WP 4

Deliverable Report 1

Inclusion of an water quality ensemble simulation in ISIMIP2

November 2019

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1. Introduction

The Inter-Sectoral Impact Model Intercomparison Project (ISIMIP, see https://www.isimip.org/) aims at projecting the impacts of climate change across various sectors including environmental (e.g. water, biodiversity, marine fisheries, etc.) as well as socio-economical subsystems (e.g. health, energy, agro-economy, etc.) by means of concerted impact model applications (Frieler et al. 2017, Warszawski et al. 2014) The major advance of the underlying climate data are:

- Three different representative concentration pathways are included (RCP2.6, RCP6.0, RCP8.5), see IPCC (2014)
- Ensemble projections from four different GCMs (GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR and MIROC5)
- Spatially resolved climate projections on a 0.5° x 0.5° grid
- Bias corrected data at daily time-step

This data provisioning from the ISIMIP project allows scientists from outside of climatology to translate climate projections into impacts on their sectors without being confronted with complex technical challenges like bias-correction, downscaling, etc.. the climate data are provided. An overview over the different climatological scenarios within ISIMIP is provided by Figure 1. Note also that the picontrol scenario contributes a control treatment to the underlying experimental design. The practical work within ISIMIP is organized in sectors, well established sectors are, for example, water, biodiversity, forests or agriculture.

The aim of WATExR was to contribute to ISIMIP 2b by adding selected case studies of lakes or reservoirs by using the ISIMIP-scenarios as meteorological inputs of lake models. Already during the initial phase of our activities within ISIMIP it turned out that our activities will go far beyond this initial aim as we decided to establish an own lake sector group within ISIMIP and use the WATExR-team as a crystallization point for attracting more lake modellers to contribute the ISIMIP lake sector.

This deliverable reports about three major achievements of our activities that altogether document the strong progress that was realized due to our engagement into ISIMIP 2b:

1. Establishing the ISIMIP Lake Sector
2. Detailed individual case studies within the ISIMIP Lake Sector
3. Simulation of the local lakes set

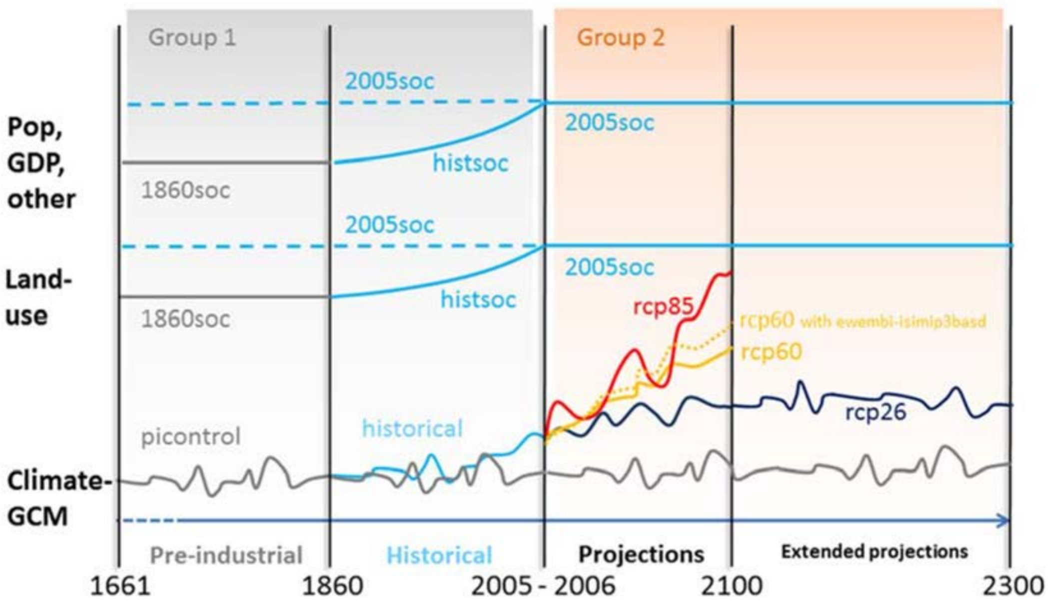

Figure 1: Scenario overview of the ISIMIP 2b climatological data basis (taken from www.isimip.org).

2. Establishing the ISIMIP Lake Sector

Already during initial contacts in 2017 the ISIMIP coordination team brought up the idea of founding an own sector for lakes. By taking up this idea, WATExR became the major driver for the formation of the lake sector within ISIMIP 2b. Don Pierson, WATExR-member form the Swedish group, attended the annual ISIMIP workshop in Potsdam (8-10 Oct 2017). At that workshop, contacts were established to Wim Thiery (VU Brussels), who had been working with the LakeMIP group (Lake Model intercomparison project). We decided to include him as a coordinator in the Lake Sector, as well, and merged lake modelers from LakeMIP and WATExR into the ISIMIP lake sector. A third important group of contributors to the ISIMIP lake sector was recruited from GLEON, an international network of limnologists and lake modelers (Global lakes ecological observatory network, www.gleon.org). At present, the ISIMIP lake is coordinated by a team of four scientists (Rafael Marcé, Don Pierson, Malgorzata Golub, Wim Thiery), three of them being involved in WATExR

By these activities the ISIMIP lake sector became a sizeable group and gained momentum within ISIMIP. A data collection of over 60 lakes (called the "local lakes set") was established providing all required input data for running lake models on these systems. A first workshop of the ISIMIP lake sector was held in November 15-16, 2018 in Magdeburg, in connection with the annual WATExR meeting. At this workshop, more than 20 lake modellers (Figure 2) met and discussed details of the lake sector protocol and details of the simulation procedures and data requirements.

