RC2: 'Comment on esd-2024-41', Anonymous Referee #2, 23 May 2025 reply

Review of the manuscript 'Joint evolution of irrigation, the water cycle and water resources under a strong climate change scenario from 1950 to 2100 in the IPSL-CM6' by Arboleda-Obando et al, submitted to Earth System Dynamics

General summary

The study of Arbeleda-Obando et al applies their recently developed irrigation scheme in a climate change study using an AMIP style simulation setup. They find that irrigation increases strongly in their future projection due to the increase in radiative forcing and land use. Furthermore, and additional to the impacts of climate change, irrigation is shown to enhance evaporation and thereby the hydrological cycle and impacts also regions outside of the irrigated areas.

This study is the logical next step after presenting the development and validation of their irrigation scheme in a uncoupled land surface simulation with fixed atmospheric forcing in their 2023 paper. It convincingly demonstrates interactions between the applied irrigation and the interactive atmosphere and highlights regions which are prone to increase in water stress and water reservoir depletion.

We thank the anonymous reviewers 2 for the time he spent reading and commenting on our paper. As for reviewer 1, we provide a point-by-point response to these comments. Sentences from the original submitted manuscript are presented in italic, while the proposition to respond to the observations are presented in bold. Lines correspond to the original manuscript.

Detailed comments

- 1. L105 If the energy balance is solved for the grid cell instead of the individual tiles, don't you reduce the effect of reduced surface temperature and higher surface humidity on the latent heat flux and thereby have a higher irrigation demand than you would have if you would compute the energy balance on tile? Do you think this effect would be significant?

We thank the reviewer for this observation. First, we must underline that we cannot elucidate the effect of computing the energy balance in the grid cell instead of individual tiles in the current IPSL-CM6, essentially because the atmospheric component only "sees" the grid cell but not the tiles in the lower atmosphere. This approach is called "simple flux aggregation" (de Vrese et al., 2016b). Note that the water balance is computed for every tile.

If the energy balance could be solved for individual tiles, lower surface temperature and higher surface humidity could induce a lower evaporative demand. If the result is a decrease of ET and an increase of soil moisture, ultimately irrigation demand could decrease, by a less intense irrigation rate or by a shorter irrigation season length. Besides, even if there is not decrease on irrigation demand (because the soil moisture is dry and water stress is high), changes in the evaporative demand could have an impact on the irrigation efficiency (i.e. the irrigation water fraction that is actually evaporated, see Jägermeyr et al., (2015)).

Then, we could observe an increase of runoff and recharge as return flows from the irrigated volume.

Note anyway that the “simple flux aggregation” approach in ORCHIDEE LSM partially represents the change in surface temperature and surface humidity, and is able to represent the effects on the water balance, but is not currently able to represent the sharp contrast in surface conditions for the energy balance. It is then difficult to speculate on the significance of the effect. In any case, we believe this shortcoming is part of the modelling uncertainties, and should be noted.

We propose to add a sixth position on the list that enumerates model shortcomings, line 406:

6. The misrepresentation of subgrid variability in the land surface-atmosphere coupling (de Vrese et al., 2016b), specifically on the energy budget computed by IPSL-CM6, could have an impact on irrigation demand, on atmospheric feedbacks and on irrigation efficiency (de Vrese and Hagemann, 2018).

And twe new references:

de Vrese, P. and Hagemann, S.: Uncertainties in modelling the climate impact of irrigation, Clim Dyn, 51, 2023–2038, https://doi.org/10.1007/s00382-017-3996-z, 2018.

de Vrese, P., Schulz, J.-P., and Hagemann, S.: On the Representation of Heterogeneity in Land-Surface–Atmosphere Coupling, Boundary Layer Meteorol, 160, 157–183, https://doi.org/10.1007/s10546-016-0133-1, 2016b

- 2. L109 You spend more time explaining the climate model than the irrigation scheme. Probably this information is available in your irrigation paper already, but please add how you avoid to accidentally irrigate too large parts of the grid cell. As you don’t seem to use an individual tile for irrigated crops (line 94 mentions bare soil, forest and crops + grasses), the soil moisture deficit in a rather dry tile would constantly remain high because even if you add enough water to saturate the irrigated fraction of the tile, the mean tile state would still show a deficit in the next time step.

