Earth observation indicators for hypoxia in Lake Biwa

Vertical circulation is a vital process to sustain oxygen supply in deep water of temperate lakes. Insufficient cooling of surface waters can prevent vertical circulation, and is becoming a threat for freshwater biodiversity against the background of global warming. In monomictic Lake Biwa (Japan), endemic benthic (bottom-dwelling) animals are endangered as a drop in vertical circulation was observed over the last two decades. Investigations with an AUV (autonomous underwater vehicle) in December 2007 revealed more than 2000 dead organisms on the lake's bottom, mostly endemic Isaza gobi fish (***Gymnogobius isaza***) and lake prawns (***Palaemon paucidens***). Low dissolved oxygen concentrations of less than 1.0 mg/l near the lake bottom in November are identified as the main cause for the die-off and an increased exposure of aquatic organisms to heavy metals (Itai et al., 2012; Kawanabe et al., 2012).

Hydrology, climate and biodiversity

The "floating" torii at Shirahige Shrine near Takashima on the western shore of Lake Biwa (photograph by Kyoww, BY-SA 3.0 license).

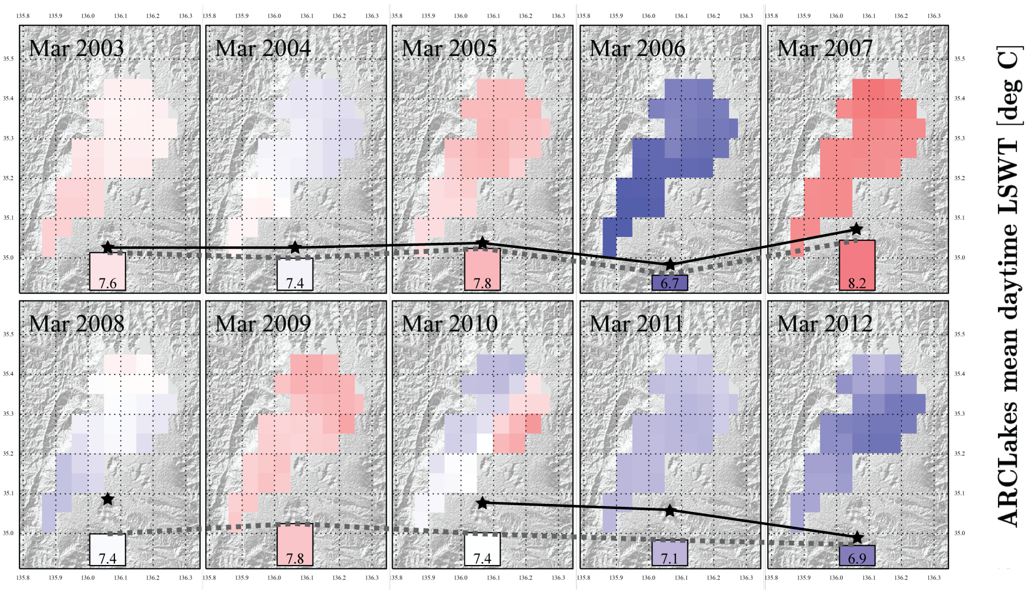
Lake Biwa is the largest freshwater lake of Japan, located on Honshu, northeast of Kyoto, Japan's former capital. It plays a prominent role in Japanese history and culture, and is of high socio-economic value mainly with regard to drinking water supply, tourism, fishery and pearl aquaculture. Approximately 70% of all structures within the watershed of Lake Biwa are connected to sewage treatment plants (Ohte et al., 2010). With an age of 4 Million years, it is among the world's twenty oldest lakes. The lake is at 86 m above sea level, has a surface area of 674 km^2 and a maximum depth of 104 m. The Northern basin, Hokuko-bon, is in average 44 m deep, the narrow Nanko-bon in the South is only 4 m. 460 rivers feed the lake, whereof 125 are first-class tributaries. Lake Biwa is drained by the Seta River in the South of Nanko-bon. The local climate is humid temperate, with 1741 mm of mean annual precipitation mainly during June, July and September. Lake level fluctuations are about 1 m, with +30 cm in summer and -60 cm in winter. Lake Biwa has a surface temperature of 6-27 °C and does not freeze in winter. It is oligo- to mesotrophic at chlorophyll-***a*** concentrations of 0.5 to 5 mg/m^3 (Kawanabe et al., 2012).

