CASE 2 LAKE BAIKAL: ANALYSES OF SEAWIFS DATA WITHIN THE SCOPE OF THE PALEOCLIMATE PROJECT CONTINENT

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ABSTRACT

Within the paleoclimate project CONTINENT we use Sea viewing Wide Field of view Sensor (SeaWiFS) data to assess information on the current behaviour of selected climate proxies in Lake Baikal, Siberia. Suitable proxies include optically-visible water constituents such as algae biomass and suspended terrigenous matter, whose dynamics reflect the present-day climate bioproductivity and the river discharge in the catchment area. Lake Baikal represents a specific bio-optical water type with high local concentrations of organic matter and low algae biomass concentrations. Field data show a remarkable influence of coloured dissolved organic matter (CDOM) on the optical properties of Lake Baikal's surface waters. For this case 2 water type, the SeaWiFS Data Analysis System's (SeaDAS) standard atmospheric correction methods result in a considerable overestimation of pigment concentration. Here we describe how we adapted the SeaDAS software and developed techniques for a regional study on Lake Baikal. The optically interacting water constituents are decorrelated with a Maximum Noise Fraction (MNF) analysis that is a modified Principal Component Analyses (PCA). The resultant SeaWiFS PC maps of terrigenous input and phytoplankton distribution reveal the autochthonous and allochthonous influences on the CONTINENT coring sites.

Keywords: Lake Baikal, inland waters, principal component analysis

INTRODUCTION

The Baikal Lake system, in the middle of the Eurasian continent, is close to the boundaries of two important weather systems, the Siberian high-pressure zone and the Asian monsoon zone. Lake Baikal's sediment record is an important high-continental paleoclimate archive, since sedimentation started ca. 25Mi years ago (Oligocene-Miocene). The research within the EU paleoclimate project CONTINENT 'High Resolution CONTINENTal Paleoclimate Record in Lake Baikal (Siberia)' focuses on lake-sediment records potentially spanning the last 150.000 years (i.e. the period covering the Weichsel & Saale glacials). However, before biogenic and silico-clastic data records in the paleosediments can be interpreted meaningfully, the present-day formation of these climate proxies within the Lake Baikal water body has to be investigated. This is done by field cruise and sediment trap data, and by Ocean Colour (OC) satellite data, allowing the present-day bio-limnological and geochemical conditions of Lake Baikal to be examined. The SeaWiFS data set will reveal the autochthonic and allochthonic influences on the CONTINENT coring sites 'Continent', 'Posolsky', 'Vydrino' within the time frame from summer 2001 to winter 2003.

Visible-wavelength-range remote sensing studies on Lake Baikal's water constituents were first conducted by Semowski (1). His studies on the visible bands of the Advanced Very High Resolution Radiometer (AVHRR) were limited by a land-surface adapted atmospheric correction approach and did not result in an applicable remote sensing chlorophyll algorithm. However, Semowski did show that his bio-optical in-water model for Lake Baikal performs very well when simulating the underwater light field, which he validated with *in-situ* attenuation depth profiles.

This paper presents the first SeaWiFS study of Lake Baikal. The challenge is to adapt the marine SeaWiFS standard processing methods and algorithms to an inland water body with patchy terrigenous input.

LAKE BAIKAL

Lake Baikal in south-eastern Siberia (51-56°N, 104-110°E) is the oldest and deepest (1650 m) lake in the world (2). 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. The Barguzin River intrudes into the Central Basin and the upper Angara River into the North Basin. Lake Baikal usually freezes in early January and the ice breaks in May. The main phytoplankton bloom (up to 10 µg/l Chl-a) develops only in winter and early spring in nutrient rich waters under transparent ice cover (2). According to Koshova et al. (2), Lake Baikal is classified as an oligotrophic waterbody, due to the low mean chlorophyll concentrations of around 1 µg/l. Baikal waters are extremely transparent, with Secchi depth measurements in pelagic waters showing values up to 40 m in June and still up to 20m in times of more phytoplankton biomass in July and August. Within the bays, along the coast and near the Selenga delta, the waters bear more algae biomass (up to 3 µg/l Chl-a), and are influenced by terrigenous matter. Despite low algae biomass concentrations and high Secchi depths, Lake Baikal is assigned to case 2 waters (3) due to the significant optical contribution of non-correlated terrigenous matter (1). The dissolved and particulate organic matter predominantly originates from the huge swampy areas and bogs within the Lake Baikal watershed. Because the δ^{13} values of DOM in the lake and in the tributaries are comparable, Yoshioka et al. (4) concluded that the main origin of DOC in Lake Baikal even in pelagic waters seems to be terrestrial.

