Supplementary Information - Irrigation-induced land water depletion aggravated by climate change

Yao et al.

Contents

List of Tables

List of Figures

1 Supplementary Notes

1.1 Supplementary Note 1: Participating ESMs and their irrigation implementation

The Community Earth System Model version 2 (CESM2), is a state-of-art Earth system model, with the Community Atmosphere Model version 6 (CAM6)[1] as the atmosphere model, and the Community Land Model version 5 (CLM5) as the land model[2,3]. In CLM5, irrigated cropland information of 31 different crops, in which 8 crop functional types are used, is provided in the land surface dataset. Over each irrigated cropland column, a soil moisture-based irrigation module is operated individually.

Every day at 6:00 AM local time, the model does a check over all irrigated cropland (i) whether the crop LAI is more than 0, and (ii) whether the actual soil moisture (SM_{actual}) is less than the threshold (SM_{thresh}). If both conditions were satisfied, the model activates the irrigation, and the amount of water used for irrigation (IW) is calculated as the deficit between SM_{actual} and the target soil moisture (SM_{target}). Then, the water is applied as the rainfall under canopy evenly during a period of 4 hours, namely 6:00 AM to 10:00 AM local time.

The difference between CESM2 and CESM2_gw is that in CESM2, water used for irrigation is abstracted from surface water and ocean when surface water is not sufficient, while in CESM2_gw an intercell lateral groundwater interaction and an aquifer pumping process are implemented. In this case, water is abstracted from both surface and groundwater, and groundwater pumping may alter the baseflows[4]. NorESM2 is developed based on CESM2, sharing the same atmosphere (CAM6) and land system model (CLM5), except for some additional developments like new chemistry/aerosol/cloud module (OsloAero6[5]) and improved conservation of energy and angular momentum[6].

The Energy Exascale Earth System Model (E3SMv2) is developed based on the previous version of CESM, with CAM5 and CLM4.5 as the atmosphere and land model[7]. During last few years, plenty of updates have been done to these models, which makes the land model (ELM) and the atmosphere model (EAM) containing some different features with CESM2[8,9]. In ELM, the irrigation is operated during the same period as CLM, 6:00am to 10:00 am local time, and the relative quantity of water from surface and groundwater is based on a fraction collected from water use statistics[10,11].

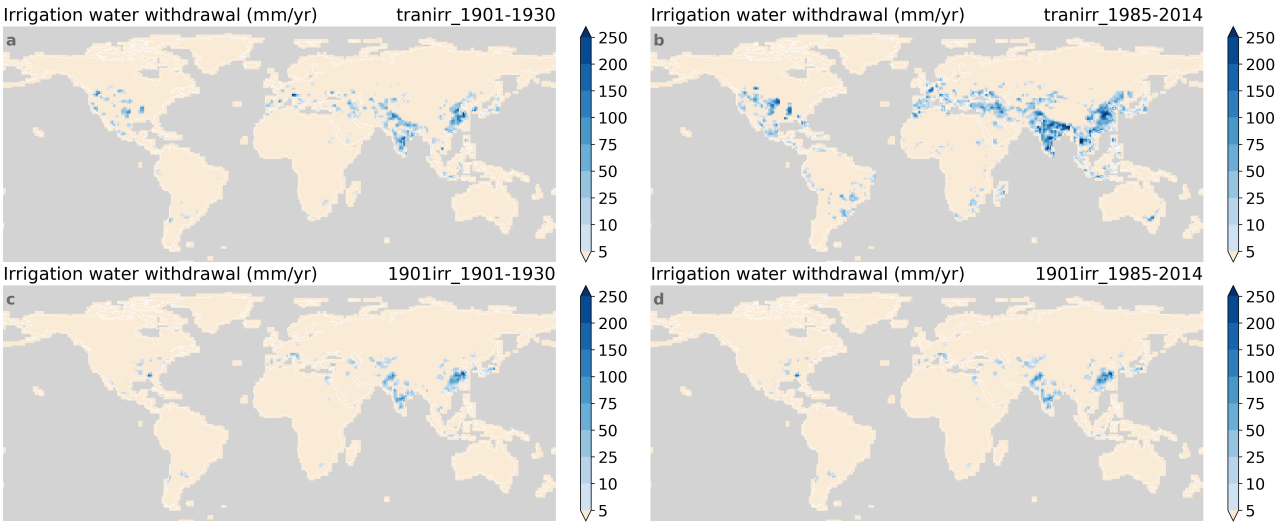
Institut Pierre-Simon Laplace Climate Model version 6 (IPSL-CM6) uses LMDZ6 as the atmosphere model[12] and the Organising Carbon and Hydrology in Dynamic Ecosystems version 2.2 (ORCHIDEE2.2) as the land model[13]. A new irrigation module similar to the one in CESM2 was recently updated in IPSL-CM6[14], with some differences in parameters. At the same time, a maximum irrigation rate is set in the model to prevent unrealistic irrigation application.

