al. (2024).

Three different routing schemes are presently available in ORCHIDEE, and their main features and applications are summarized in Table 1. The three schemes rely on the same physical principles involving three linear reservoirs with different timescales in each grid cell: a groundwater and an overland reservoirs which induce a local delay to the river reservoir, involved in the large scale routing of water down to the ocean (Ducharne et al., 2003; Ngo-Duc et al., 2007). Their main difference arises from their description of the river network by routing elements. The river network results from the topography, defined by a DEM (digital elevation model) at a given resolution, usually finer than the one of the ORCHIDEE grid mesh. The routing elements are organized by upstream/downstream relationship along the river network, and they can take two forms:

- **subgrid** fractions of the ORCHIDEE grid cells, so that one routing element belongs to only one ORCHIDEE grid cell (Polcher et al., 2023)
- directly the pixels of the DEM, in which case the routing elements can overlap several ORCHIDEE grid cells; therefore, surface runoff and drainage calculated in each ORCHIDEE must be **interpolated** towards the DEM pixels (using conservative weighted averages).

Differences also come from the possible DEM resolution, from possible interlinked processes (irrigation scheme from Arboleda-Obando et al., 2024; floodplains; groundwater-fed wetlands from Arboleda-Obando et al., 2022) and from known bugs.

Table 1 - Summary of the different routing schemes presently available in ORCHIDEE.
AO stands for Arboleda-Obando.

	subgrid_halfdeg	**subgrid_htu**	**interp_topo**	
Routing elements	Subgrid fractions of ORCHIDEE cells		DEM pixels	
DEM resolution	0.5° (50 km)	1-arcmin (2-km)	0.5° (50 km)	1-arcmin (2-km)
IPSL-CM configurations	IPSL-CM6 (Cheruy 2020)	Offline in France (Huang 2024; Sauquet 2026)	Pre IPSL-CM7 (Tiengou 2025)	LAM ICOLMDZOR (Tiengou 2025, 2026)
Irrigation	Yes (AO 2024, 2025; Yao 2025a,b,c)	Bug	Yes (Tiengou 2025)	Yes (Tiengou 2025, Tiengou et al., 2026)
Floodplains	Yes	Yes	No	No
Groundwater-fed wetlands	Yes (AO 2022)	No	No	No
Known bugs	Scale dependent routing timescales (Schneider, 2017)	On irrigation	Missing floodplains and groundwater-fed wetlands	

Table 1 also indicates which routing scheme has been used for several important configurations of the IPSL climate model, distinguishing coupled configurations (global as for CMIP simulations or regional with a LAM, limited area model) and offline configurations. In particular, several configurations have been developed and validated recently by the IPSL team of TRACCS-PC7-WP2.2:

- **The subgrid_htu routing scheme was used to run ORCHIDEE over France with a meteorological forcing at 8 km x 8 km resolution**. This application has been prepared using the SAFRAN meteorological forcing from 1959 to 2023. As detailed in Huang et al. (2024), it allowed us to simulate the river discharge of 3500 gauging stations of the national HydroPortail with good performances except in the Alps (due to snow processes) and in the Seine basin (due to an inaccurate timescale in the groundwater reservoir of the routing scheme, see section 2.2). This application was then forced by DRIAS-2020 climate projections until 2100 to simulate the possible evolutions of river discharge and groundwater resources under climate change in the framework of the national Explore2 project (Sauquet et al., 2026).

- **The interp_topo routing scheme has been prepared for the AR7 simulations with IPSL-CM, using the DEM à 0.5° already used for CMIP6** (Cheruy et al., 2020). The work involved the verification of mass conservation (in the river basins and at their outlet, where freshwater from land feeds the oceans), the comparison of the simulated discharge with the previous scheme (subgrid_halfdeg) and with observations, and the tuning of the routing parameters (timescales of the routing reservoirs). This very technical work is addressed in Chapter 3 of the PhD thesis of Tiengou (2025).
- **The interp_topo routing scheme was further prepared to be used with the 2-km DEM for high resolutions applications.** This work was conducted during the PhD of Pierre Tiengou over the Iberian Peninsula, and showed that interp_topo behaves similarly as subgrid_halfdeg (Figure 2), with the huge advantage of being easily used with DEMs at various resolutions, and for various ORCHIDEE grid shapes and resolutions. This development was later verified in an application in which ORCHIDEE was coupled to the ICO-LMDZOR atmospheric model over a limited area domain centered on the Iberian Peninsula (Tiengou, 2025; Tiengou et al., 2026). The interpolation philosophy made it very straightforward to combine the 2-km DEM to hexagonal ORCHIDEE grid-cells with a diameter of 25 km.