Figure 2: ISIMIP lake sector meeting held in Magdeburg from November 15-16, 2018

The ISIMIP lake sector has three main activities: global lakes simulation, local lakes simulation, and individual case studies. In the global lakes simulation a representative lake system within every cell of the 0.5° x 0.5° ISIMIP grid is simulated by a lake model. This work is ongoing. The local lakes simulation aims at simulating the complete collection of >60 lakes from the ISIMIP lake sector data repository (organiszed by Malgorzata Golub). First results from this initiative are included below in section 4. In comparison to the global lakes simulation, the local lakes set is far more detailed with respect to lake specific information like bathymetry, hydrology, and limnological properties. Results from the local lakes set are therefore well comparable with *in situ* observations, which is not the case for the global lakes simulations where the simulation setting is strongly simplified. Finally, the individual case studies aim at analysing specific features of a given system in detail, e.g. how certain management strategies can be used for climate adaptation as outlined in the next section.

3. Detailed individual case studies within the ISIMIP Lake Sector

Two lakes and two reservoirs from WATExR members were included in the ISIMIP lake sector: Lake Erken, Lake Feeagh, Rappbode Reservoir and Mt Bold Reservoir. We exemplify the WATExR-activities on the two case studies Lake Erken and Rappbode, because both case studies followed different research goals. The major research focus in the Lake Erken study was the proof of concept of the ISIMIP Lake Sector simulation protocol and the sensitivity of model results against the temporal resolution of meteorological input data (daily vs. hourly). The Rappbode study had its focus on climate adaptation and evaluated alternative reservoir operation strategies that can be used to dampen the effects of climate warming on stratification and mixing regimes.

3.1. Lake Erken

Lake Erken, the Swedish case study site within WATExR, served as an initial case study in the ISIMIP lake study. The results of this study have already been published in Ayala et al. (2019) and provided a proof of concept for the intended simulation studies and the underlying simulation protocol within the ISISMIP lake sector. Besides documenting the principal ability of existing lake models to be applicable in multi-decadal simulations, i.e. over time scales far longer than usual in most lake studies, the study also intended to clarify important methodological details with respect to the temporal resolution of the applied meteorological time-series. In detail, the purpose of this study was (1) to test the ability of a one dimensional-hydrodynamic model (GOTM) to simulate the water temperature of Lake Erken (Sweden) using daily vs hourly meteorological forcing data for the period 2006-2016, (2) develop a reliable method to disaggregate daily meteorological data to a hourly synthetic product that can be used to force the GOTM model, (3) convert daily GCM outputs available from the ISIMIP project into hourly meteorological variables, and (4) assess the impacts on the thermal structure of Lake Erken at different levels of global warming when GOTM is driven by hourly and daily model projections. In fulfilling these objectives this study provides the first evaluation of modelling methods and data analysis protocols that will be used by the lake sector within the ISIMIP.

