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Key Points:

- Severe lake heatwaves have increased in our studied sites by sixfold since 1995
- Anthropogenic climate change made the severe heatwaves observed almost twice as likely
- Continued anthropogenic warming will increase the likelihood occurrence of severe heatwaves this century

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Severe Lake Heatwaves Attributable to Human-Induced Global Warming

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Abstract Much of the focus of global warming impacts on lakes have focused on changes in mean temperature. However, lakes are also highly vulnerable to thermal extremes. Such extremes occur, by definition, during lake heatwaves. Heatwaves in lakes have occurred globally in recent decades and have had severe negative impacts. However, unlike their atmospheric counterparts, it is currently unknown to what extent lake heatwaves are altered by human-induced climate change. Here, we estimate the human contribution to lake heatwaves, specifically focusing on the most severe events. We demonstrate that the occurrence probabilities of severe lake heatwaves increase substantially due to human influence. Our analysis suggests that 94% of severe heatwaves observed during the satellite data-taking period have an anthropogenic contribution. Globally, we suggest that severe heatwaves are 3 and 25- times more likely in a 1.5°C and 3.5°C warmer world, respectively, compared to a world without anthropogenic influence.

Plain Language Summary Lake heatwaves are occurring globally with severe negative impacts on lake ecosystems. However, it is currently unclear whether, and by how much, human-induced global warming contributes to their occurrence. Here, we show that the occurrence probabilities of some of the most severe lake heatwaves observed are extremely sensitive to human influence. We estimated that 94% of severe heatwaves observed in recent decades have an anthropogenic contribution. Globally, severe heatwaves are 3 times more likely in a 1.5°C warmer world and 25 times more likely in a 3.5°C warmer world, compared to a world without anthropogenic warming. To prevent lake ecosystems being adversely affected by the projected increased occurrence of severe heatwaves, ambitious climate targets are of paramount importance.

1. Introduction

Lake heatwaves, prolonged periods of hot surface water temperatures in lakes (Woolway, Jennings, et al., 2021), can have devastating impacts on aquatic ecosystems. Notable implications of lake heatwaves include severe algal blooms (Jöhnk et al., 2008), mass die-off events (Till et al., 2019), and changes to the community composition of microscopic algae (phytoplankton), which form the bases of aquatic food webs (Baker and Geider, 2021; Olalla et al., 2021; Rasconi et al., 2017). Over time, an increase in the exposure of lake ecosystems to hot temperature extremes may lead to an irreversible loss of species as has already been observed in the oceans due to the increased frequency of marine heatwaves (Cheung et al., 2021 Smale et al., 2019; Smith et al., 2021; Straub et al., 2019). Moreover, heatwaves can influence some of the many benefits that lakes provide to society, including the provision of safe water for drinking and irrigation, recreational use, and economic benefits, such as fisheries and tourism, with knock-on impacts on local economies.

Despite a growing appreciation of their importance, scientific understanding of lake heatwaves is in its infancy (Woolway et al., 2021a, 2021b), particularly when compared to their atmospheric (Fischer & Knutti, 2015; Fischer & Schär, 2010; Miralles, et al., 2019; Seneviratne et al., 2012; Wehrli et al., 2019) and marine counterparts (Frölicher et al., 2018; Frölicher & Laufkötter, 2018; Holbrook et al., 2019; Jacox et al., 2020; Laufkötter et al., 2020; Oliver et al., 2019, 2021). An important open question regarding lake heatwaves is if anthropogenic climate change influences their occurrence or do they simply occur due to natural climate variability. An understanding of whether, and by how much, human-induced global warming contributes to the occurrence of lake heatwaves is of substantial public and scientific interest, not only to further motivate efforts to limit global warming but also for liability considerations (Stuart-Smith et al., 2021a, 2021b). Determining the link between anthropogenic climate change and the occurrence of lake heatwaves is indeed of critical importance.

Recent progress in probabilistic event attribution research (Frölicher et al., 2018; Fischer & Knutti, 2015; Laufkötter et al., 2020; Stott et al., 2015) makes it now possible to attribute the risk of lake heatwaves to human-induced global warming. Yet, no study to date has investigated the anthropogenic contribution to lake heatwaves. In fact, uncovering the human imprint on lake responses to a changing climate is very much an understudied field (Grant et al., 2021). In this contribution, we aim to fill this knowledge gap by estimating the anthropogenic contribution to the occurrence of the most severe lake heatwaves observed during the satellite data-taking period (1995–2019). To this end, we analyze satellite observations of surface water temperature from a global distribution of lakes and by combining with daily simulations of lake surface water temperature, we aim to quantify the human imprint. Moreover, future projections of global lake surface water temperatures are investigated to explore the probability occurrence of these severe heatwaves under continued anthropogenic warming this century.