The lake harbors more than a thousand animal and plant species, including 67 indigenous freshwater fish species or subspecies, with 16 endemic or semi-endemic forms (Okuda et al., 2014). The lake also possesses a high diversity of benthic grazing and detritus-food-chain organisms on shallow bottoms, namely cyprinids, silurids and gastropods. 172 bird species and 70 species of aquatic vascular plants are recorded, besides numerous phytoplankters. Submerged macrophytes grow in riparian areas down to a depth of 7 mn. Lake Biwa was included as a UNESCO Ramsar Wetland in 1993, and the designated area was recently extended. According to the information sheet on Ramsar Wetlands (RIS) for Lake Biwa, the most threatening invasive species are Largemouth Bass (***Micropterus salmoides***), Bluegills (***Lepomis macrochirus***) and Cormorant (***Pharacrocorax carbo***).

A regular limnological survey program for Lake Biwa is carried out by the Center for Ecological Research of Kyoto University, and acquired data is freely accessible online.

Surface water cooling as an indicator for vertical mixing

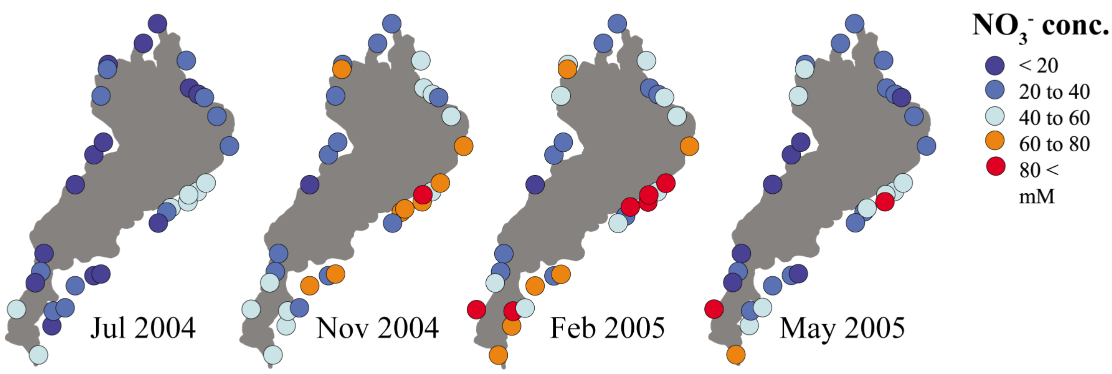
Lake Surface Water Temperature (LSWT) estimates from Earth observation satellites indicate surface water cooling in winter time, which is along with wind speed the main driver for vertical circulation. In the years 2003-2012, LSWT are always minimal in March. They are in average 0.7°C lower than the regular limnological survey program's water temperature measurements at 1 m depth on random days of March, due to the stronger exposition and cooling of the surface layer. The interannual variability of the two datasets coincides very well for the first half of the LSWT time series, including lowest values in March of 2006 followed by an extraordinarily warm in 2007, when a stable thermocline is observed in the ***in situ*** data until early March and holomixis was very weak. The second half of the time series is less consistent, with a much larger offset and missing reference data in 2009. However, Ishikawa and Kumagai (in Kawanabe et al., 2012) confirm that the stability of the termocline was increased in 2009. The monthly LSWT products provide hence a reliable means to indicate surface water cooling and the resulting life threatening decrease of vertical mixing.



Surface water temperatures in March in Lake Biwa. The spatially averaged LSWT are represented by bars and dashed lines, and contrasted with ***in situ*** measurements of the regular limnological survey program taken at 1 m depth and 35.2161° N, 135.9986 E (asterisks and solid lines; basemap from NASA SRTM).

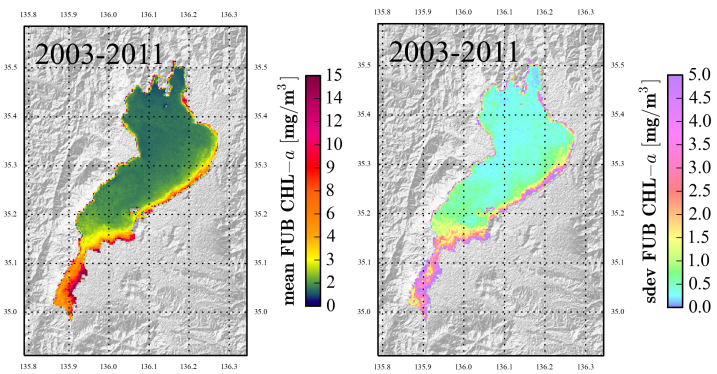
Riverine nutrient input and phytoplankton growth