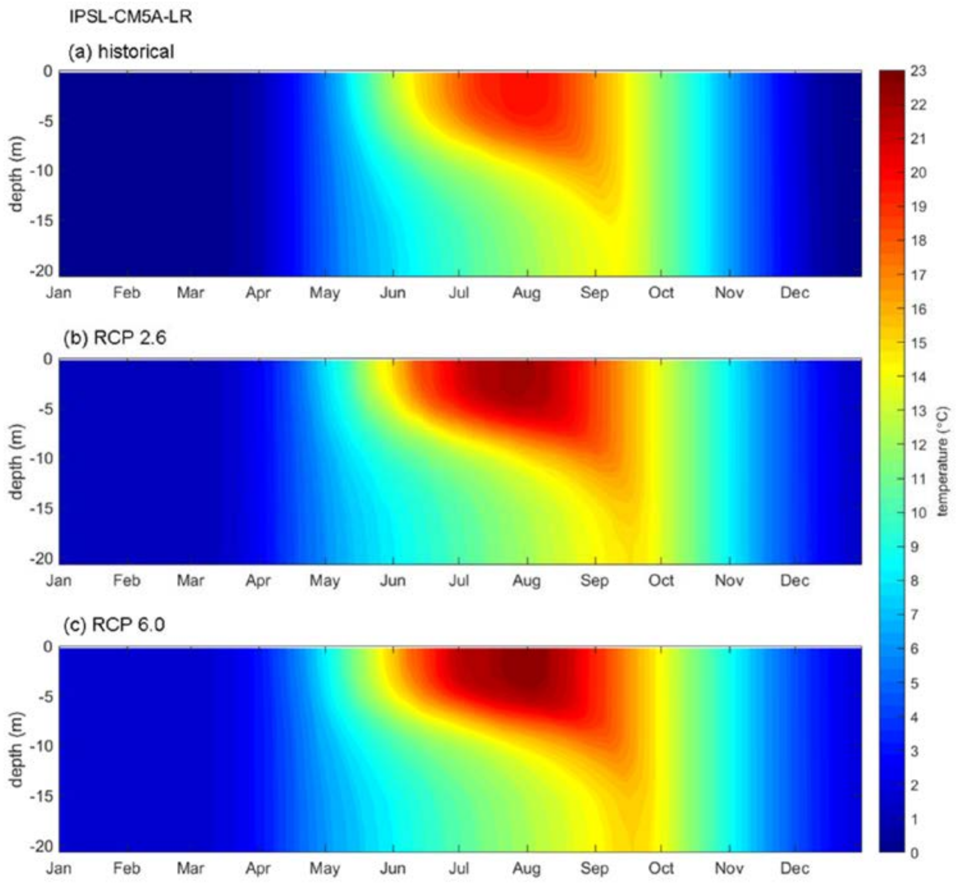

Figure 3: Temperature isopleth diagrams for the (a) historical, (b) RCP 2.6 and (c) RCP 6.0 scenarios showing results from the lake model forced with daily IPSL-CM5A-LR projections. The temperature matrix used to make these plots was created by averaging the simulated daily temperature profiles for every year in each scenario.

The GOTM model was able to simulate all required time series of the ISIMIP data basis and provided a quantitative description of climate change impacts on stratification dynamics in Lake Erken (Figure 3). The simulation of historical time series enabled a thorough calibration of GOTM to Lake Erken (Figure 4) and prediction skills for water temperature in Lake Erken were extremely high as indicated by RMSE values for water temperature around 1°C. The prediction skills of GOTM were almost the same for simulations using different temporal resolution (hourly vs. daily) of meteorological input data (Figure 4). These minor differences between the simulations proved that the applied temporal disaggregation method, i.e. deriving hourly resolved meteorological data from daily averaged data, worked well. This result was an important prerequisite for the ISIMIP lake sector simulation studies because some lake model applications require the usage of hourly input data in order to account for local meteorological conditions. The central data provisioning from ISIMIP, however, is only providing meteorological data at daily resolution.

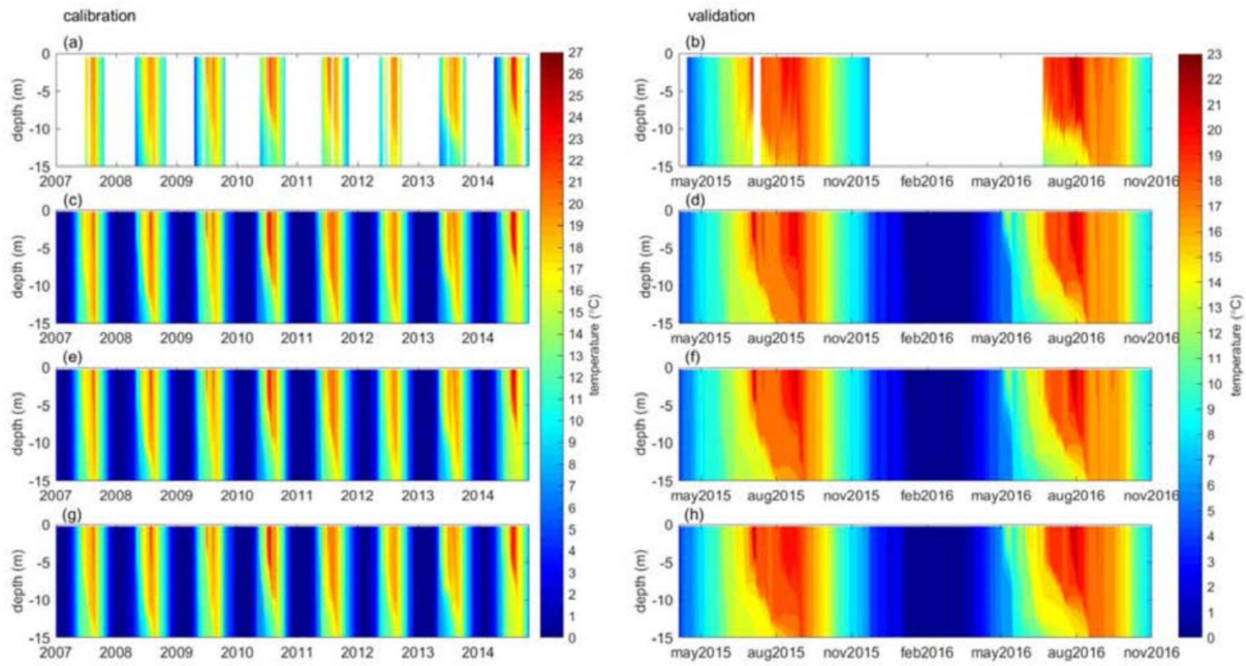

Figure 4: Daily averaged water temperature in Lake Erken for the calibration (a)-(c)-(e)-(g) and validation (b)-(d)-(f)-(h) periods: observations (a)-(b), simulations driven by daily meteorological data (c)-(d), hourly meteorological data (e)-(f) and synthetic hourly meteorological data (g)-(h).

