The Global Lake Temperature Collaboration (GLTC)

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A grassroots initiative to investigate the world's warming lakes

Introduction

One of the most direct impacts of weather and climate on lakes and reservoirs is through changes in water temperature. Lakes will warm or cool in response to changes in air temperature, cloud cover, humidity, wind speed, and other climatic factors that affect the surface energy balance and hydrodynamics of a lake. Additional physical factors such as ice cover, lake level, sediment heat flux, and groundwater can also influence lake thermal structure, and even chemical and biological factors play a role (e.g., water clarity, conductivity). In turn, changes in water temperature affect a myriad of other lake processes such as evaporation, vertical mixing and stratification, biogeochemical processes, and primary productivity. Thus, it is critical to understand the role of water temperature changes when considering climate change impacts on the aquatic ecosystems of lakes and reservoirs.

It should come as no surprise, therefore, that the long-term impacts of climate change on lake temperature (and related processes) has been of significant concern to limnologists for quite some time. One of the first attempts to "map" global patterns of lake temperature trends (Schneider and Hook 2010) used satellite-derived warm-season surface water temperature measurements from 167 of the world's largest lakes and reservoirs. The study clearly showed that the majority of the observed lake surfaces were warming during the period 1985-2009, and at an average rate of about 0.45°C per decade (0.81°F per decade). "Hotspots" of warming were also evident in the southwestern U.S., northern Europe, and Laurentian Great Lakes regions, where warming rates as high as ~1.0°C per decade (1.8°F per decade) were measured.

The observed hotspots of lake surface warming are consistent with previous case studies in similar regions, which have shown lake surface temperatures to be warming faster than the ambient, summer air temperature (Lenters 2004; Schneider et al. 2009). Although changes in ice cover and stratification timing may be contributing to the rapid warming of some of these lakes (e.g., Austin and Colman 2007), other rapidly warming lakes do not freeze (Schneider et al. 2009) or are more strongly influenced by other climatic factors, such as trends in cloud cover (Lenters et al. 2009). Regardless of the cause, these rapid changes in lake temperature have profound implications for lake mixing, hydrology, productivity, and biotic communities.

Forming the network: A best-of-both-worlds collaboration

Recognizing the urgency to better understand global patterns of rapid lake warming, a small, grassroots network of lake scientists hatched an idea in October of 2010, following a "Science in the Northwoods" meeting in Boulder Junction, Wisconsin. The basic question was simple: Can we expand upon the previous satellite-based global study (Schneider and Hook 2010) to include *in situ* lake temperature data from long-term monitoring programs, such as those coordinated through the Global Lake Ecological Observatory Network (GLEON)? And what new information might this combined satellite / *in situ* analysis tell us about global lake temperature trends and patterns?

The potential benefits of a hybrid, "best-of-both-worlds" dataset were obvious. On the one hand, remotely sensed measurements of lake surface temperature provide excellent geographic coverage of the world's largest lakes, with most data going back as far as 1985. *In situ* data, on the other hand, fill some of the gaps left by the satellite record by providing temperature data for lakes that are obscured by clouds or too small to be resolved by satellite. Many of the *in situ* records also extend back further in time than the satellite data, and a few even collect information on vertical temperature structure, which is something that the satellites cannot provide.

The challenges of combining lake surface temperature measurements from multiple data sources, however, were also recognized. Satellites record the skin temperature of the thin, top layer of the water surface (typically at nighttime), while *in situ* buoys and sampling programs measure the bulk temperature somewhere in the top meter, and often at different times of the day (or night). Matters are complicated even further when considering factors such as varying sampling frequencies (e.g., daily or bi-weekly), data gaps that don't line up, or large lakes that have spatially variable water temperature trends. Even just the basic process of assembling a large, diverse, *in situ* database that is standardized in such a way to be suitable for "global" analysis can be a significant challenge. Similar tasks have been accomplished before, however, such as the global analysis of lake ice trends

(Magnuson et al. 2000) that resulted from a grassroots gathering of similar-minded limnologists back in October of 1996.

Building a community

Undeterred by the daunting challenges, and motivated by the urgent need for a better understanding of global lake warming patterns, the small group of limnologists began to reach out to the remote sensing community, GLEON, and other lake scientists with *in situ* data to begin the process of identifying international collaborators and datasets that would eventually form the Global Lake Temperature Collaboration (GLTC). This was followed shortly thereafter by the first gathering of GLTC investigators at a special session of the 54th Annual Conference of the International Association for Great Lakes Research (IAGLR) in Duluth, Minnesota, where the theme of the conference was "Big Lakes – Big World" (30 May-3 June, 2011; http://iaglr.org/conference/downloads/2011_program.pdf).