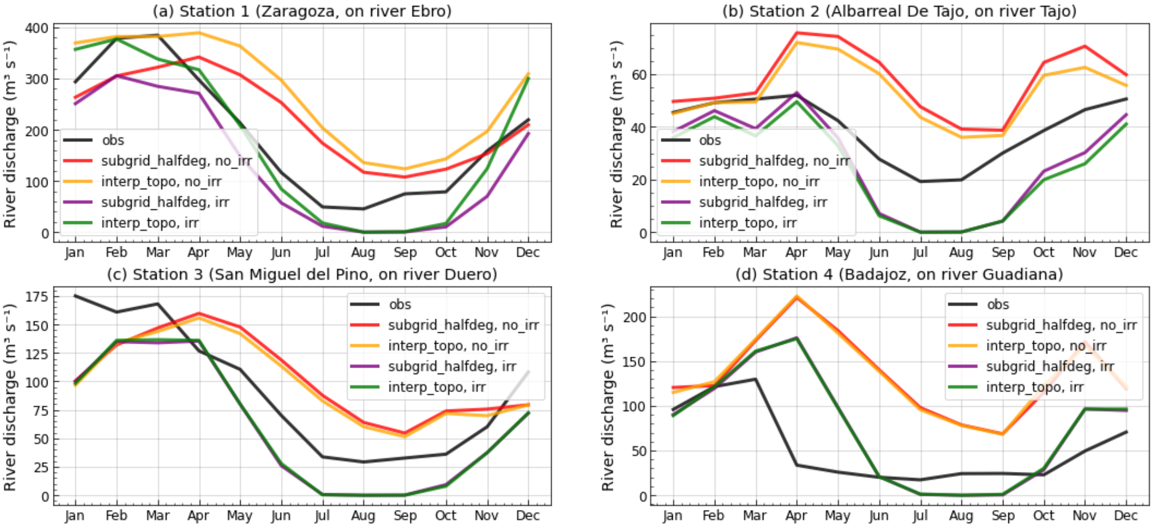


Figure 2 - Mean seasonal cycle (2003-2012) of simulated and observed river discharge at four stations in Spain: comparison of interp_topo (with the 2-km DEM) and subgrid_halfdeg (with the 50-km DEM), each with and without irrigation. Source: Tiengou (2025).

2.2 Irrigation

The irrigation scheme of Arboleda-Obando et al. (2024) was initially developed with the **subgrid_halfdeg** routing scheme. As schematized in Figure 1, this scheme restrains actual irrigation according to available freshwater in the three reservoirs of the routing scheme using allocation rules that depend on local infrastructure (to pump in surface or groundwater, and allowing adduction from the neighboring grid-cells). The available freshwater can itself be reduced to preserve environmental flow. All parameters (controlling irrigation demand, environmental flow limits and infrastructures) are defined by a combination of spatial maps and global parameters, which have been tuned globally by Arboleda-Obando et al. (2024).

The resulting simulated irrigation is within 10% of the global mean observations (Figure 3). As expected, accounting for irrigation improves the simulated evapotranspiration (ET) and leaf area index (LAI), especially in areas with a large irrigated fraction. The total water storage (TWS) is usually correctly simulated, with or without irrigation. In river basins with a marked decline of TWS due to irrigation (Ganges, Indus, Huanh He, Colorado), the new version of ORCHIDEE cannot represent it as it ignores the deep non-renewable aquifers which are tapped in these areas.

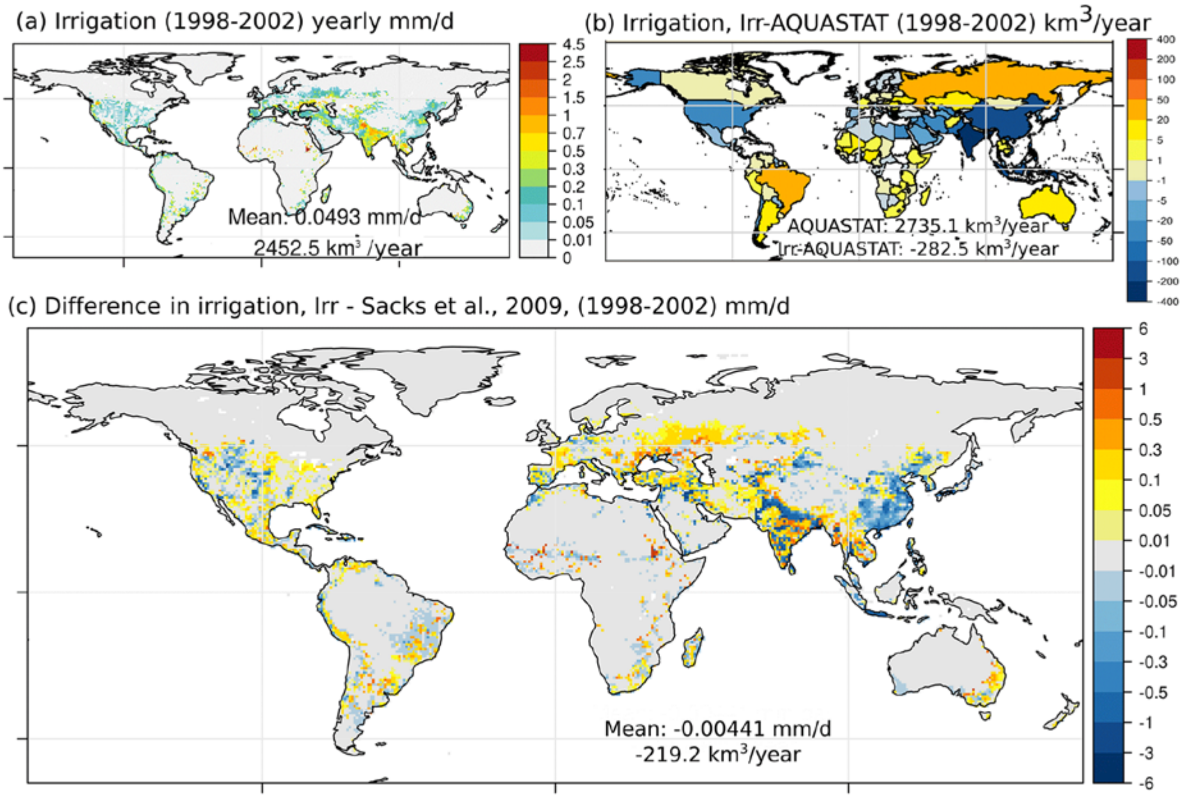


Figure 3 - Validation of total water withdrawal for irrigation (yearly average for 1998–2002): (a) simulation by ORCHIDEE, (b) difference with AQUASTAT values at country level; (c) difference with the dataset of Sacks et al. (2009) at 0.5°. Source: Arloleda-Obando et al. (2024).

This irrigation scheme has also been tested in the other two routing schemes. The PhD thesis of Pierre Tiengou allowed us to check that the routing scheme was fully functional with **interp_topo** whichever the selected DEM: 50-km for global applications including CMIP7; 2-km for high resolution applications, as in the Iberian Peninsula, where irrigation was shown to greatly improve the simulation of river flows (Figure 2). This work also underlined the need to account for additional water resources (non-renewable aquifers in Andalusia, adduction from the Pyrenees in the Ebro Basin, artificial reservoirs everywhere).