Detailed analysis of simulation outputs of the four GCMs and different climate scenarios provided detailed information on stratification characteristics in Lake Erken as exemplified in (Figure 5).

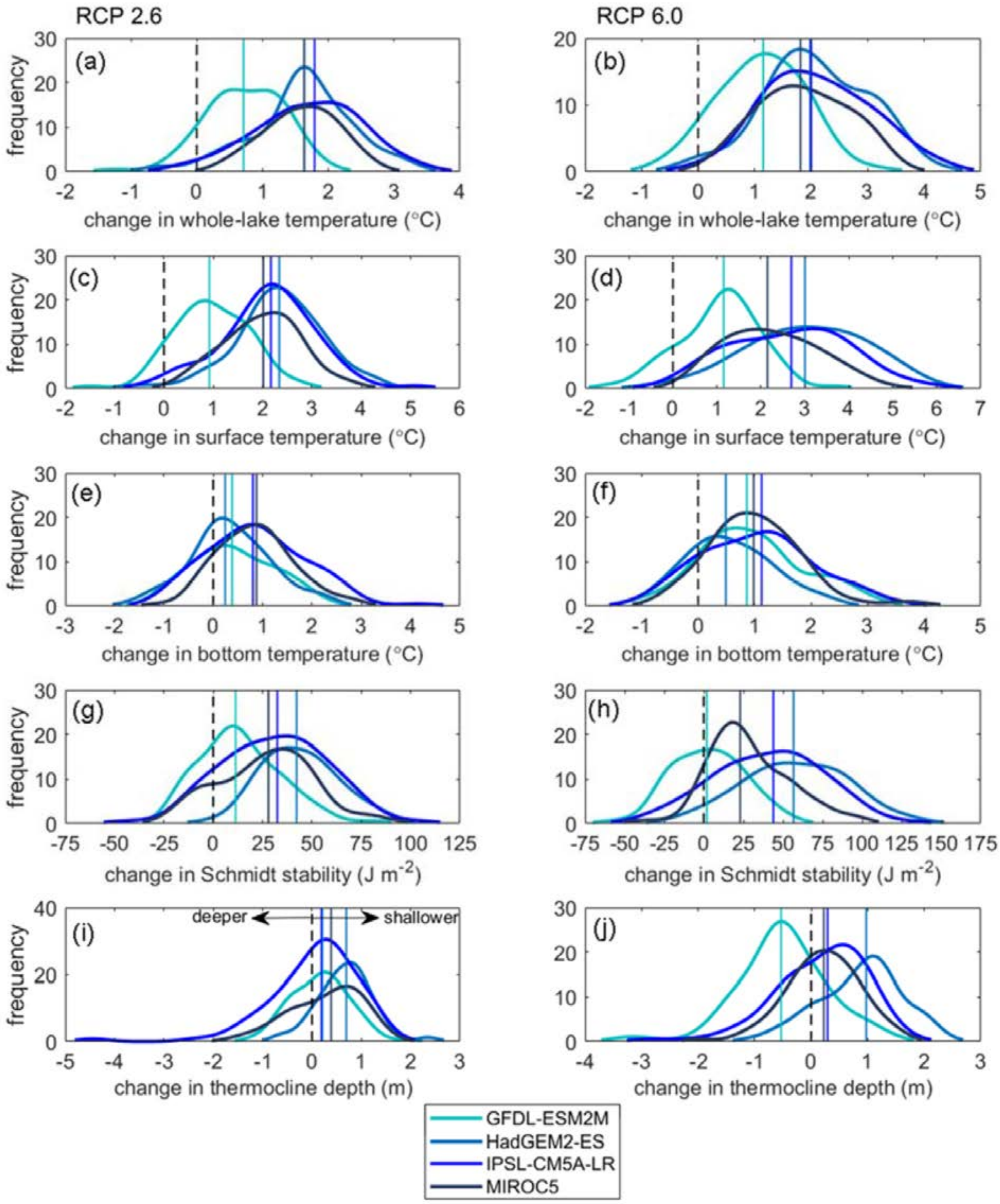

Figure 5: Changes in anomalies calculated from annually averaged (from April to September) (a)-(b) whole-lake temperature, (c)-(d) surface temperature, (e)-(f) bottom temperature, (g)-(h) Schmidt stability, (i)-(j) thermocline depth under (a)-(c)-(e)-(g)-(i) RCP 2.6 and (b)-(d)-(f)-(h)-(j) RCP 6.0, showing results from the lake model forced with daily GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR and MIROC5 projections. All changes are for 2006-2099 relative to 1975-2005. The median (vertical line) is also shown.

3.2. Rappbode Reservoir

The case study work on Rappbode Reservoir, Germany's largest drinking water reservoir, was initiated not only for identifying the impacts of climate warming on the thermal structure of this large reservoir but also for elucidating potential adaptation strategies. According to the ISIMIP-protocols the climate projections from four GCM's and three RCP's until 2100 were used as meteorological inputs to the lake model. Different to the other lake models present within the ISIMIP Lake Sector, a two dimensional lake model (CE-QUAL) was used in this case study because this kind of models can account for the typical elongated, canyon-shaped morphometry of reservoirs. A calibrated CEQUAL model showed an excellent fit to measured temperature profiles (Figure 6) indicating the model setting can be used in forecasting mode.

