Investigation of Terrigenous Input and Phytoplankton in Lake Baikal (RU) Using SeaWiFS Ocean Colour Data

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Abstract - SeaWiFS data (2001-2002) of Lake Baikal (Siberia, RU) has been investigated to support multi-disciplinary limnological investigation within the frame of the paleoclimate project CONTINENT. Using adapted SeaDAS processing for Lake Baikal, the OC2 chlorophyll algorithm performed adequately for Case 1 surface waters. On the other hand, for the case of high organic terrigenous input (Case 2 waters), there occurs a distinct switch in the spectral peak position and a chlorophyll overestimation. SPM is quantified by the regression of the SeaDAS attenuation coefficient, and field data. Applying these methods, the resulting chlorophyll and terrigenous input maps provide information as how to interrelate the findings from sediment trap and field data with the autochthonous and allochthonous material at the CONTINENT coring sites.

Keywords: Lake Baikal, OC2, attenuation coefficient, SeaWiFS, SeaDAS, terrigenous input, paleoclimate

1. INTRODUCTION

Lake Baikal in Southern Siberia (RU) exhibits a complex oligotrophic fresh-water system, spanning a length of ca. 600 km. In 1996, Lake Baikal was designated a World Heritage Site and placed under the Protected Areas Program. This lake is in fact the deepest (1600 m) and oldest lake in the world due to its formation within subsiding continental rift basins. Its lacustrine sediments are 8 to 10 km thick and date back to the Middle Eocene. These sediments provide a highly informative paleoclimate archive: the lake's high-latitude location makes it sensitive to long-term changes in insolation patterns and to climatic short-term changes associated with shifts in the Siberian high- and Asiatic low-pressure monsoon systems.

The European paleoclimate project CONTINENT, 'High Resolution CONTINENTal Paleoclimate Record in Lake Baikal, Siberia' (2001-2004), is based on earlier collaborative paleoclimate and environmental projects that started in 1995 under the auspices of the BICER (Baikal International Centre for Ecological Research). In 2001, the CONTINENT team recovered long cores from Lake Baikal to examine the sediment records with regards to biotic and abiotic environmental responses to climatic changes during the late Quaternary period (~ 150 ka). In order to interpret the biogenic and silico-clastic sediment records more comprehensively, present-day climatically sensitive proxies have been investigated by field cruises on ship in summer and on ice in winter, and by sequential sediment trap data.

Despite the large amount of work dealing with the hydro-physical environment of Lake Baikal by Russian scientists (Sherstyankin, 1975; Shimaraev et al., 1994; Semowski et al., 1998; Semowski, 1999), and the CONTINENT sediment trap and field cruise data, large-scale information and seasonal information was lacking at the CONTINENT sites. Therefore, the aim of this remote sensing study is to explore relevant synoptical information about the autochthonous (remote sensing parameter: chl-*a*) and allochthonous material (remote sensing parameter: terrigenous SPM) in Lake Baikal.

1.1 Lake Baikal

Lake Baikal is situated in the center of the Eurasian land mass (51°29'-55°46' N, 103°43'-109°56' E). The topography of this voluminous water body (23000 km^3 water volume) is distinguished by three sub-basins with steep tectonic basin walls. The lake body inherits an intense vertical circulation that supports high oxygen saturation down to the lake's bottom. The pelagic of Lake Baikal is classified as oligotrophic ocean-like water, whereas there are indications of local eutrophication around the Selenga delta and in the coastal bays along the South Basin. The oligotrophic pelagic waters show a mean pigment concentration in summer of about 0.5 to 2.5 $\mu g\ l^{-1}$ chl-*a* (Kozhova and Izmetseva, 1998). Because its morphology is steep, and rocky cliffs and shingle beaches dominate its shores, there is little influence by resuspension events and coastal erosion. The lake water is famous for its high transparency (20 to 40 m Secchi depths) even in summer when phytoplankton is more abundant.