The irrigation scheme has also been tested with the **subgrid_htu** and the 2-km DEM in France by Peng Huang (post-doc for TRACCS-PC7 for 6 months), using the ORCHIDEE configuration at 8km x 8 km used for the Explore2 project, and input maps of irrigated areas available from 1900 to 2100 from the global LUH2 database at 0.25° (Hurtt et al., 2020), although higher resolution information is available for a few dates (Figure 4).

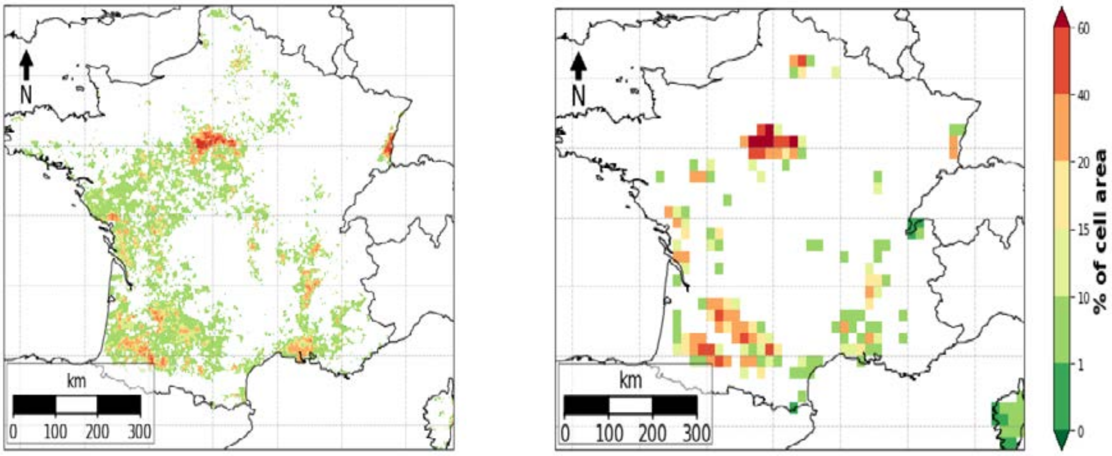


Figure 4 – Irrigated areas in France: (left) Agreste data for year 2010 (% per municipality); (right) LUH2 data for year 2005 (% per 0.25° grid cell).

This work revealed a few problems when activating irrigation with **subgrid_htu**, as illustrated here with offline simulations performed from 1950 to 2100, with and without irrigation:

- **The first problem occurs in non-irrigated areas** (in white in Figure 4): irrigation is logically zero there, but the simulated variables that are sensitive to irrigation exhibit unexpected differences between the simulations with and without irrigation (Figure 5). The average changes over France or river basins (Figure 6) are slightly influenced by this bug, which needs to be corrected.
- **Another problem relates to the groundwater reservoir**: whether irrigation is activated or not, it displays a very small volume, which is around 50 times smaller than the volume of the river reservoir (Figure 6b,d). Both features are not realistic, and related to the routing timescales, as analyzed in detail in Chapter 3.4 of Tiengou (2025). In particular, the ratio of groundwater to river timescales is 70 times larger in interp_topo over Spain than in subgrid_htu over France (using the same 2-km DEM), leading to a much larger groundwater volume in Spain (ca 200 times higher than in France, and larger than the river volume). The **too large groundwater timescale and too small groundwater volume** in France have several important consequences: firstly, it weakens the buffering effect of groundwater and may explain why peak flow occurs earlier in the simulations than observed in areas with important aquifers like the Seine basin (Huang et al., 2024, Figure 5d); secondly, the small groundwater volume is quickly depleted by irrigation, which is therefore strongly limited by the lack of groundwater.
- We also found that **the simulated irrigation is overestimated** compared to observations (Figure 7), which probably explains why irrigation increases the simulated river discharge in the highly irrigated areas (Figures 4 and 6f), by means of return flow (Grafton et al., 2018).

To solve these problems, the decision was made to use the interp_topo routing scheme for the ORCHIDEE configuration at 8 km x 8 km over France (instead of subgrid_htu). This is consistent with the decision of the ORCHIDEE development group to adopt interp_topo for the IPSL climate model and all coupled land-atmosphere configurations, because of its higher potential for parallelization and its facility to adapt to any grid mesh. It will also allow us to benefit from the work of Tiengou (2025) in Spain regarding the routing timescales. **This work will be undertaken by two PhD students**: Matthieu Belin (PhD thesis from October 2024 to September 2027 at LMD-IPSL) has recently started, with the goal to address the effect of irrigation on future drought evolutions in France, and Rémi Schalck (PhD thesis from May 2026 to April 2029) will take over to improve all parameters, in order to address the possible adaptation of irrigation and water management in France under climate change.