METHODS AND MATERIAL

Field data set

During the cruises in summer 2001 and summer 2002 on Lake Baikal, the field investigations (Table 1) included the South Basin, the Selenga delta area, the Central Basin, Barguzinzki Bay and the North Basin (Figure 1). We paid special attention to the lake regions influenced by terrigenous matter, thus we performed transects from the vicinity of the Barguzin and Selenga River inflows outwards to the pelagic waters.

Table 1: The CONTINENT participating institutions and sub-contractors involved with the data used in this work

Institution	code	activities
Swiss Federal Institute for Environmental Science and Technology, Switzerland	EAWAG	sediment traps, acoustic current meters and thermistors, gravity coring
GeoForschungsZentrum Potsdam, Germany	GFZ	project and data management, remote sensing, suspended matter in surface waters
Autonomous University of Barcelona, Institute of Environmental Science and Technology, Spain	ICTA	biomarker lipids in surface waters and sediments, carbon isotopic analyses
Institut für Gewässerökologie und Fischereibiologie, Germany	IGB	lipophilic photosynthetic pigments in surface waters and sediments
Russian Academy of Sciences, Irkutsk Limnological Institute, Russia	LIN	operation of research vessels (RV Vereshagin and RV Titov) and local infrastructure
University of Gent, Department of Geology and Soil Science, Renard Centre of Marine Geology, Belgium	RUG	geophysical site survey (seismics, sub-bottom profiling and sidescan sonar)
University College London, Department of Geography, Environmental Change Research Centre, United Kingdom	UCL	phytoplankton monitoring and analysis
University of Liege, Silicoclastic Sedimentology and Clay Geology, Belgium	ULG	mineralogical analyses, geochemical analyses

Remote Sensing ground truth data were acquired spectrometrically and fluorometrically on the underwater light field, on phytoplankton pigment concentration of chlorophylls and carotinoids, on DOC and on suspended matter concentration (SPM). The water samples were taken from 1 m, 5 m and 30 m depths, plus additional depths if the fluorescence probe measurement indicated phytoplankton subsurface maxima in these depths.

Figure 1: Landsat TM-Mosaic, UTM 48 Baikal Online GIS http://dc108.gfz-potsdam.de/website/ CONTINENT coring sites (cylinders: C=Continent, P=Posolsky, V=Vydrino), CONTINENT sediment traps (trap symbols), CONTINENT field stations of bio-optical field cruise and Selenga expedition data 2001(grey points) and 2002 (dark grey points).

Shipborne GER1500 field spectrometer measurements were performed at about 50 surface water stations. We applied different measurement methods that included measurements of the underwater light field, of the upwelling radiances close to the water surface, and of the downwelling incident solar and sky fluxes. The in-water analysis technique we used is based primarily on the Smith and Baker (5) method. The upwelling irradiance, $E_{up}(\lambda)[z\text{-}]$, is measured at different depths [z-] of the water column, and is extrapolated towards (6)

$$E_{up}(\lambda)[0\text{-}] = E_{up}(\lambda)[z\text{-}] \cdot e^{kz},$$

where k is the attenuation coefficient derived from the underwater irradiance profile. Simultaneously, the downwelling irradiance, $E_{down}(\lambda)[0+]$, is measured onboard. These irradiance values are transferred below the water surface using (7):

$$E_{down}(\lambda)[0-] = E_{down}(\lambda)[0+] \cdot 0.96$$

The retrieved water volume reflectance, $R_{vol}(\lambda)$, is the diffuse reflectance $E_{up}(\lambda)[0-]$ / $E_{down}(\lambda)[0-]$ directly at the air/water interface. The Remote Sensing Reflectance, $R_{RS}(\lambda)$, is then calculated by

$$R_{RS}(\lambda)[0+] = (E_{up}(\lambda)[0-] \cdot 0.52 / E_{down}(\lambda)[0+]) / Q$$

where Q (the ratio between upwelling radiance and upwelling irradiance) is assumed to be equal to 5 (8), and the ratio between below and above water radiance is assumed to equal 0.52 (7).