2. Methods

2.1. Lake Surface Temperature Observations

To investigate the global occurrence of lake heatwaves, we analyzed satellite-derived daily lake surface water temperatures generated within the GloboLakes and the European Space Agency (ESA) Climate Change Initiative (CCI) for lakes projects. These data contain mid-morning lake surface temperatures, at a $0.05° \times 0.05°$ latitude-longitude grid resolution, together with associated uncertainty and quality levels for 1000 lakes worldwide. The satellite data are from the Along Track Scanning Radiometer (ATSR) and Advanced Very High Resolution Radiometer (AVHRR) sensors and have been bias adjusted for consistency between sensors using overlap periods. Among the 1000 lakes with satellite data, only a relatively small proportion of these lakes were suitable for this study. Most notably, the lakes chosen for this investigation had to be sufficiently large to be resolved features at a 0.5° latitude-longitude grid resolution, that is, the spatial resolution of the lake temperature simulations as described below. To identify which of the 1000 lakes could be used in this study, we first re-gridded the satellite observations to a $0.5° \times 0.5°$ latitude-longitude grid. Within this re-gridding procedure, we also remove the satellite retrievals considered low quality, which are flagged as either "bad data," "worst quality," and "low quality" in the satellite data product. We also only investigated lakes with at least 20 years of observations, our minimum requirement for determining the climatology during the historical to contemporary period, and likewise the anomalies for each lake, which are then used to define heatwaves (see below). At the 0.5° grid scale, observations from 258 lake locations remained, which were from 78 individual lakes. The studied lakes varied in surface area between 1,010 km^2 and 67,166 km^2, in average depth between 0.1 and 739 m, in altitude between −10 m above sea level (a.s.l.), and 3,815 m a.s.l. and are located between 49.1°S and 74.6°N. When interpreting our findings, it is important to consider that our results are mostly representative of these lake types and are primarily restricted to the largest lakes of the world.

2.2. Lake Heatwave Definitions

Lake heatwaves were defined from the daily lake surface temperatures following the methods described by Woolway, Jennings, et al. (2021), using the *R* package "heatwaveR" (Schlegel & Smit, 2018). Lake heatwaves were defined as when daily lake surface temperatures were above a locally and seasonally varying 90th percentile threshold for at least five consecutive days. Two lake heatwave events with a break of less than three days were considered as a single event. Lake surface temperature anomalies were calculated for each calendar day using the daily temperatures within an 11-day window centered on the date across all years with data and smoothed by applying a 31-day moving average (Hobday et al., 2016; Oliver et al., 2018; Woolway, Jennings, et al., 2021). Lake heatwaves were also categorized as Moderate, Strong, Severe, or Extreme, defined relative to the maximum intensity of the heatwave event scaled by the threshold temperature anomaly exceeding the climatological mean (the average temperature for the day/month of year evaluated over the data period). Moderate events are those with lake temperature anomalies that exceed the identified threshold but are less than 2 times that threshold value; Strong, Severe, and Extreme events are identified according to anomalies that exceed 2, 3, and 4 times the threshold, respectively. In this study, we focus on lake heatwaves categorized as at least Severe as these are the events that are likely to have the biggest impact on lake ecosystems. We also highlight that the maximum number of years with available data for each studied lake was 25 years. Thus, the time series used to calculate the climatology is shorter than the recommended 30-year period defined by the World Meteorological Organization guide to climatological practices (WMO, 2011). This might influence the calculated severity of lake heatwaves as with fewer years of data; the presence of, for example, an anomalously warm or cold year will have a larger effect on the climatology compared to a larger sample size.

2.3. Lake Surface Temperature Simulations

To simulate the occurrence of lake heatwaves, we analyzed daily lake surface temperatures provided by the Inter-Sectoral Impact Model Intercomparison Project phase 2b (ISIMIP2b) Lake Sector. The ISIMIP2b Lake Sector simulations have been used previously to investigate the impact of climate change on lake heat budgets (Vanderkelen et al., 2020), the timing and duration of summer stratification (Woolway, Sharma, et al., 2021), and for attributing the anthropogenic influence on lake ice and surface water temperature variations (Grant et al., 2021). Here, we investigated lake surface temperatures simulated by the SIMSTRAT-UoG lake model. Following the ISIMIP2b global lake sector protocol, SIMSTRAT-UoG was used to simulate lakes worldwide at a 0.5°-by-0.5° grid resolution based on the mean depth and surface area of all known lakes within a given 0.5° grid (i.e., the average depth of all known lakes and the surface area covered). Bias-corrected climate model projections from ISIMIP2b were used as input to SIMSTRAT-UoG, specifically projections from GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, and MIROC5 for historic (1861–2005) and future periods (2006–2099), the latter under different Representative Concentration Pathways (RCPs). To obtain present-day (1995–2019) lake surface temperature projections and to compare with the satellite observations, we combine the historical simulations (1995–2005) with the "future" projections (2006–2019) under RCP 8.5 (Laufkötter et al., 2020; Oliver et al., 2017). Moreover, lake surface temperatures within ISIMIP2b were simulated under alternate climates first within a climate influenced by both natural and anthropogenic forcing (i.e., the factual world) and second within a climate with no anthropogenic influence (i.e., a counterfactual world), defined according to a preindustrial control simulation. Both simulations are used in this study to attribute the human influence on lake heatwaves (see below).