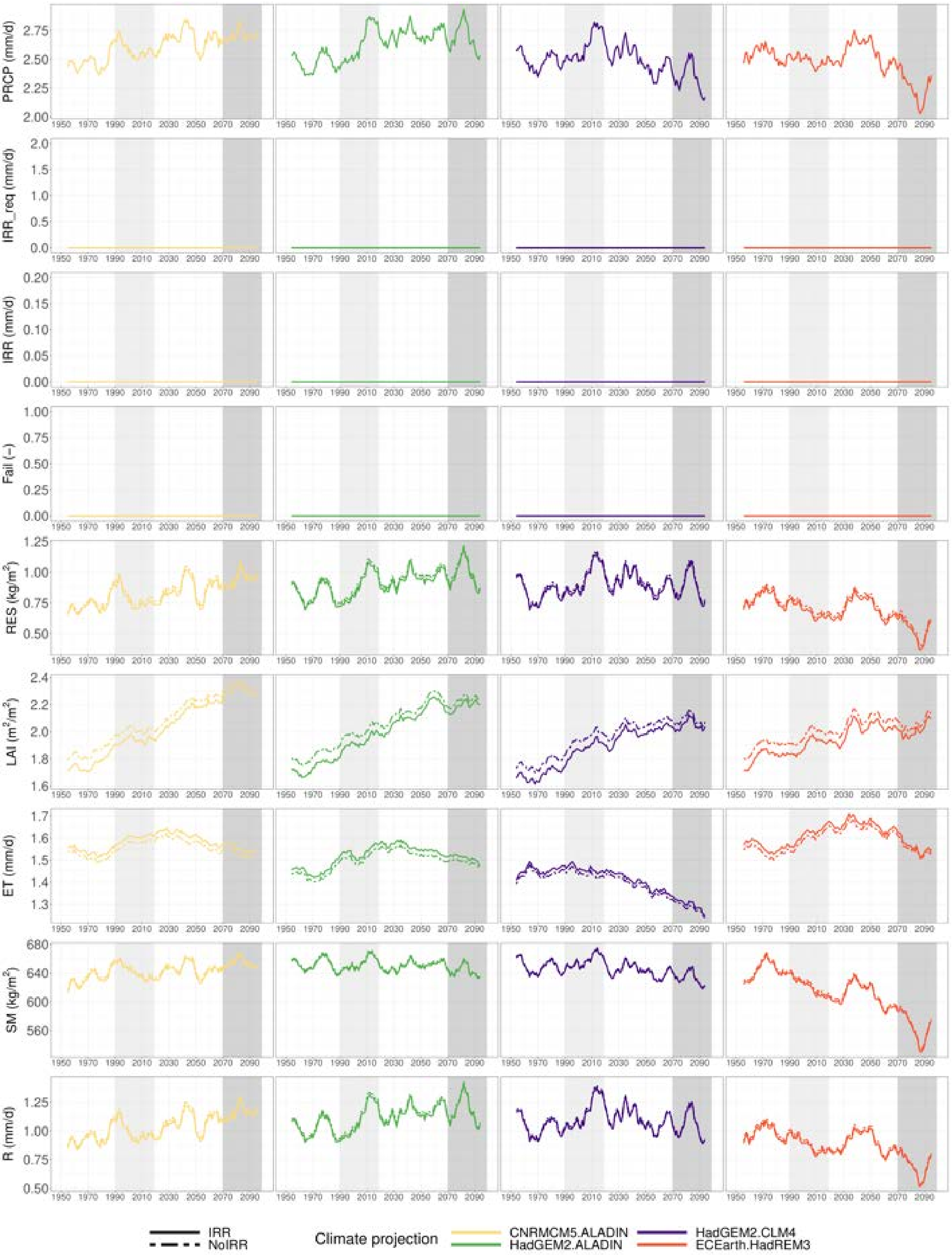
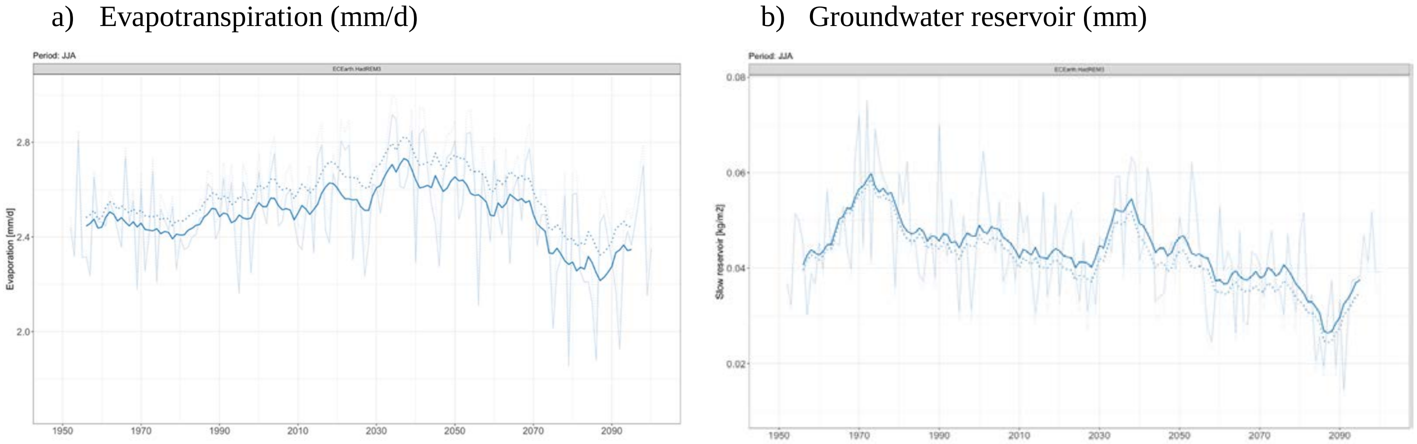
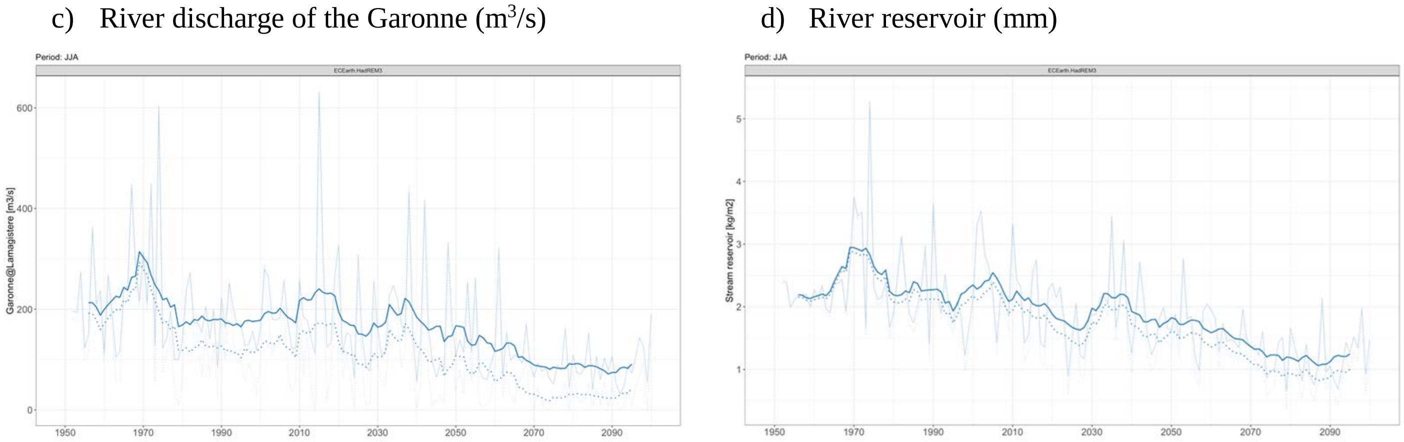