However, depending on high-energy discharge events, turbid surface water may also locally prevail in Lake Baikal. This is especially the case during the snow-melting season in May. The Selenga River is the largest tributary into the lake and has built up an enormous delta region, separating the South from the Central Basin (Fig. 1). The Barguzin River discharges into the Central Basin, while the Upper Angara River feeds into the North Basin (Fig. 1). The terrigenous input into the lake has a high organic content due to widespread swampy areas in the catchment.

1.2 CONTINENT

The summer CONTINENT fieldwork took place in July 2001, 2002 and 2003, when wind conditions across Lake Baikal were relatively moderate. The CONTINENT ship cruises on the Russian research vessel, *Vereshchagin*, covered the Southern, Central, and Northern basins (Fig. 1). In the first instance, the CONTINENT cruises were dedicated to coring activities, deploying and recovering mooring instrumentations and sediment traps. Bio-limnological and geochemical surface water investigations were also carried out. Geochemical and geological investigations were made on land, where surface water was sampled from the Mongolian border along the course of the Selenga River towards the Selenga Delta (Fig. 1).

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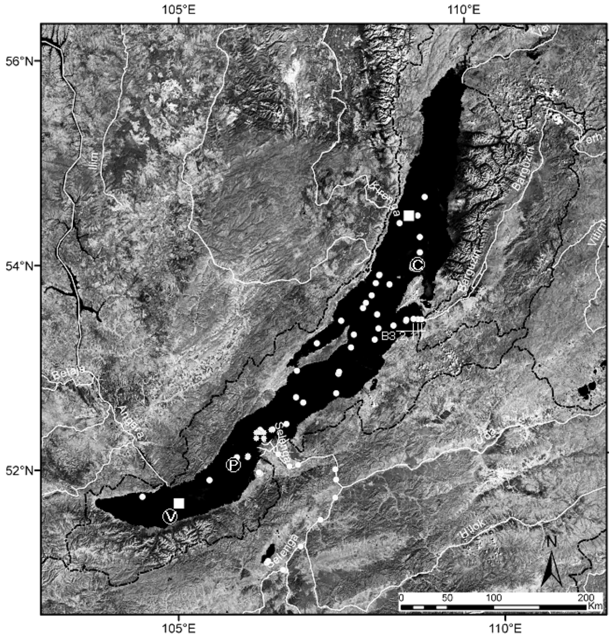

Figure 1. Landsat TM-MOSAIC RGB742; CONTINENT Online-GIS. The satellite map shows Lake Baikal, the three CONTINENT coring sites (C = Continent, P = Posolsky, V = Vydrino), the sediment traps (squares), plus the stations where bio-optical data were collected in 2001, 2002, and 2003 (circles). Note the transect sampling at B1, B2, B3, in Barguzin Bay.

The CONTINENT project data have been visualized as an on-line GIS (ArcIMS-Mapserver) to allow communication within the interdisciplinary project (*http://dc108.gfz-potsdam.de/website/*).

2. MATERIAL AND METHODS

2.1 Material for an Ocean Colour Study at Lake Baikal

The base material for the presented Ocean Colour Study at Lake Baikal is composed of

i) HRPT SeaWiFS satellite data

From summer 2001 to winter 2002, the Ministry of Nature and the Environment in Ulaan Baatar (Mongolia) provided HRPT data sets of SeaWiFS Level 1A.

ii) Ground truth information from CONTINENT field investigations (pigments, phytoplankton, SPM, field spectrometer data)

In-water GER1500 field spectrometer measurements (at 1 and 5 m depth) and measurements of the downwelling irradiance were performed at 15 to 20 stations during each ship cruise and were converted to sub-surface volume reflectances and to remote-sensing reflectances (Heim et al., 2003). Concomitant water sampling (at 1, 5, 10, and 30 m depth) was undertaken, predominantly with regard to pigment concentration (HPLC) and phytoplankton composition (Fietz and Nicklisch, 2004). To gain seasonal information, weekly phytoplankton sampling from May 2002 to June 2003 was conducted 2 km offshore from the Bolshye Koti Biological Station (South-West coast) (Fietz et al., 2005). In addition, monitoring data from 2001 to 2003 at Bolshye Koti were processed by Kobanova and Ismest'eva and have been incorporated into the CONTINENT study by Straskrabova et al. (2005).