With the list of international investigators growing rapidly, and datasets beginning to flow in, it was recognized that a formal workshop was needed to bring together the broader GLTC group in a common setting to organize data, formulate the scientific questions, and begin the analysis and publication of results. Following a period of grant writing and funding from NSF, NASA, and the University of Nebraska-Lincoln (UNL), the first GLTC workshop was held on the UNL campus in June of 2012 (Figure 1; see Lenters et al. 2012 for a workshop summary). A GLTC project website was created (http://laketemperature.org/), abstracts and posters were presented at the meeting, datasets were compiled and analyzed, and various educational, outreach, and workshop materials were archived online (http://laketemperature.org/workshop2012.html). Following the 2012 workshop, which brought together roughly 40 international investigators, the GLTC group has since grown to over 70 investigators from 20 countries worldwide.

A new lake temperature database

A few years have passed since the first GLTC workshop and – thanks to the dedicated and careful efforts of the GLTC "data analysis subgroup" – an expanded global database of lake surface temperature has now been created. More specifically, the GLTC initiative has assembled a combined satellite / *in situ* database of summer-mean lake surface temperature from 291 lakes and reservoirs around the world (Figure 2), nearly doubling the amount of data previously available from satellite alone. This initial GLTC database – now published in *Scientific Data* (Sharma et al. 2015) – focuses on the period 1985-2009, due to the abundance of both satellite and *in situ* data during that time interval. Many of the aforementioned challenges to creating such a large database from diverse sources are addressed by Sharma et al. (2015) in the technical validation section of the publication. Overall, the new GLTC database represents the first global compilation of *in situ* and satellite-based lake surface temperature data, and it is freely and publicly available to the broader scientific community for analysis and interpretation.

In addition to lake surface temperature, the GLTC database also

Figure 1. Group photo showing a majority of the participants from the GLTC workshop in June 2012, which was held on the campus of the University of Nebraska-Lincoln. Photo courtesy M.Y. Soylu.