Figure 5 – Bug of the irrigation scheme when coupled with **subgrid_htu** over France: time series of simulated variables (annual mean values) over the not irrigated area in France, for the four narratives of the Explore2 project. The displayed variables, from top to bottom, are : precipitation, irrigation demand, effective irrigation, failure to meet the demand, water volumes in the routing reservoirs, LAI, evapotranspiration ,soil moisture, total runoff.



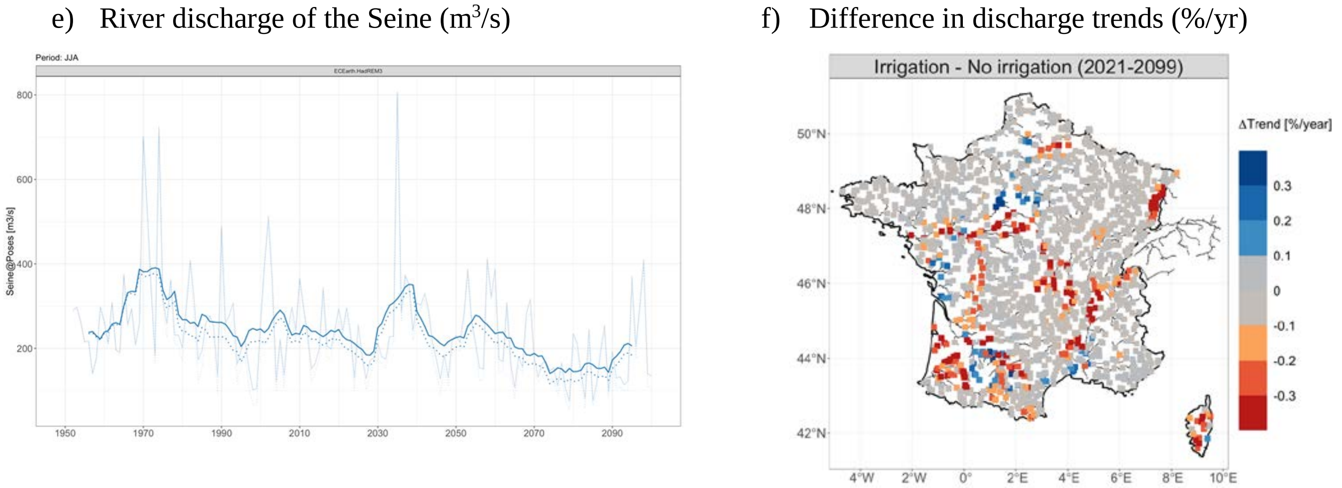
a) Evapotranspiration (mm/d)

b) Groundwater reservoir (mm)



c) River discharge of the Garonne (m^3/s)

d) River reservoir (mm)



e) River discharge of the Seine (m^3/s)

f) Difference in discharge trends (%/yr)

Figure 6 – Comparison of the summer trends simulated by ORCHIDEE over France (using **subgrid_htu** with and without irrigation) under a warm and dry climate projection (ECEarth-HadREM3 with RCP8.5, in red on Figure 5): (a-b-d) average values over France; (c-e) river discharge at the outlet of the Garonne and Seine Rivers, (f) difference in river discharge trends at 3500 river discharge stations; (a-b-c-d-e) plain/dotted lines for the simulation without/with irrigation.

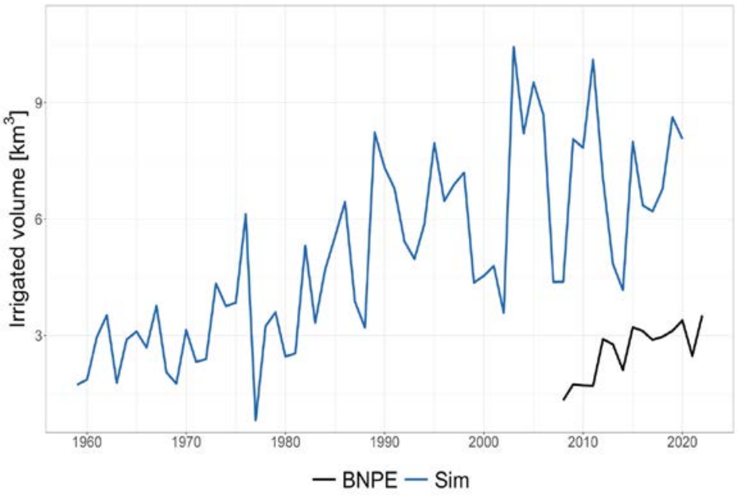


Figure 7 – Comparison of the simulated irrigation in France with the measured withdrawals, in both rivers and groundwater (BNPE database, Banque Nationale des Prélévements en Eau).