We thank the reviewer for this observation. The reviewer is right, irrigated crops don't have a specific soil tile. It means that the soil moisture deficit in a rather dry tile will remain high, and then the water demand will not decrease. Also, the reviewer is right that this information is available in the paper that presents the irrigation scheme. But we agree that listing the limitations that were already identified is important in order to discuss the results that we present hereafter. We propose to add a paragraph at the end of section 2.2, line 128:

We note here some shortcomings identified in the irrigation scheme used here (Arboleda et al., 2024). The scheme represents a single irrigation technique (the flood technique), and uses a set of simplified rules to trigger irrigation and allocate available water. Besides, the scheme uses a joint representation of rainfed and irrigated crops within the same tile, and the scheme doesn’t represent conveyance

losses. To restrain in part the effect of these shortcomings on estimated irrigation volumes, parameter values were tuned by fitting the simulation to reported irrigation datasets. But we must also note that this parameter tuning is overly simplistic, as it uses globally uniform parameters. Despite these limitations the irrigation scheme produces acceptable estimates of yearly estimation withdrawals at global scale, but tends to underestimate irrigation withdrawals in China, India and the USA, corresponding to the irrigation hotspots (Arboleda et al., 2024).

- 3. L112 are the 0.65m root depth specific for crops or is this used everywhere?

This value is specific to crops, and corresponds to approximately 90% of the root system as it is represented in ORCHIDEE, an is specific for crops. We add this information in line 112:

Here, we briefly describe its main characteristics. First, the root zone depth is set according to a user-defined parameter. In our case, we set this depth to 0.65 m (11 layers). ***This depth comprises approximately 90% of the crop root system as represented in ORCHIDEE.***

- 4. L116 you don't mention dams as water reservoirs for irrigation. Wouldn't it be important to include these, because they are used to mitigate the seasonality of river discharge and thus would enhance water availability during dry seasons?

Here we list the natural reservoirs that are represented in the model. But we agree that dams are an artificial reservoir that could help to mitigate the seasonality of river discharge (stream reservoir in ORCHIDEE) and thus enhance water availability. Besides, we think that the irrigation scheme could benefit from an explicit representation of dams operation and human water management. We propose then to include these ideas in the paper. Please see observation 6 from Reviewer 1.

- 5. L294: I would either use `strengthening effect` or `positive feedback`, but `positive effect of climate change` sounds wrong if it is about needing more irrigation

We agree that this sentence is not clear. Here, we are referring to the trends that we observe on time series of groundwater and stream reservoirs. We observe a different behaviour after and before 2040. Before, there is a small decrease in water storage reservoirs in the Irr simulation. After 2040, both simulations depict an increase in water storage, but the increase is faster in the NoIrr simulation than in the Irr simulation. We propose to slightly change the sentence, line 293.

Note that the ***effect*** *of irrigation* ***on water storage reservoirs*** *seems to counteract* ***the increase induced by climate change in*** *irrigated areas before 2040, and* ***after 2040 the increase of water storage (groundwater and stream reservoirs)*** *is slower in the Irr simulation than in the NoIrr simulation.*

- 6. L324: Why the time lack? I would assume irrigation happens during the summer, but then precipitation increases during winter? Could this mean that you over-irrigate during summer (due to reasons explained above) which means you start the winter with a much wetter soil than in the non-irrigation simulations although the extra water should have been mainly transpired by the crops instead of being stored in the soil?

Yes, irrigation happens during summer in the northern hemisphere, and as noted below, there is probably an overirrigation, even if the irrigation scheme has some restrictions. We also agree that irrigation induces an increase of soil moisture and ultimately of precipitation in the Irr simulation compared to NoIrr.

One possible mechanism is that the additional soil moisture allows the crops to transpire more until the end of fall (remember that crops are similar to grasses in our simulation, so there is no harvest calendar). The additional water into the atmosphere could induce more precipitation during winter. It could indicate a limitation in the model (because there is no crop during fall and winter), or it could indicate a case where the crops calendar has two or more harvest seasons.

In any case, we agree that this particular case is especially interesting, but understanding the mechanism would need a focus on regional wind and precipitation patterns that goes beyond the scope of the manuscript. Besides, we consider that some of the uncertainties that arise from model limitations in this case are already mentioned (see the listed limitation from the modelling framework and from the irrigation scheme in section 4 of the original manuscript, also response to observation 1 from reviewer 2).

