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Lake-wide physical and biological trends associated with warming in Lake Baikal

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ABSTRACT

Eutrophication and warming of lakes are occurring globally. Lake Baikal, a large ancient lake composed of three basins, has recently experienced benthic eutrophication at local sites and lake warming in the south basin. Here, we look for signals of warming and pelagic eutrophication across the entire lake using physical and biological data collected at a subset of 79 stations sampled ca. annually (1977–2003) during the period of summer stratification. Lake-wide, surface waters warmed 2.0 °C; and, consistent with this warming, the abundance of two warm-water, cosmopolitan zooplankton taxa increased between two (pelagic cladocerans) and 12-fold (*Cyclops kolensis*). *C. kolensis* increased throughout the lake, whereas cladocerans increased significantly only in the north basin. In contrast, abundance of the cold-water endemic copepod, *Epischura baikalensis*, that dominates the crustacean zooplankton community, did not change. With the exception of one coastal station in the north basin, there is no evidence of pelagic eutrophication. Although chlorophyll concentrations increased 46% lake-wide (0.82 to 1.20 μg/L), the increasing trend was significant only in the south basin. Surprisingly, mean Secchi transparency *increased* by 1.4 m lake-wide across the 26-year time series with significant deepening of water transparency occurring in the central and north basins. This suggests a decline in productivity in the north and middle basins, but an increase in the south basin. Taken together, these findings suggest that physical and biological changes associated with warming have occurred in Lake Baikal, but wide-spread pelagic eutrophication in the lake's three basins has not.

Introduction

Lakes world-wide are impacted by climate change, eutrophication, and their interactive effects (Jeppesen et al., 2010, 2014; Moss et al., 2011). Among ancient lakes – those containing water since at least the last interglacial period – evidence of recent warming, eutrophication, or both have been reported for Lake Biwa (warming and eutrophication; Hsieh et al., 2010, 2011), Lake Hovsgol (warming; Batima et al., 2004), Lake Ohrid (warming; Matzinger et al., 2006, 2007), Lake Tanganyika (warming; Verburg et al., 2003), Lake Malawi (eutrophication; Hecky et al., 2003; Otu et al., 2011), and the brackish Caspian Sea (warming and eutrophication; Huseynov, 2011; Leonov and Stygar, 2001).

Surface waters in the south basin of Lake Baikal, the world's most voluminous and ancient lake, have warmed 2.4 °C in summer over the last 60 years (Hampton et al., 2008; Shimaraev and Domysheva, 2013). Likewise, recent surveys confirm that benthic cultural eutrophication is occurring at localized sites in the coastal zone of this lake (Kravtsova et al., 2012, 2014). Specifically, large increases in benthic algal abundance and shifts in zonation, coupled with high concentrations of nutrients, illustrate the perils of discharging untreated sewage into the coastal zone of oligotrophic Lake Baikal (Kravtsova et al., 2012, 2014; Timoshkin et al., 2014). Despite evidence for localized warming and coastal benthic eutrophication, it is still unknown whether warming and eutrophication of the water column are occurring lake-wide.

Detecting lake-wide warming or eutrophication of the pelagic zone at Lake Baikal is challenging due to the lake's great size and its heterogeneous geomorphology. Stretching across four degrees of latitude (52–56°N), the lake contains three distinct basins and multiple bays (Fig. 1), some of the latter are considerably more productive than offshore waters. Although plankton and various physical parameters have been monitored for more than 60 years at Lake Baikal by Russian