2.3 Code availability

The above work is based on the following configurations of the ORCHIDEE land surface model, which are available from the IPSL svn server:

1. Global configuration CMIP6, with **subgrid_halfdeg** and functional irrigation: ORC2.2 r7709 freely available from https://forge.ipsl.fr/orchidee/browser/branches/ORCHIDEE_2_2?rev=7709
2. Regional configuration France-Explore2 with **subgrid_htu**, used for the Explore2 project but bugged for irrigation (Figs 5, 6, and7): ORC2.2 r9314, stored on https://forge.ipsl.fr/orchidee/browser/perso/peng.huang

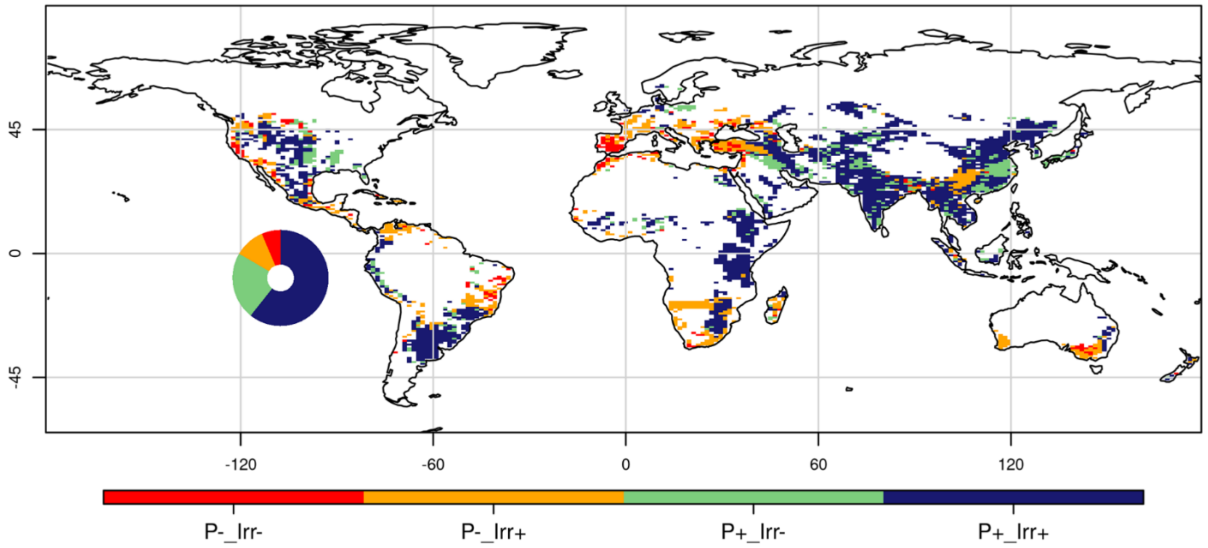
Three configurations were also developed with **interp_topo** and a functional irrigation:

3. Global configuration AR7-FT / pre-CMIP7: ORC4.3 with interp_topo and irrigation, stored on https://forge.ipsl.fr/orchidee/browser/branches/ORCHIDEE_4_3
4. Regional configuration from Pierre Tiengou over the Iberian Peninsula: ORC2.2 offline and coupled with ICOLMDZOR), with interp_topo, on https://forge.ipsl.fr/orchidee/browser/perso/pierre.tiengou
5. Regional configuration France-Explore2-FollowOn: ORC2.2 with interp_topo and irrigation, in progress

4.1 With Config 1 (global and subgrid_halfdeg)

Arboleda-Obando et al. (2025) analyzed the first ever simulation of future climate change accounting for irrigation, using IPSL-CM6 (coupled land and atmosphere with forced ocean temperatures). While irrigation slightly increases precipitation over irrigated areas and their surroundings, it does not significantly influence precipitation trends due to global warming. Yet, irrigation is strongly sensitive to climate change, and it exhibits complex feedback loops with precipitation and total water storage changes. In one-third of irrigated areas, including the Mediterranean basin, California, and Southeast Asia, future environmental conditions can increase tensions over water use and even cause the failure of irrigation (Figure 8). This work shows the importance of considering irrigation in climate projections and future water resources assessments.

a) Joint changes of P and Irr



b) Joint changes of Irr and GWS

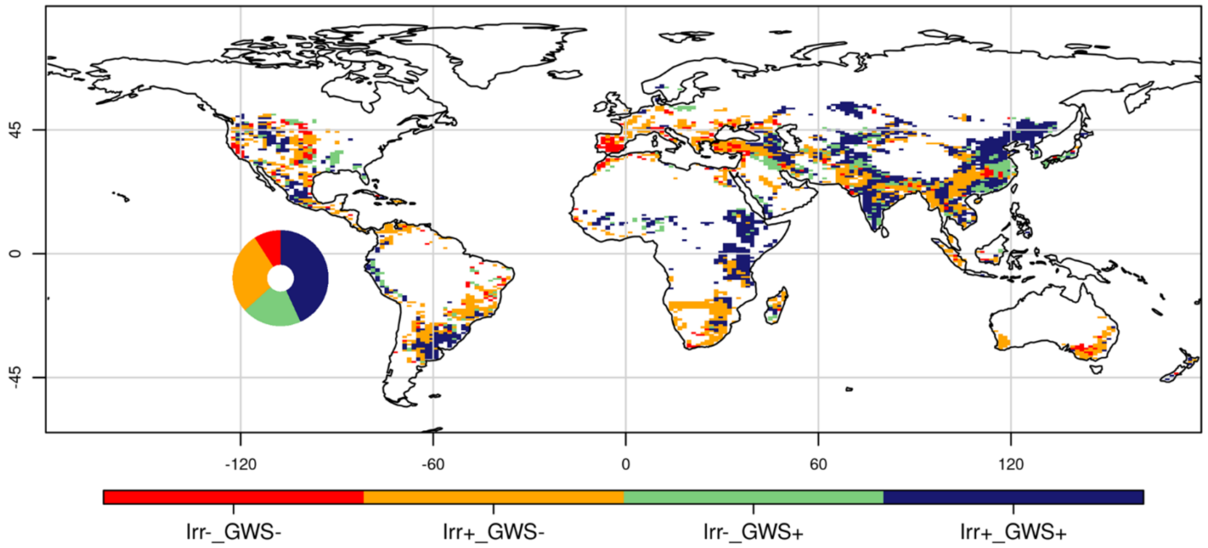


Figure 8 - Joint changes between the future (Fut, 2050–2100) and historical (Hist, 1950–2000) periods in irrigated areas: (a) joint changes of precipitation (P) and irrigation (Irr); (b) joint changes of groundwater reservoir storage (GWS) and irrigation (Irr) The symbols + and – indicate positive and negative changes, respectively. The insets indicate the fraction of each irrigated class.