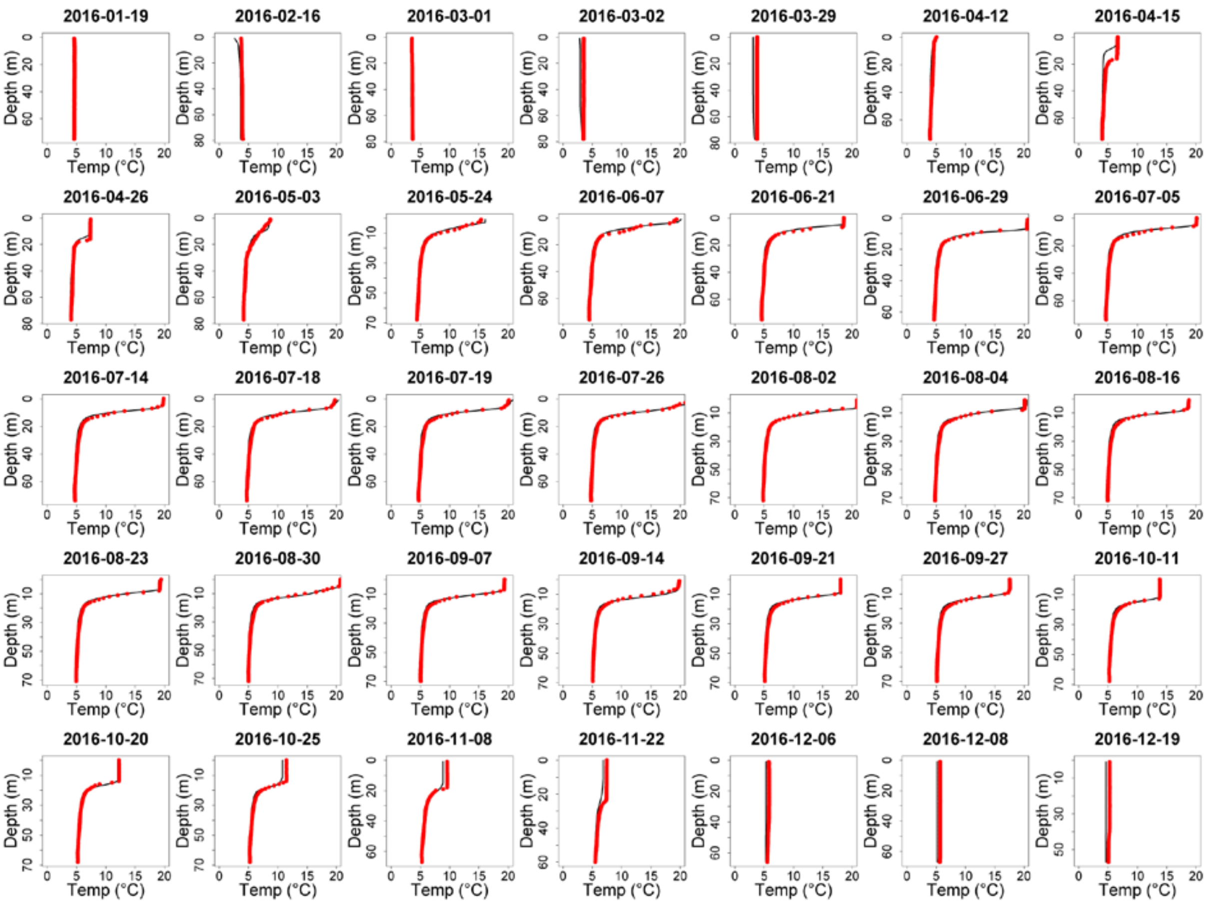

Figure 6: Comparison between simulated (black lines) and observed (red points) water temperature profiles in 2015 and 2016.

A lake model ensemble driven by four GCM outputs show a consistent warming in all RCPs with moderate warming under RCP2.6, extreme warming under RCP8.5 and intermediate warmingunder RCP6.0 (Figure 7). In the worst scenario (RCP8.5) surface water temperatures warm up by approximately 4K (range 2-5K) while in the optimistic scenario (RCP 2.6) warming is kept below 2K. Bottom tempertures, taken at 50m depth, remain at current temperatures throughout the century under RCP2.6 and 6.0. But under the strong warming in RCP8.5, hypolimnion temperatures start to warmup in the second half of the century indicating a transition of Rappbode Reservoir inot a warm-monomictic mixing type