2.4. Attribution of Severe Lake Heatwaves

To attribute the human influence of severe lake heatwaves observed during the satellite data-taking period, we follow a four-step approach: (a) lake temperatures are extracted from each 0.5° grid from both the re-gridded satellite data and the lake simulations (1995–2019) (b) the occurrence probability (e.g., 1 in a 20-year event), of severe lake heatwaves is computed from the observed and modeled (both the factual and counterfactual simulations) data, (c) the distribution of the observed and simulated lake heatwaves is compared (via a Kolmogorov-Smirnoff test) to ensure that the model can adequately capture the occurrence of observed heatwaves within the factual climate (Laufkötter et al., 2020), and (d) the role of anthropogenic climate change in modifying the likelihood occurrence of severe lake heatwaves is evaluated via an attribution analysis. Specifically, for the latter, the role of anthropogenic climate change in modifying the likelihood of severe lake heatwaves is evaluated by calculating the fraction of attributable risk (FAR; Allen, 2003; Stott et al., 2004). The FAR has been used previously to quantify human influence on the occurrence of extremes over land and in the ocean (Fischer & Knutti, 2015; Frölicher et al., 2018). The FAR is defined as FAR = 1 - (1/PR), where PR = P_1/P_0 is the probability ratio, with P_1 representing the probability of a lake heatwave occurring in the factual world and P_0 representing the probability of occurrence within a counterfactual world. In brief, PR is the factor by which the probability of a heatwave differs under these alternate climates and FAR indicates the fraction attributable to human influence. Thus, we calculate the FAR relative to the probability of a severe heatwave (i.e., that the simulated heatwave is at least as severe as the observed one) occurring in the satellite data and their simulated occurrence during the same period in both the factual and counterfactual worlds. In this study, we also investigate the future (up to the year 2099) lake temperature simulations from ISIMIP2b to evaluate how additional warming will influence the occurrence probabilities of the observed severe heatwaves. For each lake, the time series of FAR is compared against different levels of future atmospheric warming, calculated relative to the 1861–1900 base-period average.

Finally, we repeat our calculations for lakes worldwide by calculating the occurrence probabilities of severe lake heatwaves for all simulated lake pixels (~17,000) in the ISIMIP2b database (Golub et al., 2022). Specifically, using the SIMSTRAT-UoG global lake simulations, we calculate the occurrence probabilities of severe lake heatwaves in both the factual and counterfactual worlds and then perform the attribution analysis described above

