Global heat uptake by inland waters

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Key Points:

- We use a unique combination of lake models, hydrological models, and Earth System models to quantify global heat uptake by inland waters.
- Heat uptake by inland waters over the industrial period amounts up to 2.8x10^{20} J, or 3.1% of the continental heat uptake.
- The thermal energy of the water trapped on land due to dam construction (27x10^{20} J) is ∼9.6 times larger than inland water heat uptake.

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Abstract

Heat uptake is a key variable for understanding the Earth system response to greenhouse gas forcing. Despite the importance of this heat budget, heat uptake by inland waters has so far not been quantified. Here we use a unique combination of global-scale lake models, global hydrological models and Earth system models to quantify global heat uptake by natural lakes, reservoirs and rivers. The total net heat uptake by inland waters amounts to $2.8 \pm 4.3 \times 10^{20}$ J over the period 1900-2020, corresponding to 3.1% of the energy stored on land. The overall uptake is dominated by natural lakes (126%), followed by reservoir warming (2.6%). Rivers contribute negatively (-28.7%) due to a decreasing water volume. The heat of the water volume stored in reservoirs exceeds inland water heat uptake by a factor of $\sim$9.6. Our results underline the importance of inland waters for buffering atmospheric warming caused by enhanced greenhouse gas concentrations.

Plain Language Summary

Human-induced emissions of CO_2 and other greenhouse gases cause energy accumulation in the Earth system. Oceans trap most of this excess energy, thereby largely buffering the warming of the atmosphere. However, the fraction of excess energy stored in lakes, reservoirs and rivers is currently unknown, despite the high heat capacity of water. Here we quantify this human-induced heat storage, and show that it amounts up to 3.1% of the energy stored on land. The increase in heat storage from 1900 to 2020 is dominated by warming of lakes. The thermal heat contained in the water added on land due to dam construction is nearly ten times smaller. Our study overall highlights the importance of inland waters – next to oceans, ice and land – for buffering atmospheric warming, especially on regional scale.

1 Introduction

Increasing greenhouse gas concentrations in the atmosphere cause a net heat uptake in the Earth System. Over 90% of this extra thermal energy is stored in the oceans, causing ocean warming and global sea level rise through thermal expansion (Rhein et al., 2013). The most recent estimates of heat uptake are described in the Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) by the Intergovernmental Panel on Climate Change (IPCC). The report concludes that the ocean has taken up $4.35 \pm 0.8 \times 10^{21}$ J yr^{-1} in the upper-700 m of water and $2.25 \pm 0.64 \times 10^{21}$ J yr^{-1} between the depths of 700-2000 m, respectively (averages of 1998-2017 compared to 1971-1990), and attributes this increase to anthropogenic forcings (Bindoff et al., 2019). The remaining excess heat is taken up by melting sea and land ice, by specific heating and water evaporation in the atmosphere and by warming of the continents (Trenberth, 2009).

Despite the key role of heat uptake in driving Earth system response to greenhouse gas forcing, currently little is known about global-scale heat uptake by inland waters. Inland waters include natural lakes, man-made reservoirs, rivers and wetlands, with lakes covering 1.8% of the global land area (Messager et al., 2016) and rivers 0.58% of the global non-glaciated land area (Allen & Pavelsky, 2018). However, the abundance and total area covered by inland waters (natural and/or artificial) is continuously changing (Pekel et al., 2016). For example, reservoir expansion following dam construction experienced a marked acceleration during the 1960s and 1970s, but levelled off after the 1980s, now covering 0.2% of the global land area (Lehner et al., 2011). Despite occupying <3% of the global land surface, inland waters play an important role in the climate system (e.g., Subin et al., 2012; Docquier et al., 2016; Vanderkelen et al., 2018a; Choulga et al., 2019) and are sentinels of climate change (e.g., Adrian et al., 2009; Schewe et al., 2014; O'Reilly et al., 2015; Woolway & Merchant, 2019). Compared to other types of land surfaces, water (i) has a higher specific heat capacity, (ii) typically has a lower albedo, (iii) allows for radiation penetration below the surface, and (iv) seasonally mixes warmer surface masses to deeper layers. Consequently, inland waters are generally regarded as heat reservoirs compared to adjacent land. In addition, lake surface temperatures have been observed to have increased rapidly in recent decades, in some locations even faster than ambient air temperatures (O'Reilly et al., 2015; Schneider & Hook, 2010). This is not only the result of an increased lake heat uptake due to increasing air temperatures, but can be attributed to an interplay between changes in ice cover duration and stratification, solar radiation and lake characteristics (Austin & Allen, 2011; Shatwell et al., 2019). Moreover, the warming rates are spatially very heterogeneous (O'Reilly et al., 2015).

To quantify the heat uptake by inland waters, an estimation of both the water volumes and evolution of water temperature profiles is necessary. Water temperature observations of lakes, reservoirs, rivers and wetlands are however sparse and spatially limited. So far, studies of energy fluxes and heat storage have been limited to individual lakes (Heiskanen et al., 2015; Nordbo et al., 2011; Strachan et al., 2016). To overcome this, global models are developed for estimating water temperatures on local, regional and global scales.

In this study, we develop the first estimate of the global-scale heat uptake by inland waters over the period 1900-2020. To this end, we combine global lake and hydrological simulations from the Inter-Sectoral Model Intercomparison Project (ISIMIP) with a river temperature parameterisation and spatially-explicit data sets of lake abundance, reservoir area expansion and lake depth. This enables us to quantify the heat uptake by natural lakes, reservoirs and rivers. We do not consider the contribution of wetlands and floodplains, given their highly disperse spatial and temporal character and limited data availability. Next, we also quantify the redistribution of heat from ocean to land due to increased inland water storage as a result of the construction of reservoirs. By providing a first estimate of inland water heat uptake, this study provides new advances in the quantification of the global heat budget.