All of the above-water measurements were taken according to the recommended viewing angles (θ, ϕ)=(40° zenith sensor,135° sun azimuth) of the SIMBIOS Project Technical Memoranda (9). According to this technique, the direct sun glint is minimized and the upwelling radiance measurement is corrected for the specular reflectance of the diffuse skylight. In this case:

$$R_{RS}(\lambda)[0+] = (L_{up}(\lambda l[0+] - f \cdot L_{sky}(\lambda))/ E_{down}(\lambda)[0+]$$

where the reflection factor f is dependent upon the water-surface state and sky conditions (10).

HRPT SeaWiFS satellite data

The Ocean Colour sensor SeaWiFS is on a 705 km circular, noon, sun-synchronous orbit with a revisit time of one day. SeaWiFS has six spectral bands in the visible wavelength range and two spectral bands in the near infrared wavelength range. Since 2001, the SeaWiFS receiving station in Ulaan Baatar, Mongolia has provided High Resolution Picture Transmission (HRPT) SeaWiFS data (1.3 km^2 spatial resolution). The HRPT SeaWiFS data level 1A processing is performed using SeaDAS 4.1 and 4.4, the processing software for SeaWiFS data. The SeaWiFS HRPT data is processed to level 2.0 geophysical products using SeaDAS processing that is adapted (see atmospheric correction section) for this inland water case. All images were successively georectified to UTM projection, zone 48, WGS 84. Further processing includes spectral analyses (minimum noise function, principal component analysis, spectral profiles, algorithm testing) with the image analysing software ENVI (RSI).

Atmospheric correction

Each of the SeaDAS standard atmospheric correction methods (e.g. single-scattering/multi-scattering, white aerosols, fixed model, band 7/8 model) leads to a considerable over-correction of the atmospheric signal, especially in the blue wavelength region. The reason is that the SeaDAS atmospheric correction performs well for standard atmospheric pressure at sea level and for case 1 waters, i.e. zero water leaving radiances in the near infrared. Due to Lake Baikal's particular conditions (465 m altitude, high-continental pressure oscillations, case 2 water), the SeaDAS atmospheric signal overestimation is caused in part by the overestimation of the molecular optical thickness of the SeaDAS standard atmospheric layer at a pressure, P_0, of 1013.25 mbar (at 0 m altitude). Also, Lake Baikal's surface waters are influenced by the backscattering of terrigenous matter, with a considerable part of the water-leaving radiances being non-zero in the near infrared. Therefore, the assumption does not hold for Rayleigh-corrected radiances in the near-infrared wavelength range to be solely attributed to the atmospheric signal.

We accounted for the reduced Rayleigh scattering by applying an air-pressure correction corresponding to the average air pressure of the respective month. This accommodates the high seasonal continental-pressure oscillations. Additionally, we reduced the molecular optical thickness of each band within the SeaDAS SeaWiFS tables towards the values (11,12) of a continental atmosphere. Using the Management Unit of the North Sea Mathematical Models, MUMM, turbid water correction (13), we overcame the problem associated with unrealistically large single-scattering aerosol reflectance ratio values, $\varepsilon^{(band\ 7,8)}$, due to non-zero water leaving radiances in the near infrared. Within the MUMM tool, $\varepsilon^{(band\ 7,8)}$ is fixed for each image by choosing it manually from scatterplots of Rayleigh-corrected reflectances at 765 and 865 nm. The manually chosen $\varepsilon^{(band\ 7,8)}$ values from the 2001 and 2002 SeaWiFS data set range from ε=1.1 to 1.15 (instead of the automatically chosen value $\varepsilon \approx 1.7$, which would be due to turbid waters).

Forward modelling and principal component analyses

The strong inverse dependence of the water-leaving signal on the inherent optical properties of the specific water body provides the physical basis for all OC algorithms. Therefore, the water-optical properties of Lake Baikal can be assessed by building up an *in situ* data set of pigment, suspended matter and organic matter concentrations, and their spectral properties. With the choice of appropriate values for the water constituents, we intend to achieve the correct forward modelling of R_{RS} according to our GER field spectrometer data from 2001 to 2003, and according to the atmospherically corrected SeaWiFS data. For the bio-optical forward modelling, we use the hydro-optical software of the Water Colour Simulator WASI (14) that is based on fresh water optical specific coefficients of Lake Constance (Germany).