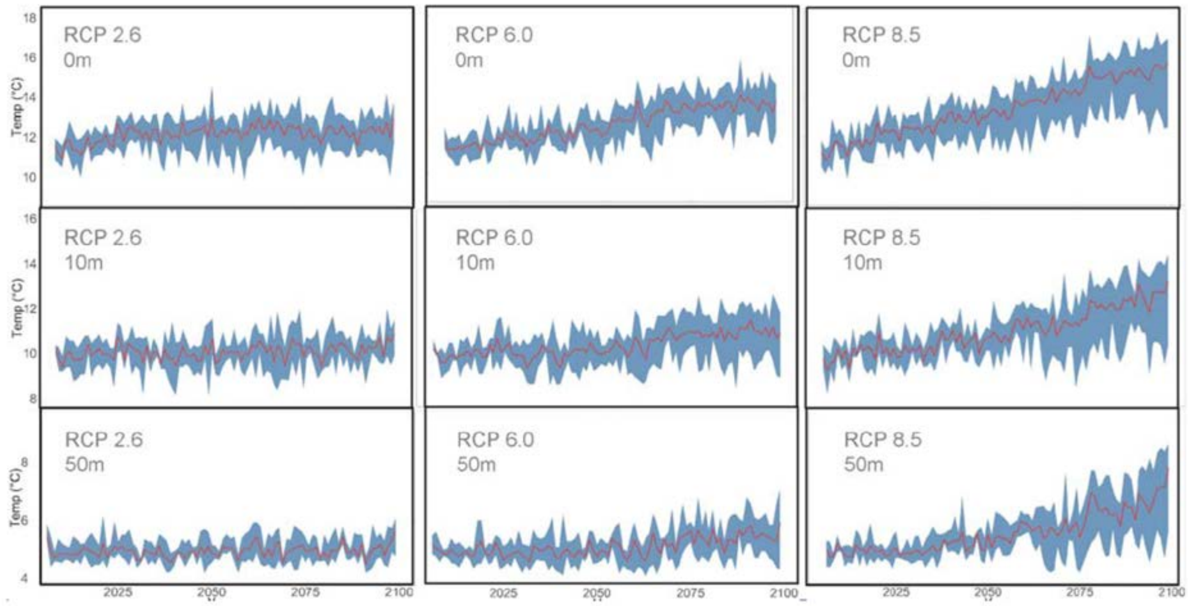

Figure 7: Results of ISIMIP-runs on Rappbode Reservoir using 4 GCMs and three RCP scenarios (left: RCP 2.6, center: RCP 6.0, right: RCP 8.5). The red line denotes the mean over all 4 GCM.driven simulations and the blue area represents the range (i.e. uncertainty band). The upper row shows surface temperatures while the bottom row shows water temperature at 50m depth, i.e. in the deep hypolimnion. The central row shows the water temperature at 10m depth, which is usually the depth of the thermocline during summer.

Alternative reservoir operation strategies were then evaluated with respect to dampen the effects of climate warming and focused on alternative withdrawal strategies. In the current withdrawal, both outlet streams, one towards the drinking water plant and one towards the next downstream reservoir in the cascade, were taken from the deep hypolimion. A shift of water withdrawal from hypolimnetic to epilimnetic withdrawal in fact helps to mitigate the warming effects on the reservoir (Figure 8). Even when only the downstream withdrawal was shifted upwards into the epilimnion and the drinking water withdrawal remains hypolimnetic (because raw water is preferred to be hypolimnetic due to cold temperature and low plankton concentrations), this effect could be achieved (Figure 8).