2 Data and Methods

2.1 Lake and reservoir heat content

The ISIMIP initiative is a recent effort to provide consistent climate impact simulations across different sectors which allows for the integration and comparison of global hydrological and lake model simulations (Frieler et al., 2017). For lake water temperatures, we used the global ISIMIP2b simulations from two one-dimensional lake models: the Community Land Model 4.5 (CLM4.5, Oleson et al., 2013) including the Lake, Ice, Snow and Sediment Simulator (LISSS, Subin et al., 2012), and SIMSTRAT-UoG, a physically sophisticated k-ϵ model (Goudsmit et al., 2002, see table **??** for an overview). Following the ISIMIP2b protocol, simulations are performed at a 0.5° by 0.5° spatial resolution using bias-adjusted atmospheric forcing data from four Earth System Models (ESMs: GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR and MIROC5). SIMSTRAT-UoG does not represent human-influences, while CLM4.5 assumes that land use and human influences (irrigation extent, land use, population and GDP) are constant at the 2005 level. We use ESM simulations for the historical period with historical climate and greenhouse gas conditions, ranging from 1900 to 2005 and Representative Concentration Pathway 6.0 simulations for the period 2006-2020 (Frieler et al., 2017). The lake models simulate a representative lake with a constant depth in each grid cell, of which the extent is given by the lake area fraction of that grid cell. Using the four climate forcings for each lake model results in a total of 8 simulations of spatially-explicit global-scale lake temperatures.

Global lake area distribution is given by the HydroLAKES dataset (Messager et al., 2016), containing 1.42 million individual polygons of natural lakes. This data set is linked to the Global Reservoir and Dam data set v. 1.3 (GRanD, Lehner et al., 2011) consisting of 7250 reservoir polygons (Lehner et al., 2011). We convert both HydroLAKES and GRanD polygons to lake area fraction on a 0.5° by 0.5° grid to match the ISIMIP resolution. Reservoir construction is provided by GRanD, and changes in reservoir area are accounted for by creating annual lake area fraction maps, in which reservoir areas are added in their year of construction. Natural lakes which become controlled by a dam are categorized as 'natural lakes' based on information from GRanD. As GRanD provides construction years up to 2017, we assume a constant reservoir area from 2017 to 2020. Lake and reservoir depths are obtained from the Global Lake Database v.3 (GLDB, Kourzeneva, 2010; Choulga et al., 2014, 2019), providing estimates of mean lake depth for every land grid cell. This data is remapped from its original 30" ($\sim$ 1 km grid) to the 0.5° by 0.5° resolution using bi-linear interpolation.

Annual lake heat content Q_{lake} $[J]$, per grid cell is calculated as

$$Q_{lake} = c_{liq}\, A_{lake}\;\; \rho_{liq} \sum_{n=1}^{n=nlayers} T_n\, d_n$$

with c_{liq} $(J\ kg^{-1}K^{-1})$ the specific heat capacity of liquid water (here taken constant at 4188 $J\ kg^{-1}K^{-1}$), A_{lake} (m^2) the lake area, ρ_{liq} $(kg\ m^{-3})$ the density of liquid water (here taken at 1000 $kg\ m^{-3}$), and the sum of annual mean temperatures T_n (K) over all lake layers, where d_n (m) is the layer thickness. As the layering of each lake model is different (table **??**), lake heat per layer is rescaled by calculating the weights of the model layer depths relative to the models' grid cell lake depth. These weights are then applied on the grid cell lake depth from GLDB. This allows for a consistent volume computation. To also ensure a consistent lake coverage across the different lake models, the water temperatures are spatially interpolated to the lake coverage map derived from HydroLAKES using nearest neighbour remapping. The Caspian Sea is included in the analysis, as this inland sea is often not accounted for in ocean heat content estimates (e.g. Cheng et al., 2017). We define the spatial extent of natural lakes by the lake extent in 1900. Heat content anomalies, hereafter denoted as heat uptake, are computed relative to the average lake heat content in 1900-1929, hereafter referred to as pre-industrial period) and represent changes in lake and reservoir temperatures. Changes in the amount of water stored on land by the construction of reservoirs are also taken into account, thereby assuming the water temperature of the constructed reservoir is given by the grid cell lake temperature. We do not consider inter-annual variations in lake and reservoir volumes. Total annual global heat uptake is calculated by summing all grid cells.

2.2 River heat content

River water mass is retrieved from the grid-scale monthly river storage $(kg\, m^{-2})$ given by the two Global Hydrological Models from the ISIMIP 2b global water sector providing this variable: the Minimal Advanced Treatments of Surface Interaction and Runoff (MATSIRO, N. Y. Pokhrel et al., 2015) and WaterGAP2 (Müller Schmied et al., 2016, see table **??**), by multiplying with the grid cell area and taking the annual mean. Annual grid cell river water temperatures are estimated using the global non-linear regression model of Punzet et al. (2012) with the global coefficients and an efficiency fit of 0.87. This regression prescribes river temperatures based on monthly gridded air temperatures, which are given by the four different ESM forcings (GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR and MIROC5). River heat content, Q_{river} $[J]$, is calculated as

$$Q_{river} = c_{liq}\, m_{river}\, T_{river}$$

with m_{river} (kg) the water storage in the grid cell rivers and T_{river} (K) the river temperature. As for lakes, river heat uptake is defined as the anomaly compared to the average river heat content in the reference period 1900-1929 and consists of the change in temperature and the change in water stored in the rivers. This approach uses a total of 8 ISIMIP simulations to calculate river heat uptake. The set-up of the models, dictated by the ISIMIP protocol, allows the direct comparison of the resulting lake, reservoir and river heat uptake.

