Bridging the gap: a new module for human water use in the Community Earth System Model version 2.2.1

Geoscientific Model Development

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Contents

1 Reviewer 1

We thank the Reviewer 1 for the constructive feedback to improve the manuscript. Below, we address every comment carefully and explain the corresponding changes in the manuscript.

1.1 Major comments

Reviewer 1 Comment 1

Validation: The paper is well-written and novel in that the module integrates multiple sectors, providing a holistic view of water use and scarcity. The model is validated against historical data and known water scarcity hotspots. However, more validation could be done, for example, using stream gauge data, evapotranspiration data, and satellite land surface temperature datasets. Alternatively, it could be discussed whether such validation will be done in future work and how it would benefit the model.

Response We agree that in the future, the CESM/CLM community would benefit from such analysis. In this case, we considered adding such evaluation, especially using stream gauge data to see if adding sectoral abstractions would improve streamflow in highly managed rivers. But in the end, we decided to delay this till the next version of the model is released because of some documented issues regarding relevant fluxes (e.g. runoff), and since model recalibration in the case of LSMs/ESMs is very challenging. We now explain our reasoning more in the text:

> While more model development may be needed to represent relevant processes related to human-water interactions, another important aspect to consider is model evaluation and calibration for hydrological variables. The variables which are the most important for water availability modelling are precipitation, evapotranspiration, snowpack dynamics, glacial melt, soil moisture, surface runoff, river flow, and groundwater levels and recharge. For example, Vanderkelen et al. (2022) showed that while globally the runoff biases in CLM5 are very small (+0.077 mm/day), large regional biases exist. Aggregated at the level of a catchment, such biases can result in significant river discharge biases, limiting the model usability for water management purposes (Mizukami et al., 2021). Efforts are being made to solve this problem with targeted evaluation studies to understand hydrological parameter uncertainty in CLM5 (Yan et al., 2023). At the same time, more efficient and transparent objective calibration protocols to improve model performance for a given set of targets are being developed (Dagon et al., 2020; Cheng et al., 2023). Unfortunately, running large parameter perturbation ensembles for sensitivity testing and application of objective calibration protocols remains very expensive for LSMs/ESMs, and are usually done only for the release versions of the model. In the future when the model is calibrated, it could be interesting to expand our analysis by assessing the added value of the implementation of human water management on river flow and other relevant hydrological variables. For example, in the case of GHMs, it was found

that considering human related impacts, including land-use-change, reservoir operations and water abstractions results in a general performance increase to represent streamflow and hydrological extremes (Veldkamp et al., 2018).

Reviewer 1 Comment 2

Groundwater Abstractions: The model currently focuses only on river water abstractions, potentially underestimating groundwater use in arid regions. The authors might need to discuss future model development plans or explain why river water abstractions are more important than groundwater use. The study found that non-irrigative sectoral consumption has an insignificant effect on regional climate. Could this be because the study neglects groundwater use?

Response This is an interesting suggestion which is worth investigating. We now added to the text:

> Our findings show that only irrigation has the potential to significantly affect local climates (for scales above a 100 km), while the effect of non-irrigative sectors is negligible. This might not be true at higher resolutions, especially if we would consider groundwater abstractions and land-atmosphere coupling. For example, Keune et al. (2018) study reveals that groundwater abstraction can significantly weaken the continental sink for atmospheric moisture by reducing soil moisture and altering surface energy fluxes. This reduction in soil moisture leads to decreased evapotranspiration, which in turn can diminish the local recycling of moisture back into the atmosphere. The diminished recycling can lead to reduced precipitation in some regions, thereby exacerbating local drought conditions. Furthermore, the weakening of the continental moisture sink due to groundwater depletion can have far-reaching implications for weather patterns and regional climate stability. While we find that the climatic impacts of other sectors like domestic and industrial water use are comparatively small, their inclusion in the model remains important for water scarcity assessment capabilities.