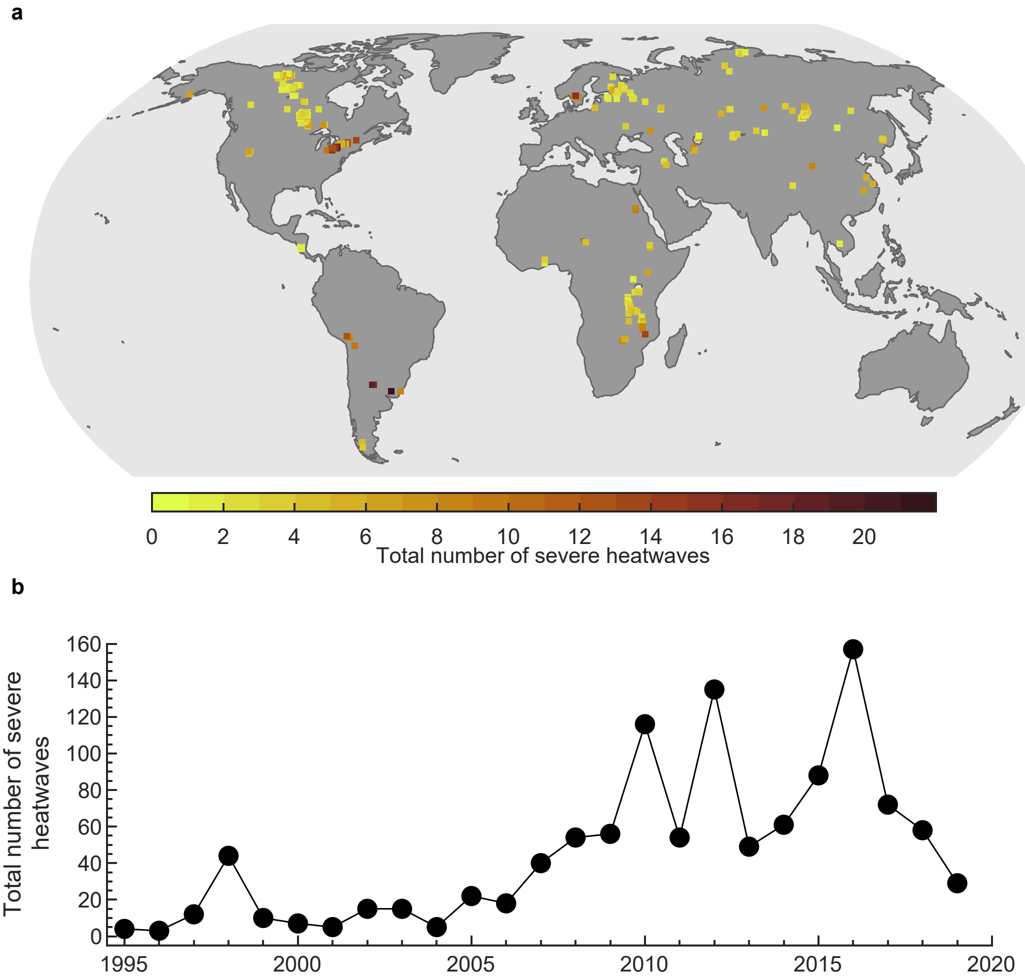

Figure 1. The global occurrence of severe lake heatwaves since 1995. Shown in panel (a) is the total number of severe heatwave events observed in each studied lake from 1995 to 2019. In panel (b), we show the total number of severe lake heatwaves observed across the studied lakes each year during the study period.

(notably points i, ii, and iv). That is, for each 0.5° grid pixel in ISIMIP2b, we calculate the number of severe heatwaves within the factual and counterfactual worlds and then compute the PR and FAR for every lake location. In this study, we perform the attribution analysis with each individual lake-climate model and then present the results as the average and standard deviation across the ensemble.

3. Results

3.1. Severe Lake Heatwaves During the Satellite Period

Our analysis suggests that each of the 78 studied lakes, with satellite-derived surface water temperature data, experienced at least one severe heatwave during the satellite data-taking period (Figure 1). From 1995 to 2019, the greatest number of severe heatwave events to have occurred in any studied site was 25 (i.e., one event per year), and the least frequent number of severe heatwaves in any individual lake was 1 (i.e., 1 in a 25-year event). On average, severe heatwaves occurred approximately 4 times from 1995 to 2019 across the studied lakes. We also observe that the number of severe heatwaves observed since 1995 has increased considerably at a rate of 38 additional severe heatwaves per decade across our global lake distribution (Figure 1). Furthermore, our data suggest that the number of severe heatwaves observed has increased sixfold (from 12 to 80 events) between the first and last decade (1995–2004 and 2010–2019, respectively) of our study period, but with no clear trend in the global heatwave occurrence. Moreover, an increase in the number of severe heatwaves worldwide appears to be mostly