3 Inland water heat uptake

Natural lakes have taken up 2.9 ± 2.0x10^{20} J (± one standard deviation of the 8 simulations used) averaged over the period 2011-2020, relative to pre-industrial times (1900-1929; Table 1) due to an increase of lake water temperatures integrated over the lake column. Lake heat uptake increased continuously from the 1980s onwards, following the trend of increasing atmospheric temperatures (Figs. 1a, **??**). In the last 30 years, the mean trend in global lake heat uptake of the model simulations is 8.1x10^{18} J year^{-1}.

The construction of dams and the resulting artificial reservoirs have increased global lake volume by 3.2% (Messager et al., 2016, Fig. **??**b). The steep increase in reservoir heat uptake from the 1980s onwards stems from the combination of accelerated reservoir construction, making more water on land available for warming, and regional emergence of warming signals due to climate change during this period (Fig. 1b). In total, reservoirs have taken up 5.9 ± 2.7x10^{18}J on average in the period 2011-2020, compared to pre-industrial times (Table 1), which is about 2% of the total heat uptake by inland waters.

Global heat uptake by rivers encompasses large uncertainties and no detectable trend. In the late 1960s the ensemble mean heat uptake shifts to overall negative heat uptake values compared to pre-industrial values (Fig 1c). Global-scale stream temperatures show a clear positive trend, reflecting the increase in air temperatures (Fig. **??**, a-d). However, global-scale river storage is marked by large inter-annual variability for both global hydrological models (Fig. **??**, e-l), thereby effectively masking the positive temperature trend in the resulting river heat uptake. River storage evolution is dictated mainly by the ESM forcing, as differences in river storage between the four different ESM forcings are more pronounced than between the two global hydrological models (Fig. **??**). Both GFDL-ESM2M-driven river storage simulations have higher variability compared to the other simulations. Altogether, with a heat uptake of −0.15 ± 2.3x10^{20} J averaged for 2011 to 2020, compared to pre-industrial times, rivers contribute negatively to total heat uptake by inland waters, but their contribution is accompanied by a large variability, as well as uncertainty originating from the spread across climate forcings.

The total heat uptake in inland waters is thus dominated by the heat uptake of natural lakes, accounting for 126% of the average total net increase by 2020, while reservoir heating has taken up 2.6% and rivers contributed negatively with -28.7% in 2020, but the latter with a large uncertainty (Fig. 3a).

Most lake heat uptake is concentrated in the major lake regions of the world. The Laurentian Great Lakes, including Lakes Superior, Michigan, Huron, Erie and Ontario in central North America make up 12.40% of global lake volume (Messager et al., 2016). These lakes all demonstrate a steady increase in heat uptake from the 1980s onwards (Fig. 2b), resulting in a total uptake of 1.45 ± 0.74x10^{19} J (5.2% of global inland water heat uptake) compared to pre-industrial times with a trend of 4.2x10^{17} J year^{-1} over the last 30 years. The spatial pattern of heat uptake is mainly dictated by the bathymetry and resulting lake volume: the deeper Lake Michigan and Lake Superior have taken up more heat compared to the other lakes, while the much shallower Lake Erie has the lowest heat uptake estimates (Fig. 2a). The warming of these seasonally-ice covered lakes, and their impact on the surrounding weather and climate has been extensively studied (e.g. Zhong et al., 2019; Gronewold et al., 2015; Austin & Allen, 2011) and recently, O'Reilly et al.

(2015) reported that their surface is warming faster than most other major lakes worldwide.

The African Great Lakes region in East Africa, consisting of Lake Victoria, Tanganyika, Kivu, Kyoga, Albert and Edward (12.38% of global lake volume Messager et al. (2016)), are known to affect the local weather and climate conditions (Thiery et al., 2014, 2015, 2016, 2017; Vanderkelen et al., 2018b; Van de Walle et al., 2019) and their water temperatures are observed to be warming (Katsev et al., 2014; O'Reilly et al., 2003; Tierney et al., 2010). We find that the heat uptake is largest in Tanganyika, the lake with the highest volume in the region (Fig. 2c). Overall, the African Great Lakes show an increase in heat over the whole study period, of the same order of magnitude as the Laurentian Great Lakes (Fig. 2d, a total heat uptake of $4.23 \pm 1.48\text{x}10^{19}$ J, 15.1% of global inland water heat uptake). The Great European lakes, including Lake Ladoga and Onega, the largest lakes in Europe, show a smaller increase compared to other major lake regions, corresponding to the smaller volume of the lakes, but the lake heat content shows a sudden increase from the 1990s (Fig. 2e,f; total heat uptake of $2.20 \pm 0.91\text{x}10^{18}$ J, 0.79% of global inland water heat uptake). The Amazon, world's highest discharge river, depicts no temporal trend in river heat uptake, but the uncertainty is large, mainly owing to the diverging river mass estimations (Fig. 2h; heat uptake of $0.18 \pm 2.50\text{x}10^{20}$ J, 6.4% of global inland water heat uptake). Heat uptake increases towards the river mouth, as the water volume increases (Fig. 2g). To summarize, the global picture of positive lake heat uptake is confirmed at the regional scale by all model combinations. At the river basin scale, however, the uncertainties of river heat uptake are large and there is no agreed signal, in line with global estimates.