To separate the autochthonous water constituents (phytoplankton biomass) from the allochthonous components (terrigenous dissolved and suspended input), we use the Minimum Noise Function (MNF) Transform, which is a Principal Component (PC) transform that equalizes the random noise in each principal component (15). Input data values into the MNF are the atmospherically corrected visible SeaWiFS spectral bands (b1,b2,b3,b4,b5,b6).

RESULTS

Bio-limnological and geochemical field data

The time frame of the CONTINENT cruises was set in a season with moderate wind conditions for Lake Baikal. In the Lake Baikal area, these months, June and July, have the drawback for remote sensing applications of frequent cloudy, foggy and rainy weather conditions. The field spectrometer measurements from 2001 and 2002 could rarely be undertaken under good weather and time-of-the-day conditions. Nevertheless, the bio-optical CONTINENT cruise data provide a unique data set for ocean-colour investigations in Lake Baikal. Summer-months phytoplankton assemblages in Lake Baikal could be assessed for 2001 and 2002 (16). Chlorophyll concentrations in the pelagic areas ranged for the oligotrophic North Basin from 0.2 to 0.7 µg/l Chl-a, for the Central Basin the average values were around 0.8 µg/l Chl-a while for the South Basin the range was from 1 to 1.5 µg/l Chl-a. Only in areas influenced by the Selenga input were the concentrations higher, in the range of 1.5 to 3.5 µg/l Chl-a (17,18) SPM concentrations varied from less than 0.5 mg/l for the North Central Basin to average concentrations from 0.6 to 1 mg/l for the Central and the South Basin (17,18). DOC measurements for the pelagic waters showed values lower than 0.1 ppm for the North and Central Basins in 2002, but were up to 2 ppm DOC in several parts of the South Basin (17,18). Figure 2 shows the field-spectrometer measurements and sea-truth data along transects from the Barguzin river inlet. The field spectrometer measurements indicate a very-high absorption in the spectral range of short wavelengths.

SeaWiFS data analyses

Because the field spectrometer measurements were mostly undertaken under unfavourable weather conditions, the accuracy of the new atmospheric correction method has been estimated by applying the OC4 (19) chlorophyll algorithm to the atmospherically corrected water leaving radiances. These modelled chlorophyll concentrations are compared with the CONTINENT field cruise chlorophyll data (average concentrations from the first attenuation length). Lake Baikal is not influenced by strong surface currents as is the case for marine coastal waters. Therefore, we chose the cruise chlorophyll concentrations that originate from a stormfree period between 17/07/2001 to 24/07/2001 as a sea truth data set. This corresponds to a week-long time window, around the date of the relatively cloudfree SeaWiFS data acquisition on the 19/07/2001.

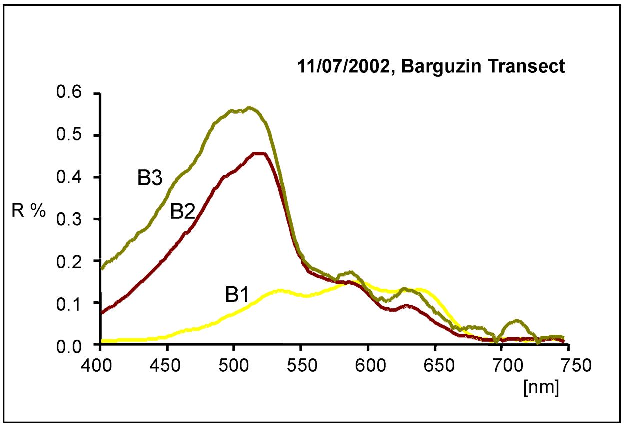

Figure 2: GER 1500 field spectrometer measurements (R_{vol}[0-]) along the Barguzin transect, 11.7.2002. Distances to the Barguzin River inlet: B1 0.9 km, B2 11.2 km, B3 19.2 km. Bio-geochemical analyses: B1 4.7 ppm, 3.9 mg/l, 1.9 µg/l; B2 1.4 ppm, 1.3 mg/l, 1.8 µg/l; B3 0.6 ppm, 0.8 mg/l, 2 µg/l (DOC, SPM, Chl-a).

For pelagic waters, our enhanced SeaDAS atmospheric correction combined with the MUMM tool shows good results. Figure 3 shows, that one part of the OC4 Chl-a data (mean of 16km^2 pixel area) is within the concentration range of the CONTINENT cruise chlorophyll concentrations. These samples are situated in lake areas where the main component is phytoplankton. Nevertheless, it further shows, that there is considerable OC4 Chl-a overestimation for several data points, even after the MUMM atmospheric correction for turbid waters. These are the samples in terrigenous influenced areas of the lake, especially in the South Basin.