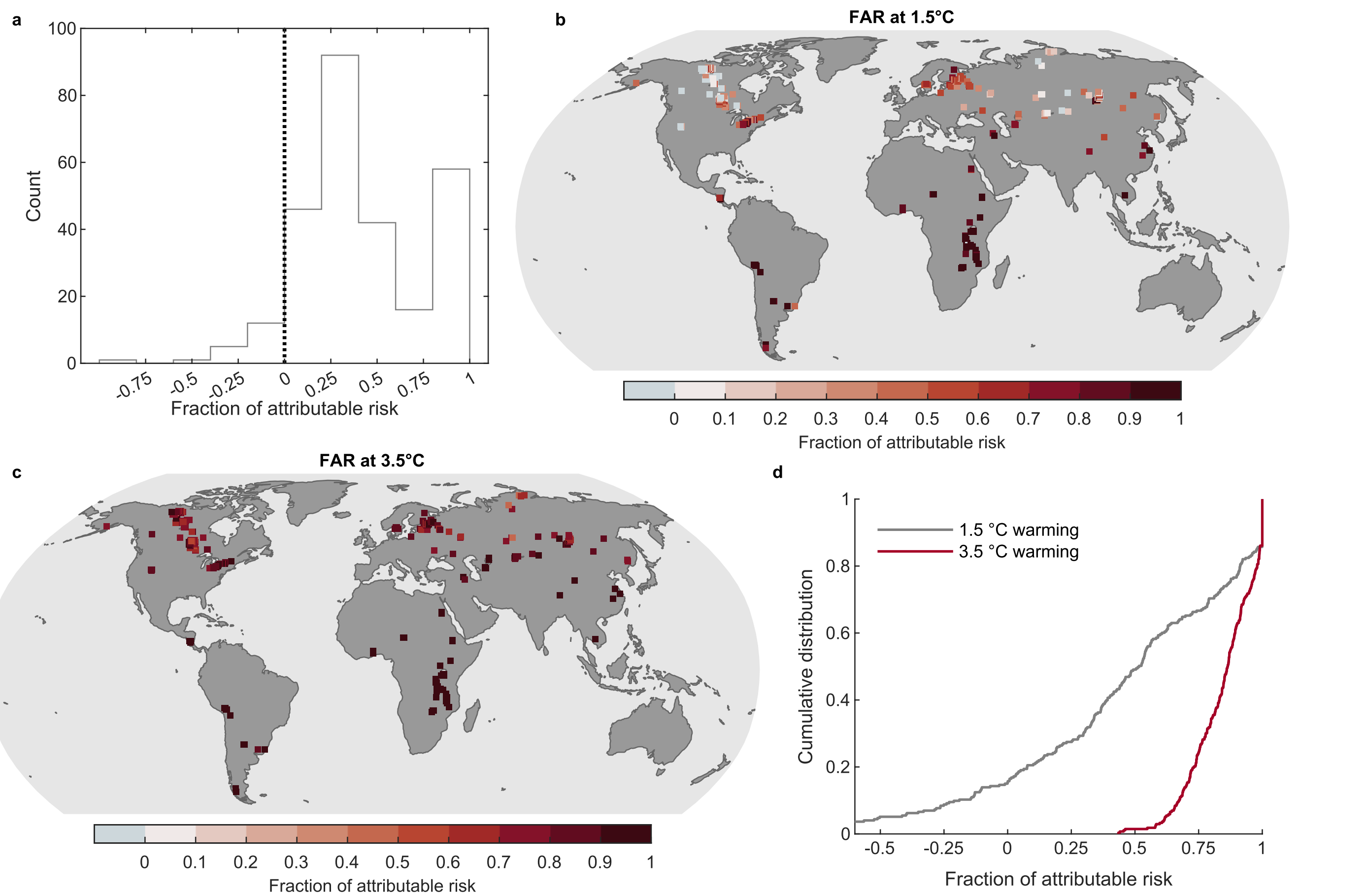

Figure 2. Anthropogenic contribution to severe lake heatwaves observed since 1995. Shown are (a) the fraction of attributable risk (FAR) of the observed severe lake heatwaves identified from satellite observations and model simulations from the historical to contemporary period with the vertical dashed line representing an FAR = 0; (b and c) the FAR of severe heatwaves under a global warming of 1.5 and 3.5°C; (d) the cumulative distribution of FAR under 1.5 and 3.5°C, as shown in panels (b and c). Results are shown for the average across the multi-model ensemble. The FAR values quoted under 1.5 and 3.5°C are calculated during a 15-year period centered around the year when the respective global warming level is reached. Global warming levels are calculated as the globally averaged surface air temperature anomalies relative to the 1861 to 1900 base period.

driven by a rapid increase during the second half of the data record and by anomalously warm years, leading to a high number of heatwave events. The greatest number of severe heatwaves observed in any given year across the studied lakes was 157 events, which occurred in 2016. Other years with a noticeably high number of observed severe heatwaves include 2010 and 2012. The observed peaks in heatwave occurrence during 2010, 2012, and 2016 agree with a previous study in the Laurentian Great Lakes (Woolway, Anderson, & Albergel, 2021), which hypothesized that heatwave severity is influenced by anomalously high air temperatures and/or earlier/stronger thermal stratification, leading to an amplified lake surface temperature response.

3.2. Attribution of Observed Severe Heatwaves

To attribute the human influence on the occurrence probabilities of the observed severe heatwaves, we now compare our observations to the distribution of simulated severe heatwaves from our global-scale lake temperature projections. Specifically, we now calculate the probability ratios and, likewise, the FAR of these severe heatwave events. Our analysis suggests that the average FAR for severe heatwaves in the studied lakes is 0.4 ± 0.1 (here, the uncertainty represents the standard deviation of the computed FAR across the lake-climate model ensemble). An FAR of 0.4 equates to severe lake heatwaves being 1.6 times more likely in the factual compared to the counterfactual world. Our simulations also suggest that 94% of the observed severe lake heatwaves have an average FAR > 0 (Figure 2a). Thus, our analysis suggests that 94% of the observed severe lake heatwaves have an anthropogenic contribution.