2.2 Methodology for Ocean Colour Data Analyses

This Ocean Colour study includes

i) Investigation of the regional characteristics of the atmospheric layer

Investigations using Total Ozone Mapping Spectrophotometer (TOMS) data showed that absorbing Aerosol Index (AI) dust events were not present in the Baikal area during late spring and summer months, 2001 and 2002. In fact, Asian dust events occur only in spring after the break down of the Siberian high-pressure zone (Holden 2001), and move eastwards towards China and Thailand.

ii) Definition of the best-fit SeaDAS parameter set up for Lake Baikal

By using the Multi-Sensor Level-1 to Level-2 (MSL12) processing code developed by the SIMBIOS project, SeaDAS provides user-friendly applications for calculating atmospheric and bio-optical parameters. In this study, specific barometric pressure values were applied (Irkutsk meteorological station, with a correction to the averaged lake level of Lake Baikal (456.5 m), to account for the seasonal air pressure oscillation in Southern Siberia. The set-up of aerosol models represents atmospheric conditions over the World oceans. In addition, there are the choices in SeaDAS of the CZSC 'single scattering white aerosol model', and the 'band 7/8' model.

iii) Investigation of the Ocean Colour algorithms

Global chlorophyll algorithms were evaluated using CONTINENT phytoplankton pigment ground truth data. OC2 and OC4 chlorophyll algorithms are composed from the SeaBAM data set, and cover a variety of oceanographic bio-optical provinces in different seasons (O'Reilly et al. 2000). The current OC2 uses a modified cubic-polynomial equation, while the current OC4 uses a fourth-order polynomial with switching SeaWiFS band ratio combinations. These global band ratio chlorophyll algorithms achieve accuracies of better than ± 35 % in Case 1 conditions.

In addition, empirical chlorophyll algorithms were calculated from the Case 1 *in-situ* chl-*a* data sets of Lake Baikal by using linear regression calculations with ratio combinations of atmospherically corrected SeaWiFS reflectance data of the nearest acquisition dates. As the *in-situ* reference, chl-*a* concentrations of discrete samples of the respective sampling points have been averaged over a depth down to 30 m.

The physically accepted principle for standard SPM algorithms holds that for increasing concentrations of SPM, the reflectance increases in the visible and near infrared spectrum. The CONTINENT SPM ground-truth data set of terrigenous input samples is very limited in size (n = 6 in July 2001, of which n = 4 came from Case 2 waters). Therefore, in the first instance, established coastal SPM algorithms that correlate the reflectance height with SPM concentration have been applied (Heim et al., 2005). In addition, spectro-radiometrical investigations were carried out in Barguzin Bay in July 2002 to investigate the dilution of terrigenous input.

3. RESULTS

3.1 SeaDAS Atmospheric Correction

The SeaDAS 'band 7/8' model and the majority of fixed SeaDAS aerosol models completely failed during the processing. This was represented in large areas by no data values and error flags. In this study on the HRPT SeaWiFS data of Lake Baikal, the SeaDAS atmospheric correction processes performed best with the parameter choice of a spectrally flat aerosol, *i.e.* with the option of SeaDAS model 1 (oceanic model), model 5 (maritime model, 99% humidity) and the single scattering CZSC 'white aerosol' model.

3.2 Ocean Colour Algorithms

The evaluation ground-truth data sets from the 2001 and 2002 fieldwork originate from a two to three week time span around the acquisition dates. Therefore, the accuracy of the evaluation data set is limited. However, Lake Baikal is not influenced by strong surface currents, as is the case for tidally influenced marine coastal waters.