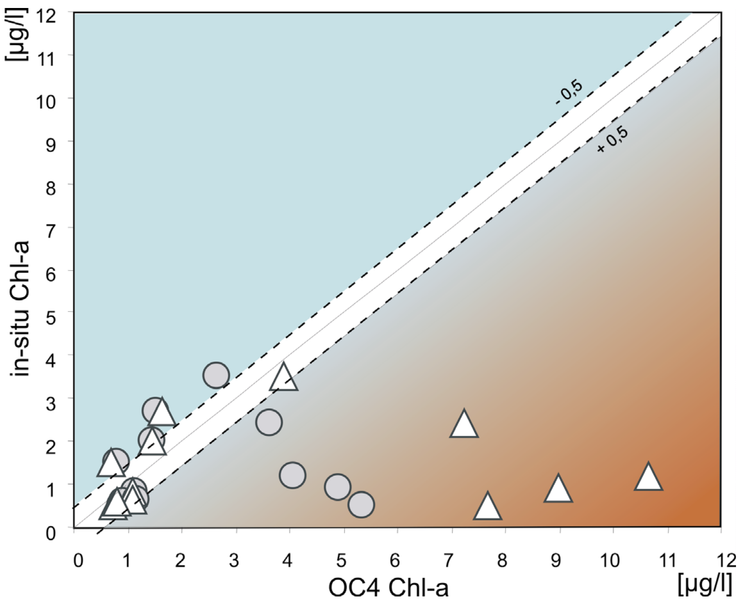

Figure 3: Comparison of modelled OC4 Chl-a vs. in-situ Chl-a data. In-situ data are CONTINENT cruise data [15/07-24/07/2001]. Circles and triangles show two different atmospheric corrections [19/07/2001]. Triangles represent OC4 chlorophyll after SeaDAS atmospheric correction (multi-scattering band7/8 model with NIR iteration) with correct air pressure adaptation. Circles represent OC4 chlorophyll after a modified atmospheric SeaDAS-correction with the MUMM tool.

Therefore, one has the problem that the main optically visible water constituents (phytoplankton, SPM, CDOM) in Lake Baikal are interacting in the water-leaving signal. As a solution, the PC bands of the atmospherically corrected SeaWiFS data after MNF processing are assumed to show the separation of the optical main contributors. In the PC1 Series, the Eigenvector 1 loadings heavily weight the contributions of variations in the SeaWiFS Band 1 (blue), which we infer is linked to the short wave length absorption by CDOM and in the SeaWiFS Band 3 (green) and

Band 4 (green-yellow), which may be indicative of the scattering by organic and inorganic suspended matter. Therefore, the PC1 is assumed to describe the different concentrations of suspended and absorbing matter. Because the loading of the PC4 is maximal for the second blue SeaWiFS band (chlorophyll absorption at around 440 nm), the PC4 is interpreted to be a good estimator of the phytoplankton component. The PC image data from 19/07/2001 shown in Figure 4 are colour coded according to our field data from 2001 and are used for semi-quantitative analysis.