4 Heat redistribution due to reservoir area expansion

In the second half of the 20^{th} century, reservoir capacity strongly increased, raising the water volume stored on land and offsetting sea level rise by 30 mm (Chao et al., 2008; Lehner et al., 2011, Fig. **??**b). This extra water stored on land does not only increase the potential for taking up excess atmospheric heat (Sect. 2), but also carries energy in itself. By constructing reservoirs, humans are thus not only redistributing mass from the oceans to the land, but also the thermal energy carried within this water. This heat redistribution by reservoir expansion is growing over time, following the increasing number of reservoirs constructed (Fig. 3b). During the historical period, $27 \pm 2.1\text{x}10^{20}$ J of heat was redistributed from ocean to land, exceeding inland water heat uptake from climate change by a factor of $\sim$9.6.

5 Discussion and conclusions

Large lakes take up most heat, as they have the largest volume to warm up. The increase in lake heat content complies with recent observations of increasing lake surface temperatures and reported changes in mixing regimes (O'Reilly et al., 2015; Woolway & Merchant, 2019) and is robust for different lake regions. For lakes that are seasonally ice-covered, lake heat uptake mainly occurs during the open water season (Mishra et al., 2011). Therefore, an earlier ice break up and later ice formation could possibly explain the sudden rise in lake heat in the Great European Lakes. The difference between the two lake models (Fig. **??**) could arise from differences in the structure of the models, like lake layers and internal physics.

River heat uptake is negative in most simulations during the second half of the 20^{th} century. This seemingly contradictory result stems from a decrease in river storage, which could be attributed to less precipitation or the construction of reservoirs, lowering water flow in rivers or to drying of rivers by increased land evaporation due to global warming or increased water use. These changes in river storage should, however, be taken with care, as the uncertainties are very large. In addition, no conclusions can be made about global trends in observed streamflow, because changes in streamflow and the hydrological conditions causing it, are characterized by complex spatial patterns (Gudmundsson et al., 2019; Müller Schmied et al., 2016).

The quantification of heat uptake facilitates comparison of the effects of climate change on different components of the climate system. Globally, inland waters have taken up ~0.08% of heat compared to oceans. The continental heat uptake occurs through a heat flux into the solid surface of the lithosphere and has been estimated between 9.1 and 10.4x10^{21} J (Beltrami, 2002; Huang, 2006) for the period 1950-2000 based on borehole temperature observations. Estimates based on the Coupled Model Intercomparison Project Phase 5 (CMIP5) are consistently lower (1 ± 5x10^{21}J), mainly due to the limited depth of the bottom boundary of the land surface schemes of the Earth system models (Cuesta-Valero et al., 2016). Relative to the geophysical estimate reported by Beltrami (2002), the share of inland waters is ~3.1%, while inland waters cover about ~2.58% of the global continental area. This comparison has to be taken with care, as the borehole-based estimations of heat uptake are only quantified until 2000 and surface air temperatures have risen at record rates since then (Rhein et al., 2013).

The redistribution of heat by reservoir construction, is equivalent to ~38% of the land mass heat uptake. It increases the potential of storing extra heat on land by warming the water of the created reservoirs. In particular, this might cause local impacts such as masking surface temperature increase over the historical period by their buffering capacity. In addition, the extra continental water storage by reservoir expansion could have a dampening effect on local temperature extremes and could affect river temperatures downstream. Furthermore, reservoirs could cause alterations in extreme precipitation (Degu et al., 2011), but the physical mechanisms behind this are not yet well understood. It is therefore important to account for reservoir expansion and resulting heat redistribution in Earth System Models, to increase our understanding of how reservoirs affect the climate (Y. N. Pokhrel et al., 2016; Nazemi & Wheater, 2015; Wada et al., 2017). Capturing heat redistribution by reservoir expansion could also increase the quality of climate change projections on regional to global scales.

Furthermore, lakes and rivers do not only have the potential for storing heat coming from warming by excess greenhouse gases, but they also play a role in engineered heat storage. Locally, lakes may serve as a source or sink for anthropogenic heat, for instance as thermal heat pumps or cooling systems (Fink et al., 2014), while rivers have been used by industries for their cooling water discharge potential (van Vliet et al., 2016).

There are several opportunities to refine the heat uptake calculations presented in this study. First, the volume calculation does not account for lake hypsometry. By using average lake depths to multiply with lake area, the resulting total lake volumes are reasonable, as most lakes have a linear hypsometric relationship (Busker et al., 2019; Messager et al., 2016; Choulga et al., 2014). This rectangular hypsometry assumption results in relatively higher weights for the deeper lake layers, which makes our heat uptake estimates more conservative. Second, apart from reservoir construction, the heat calculation does not account for variations in lake and reservoir volumes, while changes in river storage are included. This could have important effects, especially for lakes with a high inter-annual variability. Recent advancements in remote sensing allow mapping global surface water and its temporal variations (e.g. the Global Surface Water data set; Pekel et al., 2016), but these assessments are time-limited to the satellite era. Third, as reservoirs are modelled in the same way as natural lakes, the deep withdrawals related to reservoir operation are not considered. Deep withdrawals imply higher temperatures than simulated in natural lakes (Moreno-Ostos et al., 2008), leading to a potential underestimation of the heat uptake by reservoirs. Furthermore, variations in heat capacity are not considered in our analysis, which could lead to a lower estimate of heat uptake as the specific capacity of ice is lower than that of water (2117 $J\ kg^{-1}K^{-1}$ compared to 4188 $J\ kg^{-1}K^{-1}$, respectively). In addition, the formation and melting of lake ice also re-

Table 1. Total heat uptake and trend for the different inland water components. Heat uptake is calculated as the average uptake during 2011-2020 relative to the reference period 1900-1929. Uncertainties are given by the ensemble standard deviation of the used simulations. Trends are calculated using a linear regression over the 30-year period 1991-2020.