These simulations were also analyzed as part of the IRRMIP multi-model ensemble, in order to reduce the model-dependence of the results. This framework allowed us to demonstrate that irrigation enhances moist-heat stress although its cooling effect reduces 2-meter air temperature heat extremes across heavily irrigated areas. This is true retrospectively since 1901 (Yao et al., 2020a), and prospectively until 2074, under various Shared Socioeconomic Pathways (SSPs) (Yao et al., 2020b). These studies indicate that irrigation deployment is not an efficient adaptation measure to escalating human heat stress under climate change, calling for carefully dealing with the increased exposure of local people to moist-heat stress. The IRRMIP project also quantified the relative contributions of irrigation and past climate and land use changes to past land water depletion thus enlarging the scope of attribution studies (Yao et al., 2025c).

4.2 With Config 4 (regional and interp_topo)

During the PhD thesis of Pierre Tiengou, the work case of the Iberian Peninsula not only allowed us to develop and tune the interp_topo routing scheme with irrigation in offline mode (section 2), but it also allowed us to study the regional impacts of irrigation on the atmospheric and terrestrial water cycle, owing to innovative regional land-atmosphere simulations with the ICOLMDZOR regional simulations (Tiengou et al., 2025).

In summer (JJA), large atmospheric responses are found over intensely irrigated areas, mainly consisting of a shift in energy partitioning between the turbulent fluxes (increase in latent heat flux and decrease in sensible heat flux, up to 50 W m^{-2}), and a lowering of both the atmospheric boundary layer (−100 m) and the lifting condensation level (−250 m). We underline an active regional atmospheric moisture recycling as the increase in ET in the presence of irrigation exceeds the amount of water added by irrigation (Figure 9). This is made possible by an increase in precipitation over land, which is rather located in lightly irrigated areas than in intensively irrigated areas. These results point to remote atmospheric effects of irrigation and motivate closer inspection of small-scale land-atmosphere coupling processes between irrigated and non-irrigated plots, owing to observations recorded during the LIAISE campaign and detailed Meso-NH simulations. Focusing on two specific days, this analysis confirmed that the influence of irrigation on the boundary layer is the structure of surface heterogeneities on the local wind regime, which calls for adapted sub-grid scale parametrizations (Tiengou, 2025, Chapter 6).

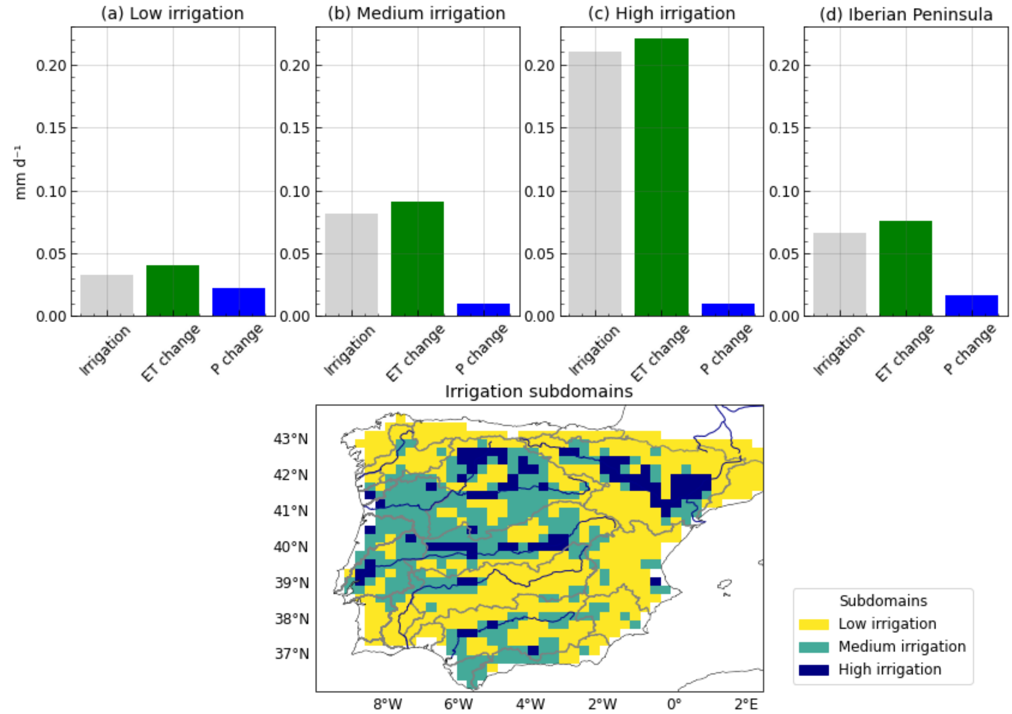


Figure 9 - Changes in the atmospheric moisture budget due to irrigation on average along 2010-2022 (in mm/d). The Iberian Peninsula is separated in three subdomains with different irrigation intensities, shown in the bottom panel.