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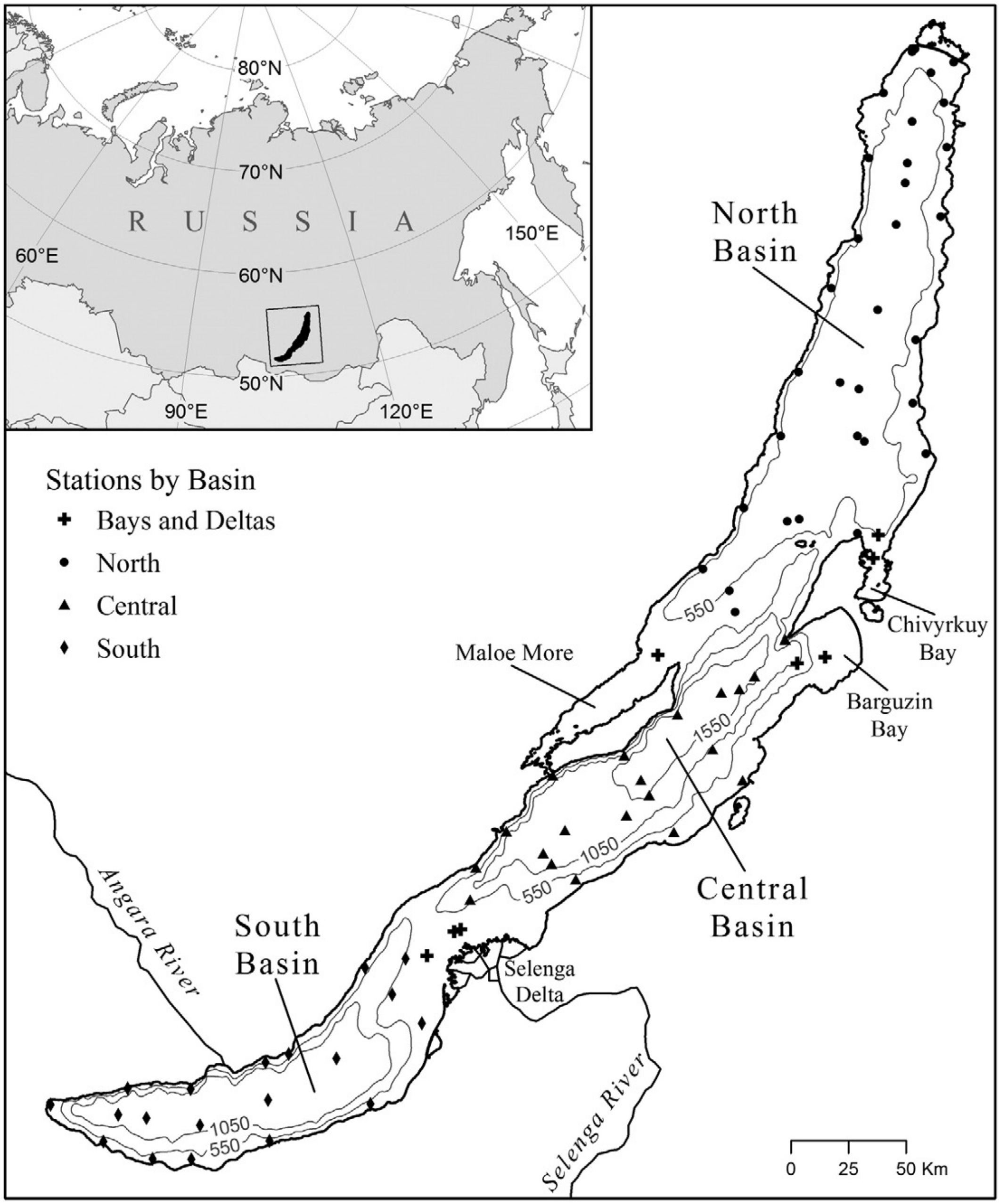

Fig. 1. Map of Lake Baikal showing sampling stations, depth contours (meters), basins, and largest bays (Barguzin, Chivyrkuy Bay, Maloe More Strait). Stations within areas sampled are identified by diamonds (south basin), triangles (middle basin), circles (north basin), and crosses (Selenga River delta, bays, or Maloe More Strait). The lake, located near the Russian–Mongolian border, stretches from 52 to 56° north latitude (inset map).

researchers (Galazyi, 1993; Kozhov, 1963; Kozhova and Izmest'eva, 1998; Popovskaya, 2000; Shimaraev et al. 2002), a spatially intensive, multi-decadal investigation that integrates the responses of multiple physical and biological variables across the entire lake has not been published previously.

Here we use lake-wide physical and biological data collected across 26 years to assess two environmental challenges facing the lake today: climate warming and pelagic eutrophication. We address three questions: 1) Is warming similar in magnitude to that reported for the south basin occurring throughout Lake Baikal? 2) Is the pelagic zone of the lake eutrophying? 3) Are zooplankton (i.e., copepods and cladocerans) community structure and abundance changing in ways that are consistent with warming, eutrophication, or both? Results from our spatial–temporal analyses suggest that physical and biological changes associated with warming have occurred in Lake Baikal, but there is no evidence of wide-spread pelagic eutrophication.

Methods

Samples were collected once per year at a subset of 79 stations (typically >54 stations) throughout the lake (Fig. 1). Water temperature, Secchi transparency and zooplankton species composition and abundance were sampled from 1977 to 2003; chlorophyll *a* was sampled from 1977 to 2004. All sampling occurred during the months of August and September when the lake was stratified, with a median sampling date of 29 August in the south basin, 4 September in the central basin, and 10 September in the north basin. Lake-wide sampling for water temperature, Secchi depth, and chlorophyll did not occur for