Global warming during the 21st century is expected to raise the likelihood of occurrence of severe lake heatwaves. Indeed, under a future global warming of 1.5°C, relative to preindustrial levels, our analysis suggests that the average FAR increases to 0.5 ± 0.1, that is, with severe heatwaves being twice as likely in a climate with anthropogenic influence compared to that influenced solely by natural factors. Under a 1.5°C warming scenario, our simulations also suggest that 95% of lakes have an average FAR > 0 (Figure 2d). Under a more extreme future warming scenario of 3.5°C, our analysis suggests that the global average FAR will increase to 0.8 ± 0.05, meaning that severe heatwaves will be five times more likely in a world influenced by anthropogenic forcing. Our projections also suggest that within a 3.5°C warmer world, all lakes (i.e., 100%) will have an FAR > 0. Ultimately, as the climate continues to warm, the probability occurrence of the severe heatwaves observed during the satellite data-taking period becomes increasingly likely and indeed inevitable in a +3.5°C world. Our simulations also suggest that the FAR of the severe heatwaves observed increases toward lower latitudes under both the 1.5 and 3.5°C warming scenarios (Figure 2). Most notably, our simulations suggest a substantial increase in FAR toward lower latitudes in a +1.5°C climate. Within a 3.5°C warmer world, most of the studied sites situated south of 40°N have an FAR of near 1.

3.3. Global Occurrence of Severe Heatwaves and the Role of Anthropogenic Forcing

We now analyze all gridded lake surface temperature projections from ISIMIP2b in order to investigate the anthropogenic contribution to severe heatwaves at a truly global scale. The historic and future global projections suggest, similar to the site-specific simulations, that the number of severe lake heatwave days increases considerably with an increase in global average air temperature (Figure 3a). That is, as global air temperatures rise, the number of severe lake heatwave days increases substantially. In particular, once the 1.5°C global temperature anomaly threshold is exceeded, the global average count of severe lake heatwave days increases almost linearly (Figure 3a). Moreover, our simulations suggest that under a global warming of 1.5°C above preindustrial levels, the average number of severe lake heatwave days is 49 (±17). This increases to a global average of 187 (±32) days under a warming of 3.5°C. Thus, we calculate an almost fourfold increase in severe lake heatwave days with just over a twofold increase in the global average air temperature. Similar to the results shown from the individual lakes, our global simulations suggest that an increase in the number of severe lake heatwave days under future warming is greatest at lower latitudes. On average, low-latitude (±23.5°) lakes are projected to experience approximately 100 severe heatwave days under a global warming of 1.5°C (Figure 3b). Under the higher 3.5°C warming scenario, some low-latitude lakes will experience 365 severe lake heatwave days per year on average (Figure 3c). As the global climate warms, the ratio of severe lake heatwave occurrence between the alternate climates increases worldwide and likewise so does the FAR (Figure 3d). Under a 1.5°C warming scenario, the global average FAR is 0.7 (±0.1), which equates to the number of lake heatwave days being roughly three times more likely in a world with human-induced global warming, compared to that influenced solely by natural factors. With additional warming of up to 3.5°C, the global average FAR increases to 0.96 (±0.02), which suggests that severe heatwaves are 25 times more likely under anthropogenic climate change and are highly unlikely to occur this frequently in a naturally varying climate.

4. Discussion

Our study highlights the strong anthropogenic influence on the likelihood occurrence of the most severe lake heatwave events that have occurred during the satellite period and are projected to occur this century. Little is known about the global consequences of lake heatwaves, and it is challenging to forecast the precise effects due to the complex interactions that occur within a lake in response to environmental change. Nevertheless, based on previous regional- or lake-specific studies, one can anticipate the repercussions of severe lake heatwaves for aquatic ecosystems. For example, the extreme atmospheric heatwave in the summer of 2003 in central Europe, which likewise resulted in extreme hot lake surface temperatures, illustrates the complexity of responses that might occur. Most notably, at this time, Swiss lakes experienced increased surface temperatures, which in turn strengthened lake thermal stability and increased hypolimnetic oxygen depletion (Jankowski et al., 2006). Elsewhere, it increased the ability of the cyanobacterium *Microcystis* to produce blooms in a deep eutrophic Dutch lake (Jöhnk et al., 2008) most likely a consequence of intense thermal stratification due to surface warming, while indirect effects of reduced flushing in combination with warming can also lead to increases in cyanobacteria (Posch et al., 2012). Heatwaves may also trigger regime shifts in lakes as has also been observed in marine