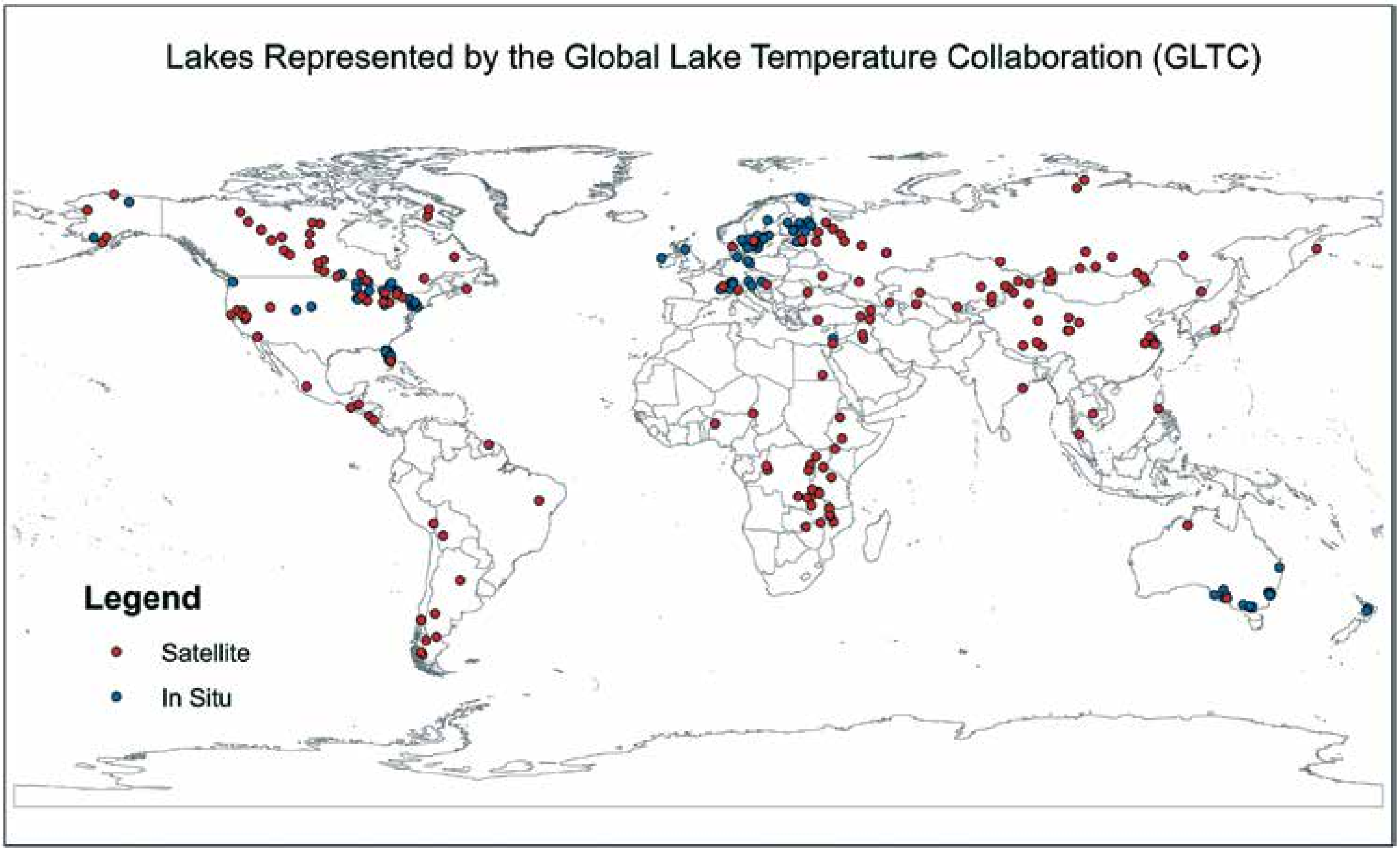

Figure 2. Map showing the location of lakes in the GLTC database (Sharma et al. 2015). Red dots represent satellite-based lake temperature sites, while blue dots show in situ locations. Image courtesy N. Healey.

provides information on climatic conditions at each lake site (air temperature, solar radiation, and cloud cover), as well as geomorphometric characteristics that may influence lake temperature (latitude, longitude, elevation, lake surface area, maximum depth, mean depth, and volume). Future iterations of the GLTC database are anticipated to include additional lakes, longer time periods, and vertical temperature profile data. Additional analyses and publications from the GLTC effort are currently in progress, and we are pleased to note that new, fruitful collaborations have formed –in part – from interactions that emerged from the GLTC initiative (e.g., Kraemer et al. 2015a; 2015b). We are hopeful that this unique, evolving global dataset of lake temperature will offer an invaluable, baseline perspective of lake thermal conditions in our ever-changing global climate, and we look forward to working with new researchers and datasets to expand the GLTC initiative in the future.

Acknowledgements

We would like to thank the numerous field and research scientists who worked tirelessly to collect, document, and contribute data from their study lakes to the GLTC database (Sharma et al. 2015). Special thanks are due to the data analysis subgroup that formed at the 2012 GLTC workshop and that contributed a tremendous amount of time analyzing the GLTC data and metadata since then (D. Gray, S. Hampton, S. Hook, J. Lenters, P. McIntyre, C. O'Reilly, J. Read, P. Schneider, and S. Sharma). The initial idea for the GLTC project evolved from discussions among T. Kratz, J. Lenters, and P. McIntyre at the 2010 "Science in the Northwoods" meeting, as well as preceding interactions at the 2009 AGU Fall Meeting (J. Lenters and P. Schneider). Funding for the 2012 GLTC workshop was provided by the National Science Foundation (DEB-1147666), National Aeronautics and Space Administration (NASA ROSES), and the University of Nebraska-Lincoln's Institute of Agriculture and Natural Resources (IANR). The GLTC project has benefitted from fruitful interactions with GLEON members at various annual meetings. We thank B. Potter, M. Soylu, K. Van Cleave-Shook, and K. Yanez for their assistance with the GLTC website, education / outreach materials, and coordination of the 2012 workshop, as well as the numerous GLTC participants that have joined the project since its inception and have contributed their time, energy, and intellectual input to advancing the goals of the project. N. Healey, B. Potter, and N. Barabas provided comments on an initial draft of this manuscript. Finally, we thank J. Magnuson and his collaborators for inspiration and insights gained from the Lake Ice Analysis Group (LIAG) 1996 workshop, which helped provide much of the initial and sustaining motivation for the GLTC initiative.

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most prolifically under these conditions? Nitrogen-fixing cyanobacteria! What are the consequences? You know the answer to that question. The longer and hotter the water is during these days, the longer and more intense potential harmful algal blooms may become.

Very rarely do you see internal phosphorus loading part of a TMDL equation for a nutrient impaired lake or reservoir. One of the biggest challenges we face at NALMS is to bring the importance of internal phosphorus loading up to the level and attention external or watershed loading has. We're never going to clean up and restore our nutrient impaired (eutrophic/hypereutrophic) lakes and reservoirs without reducing the sources of the internal phosphorus loads, while continuing to work on reducing the external loads.

Looking forward to seeing everyone in Saratoga Springs in November!

Reed Green has worked for the USGS in Little Rock, Arkansas, for over 25 years monitoring, assessing, and modeling water quality in lakes and reservoirs. Prior to that, he worked in the USACE Aquatic Plant Control Research Program in Vicksburg, Mississippi.