	Heat uptake	**Trend (1991-2020)**
Natural lakes	2.9 $\pm$ 2.0x10^{20} J	9.4x10^{18} J yr^{-1}
Reservoirs	0.059 $\pm$ 0.027x10^{20} J	0.19x10^{18} J yr^{-1}
Rivers	-0.15 $\pm$ 2.3x10^{20} J	2.7x10^{18} J yr^{-1}
Uptake by climate change	2.8 $\pm$ 4.3x10^{20}J	12.4x10^{18} J yr^{-1}
Redistribution by reservoir expansion	27 $\pm$ 2.1x10^{20}J	11.0x10^{18} J yr^{-1}

lease and require heat, respectively. Phase changes are not considered explicitly, but they are included in the physics of the lake models and therefore in the simulated temperature profiles. Next, variations in salinity of inland waters are not included. Salty water has a lower specific heat capacity than freshwater (3986 $J\ kg^{-1}K^{-1}$ for a salinity of sea water (3.5%) compared to 4188 $J\ kg^{-1}K^{-1}$, (Brewer & Peltzer, 2019)), but applying this difference falls within the uncertainty range. Furthermore, by using global lake and hydrological models driven by ESM forcings, an extra uncertainty related to climate sensitivity is added to the calculations. Despite these limitations, this study is the first step towards estimating heat uptake by inland waters.

In this study, we show that inland water heat uptake during the historical period is substantial compared to continental heat uptake, calling for inclusion of this effect in global-scale assessments of heat uptake within the Earth system. Furthermore, we highlight that by constructing reservoirs, humans have redistributed heat from the ocean to land as well as increased the potential of storing more heat on land, given the higher heat capacity of water compared to land. Compared to the other components of the Earth system, this is a small term, but locally the impacts might be large. Our results overall underline the potential importance of inland waters for buffering atmospheric warming through enhanced anthropogenic greenhouse gas concentrations.

Acknowledgments

All ISIMIP2b simulations used for this assessment are publicly available through the Earth System grid Federation (ESGF, `https://esgf-data.dkrz.de/`). The HydroLAKES data is available at `https://www.hydrosheds.org/page/hydrolakes`, the GRanD data at `http://globaldamwatch.org/`, and the GLDB data at `http://www.lakemodel.net/`. The scripts used in the analysis are available on github: `https://github.com/VUB-HYDR/2020_Vanderkelen_etal_GRL`. Inne Vanderkelen is a research fellow at the Research Foundation Flanders (FWO) (FWOTM920). Wim Thiery acknowledges the Uniscientia Foundation and the ETH Zurich Foundation for their support to this research. We are grateful to the Potsdam Institute for Climate Impact Research (PIK) for initiating and coordinating the ISIMIP initiative, and to the modelling centres for making their impact simulations publicly available through ESGF. Computational resources and services were provided by the Shared ICT Services Centre funded by the Vrije Universiteit Brussel, the Flemish Supercomputer Center (VSC) and FWO.

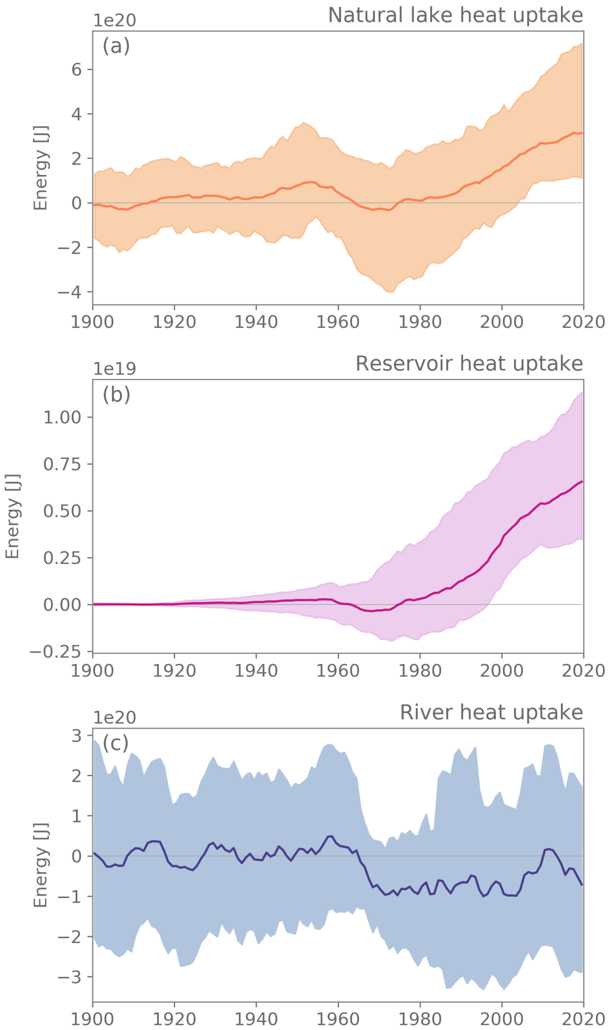

Figure 1. Heat uptake by natural lakes (a), reservoirs (b) and rivers (c). Shown are 10-year moving means relative to the 1900-1929 reference period. Note the different y-axis scales. Color shades represent uncertainty range shown as the standard deviation of the used simulations.