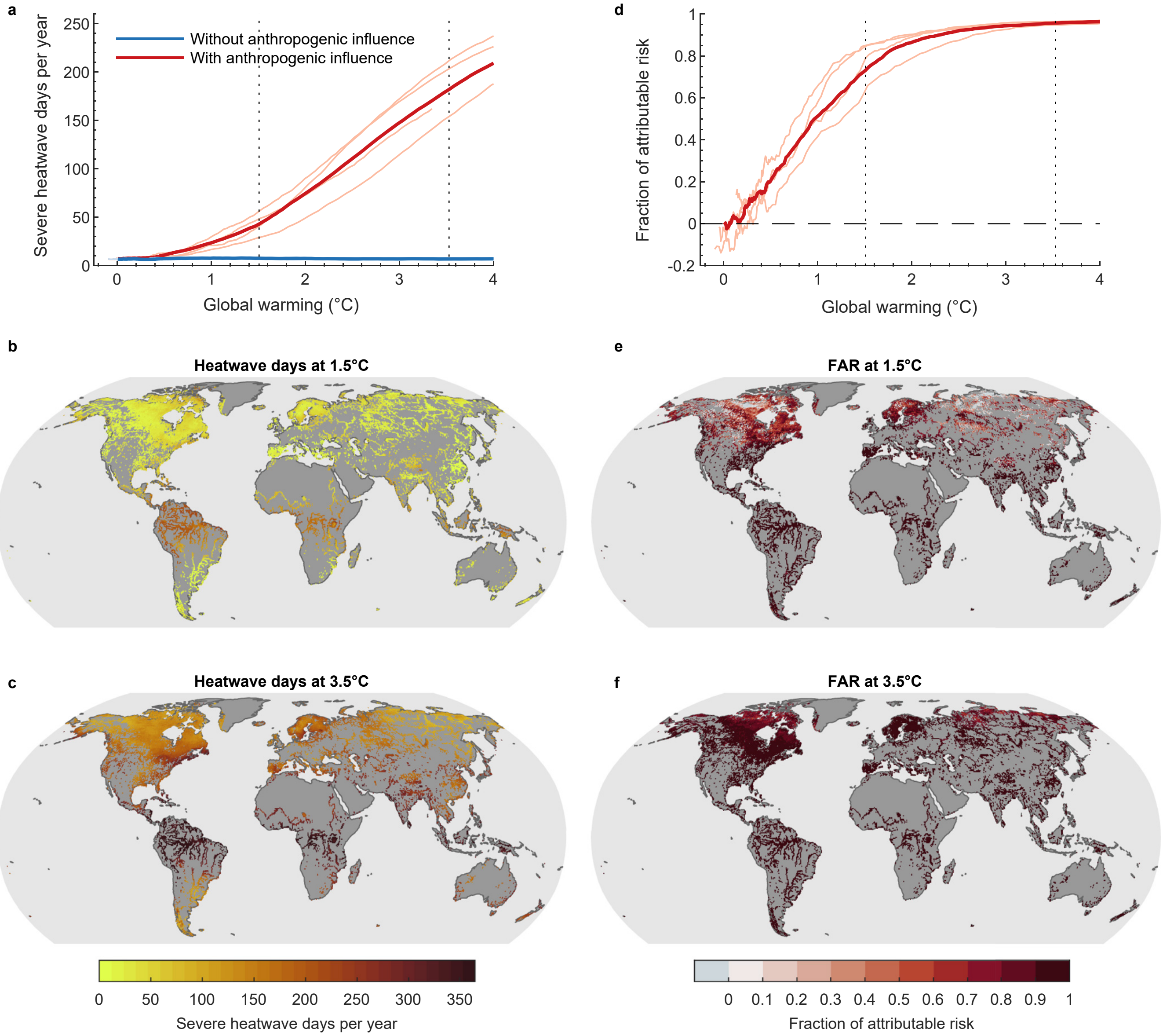

Figure 3. Global change in the occurrence of severe lake heatwaves and the role of anthropogenic forcing. Shown are (a) the globally averaged occurrence of severe lake heatwave days under different levels of global warming; (b) and (c) the spatial patterns in the number of severe heatwave days under a global warming of 1.5 and 3.5°C; (d) the fraction of attributable risk (FAR) under different global warming levels; and (e), (f) the spatial patterns in FAR under a global warming of 1.5 and 3.5°C. The thick lines in panels (a) and (d) illustrate the mean across the lake-climate model ensemble and the thin lines represent the global averages from the individual models. The time series are smoothed with a 30-year running mean. Panels (b, c, e, and (f) show the averages from the multi-model ensemble over the 15-year period centered around the year when the respective global warming level is reached. Global warming levels are calculated as the globally averaged surface air temperature anomalies relative to the 1861 to 1900 base period. The vertical dashed lines in (a) and (d) illustrate a global warming of 1.5 and 3.5°C. The horizontal dashed line in panel (d) illustrates an FAR of 0.