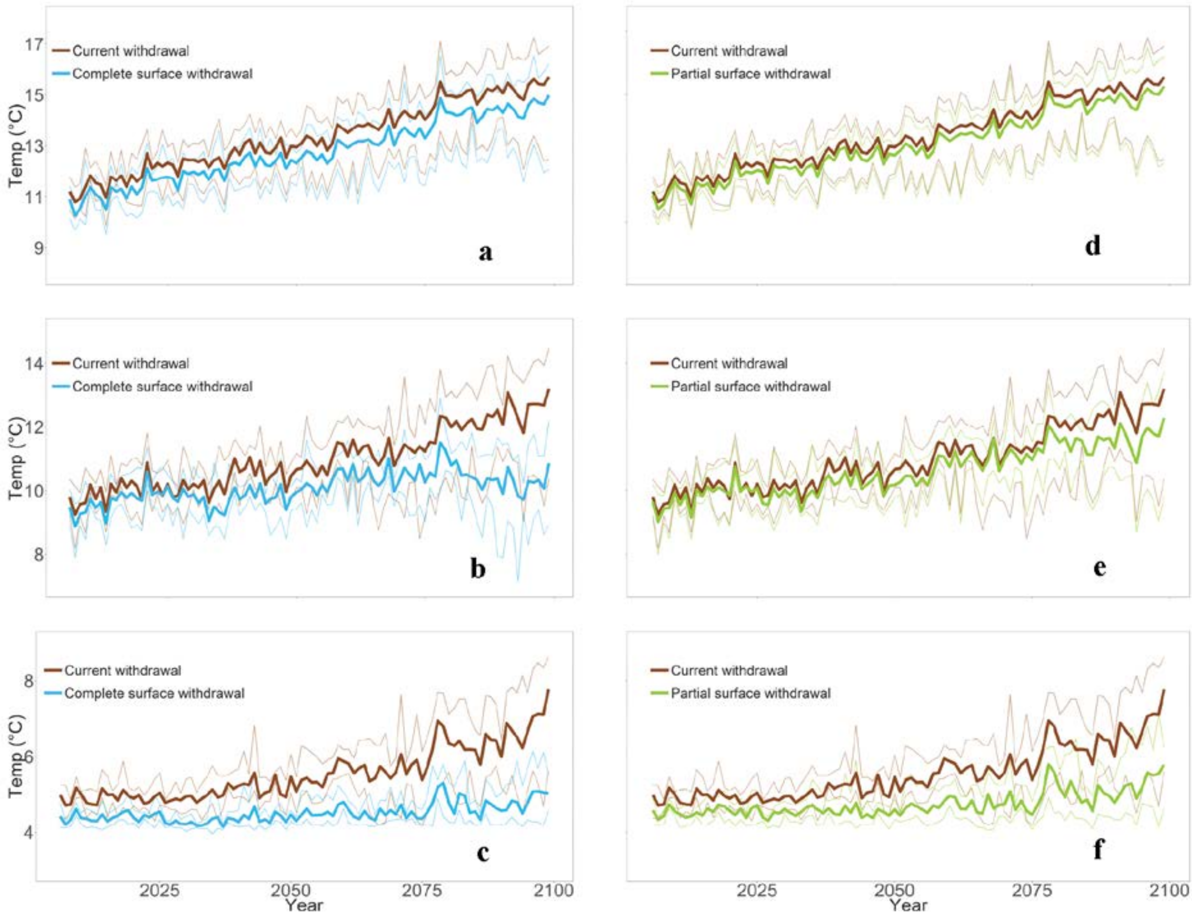

Figure 8: Comparison of the simulated annual mean water temperatures at 1 m (a & d), 10 m (b & e), and 50 m (c & f) depth in the Rappbode Reservoir during 2006-2099 under the RCP 8.5 climate scenario. Red lines depict the current withdrawal management. In the "complete surface withdrawal" all the water is discharged from the top outlet, while in the "partial surface withdrawal" all raw water for drinking water supply is still taken from the bottom waters and only downstream flow is withdrawn from the surface layer. The thick lines show the annual mean values, the thinner lines show annual the minimum and maximum values from the ensemble.

4. Simulation of the local lakes set

The ISISMIP lake sector, under guidance of the WATExR-members Don Pierson, Gosia Golub, and Rafael Marce, has managed to collect detailed data sets for over 60 lakes from Africa, Asia, Australia, Europe, and North Amerika (see list in Table 1). This data comprise all required input data for setting up a hydrodynamic lake model (e.g. bathymetry, light extinction coefficient, inflows/outflows if required) as well as *in situ* observations of water temperature at different depths in order to allow model calibration and/or validation. This provides the basis for multi-lake simulation studies within ISIMIP 2b using different hydrodynamics lake models.

Table 1: List of lake names and corresponding countries of the local lakes set.

No.	Country	Lake name	No.	Country	Lake name
1	US	Lake Allequash	34	US	Lake Mendota
2	PT	Lake Alqueva	35	US	Lake Monona
3	FR	Lake Annecy	36	RU	Lake Mozaisk
4	US	Lake Annie	37	AU	Mt Bold Reservoir
5	AU	Lake Argyle	38	DE	Lake Muggelsee
6	CH	Lake Biel	39	CH	Lake Neuchatel
7	US	Big Muskellung Lake	40	CN	Lake Ngoring
8	US	Black Oak Lake	41	EE	Lake NohipaloMustjarv
9	FR	Lake Bourget	42	EE	Lake NohipaloValgejarv
10	AU	Lake BurleyGriffin	43	US	Lake Okauchee
11	US	Crystal Lake	44	FI	Lake Paajarvi
12	US	Crystal Bog	45	DE	Rappbode Reservoir
13	US	Lake Delavan	46	CZ	Rimov Reservoir
14	CA	Dickie Lake	47	NZ	Lake Rotorua
15	CA	Eagle Lake	48	US	Lake Sammamish
16	SE	Lake Ekoln	49	ES	Sau Reservoir
17	SE	Lake Erken	50	US	Sparkling Lake
18	UK	Esthwaite Water	51	DE	Lake Stechlin
19	US	Falling Creek Reservoir	52	US	Lake Sunapee
20	IE	Lake Feeagh	53	US	Lake Tahoe
21	US	Fish Lake	54	NZ	Lake Tarawera
22	FR	Lake Geneva	55	NZ	Lake Taupo
23	US	Great Pond	56	US	Toolik Lake
24	US	Green Lake	57	US	Trout Lake
25	CA	Harp Lake	58	US	Trout Bog
26	FI	Lake Kilpisjarvi	59	US	Two Sistes Lake
27	IL	Lake Kinneret	60	RU	Lake Vendyurskoe
28	RW	Lake Kivu	61	EE	Lake Vortsjarv
29	CZ	Lake Klicava	62	NZ	Lake Waahi
30	FI	Lake Kuivajarvi	63	US	Lake Washington
31	NO	Lake Langtjern	64	UK	Lake Windermere
32	US	Laramie Lake	65	US	Lake Wingra

According to the ISIMIP2b protocol lake simulations can be conducted for three different representative concentration pathways (RCP2.6, RCP6.0, RCP8.5) by using outputs from four different GCMs (see section 1). At present, different groups work on local lake simulations using the lake models GOTM, GLM and Flake.