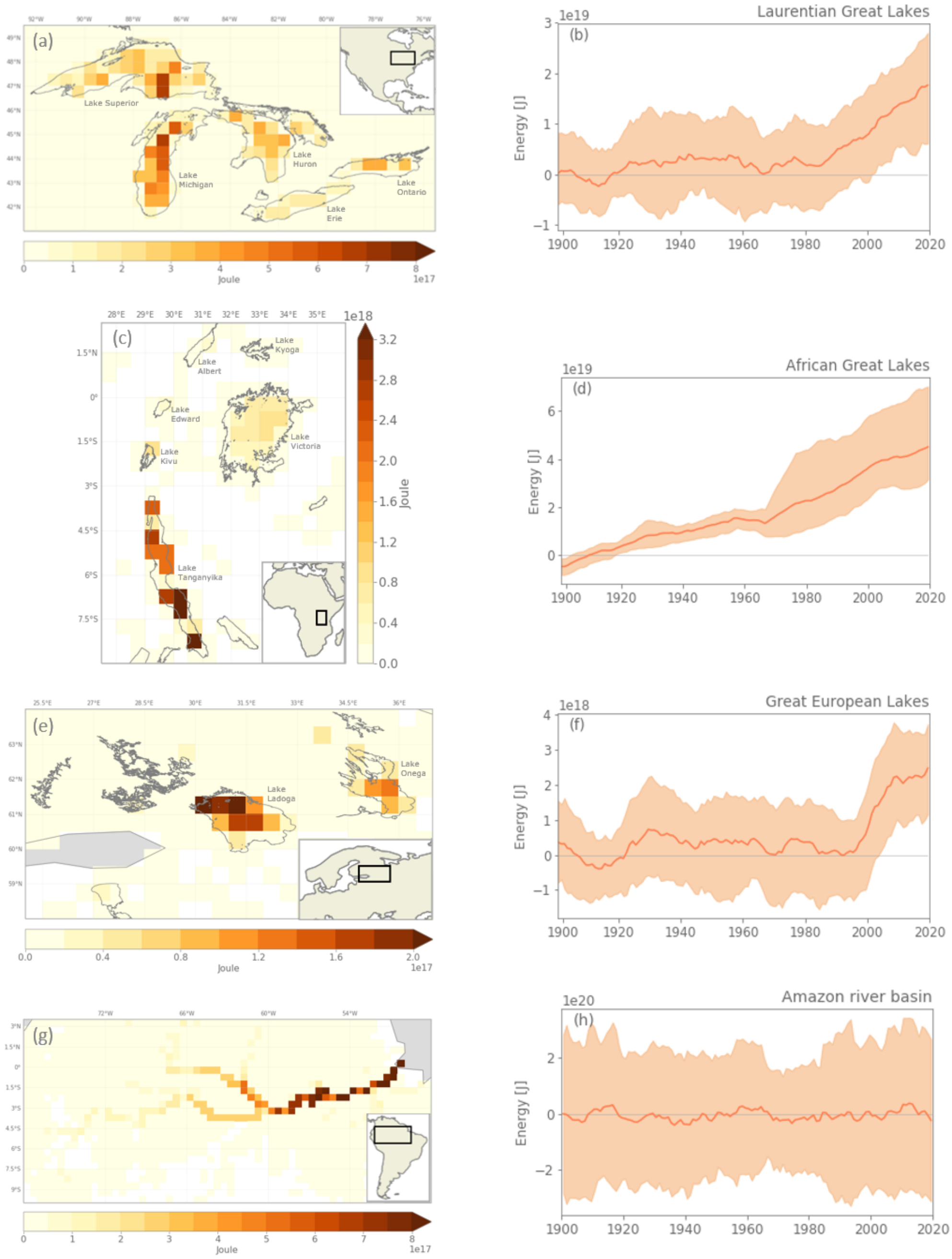

Figure 2. Heat uptake by the Laurentian Great lakes (a-b), the African Great Lakes (c-d), the Great European Lakes (e-f), and the Amazon River (g-h). The maps (a, c,e and g) represent the average heat uptake during the 2001-2020 period with the grey colors indicating ocean grid cells, and white colors grid cells without water. The graphs (b, d, f and h) show 10-year moving means, where the color shades represent uncertainty range shown as the standard deviation of the used simulations. The reference period is 1900-1929. Note the different y-axis scales.

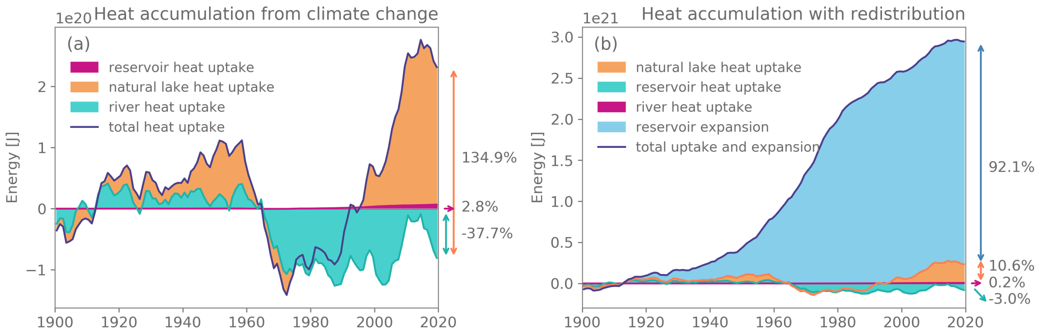

Figure 3. Inland water heat accumulation from climate change (a) and including redistribution by reservoir construction (b). Shown are 10-year moving ensemble means relative to the 1900-1929 reference period. Note the different y-axis scales.