systems (Straub et al., 2019). In lakes, this may also be caused by indirect effects of heatwaves linked to increased evapotranspiration (Mastrotheodoros et al., 2020). For example, Bertani et al. (2016) documented how the 2003 European heatwave triggered a switch from pelagic to benthic productivity in a small Italian lake. Reduced water levels at this time increased light availability at depth, providing an optimum environment for the development of the benthic green macroalga, *Nitella*, which depleted nutrient concentrations in the water and suppressed the typical summer phytoplankton biomass peak. This persistent change had further effects, including a decline in herbivorous zooplankton and an increase in oxygen concentration at depth. In the same lake, the heatwave led to an increase in numbers of the warm stenotherm cladoceran *Diaphanosoma brachyurum* that had been absent or present at a very low density in previous years.

At the species level, ectothermic aquatic organisms, the dominant type in lakes, are most susceptible to lake heatwaves when they live in regions close to their maximum thermal limit, because temperature anomalies there are more likely to exceed organismal physiological thresholds and hence increase mortality rates (Till et al., 2019). Specifically, with increased severe lake heatwave activity, due to anthropogenic forcing, we predict dramatic losses of marginal populations at thermal range edges in lake ecosystems as has been documented in the marine environment (Hobday et al., 2016). Where local extinctions and range contractions involve "keystone species," ecosystem effects are expected to be particularly severe, as habitats are lost, and food web dynamics and species interactions are altered. Major knowledge gaps in our current understanding of how severe lake heatwaves will affect aquatic organisms and communities are associated with the ability of species to acclimate or adapt to extreme conditions. Long-lasting lake heatwaves could also change the geographic distribution of species. However, within the dendritic network of a catchment, dispersal to cooler regions will involve active movement through rivers upstream to a higher elevation against the hydraulic flow, or in large river systems with a flow from lower to higher latitudes (Woolway & Maberly, 2020), but natural barriers and the increasing number of dams (Zarfl et al., 2015) have the potential to restrict dispersal. In addition, for dispersal within and between catchments, colonization and expansion in cooler areas will depend on the presence of a suitable habitat, an issue for the patchy distribution of lakes, and may be impeded by interactions with the resident community of species that can restrict the establishment of new species, despite an adequate propagule pressure. Many lakes stratify during summer, or continuously in some cases, with cooler water at depth providing a potential thermal refuge from lake heatwaves (Kraemer et al., 2021). However, environmental conditions at depth may not always be suitable. For example, oligomictic or meromictic lakes, which are permanently or semipermanently stratified, respectively, are often anoxic at depth, thus restricting any potential refuge. Although anoxia is less prevalent in mono- or dimictic lakes, which mixes vertically once or twice per year, respectively, oxygen depletion is also widespread (Jane et al., 2021). Lakes are also expected to primarily shift to the right along the amictic-polymictic-dimictic-monomictic-oligomictic-meromictic continuum this century (Woolway & Merchant, 2019). Furthermore, the critical thermal period may occur during non-stratified periods, where a lake heatwave at the surface would result in a thermal extreme throughout the water column. This is likely to be the case for some fish species where the eggs, the most thermally sensitive stage of the life cycle (Dahlke et al., 2020; Elliott & Elliott, 2010; Kelly et al., 2020), are normally present in the unstratified period between autumn and spring.

To maintain the existence of resilient and productive lake ecosystems and to prevent many lake regions being adversely affected by the projected increased occurrence of severe lake heatwaves, particularly when combined with the host of other human effects on lakes, such as eutrophication, anthropogenic global warming needs to be severely limited.

5. Conclusions

We analyzed satellite-derived and modeled surface water temperatures from a global distribution of lakes to investigate the occurrence of severe lake heatwaves, defined as periods of extreme warm surface water temperature. Our analysis revealed that the occurrence probabilities of severe lake heatwaves are extremely sensitive to anthropogenic climate change. Most notably, our analysis suggests that 94% of the observed severe lake heatwaves have an anthropogenic contribution. With continued warming this century, the severe heatwaves observed are projected to become increasingly common. Our analysis suggests that the observed severe heatwaves will be two and five times more likely in a 1.5°C and 3.5°C warmer world, respectively. Globally, our simulations suggest that severe heatwaves will be 3 and 25 times more likely under these future warming scenarios compared to a world without anthropogenic warming. Given the sensitivity of lake ecosystems to hot temperature extremes, we anticipate that the increased occurrence of severe lake heatwaves will have widespread implications for heat-related impacts on aquatic species.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Lake temperature simulations used in this study are publicly available at https://www.isimip.org/protocol/#isimip2b. Satellite-derived lake surface temperatures used in this study are available from https://cds.climate.copernicus.eu/cdsapp#!/dataset/satellite-lake-water-temperature?tab=overview.

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