5. Perspectives

The reported work has supported the **selection of interp_topo as the privileged routing scheme for the IPSL models**: IPSL-CM7, ICOLMDZOR, high-resolution applications of ORCHIDEE. While being compatible with the irrigation scheme of Arboleda-Obando et al. (2024), this routing scheme brings a high potential for parallelization and a flexibility to adapt to any grid mesh, with a straightforward and validated link between the river network, the river station position, and the routing timescales. The following paragraphs provide an overview of the main short-term development plans to continue enhancing the ORCHIDEE land surface model with specialized features for water resource management, to make this model fully relevant for simulating the land surface hydrology of the Anthropocene era.

5.1 Groundwater

Some tuning is still required, particularly for the groundwater timescales, which should much more depend on hydrogeological properties than on topographical slopes. The PhD thesis of Schneider (2017) made an important contribution to this problem by proposing groundwater timescales based on the Boussinesq equation and global hydrogeological databases, but they were not only spatially variable but also much larger than the original groundwater timescales of subgrid_halfdeg (ca 70 to 700 times larger for the median values, cf Schneider, 2017, p 81), leading to an excessive buffering of groundwater flow and river discharge with this routing scheme. The fact that the ratio of groundwater to river timescales is 70 larger in interp_topo over Spain than in subgrid_htu and subgrid_halfdeg (Tiengou, 2025, p 94) is indicative that the **physically-based groundwater timescales proposed by Schneider (2017)** may be adapted to the interp_topo routing. This will be first be tested over France, using the configuration developed in the ongoing PhD thesis of Matthieu Belin (funded by MACIF), focused on droughts and how their evolution is altogether influenced by and impacting human societies.

Other important developments relate to the water supply by **deep/fossil aquifers**, important for irrigation in many heavily irrigated areas with major sustainability concerns, but overlooked in ORCHIDEE because they are not naturally connected to the global water cycle and their volume is hard to estimate. The **coupling of ORCHIDEE with a physically-based 2D groundwater flow model** is particularly relevant for high resolution applications in which the assumptions supporting the linear reservoir approximation are no longer valid. This research direction has been pioneered in the Seine River basin using the routing of the groundwater model (Kiliç et al., 2023) and is further advanced by the PhD thesis of Simeon Lang at LMD-IPSL since January 2024 (with ORCHIDEE 4.3 and interp_topo).

5.2 Human-built infrastructures

Further developments will be undertaken during the PhD thesis of Rémi Schalck (from May 2026 to April 2029, funded by the French Ministry for Ecological Transition), with the overall goal of proposing adaptation strategies for managing freshwater resources in the context of climate change across mainland France. To this end, ORCHIDEE will be enhanced to better take multi-sectoral water uses into account. The priorities will be to:

1. Improve the simulation of groundwater resources (via their timescales);
2. Add the **non-agricultural withdrawals**, based on recent measurements;
3. Represent how **artificial reservoirs and inter-basin transfers** (adduction) can sustain irrigation and non-agricultural withdrawals; the description of large reservoirs may benefit from the developments of Baratgin et al. (2024) for hydropower planning with the subgrid_htu routing scheme.

Another type of human-built infrastructure to manage soil moisture is **French drainage**, aimed at artificially draining saturated soils to lower soil moisture and facilitate farming. This widespread farming practice should be implemented in ORCHIDEE during the PhD of Leila Petit (expected start in September 2026 with funding by the Corps des Ingénieurs des Ponts, des Eaux, et des Forêts). Finally, the recent work of Lalonde et al. (2026) on **urban impervious areas** paves the way for a comprehensive urban scheme in ORCHIDEE.

5.3 Nature-based solutions

Nature-based solutions are frequently advocated as an alternative to human-built infrastructures to adapt watersheds to climate change, in both rural and urban environments. **Most solutions aim at increasing soil water-holding capacity and infiltration into soils and groundwater**, to both reduce runoff and floods during wet spells and increase soil moisture and delayed base flow during dry spells. Different overlapping techniques can be mobilized at various scales, including land cover changes (afforestation, greening at many scales, reducing impermeable surfaces), the enhancement of local infiltration (owing to hedges, water harvesting pits, and terraces), the restauration of wetlands and meandering streams, or soil conservation.

The ORCHIDEE land surface model is potentially able to account for many of these techniques, either explicitly or in a sub-grid statistical way, offering an interesting tool to quantify their efficiency at the watershed scale of water management. This will be explored in two above-mentioned PhD theses: the one of Simeon Lang in Southwest France, with a focus on remeandering and artificial aquifer recharge; the one Leila Petit, in the Orgeval watershed (ca. 100 km², east of Paris), which is subject to frequent flooding and heavily drained yet remains vulnerable to droughts because of intensive farming. The required developments will benefit from the ongoing coupling with physically groundwater flow schemes (section 5.1) and from many existing parametrizations of ORCHIDEE regarding lakes (Bernus & Otllé, 2022) and wetlands, whether they result from flooding (Schrapffer et al., 2023; Lauerwald et al., 2017), from hillslope flow or groundwater supply (Arboleda-Obando et al., 2022).

5.4 Small-scale features of land-atmosphere coupling

Most above-mentioned developments lead to increase the heterogeneity of the land surface. This calls for a higher number of sub-grid elements or tiles, which is challenging for an efficient calculation of the water and energy budgets at grid cell scale. The main challenges are twofold: the first one relates to the water budget and the need to transfer water between tiles, sometimes at a finer scale than the one of the routing scheme topography (e.g. to represent wetlands or some urban water networks); secondly, the energy budget is presently calculated at the grid cell scale, meaning that one unique surface temperature is considered, while many small-scale features of the water budget induce strong thermal contrasts, which feedback on the surface water budget and also on the atmosphere, via mesoscale circulations. If one wants to couple ORCHIDEE with an atmospheric model to properly simulate urban heat islands or the mesoscale circulations induced by highly irrigated areas (Tiengou, 2025), the **multi-tile energy budget** pioneered in ORCHIDEE by Bernus & Ottlé (2022) and Xi et al. (2024) must be consolidated and combined with the multi-tile water budget involved in the aforementioned specialized features for water resource management.

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