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Supporting information for "Global heat uptake by inland waters"

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Contents of this file

1. Table S1
2. Figures S1 to S3

Introduction

This supplementary file contains 1 table and 3 figures providing extra information on the data and model results. Table T1 shows the used models from the Inter-sectoral Impact Model Intercomparison Project phase 2b (ISIMIP2b). Figure S1 shows maps of the input data used in the study: the area fraction for natural lakes (a), reservoirs (b) and the lake depth (c). Figure S2 illustrate the annual heat uptake by natural lakes for every individual simulation used in the analysis (per lake model and GCM forcing). Finally, figure S3 shows the terms used in the river heat uptake calculation and the resulting river heat uptake, all for both hydrological models and every GCM forcing.

Table S1. Overview of ISIMIP2b impact models used in this study.

Lake models	# layers	Lake depth	Reference
CLM4.5	10	Constant at 50 m	Subin, Riley, and Mironov (2012)
SIMSTRAT-UoG	1 - 13	GLDB	Goudsmit, Burchard, Peeters, and Wüest (2002)

Hydrological models	Human influences	Reference
MATSIRO	No human influences	Pokhrel et al. (2015)
WaterGAP2	Historical human influences	Müller Schmied et al. (2016)

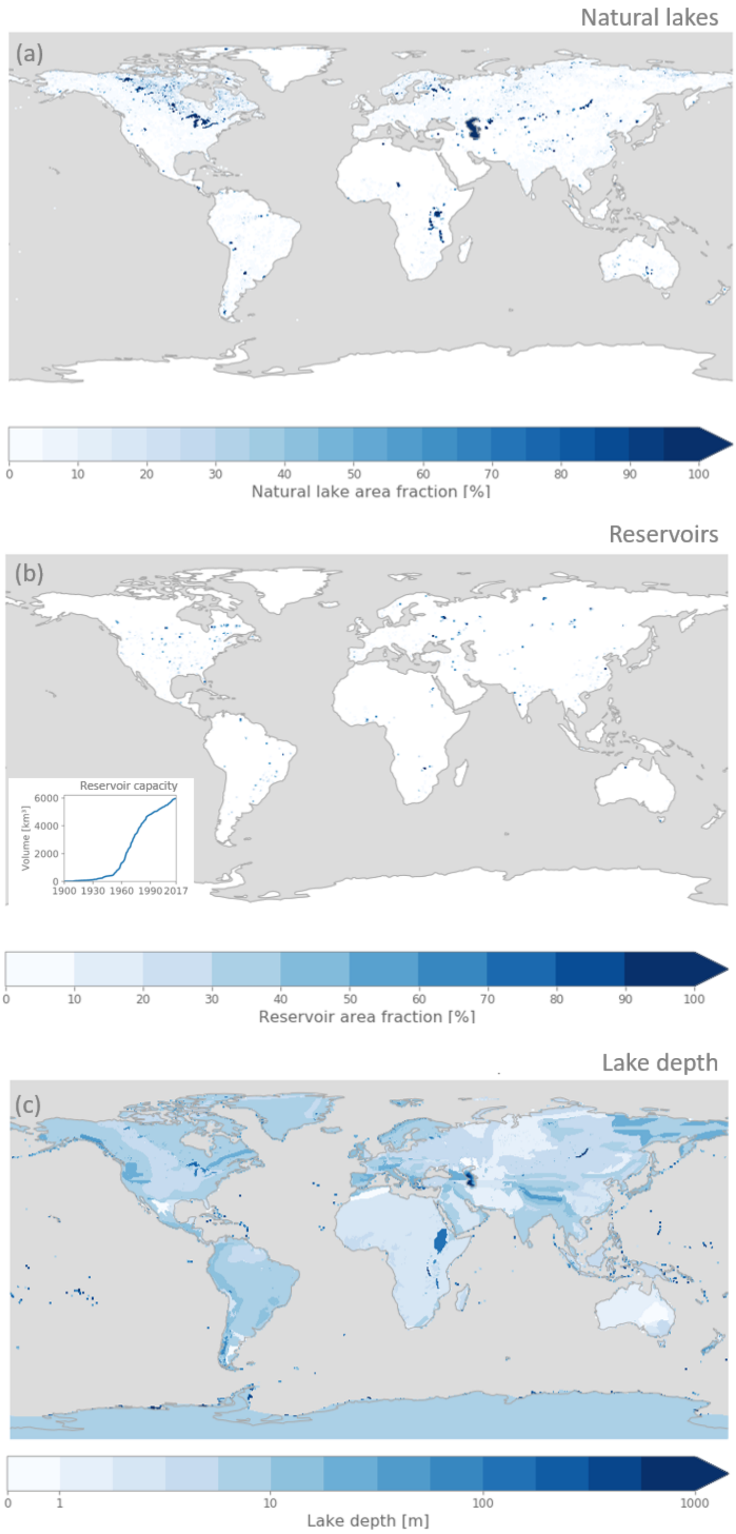

Figure S1. Lake data used in the lake heat assessment: lake area fraction, based on HydroLAKES (a; Messager et al., 2016), reservoir area fraction map representing the reservoir expansion in the period 1900-2017, based on GRanD coupled with HydroLAKES, inset: reservoir volume increase over time based on GRanD (b; Lehner et al., 2011; Messager et al., 2016) and (potential) lake depth adapted from GLDB v3 (c; Choulga et al., 2019).