In the Centre National de Recherches Météorologiques Climate Model version 6 (CNRM-CM6-1), ARPEGE-Climat is used to simulate atmospheric processes, and SURFEX[15] is used to simulate land surface processes[16]. Irrigation in CNRM-CM6-1 relies on external datasets, which then is applied as additional rainfall in the model. In this study, the irrigation fluxes used are from a global reconstructed hydrological dataset based on simulations[17].

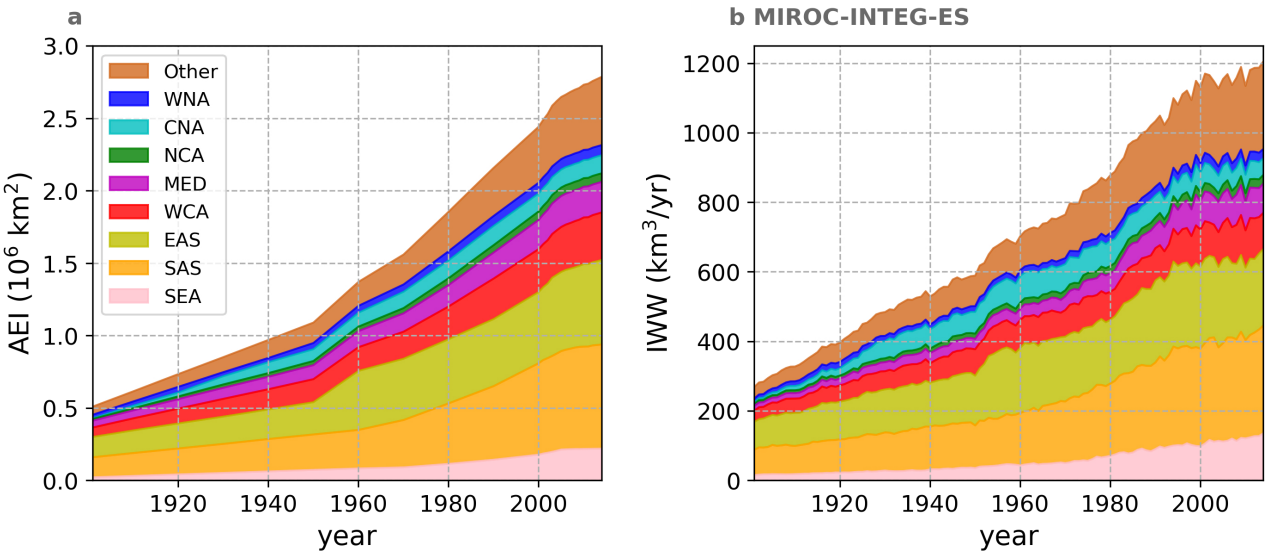
The Model for Interdisciplinary Research on Climate Integrated Earth system model (MIROC-INTEG-ES) couples MIROC[18] and MIROC-INTEG-LAND[19]. MIROC-INTEG-LAND is the land component of the MIROC with new features regarding human water management, crop growth, and land-use change. Irrigation is recently added to the model, which is similar to the implementation in CLM5, except that there is only one crop type.

1.2 Supplementary Note 2: Simulated irrigation water withdrawal from MIROC-INTEG-ES

In this study, outputs from a new ESM, MIROC-INTEG-ES, are used, which were not presented in the first paper of IRRMIP[20]. Here we show the simulated irrigation water withdrawal of MIROC-INTEG-ES.