The Irish WATExR member Tadhg Moore is advancing the simulation of the local lakes set using the two lake models GLM and GOTM. Local calibration of these two models is already accomplished and enabled the full processing of all local lakes with both lake models, all three RCPs and all four GCMs, which taken together constitute a considerable computational effort. A first summary of the simulation outputs can be seen in Figure 9, where the results for stratification duration from GOTM and GLM are compared for RCP2.6 and RCP6.0. Both lake models show a consistent prolongation of stratification duration, which arises from both, earlier onset of stratification and later offset of stratification. It appeared that GLM reacted more sensitive than GOTM to the external forcing from the meteorological input data from ISIMIP and consistently showed a more intense prolongation of stratification duration. Aside of the variation among the two lake models also the four GCMs show a considerable variation with strong warming intensity in HadGEM2-ES and low warming intensity in GFDL-ESM2M. The two other GCMs (IPSL-CMSA-LR and MICRO5) showed intermediate warming intensities.

In conclusion, the results of the local lakes simulation offer a unique opportunity to attain far-reaching insights into the impact of climate warming on lakes and reservoirs. The outstanding advantage of this simulation set-up is the accurate inclusion of individual lake characteristics that allow to study the interactions between climate warming and further factors like morphometry (i.e. water volume, surface area, average and maximum depth, etc.) or geography (i.e. elevation, climate zones, etc.). The first results further indicate the particular advantage of using multi-model ensembles as simulation outputs differ among different (lake as well as climate) models.

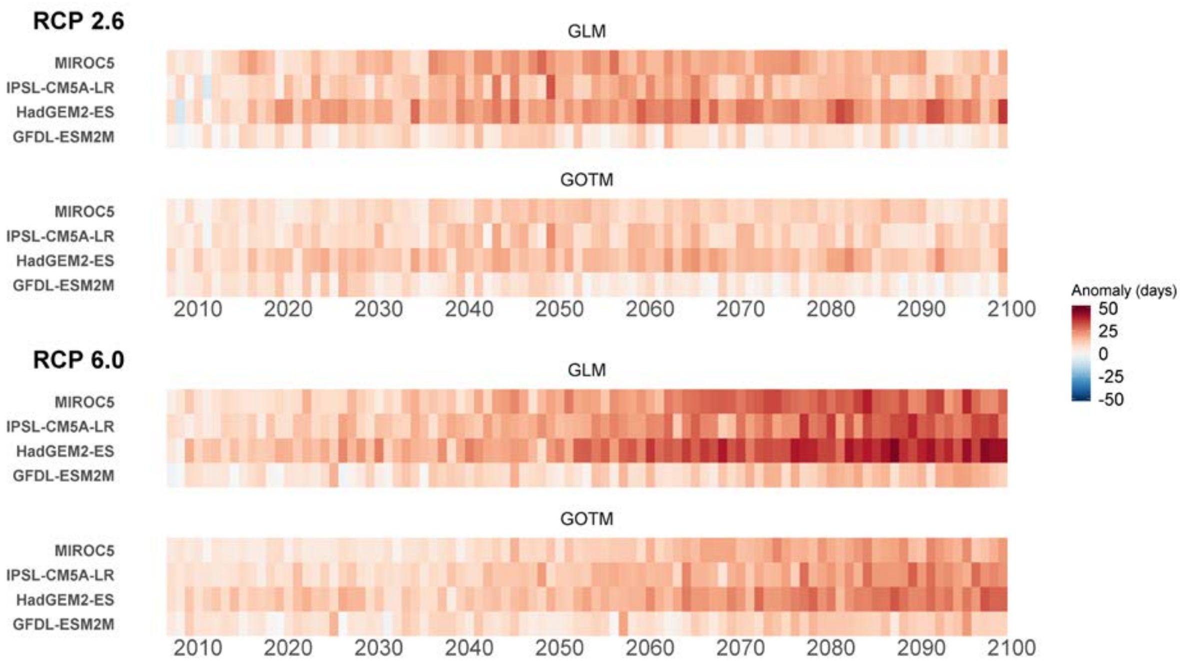

Figure 9: First simulation results from applying the lake models GLM and GOTM to the local lakes set. Results are shown for all 4 GCMs within each lake model simulation and for two RCPs (RCP2.6 and RCP6.0). The color scale shows the change in stratification duration between 2007 and 2100, given as duration anomaly, i.e. positive numbers (red colors) indicate a prolongation of the stratification duration.

5. Further activities

Until the end of WATExR the following activities are planned with respect to the ISIMIP Lake Sector:

- Systematic documentation of the simulation protocol and data evaluation strategies of the ISISMIP Lake Sector by a publication in an international journal (main WATExR responsibility: Malgorzata Golub)
- Advancing local lakes simulations and prepare a publication of results in an internationally reputed scientific journal (main WATExR responsibility: Tadhg Moore)
- Performing a full ISIMIP ensemble of a global lakes simulation on a 0.5° x 0.5° grid resolution using the lake model GOTM (main WATExR responsibility: Malgorzata Golub and Daniel Mercado)

- Publishing the results of the Rappbode Reservoir case study about alternative reservoir operation strategies that can be used to dampen the effects from climate warming (main WATExR responsibility: Karsten Rinke)

- Organizing and co-editing a special issue in an open-access Journal collecting major outcomes form the ISIMIP lake sector (main WATExR responsibility: Don Pierson and Karsten Rinke)

6. References

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