- 7. L421: You found precipitation increase due to irrigation mainly in regions very close to the irrigated regions. However, others studies, e.g. de Vrese et al. (2016) found rather strong remote effects for today's irrigation. Do you see these effects as well?

Note that figure 7 in the original manuscript is now figure 6.

We thank the reviewer for this observation. Our results suggest that some of these teleconnections are also present in our simulation, e.g. increase of P in central and West Africa, and central Asia (see Fig. 6-b, second column), and higher discharge in the Irr simulation in the Niger and Senegal rivers. But These changes are not easily detected, and we focused on impacts of irrigation on water resources rather than on a comprehensive analysis of teleconnections between irrigation and precipitation in far away regions.

This issue is important, and could need an effort to: to robustly define the areas that are prone to teleconnections between irrigation and precipitation, an assessment of the relationship between irrigation and atmospheric circulation, and the use of additional tools as back-trajectory methods and water tagging.

We propose to add a paragraph in line 422 to include these ideas (with two new references):

Analyzing the atmospheric impact of irrigation in more remote regions is challenging and was not comprehensively addressed in this study. De Vrese et al. (2016a) tackled this issue by carefully studying how wind patterns are modified by irrigation in coupled simulations of historical climate, and showed that irrigation in India leads to increase P in East Africa and Central Asia, owing to water vapor advection and disturbances in the Asian Monsoon. Our results focused on the effects of irrigation on water resources, and therefore the effects on atmospheric circulation were not analyzed in detail, although similar processes may exist in our simulations. A better understanding of the effects of irrigation on precipitation in remote areas must define

what a “remote area” means, then analyze the relationship between irrigation (taking into account the intensity and spatial distribution of irrigation), and changes in atmospheric circulation and moisture transport in a given climate (either historical or future). This analysis can be more robustly complemented by the use of inverse trajectory methods (Wei et al. 2013), to estimate the contribution of irrigation to total precipitation, and by the use of water tagging, to track the origin of water vapor and continental recycling (Risi et al. 2013) and study the changes induced by irrigation.

We also propose to add the reference in the introduction, line 40.

- 8. Fig 3: For consistency if would be nicer if you use gray either as zero change values in your colorbar or to indicate areas without irrigation and just use the continent outline as in the b) panel.

We appreciate this advice. But we think it is clearer to use gray to show the non-significant points according to the statistical test. That way, we can differentiate grid cells with small but significant values and grid cells where the change is not significant.

Using gray to indicate non-irrigated areas could also be confusing, since non-irrigated areas with non-significant changes would be represented in gray, while irrigated areas with non-significant changes would be represented in white. Non-significant areas would be identified by two different colors.

We therefore prefer to leave the use of gray as it is now, in order to be clearer in the information we present on the maps.

Finally, note that Fig 3 and Fig. 1 were composed into a new 4 panels plot, following observation 26 from reviewer 1.

- 9. Fig 4: You seem to have included the wrong maps: ET and R (which are also part of Fig 5) instead of precip and temperature as written in caption and text.

Note that figure 4 in the original manuscript is now figure 3.

We thank the reviewer for this typo. Figure 3 corresponds to precipitation and air temperature. The section correctly refers to P and Tas in section 3.3. We will correct the titles in the new version of the manuscript (reviewer 1 did the same observation, see observation 16 from reviewer 1).

- 10. Fig 6: why a fitted polynomial surface? Looks like a curve to me.

Note that figure 6 in the original manuscript is now figure 5.

The general method is a fitted polynomial surface. In this case, it produces a curve because we have a relationship y = f(x) function, but the function Loess implemented in R can use up to 4 predictors.

We decided to cite the name of the method used to plot the curve.

- All Figs: all difference plots use exactly the same colorbar. While you can do so, of course, please at least mirror it depending on whether it depicts e.g. temperature is shown with colder in blue and warmer in red, which is intuitive, but for e.g. Precip an increase should be blue and not red, and vice versa

We will change color bars according to this advice.

References

- de Vrese, P., S. Hagemann, and M. Claussen (2016), Asian irrigation, African rain: Remote impacts of irrigation, Geophys. Res. Lett. 43, 3737–3745, doi:10.1002/2016GL068146.