Supplementary Figure S1 | **a-d** Average annual irrigation water withdrawal simulated by MIROC-INTEG-ES in the period 1901-1930 (**a, c**) and 1985-2014 (**b, d**) of the experiment with (**a, b**) and without irrigation expansion (**c, d**). All values shown are average values of three ensemble members.



Supplementary Figure S2 | **a** Global and regional time series of area equipped for irrigation (AEI) in 1901-2014. The area equipped for irrigation data is from the Land-Use Harmonization phase 2 (LUH2) project[21]. **b** Global and Regional annual irrigation water withdrawal (IWW) simulated by MIROC-INTEG-ES in the period 1901-2014 of the experiment with irrigation expansion. Irrigation water withdrawal shown are average values of three ensemble members. The regions selected are IPCC AR6 reference regions[22].

Supplementary References

Bogenschutz, P., Gettelman, A., Hannay, C., Larson, V., Neale, R., Craig, C. & Chen, C. The path to CAM6: Coupled simulations with CAM5. 4 and CAM5. 5. *Geoscientific Model Development*. **11**, 235-255 (2018)

Lawrence, D., Fisher, R., Koven, C., Oleson, K., Swenson, S., Bonan, G., Collier, N., Ghimire, B., Kampenhout, L., Kennedy, D. & Others The Community Land Model version 5: Description of new features, benchmarking, and impact of forcing uncertainty. *Journal Of Advances In Modeling Earth Systems*. **11**, 4245-4287 (2019)

Danabasoglu, G., Lamarque, J., Bacmeister, J., Bailey, D., DuVivier, A., Edwards, J., Emmons, L., Fasullo, J., Garcia, R., Gettelman, A. & Others The community earth system model version 2 (CESM2). *Journal Of Advances In Modeling Earth Systems*. **12**, e2019MS001916 (2020)

Felfelani, F., Lawrence, D. & Pokhrel, Y. Representing intercell lateral groundwater flow and aquifer pumping in the community land model. *Water Resources Research*. **57**, e2020WR027531 (2021)

Kirkevåg, A., Grini, A., Olivié, D., Seland, Ø., Alterskjær, K., Hummel, M., Karset, I., Lewinschal, A., Liu, X., Makkonen, R. & Others A production-tagged aerosol module for Earth system models, OsloAero5. 3–extensions and updates for CAM5. 3-Oslo. *Geoscientific Model Development*. **11**, 3945-3982 (2018)

Toniazzo, T., Bentsen, M., Craig, C., Eaton, B., Edwards, J., Goldhaber, S., Jablonowski, C. & Lauritzen, P. Enforcing conservation of axial angular momentum in the atmospheric general circulation model CAM6. *Geoscientific Model Development*. **13**, 685-705 (2020)

Golaz, J., Caldwell, P., Van Roekel, L., Petersen, M., Tang, Q., Wolfe, J., Abeshu, G., Anantharaj, V., Asay-Davis, X., Bader, D. & Others The DOE E3SM coupled model version 1: Overview and evaluation at standard resolution. *Journal Of Advances In Modeling Earth Systems*. **11**, 2089-2129 (2019)

Golaz, J., Van Roekel, L., Zheng, X., Roberts, A., Wolfe, J., Lin, W., Bradley, A., Tang, Q., Maltrud, M., Forsyth, R. & Others The DOE E3SM Model Version 2: Overview of the physical model and initial model evaluation. *Journal Of Advances In Modeling Earth Systems*. **14**, e2022MS003156 (2022)

Leung, L., Bader, D., Taylor, M. & McCoy, R. An introduction to the E3SM special collection: Goals, science drivers, development, and analysis. *Journal Of Advances In Modeling Earth Systems*. **12**, e2019MS001821 (2020)

Leng, G., Leung, L. & Huang, M. Significant impacts of irrigation water sources and methods on modeling irrigation effects in the ACME L and Model. *Journal Of Advances In Modeling Earth Systems*. **9**, 1665-1683 (2017)