The performance of the chlorophyll algorithms is evaluated in detail in Heim et al. (2005). For instance, the performance of empirical chlorophyll algorithms strongly deviates between the years 2001 and 2001. Whereas the calculated OC2 and OC4 chl-*a* concentrations in pelagic Case 1 waters are within ± 35 % the ground-truth data for July 2001 and 2002. Despite adequate quality for all data sets in July 2002, the comparison of ground truth data with calculated chl-*a* data showed that there is considerable chl-*a* overestimation for several data points in July 2001, where the chl-*a* output seems to be amplified by a factor up to 5 (Fig. 2).

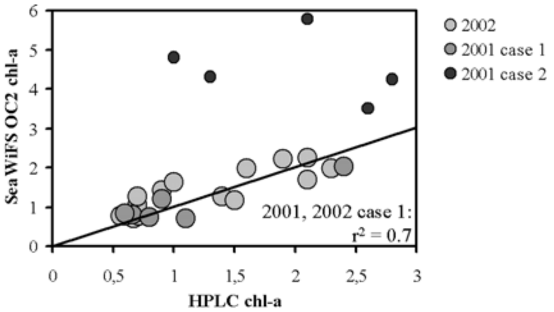

Figure 2. Scattergramm of ground-truth chl-*a* (HPLC) against calculated OC2 chl-*a* data in [µg l^{-1}].

When calculating SPM products that are correlated with the height in reflectance, on calculated SPM maps, the fluvial input into the Barguzin and Upper Angara bays shows inverse grading with the lowest calculated SPM concentrations towards the river inlet. Therefore, SPM has been quantified by linearly linking the remote sensing attenuation coefficient, K490, instead of the reflectance value with the SPM ground-truth data set from July 2001 (Heim et al. 2005). This algorithm is considered as preliminary due to the limited data set.

3.3 Seasonal and Spatial Information

The quantitative Ocean Colour information reveals the dynamical behaviour of autochtonous processes in Lake Baikal for 2001 and 2002. In both years, the extracted phytoplankton information from remote sensing data shows a rising of phytoplankton productivity during summer overall in Lake Baikal, however with distinct differences between the basins.

Remarkably, the seasonal field information from the Bolshye Koti site yielded a temporal displacement in contrast to the averaged seasonal pattern derived from remote sensing data. Chlorophyll maps show that the northern coastline of the South Basin, where Bolshye Koti is situated, was characterized in July 2001 and 2002 by irregular structures of significantly lower chl-*a* concentration than all over the South Basin. Seasonal field data confirm cold-water events from mixing with deeper layers that occur Bolshye Koti during a short period (July 2001, 2002, and 2003) (Straskrabova et al. 2005).

On the other hand, in the North Basin, chlorophyll maps show that within central eddies, chl-*a* concentrations are considerably lower, whereas the eastern North Basin (where the coring site '*Continent*' is located) consistently had more phytoplankton in patchy and heterogeneous patterns in 2001 and 2002.

4. DISCUSSION

4.1 Atmospheric Conditions

Petelina (1998) gives a general overview of the atmospheric conditions in rural Siberia, emphasizing the presence of larger sized aerosol particles compared to WMO (World Meteorological Organization)-continental 1. Furthermore, the Baikal basin is situated northwards of the Siberian rural belt within the boreal biome. For instance, Matthias-Maser et al. (2000) describes the dominance in volume fraction of conifer spores and pollens in June and July 1996 at Lake Baikal. What is also obvious in June/July is that surface films of pollens temporally cover the surface waters of Lake Baikal, especially the North Basin. Therefore, the atmospheric conditions, especially above the Central and North Basin of Lake Baikal with relatively low atmospheric anthropogenic load, do not reflect standard continental WMO atmospheric conditions that generally have a low humidity and a relatively high amount of small sized aerosols. Therefore, the choice of a white aerosol model in SeaDAS may be considered reasonable.

4.2 Ocean Colour Chlorophyll and SPM Products

Due to a considerable heterogeneity in the phytoplankton composition of Lake Baikal (Fietz and Nicklisch 2004), in addition to distinct seasonal variations, the chlorophyll algorithm should be preferably derived from a large, and multi-temporal, ground-truth data base, representing the oligotrophic ocean-like state of Lake Baikal. The SeaWiFS OC2 chlorophyll algorithm that is optimised for the trophic range of 0.5 to 2 µg l^{-1} chl-*a* in fact performed best for the SeaWiFS data sets in 2001 and 2002 (Heim et al., 2005), and is therefore favoured.