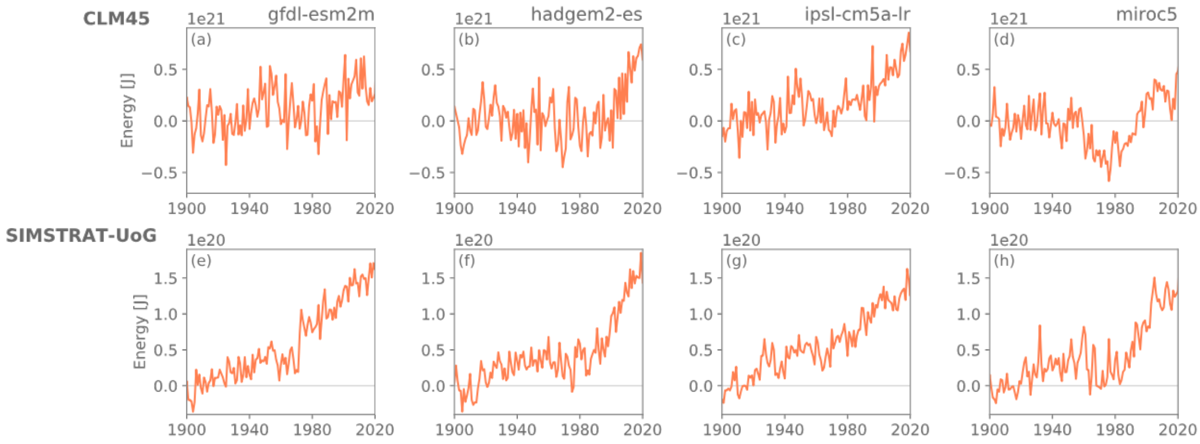

Figure S2. Annual heat uptake by natural lakes for the two different lake models (CLM45; a-d and SIMSTRAT-UoG; e-h) and ESM forcings (GFDL-ESM2M, HadGEM2-ES,IPSL-CM5A-LR,MIROC5; columns). Note the different y-axis scales.

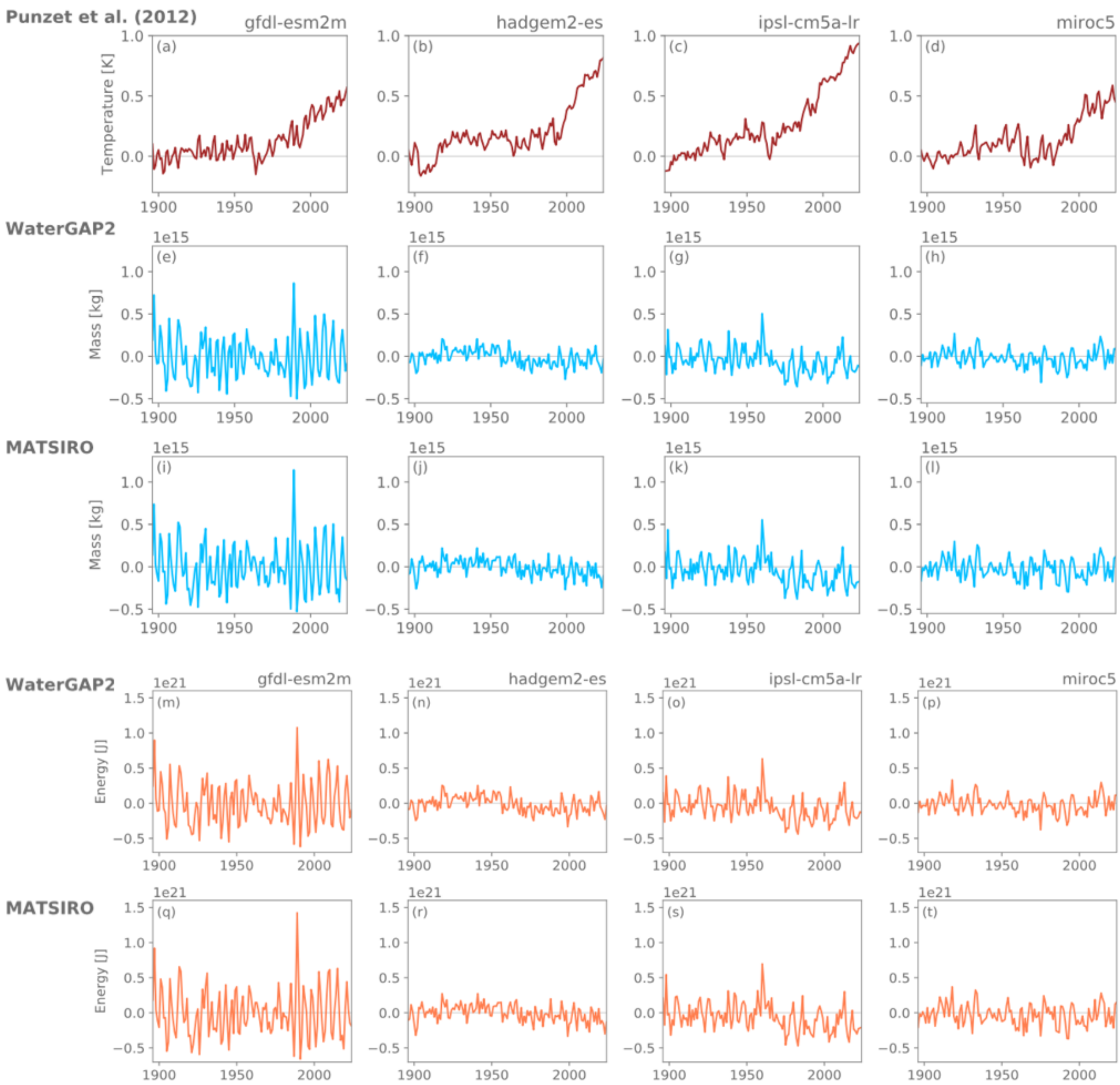

Figure S3. Global average river temperatures calculated with the parametrisation of (Punzet et al., 2012, ;a-d), global total river mass from WaterGAP2 (e-h) from MATSIRO (i-l) and resulting global river heat for WaterGAP2 (m-p) and MATSIRO (q-t), all per ESM forcing.

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