When it comes to groundwater use in our model, we do recognize that this is one of the main limitations, and we discuss this on multiple occasions in the text, inviting further model development and studies on the subject:

> In the latest iteration of the CLM model, an alternative mechanism allows for the extraction of unmet water demand for irrigation from unconfined groundwater in addition to the supply from the rivers (confined aquifers are currently not supported by the model). This approach provides a more realistic depiction; however, a potential limitation is its exclusive reliance on model-calculated renewable groundwater availability. Given the present model's omission of water abstractions from reservoirs and lakes, there's a likelihood of overestimating groundwater dependence in certain areas. Conversely, there is a potential for significant underestimation of groundwater abstractions in arid and semi-arid regions. These regions often experience minimal groundwater recharge (Bierkens and Wada, 2019), and the model currently does not account for fossil ground-

water reserves. Nevertheless, comprehensively accounting for every source of sectoral water withdrawal is crucial for the valid application of CLM5 in water scarcity assessments. Therefore, evaluating the efficacy of this new groundwater abstraction approach, along with its expansion to recently incorporated sectors, emerges as an imperative future effort.

In the context of groundwater abstractions, it is also important to consider how the partitioning between surface vs. groundwater dependence is implemented. The method currently available in CLM for irrigation is what can be called an implicit method, where the amount supplied from groundwater is based on what remains unsatisfied from surface water (rivers). The advantage of following this approach is that it gives better estimates, especially in regions where significant groundwater pumping remain unreported (Wada, 2016). However, the implicit method may neglect physical, technological and socioeconomic limitations in groundwater use that exist in various countries (Wada, 2016). Alternative methods exist, which rely on national and subnational statistics to calculate for each sector the fraction of withdrawal satisfied by source (Döll et al., 2012). Such methods are more likely to capture regional/national patterns of groundwater use, but may be too conservative due to the problem of unreported usage and lack of reliable data for many countries (Döll et al., 2012; Wada, 2016). We think that a mixed approach, where the fractions of surface vs. groundwater usage per sector are given but not fixed, may be of interest. With increased quality and availability of remote sensing data, such as GRACE (Gravity Recovery and Climate Experiment), we can imagine using the fractions of surface vs. groundwater usage as a model calibration parameter to better constrain groundwater abstractions using the observed terrestrial water storage changes (TWS) (Anderson et al., 2015; Wada, 2016).

Reviewer 1 Comment 3

CESM Coupling: In this paper, only offline CLM simulations have been done, but the title mentions "CESM." The authors might need to discuss whether there are future plans to use this new module in coupled CESM simulations and what potential issues might arise when coupling with atmospheric or other models.

Response While we did only offline CLM simulations because it seemed most relevant for this study objectives, the module is operational within the larger CESM modelling framework and no issues are to be expected in fully coupled simulations. To reflect this capability, and to emphasize the currently lagging implementations of human water management in Earth System Modelling community, we went for this title and organization of the manuscr ipt. We now shortly mention this as confirmation in the text:

CLM5 simulations are conducted for the period between 1971 and 2010, with the first 2 years excluded for spin-up (the analysis period thus being from 1973–2010). Two simulations were conducted: a control simulation without sectoral abstractions and no irrigation, referred to as CTRL, and another simulation with complete sectoral water abstractions, including irrigation and the five new sectors, referred to as SectorWater.

> Both simulations used a scientifically validated configuration designed for land-only simulations (IHISTCLM50BgcCrop compset). This configuration captures the historical changes in climate, CO_2-levels, transient land use and land cover change including cropland expansion, uses the Global Soil Wetness Project atmospheric forcing data set (GSWP3v1), models terrestrial biogeochemical cycles, and includes a prognostic crop model (Lawrence et al., 2019). The simulations were run with a horizontal resolution of 0.9x1.25° and a default 30-minute time step. While it would have been possible to run simulations at higher resolutions (e.g. 0.5x0.5°), we opted for the 0.9x1.25° grid because it is one of the two scientifically supported grids for the IHISTCLM50BgcCrop configuration. In future applications, where the focus extends beyond demonstrating the module's capabilities, a higher resolution setup may be preferred to provide more detailed regional insights.
>
> Here we showcase the new module capabilities using land-only simulations. While testing the module in fully coupled CESM simulations is outside the scope of this study, this development is fully compatible with such applications.

Reviewer 1 Comment 4

Introduction Enhancement: The introduction could benefit from an overview of global hydrological models (e.g., WaterGAP, GHM, PCR-GLOBWB), including whether and how human water use has been modeled and what the limitations are compared to land surface models (LSMs). This is particularly important since there are discussions on GHMs in the Results and Discussion sections but not in the Introduction.