Zhou, T., Leung, L., Leng, G., Voisin, N., Li, H., Craig, A., Tesfa, T. & Mao, Y. Global irrigation characteristics and effects simulated by fully coupled land surface, river, and water management models in E3SM. *Journal Of Advances In Modeling Earth Systems*. **12**, e2020MS002069 (2020)

Hourdin, F., Rio, C., Grandpeix, J., Madeleine, J., Cheruy, F., Rochetin, N., Jam, A., Musat, I., Idelkadi, A., Fairhead, L. & Others LMDZ6A: The atmospheric component of the IPSL climate model with improved and better tuned physics. *Journal Of Advances In Modeling Earth Systems*. **12**, e2019MS001892 (2020)

Boucher, O., Servonnat, J., Albright, A., Aumont, O., Balkanski, Y., Bastrikov, V., Bekki, S., Bonnet, R., Bony, S., Bopp, L. & Others Presentation and evaluation of the IPSL-CM6A-LR climate model. *Journal Of Advances In Modeling Earth Systems*. **12**, e2019MS002010 (2020)

Arboleda-Obando, P., Ducharne, A., Yin, Z. & Ciais, P. Validation of a new global irrigation scheme in the land surface model ORCHIDEE v2. 2. *Geoscientific Model Development*. **17**, 2141-2164 (2024)

Masson, V., Le Moigne, P., Martin, E., Faroux, S., Alias, A., Alkama, R., Belamari, S., Barbu, A., Boone, A., Bouyssel, F. & Others The SURFEXv7. 2 land and ocean surface platform for coupled or offline simulation of earth surface variables and fluxes. *Geoscientific Model Development*. **6**, 929-960 (2013)

Voldoire, A., Saint-Martin, D., Sénési, S., Decharme, B., Alias, A., Chevallier, M., Colin, J., Guérémy, J., Michou, M., Moine, M. & Others Evaluation of CMIP6 deck experiments with CNRM-CM6-1. *Journal Of Advances In Modeling Earth Systems*. **11**, 2177-2213 (2019)

Wisser, D., Fekete, B., Vörösmarty, C. & Schumann, A. Reconstructing 20th century global hydrography: a contribution to the Global Terrestrial Network-Hydrology (GTN-H). *Hydrology And Earth System Sciences*. **14**, 1-24 (2010)

Tatebe, H., Ogura, T., Nitta, T., Komuro, Y., Ogochi, K., Takemura, T., Sudo, K., Sekiguchi, M., Abe, M., Saito, F. & Others Description and basic evaluation of simulated mean state, internal variability, and climate sensitivity in MIROC6. *Geoscientific Model Development*. **12**, 2727-2765 (2019)

Yokohata, T., Kinoshita, T., Sakurai, G., Pokhrel, Y., Ito, A., Okada, M., Satoh, Y., Kato, E., Nitta, T., Fujimori, S. & Others MIROC-INTEG-LAND version 1: a global biogeochemical land surface model with human water management, crop growth, and land-use change. *Geoscientific Model Development*. **13**, 4713-4747 (2020)

Yao, Y., Ducharne, A., Cook, B., De Hertog, S., Aas, K., Arboleda-Obando, P., Buzan, J., Colin, J., Costantini, M., Decharme, B. & Others Impacts of irrigation expansion on moist-heat stress based on IRRMIP results. *Nature Communications*. **16**, 1045 (2025)

Hurtt, G., Chini, L., Sahajpal, R., Frolking, S., Bodirsky, B., Calvin, K., Doelman, J., Fisk, J., Fujimori, S., Klein Goldewijk, K. & Others Harmonization of global land use change and management for the period 850–2100 (LUH2) for CMIP6. *Geoscientific Model Development*. **13**, 5425-5464 (2020)

Iturbide, M., Gutiérrez, J., Alves, L., Bedia, J., Cerezo-Mota, R., Cimadevilla, E., Cofiño, A., Di Luca, A., Faria, S., Gorodetskaya, I. & Others An update of IPCC climate reference regions for subcontinental analysis of climate model data: definition and aggregated datasets. *Earth System Science Data*. **12**, 2959-2970 (2020)