Phytoplankton growth is limited by light, nutrient availability and water temperature in the euphotic layer. Under oligotrophic conditions, nutrient limitation is set aside either when vertical mixing provides supply from lower layers, or through terrestric input. In Lake Biwa, phytoplankton biomass in the epilimnion is highest in spring and autumn, but widely

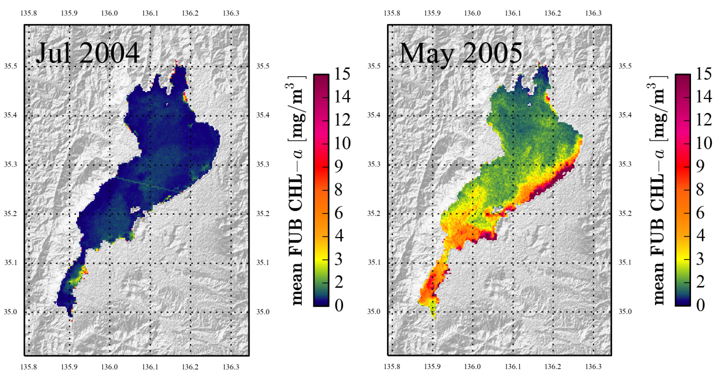


NO_3^- concentration for 32 tributary rivers of Lake Biwa, which account for 68.4% of the whole watershed. The higher population density East and South of the lake lead to considerably higher nutrient input (from Ohte et al., 2010).

controlled by grazing in summer. Limiting nutrients are both Phosphorous and Nitrogen, the latter mostly in late summer (Kawanabe et al., 2012). Nutrient availability is increased along the south-eastern shore, as a result of the significantly higher population density in this area. The same pattern is visible in remotely sensed maps of chlorophyll-***a*** concentrations. In the long-term average, pelagic areas of Hokuko-bon consist of 1-1.5 mg/m^3, while values up to 10 mg/m^3 are retrieved along the south-eastern shore. The concentrations in Nanko-bon are up to 20 mg/m^3, and should be handled with caution as bottom reflected light might affect the results for this shallow basin. Nevertheless, the concentration levels generally agree with those by the regular limnological survey program.



Chlorophyll-***a*** mean and standard deviation for 9 years of ENVISAT data of Lake Biwa. The mean number of acquisitions per pixel is 115.



Monthly mean chlorophyll-***a*** concentrations corresponding to two of the Nitrogen sampling periods in tributaries. July 2004 features clear water after a nutrient depleting spring bloom, May 2005 shows a bloom in full effect.

The temporal coverage of Japan by MERIS full resolution data is limited in comparison to the number of images available e.g. over Europe or Central Asia, and only 115 cloud-free images for Lake Biwa are available for 2003-2011, i.e. in average 12.8 per year. The unregular distribution of these acquisitions leads to a rather fragmentary monthly time series, and for example data for comparison with the November 2004 and February 2005 Nitrogen sampling periods by Ohte et al. (2010) are missing. Nevertheless, the products provide unique information on reoccurring spatial patterns of phytoplankton growth, and indicate that the increased productivity along the southeastern shore might even accelerate deep-water oxygen consumption in consequence of biomass decomposition.

Conclusions

Lake Biwa is a rich and complex environment, which has been investigated thoroughly in recent years, and is subject to a publicly accessible monitoring program. In this case, the added value provided by ENVISAT derived water quality products lies primarily in the spatial domain, which allows for location specific interpretation that would otherwise require extensive fieldwork beyond any regular monitoring program. The temporal resolution, although lower than for other regions, allows for a credible quality assessment of both LSWT and water constituent products. The information content of the LSWT coincides largely with ***in situ*** measurements at the spatial scale of Lake Biwa, which underlines their soundness and highlights the potential for application with lakes where no monitoring program is in place, or where available measurements may not sufficiently account for the spatial variability.

From 2015, ESA's Sentinel satellites will acquire images at a much higher temporal resolution than ENVISAT and therefore allow for an even more consistent data basis for the retrieval of water quality parameters.

Further reading

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