Response We now extended the introduction, by mentioning the GHMs capabilities when it comes to human water management. While we cover the relevant literature for all main models, we don't really go into details on individual models because there are many differences between each of them, and we think that this is well covered already in Telteu et al. 2021 (`https://doi.org/10.5194/gmd-14-3843-2021`) and more recently in Müller Schmied et al. 2024 (`https://doi.org/10.5194/egusphere-2024-1303`):

> To further contribute to the effort of improving human-water interactions in LSMs/ESMs, we here present a new sectoral water use module for the Community Earth System Model version 2 (CESM2). Our data-driven module advances the representation of human water use by incorporating a comprehensive account of water abstractions for domestic, livestock, thermoelectric, manufacturing, and mining sectors, thereby complementing the existing irrigation module (Lawrence et al., 2019). Through this development, the CESM2 model and its land component approaches more the capabilities of state of the art Global Hydrological Models, that not only represent essential hydrological processes, but also commonly integrate human-related water management practices, including reservoir operations, water abstractions, pollution, and the exploration of alternative water sources like desalination and wastewater reuse (Hanasaki et al., 2016; Sutanudjaja et al., 2018; Hanasaki et al., 2018; Burek et al., 2020; Droppers et al., 2020; Müller Schmied et al., 2021; Van Vliet et al., 2021; Jones et al., 2023). Additionally, it enables fully coupled applications, allowing for the exploration of

> feedbacks between human water use and land-atmosphere interactions (Keune et al., 2018), which is not achievable with GHMs.

1.2 Minor comments

Reviewer 1 Comment 5

1. Line8: have-> has
2. Line 61 "the" land-use and land-cover change (LULCC)
3. Line 77: Maybe change "is focused" to "focuses"
4. Line 111: have-> has
5. Line 113: Is "missing part" the "shortfall"?
6. Line 140: CFTs
7. Line 163: "The" same approach
8. Line 164: being-> is
9. Line 183: indicating-> meaning?
10. Line 185: will depend-> depends
11. Line 186: little losses-> few losses
12. Line 186: little losses-> few losses
13. Line 190: is -> are
14. Line 299: show?

Response We thank the reviewer for the careful read. We corrected these mistakes, and proofread the article for any other mistakes.

Reviewer 1 Comment 6

Line 105: It might be worth mentioning why CLM on a 0.9x1.25° grid is chosen. Is it for future application in coupled CESM, or to match the input data? Also, please add "°" throughout the manuscript.

Response We now added to the text:

> The simulations were run with a horizontal resolution of 0.9x1.25° and a default 30-minute time step. While it would have been possible to run simulations at higher resolutions (e.g. 0.5x0.5°), we opted for the 0.9x1.25° grid because it is one of the two scientifically supported grids for the IHISTCLM50BgcCrop configuration. In future applications, where the focus extends beyond demonstrating the module's capabilities, a higher resolution setup may be preferred to provide more detailed regional insights.

We also added now "°" where needed.

Reviewer 1 Comment 7

Line 192: What if the land grid consists only cropland and/or urban?

This might probably happen only at very high resolutions. In general, the land cover is highly heterogenous. In our case, since the resolution is of the order of 100 km there will be no grid cell which would have a single land unit.

At the same time, if this would happen and there will be no natural vegetation, this might cause some issues because it wouldn't be possible to correctly process the consumption flux. At the moment, the code for this development is pending for being integrated into the source. We added your comment to the pull request discussion on GitHub, so in case this the development will be integrated, this will be taken care of (likely through the addition of some exception case, e.g., if no natural vegetation, do this). We thank the reviewer for highlighting this potential issue.

Reviewer 1 Comment 8

How does the new module deal with iced rivers/iced soil if there is human water use?

We now added to the text:

> The information about how much water is potentially available for sectoral use is provided by the coupler to the CLM5 model at grid-cell level by calculating the corresponding total river network storage in the MOSART model. This includes only the liquid water from the rivers, excluding iced river water or the water stored directly in the soils, which are not used to meet sectoral demands.

In the routing model, only the liquid water runoff contributes to VOLR. For the ice routing, a different variable is present. Therefore, if in a given grid cell all the river water is frozen, VOLR will be zero, and no abstractions will occur. About iced soils, this also doesn't cause any issues, because we do not take the water from the soil, but only from the liquid water routed in the rivers (VOLR).

Therefore, the module is robust and will continue working as expected for both iced rivers/soils.

Reviewer 1 Comment 9

Be consistent with "grid cell" or "gridcell." Are they referring to different things?

Response Thanks for noticing, we now keep the term consistent — "grid cell".

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