For the case of chl-*a* overestimation, Pozdnyakov et al. (2003) reported similar findings in a study of the coastal waters of the White Sea (Russia). They estimated a three- to five-fold chlorophyll model overestimation that is caused by the optical interactions of terrigenous input. In fact, in July 2001, exceptional storm events occurred in Irkutsk Oblast and Northern Mongolia, leading to catastrophic floods that manifested as high fluvial discharge signals in Lake Baikal. The optical signal from the terrigenous material persisted for a minimum of two weeks, and wide areas in the South Basin became Case 2 waters.

The spectral peak position for the case of Lake Baikal has been found to be a suitable indicator for identifying Case 1 waters (490-510 nm) and fluvial influenced Case 2 waters (> 510 nm). For discriminating these water types, the criteria 'reflectance ratio values of $R_{RS}510/R_{RS}555$ below 0.9' has been defined to exclude on one hand unrealistic chl-*a* concentrations.

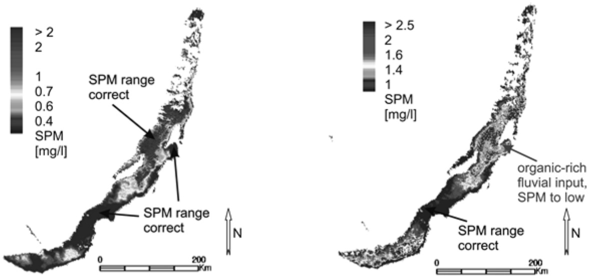

Figure 3. SPM concentrations [mg l^{-1}] (2001-07-19); left: SPM algorithm using the SeaWiFS attenuation coefficient; right: SPM algorithm using the peak reflectance height as optical parameter.

On the other hand, the CONTINENT SPM algorithm linked to the SeaWiFS attenuation coefficient is applied to the extracted Case 2 waters. These calculated SPM maps show realistic SPM distribution with the highest concentrations near the river outlets in contrast to standard SPM calculations that usually correlate the reflectance height with SPM (Fig. 3). The water volume reflectance spectra of the Barguzin transect in 2002 (in Heim et al., 2005) confirm the very low reflectance values despite high SPM concentrations. The field measurements confirm that the closer to the river inlet, the lower in turn is the overall reflectance, and the more the spectral peak shifts towards longer wavelengths, as the absorption activities due to humic substances are enhanced.

4.3 Seasonal and Spatial Ocean Colour Information

The chl-*a* spatial distribution indicates how to interrelate the findings of the different CONTINENT core and sediment trap locations. The SeaWiFS chlorophyll maps indicate that absolute correlation between the autochthonous production at the Bolshiye Koty sampling site with the findings from sediment-traps, and with the coring site '*Vydrino*' in the South Basin, cannot be directly applied. Correlations only may be done with great care and the support of additional limnological data and Ocean Colour data. As another result, the CONTINENT core records (East coast of North Basin) and the findings from the sediment-trap (centre of the North Basin) with respect to bio-markers and phytoplankton productivity, must also be carefully considered for correlation.

The flooding event in 2001 shows how storm conditions may have an unexpectedly large spatial extent and will influence the terrigenous signals in the CONTINENT sediment cores '*Vydrino*' and '*Posolsky*'.

5 CONCLUSIONS

In this study, it has been shown that optical remote sensing is a suitable technique for the examination and monitoring of the dynamic water body Lake Baikal. Within the CONTINENT project, the SeaWiFS chlorophyll and SPM maps showed the potential of remote sensing data to detect meso- and large-scale features and to provide information about seasonal dynamics. Considering the enormous size of Lake Baikal, the spatial information of Ocean Colour satellite data are relevant for the interpretation of field and sediment trap data.

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