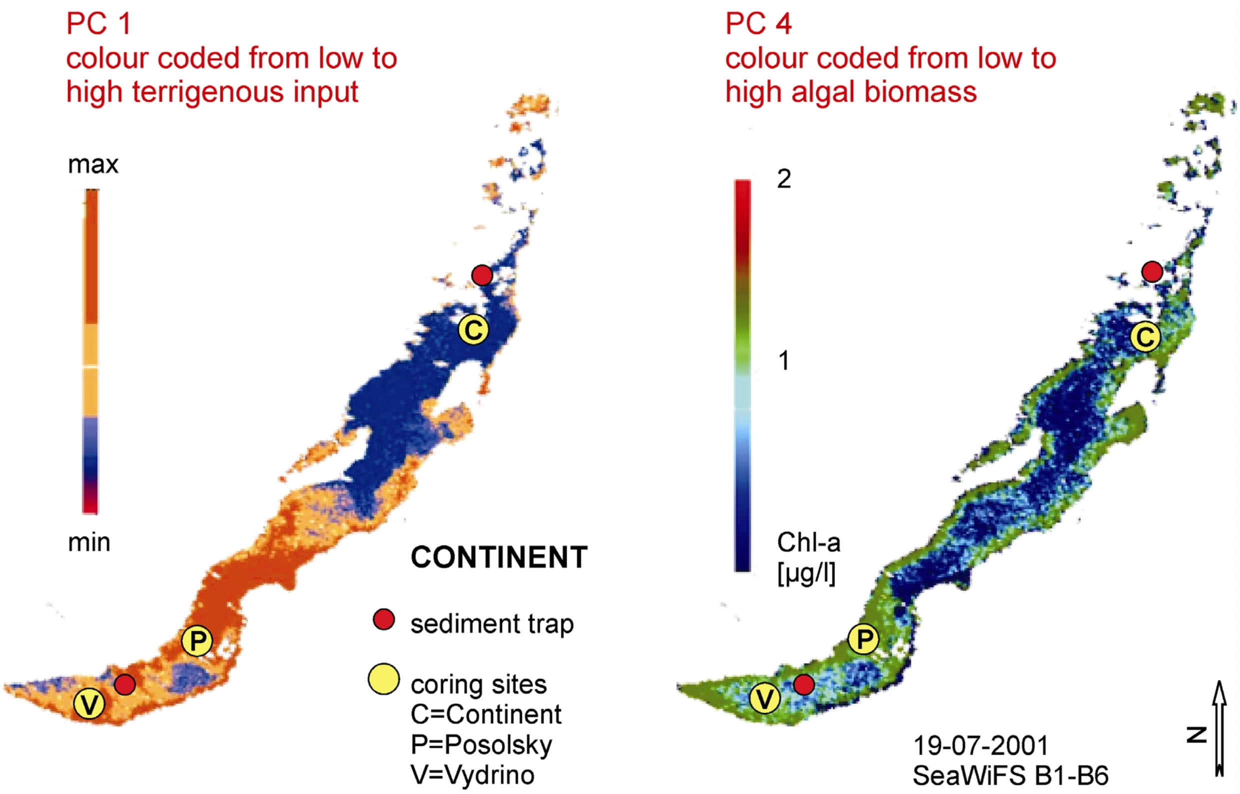

Figure 4: Colour coded maps of PC1 and PC4 loadings, date: 19/07/2002. The PC1 is assigned to show semi-quantitatively the fluvial input, the PC4 shows the distribution of phytoplankton biomass.

Analysing the SeaWiFS R_{RS}, Chlorophyll and PC data sets allows us to identify seasonal variations and to divide Lake Baikal into different bio-optical provinces. First of all, in May when the North Basin is still under ice cover, the Central and South Basins are influenced by the fluvial input from the Selenga and local mountain rivers. The Selenga River inflow is distributed along the western coastline towards the Central and South Basins. According to the satellite data, the coring site 'Posolsky' is inter- and intra- annually highly influenced by the Selenga River input. This is supported by a high sedimentation rate in the 'Posolsky' sediment core (18). Between June and July, a horizontal homogeneity can be observed. From late July to August, a strong lateral heterogeneity develops with oligotrophic and mesotrophic eddy formations and phytoplankton blooms. There is considerably less fluvial input in the South and Central Basins, with the exception of heavy storm events. The coring site 'Vydrino' is obviously strongly influenced by discharge from the local mountain rivers. Spectral information from the SeaWiFS data indicates significant cyano-bacterial picoplankton development in August 2001, and from the end of July to August 2002, which is supported by field data from July 2002 (18). Around the Selenga delta, the waters can be classified by SeaWiFS data analyses as mesotrophic and are highly influenced by fluvial input. The shallower Strait of Maloe More behaves as a mesotrophic to eutrophic water body during these seasons.

Within the central eddies of the North Basin, the trophic state is very low and represents the most oligotrophic waters. The northern sediment trap, from which the limnological record from the North Basin is referred, is placed within this oligotrophic environment. In contrast, the Eastern coast of the North Basin is assigned from OC satellite data to bear constantly (inter- and intra-annual) more phytoplankton biomass in patchy and heterogeneous patterns. The coring site 'Continent' that resolves the paleoclimatic conditions for the North Basin, is situated here. This further shows that the correlations between CONTINENT core records and sediment trap findings must be done with great care.

CONCLUSIONS AND OUTLOOK

In paleoclimate studies, the interpretation of selected climate proxies, such as diatoms, pigments, biomarkers, carbon and clay material in marine and liminic sediment cores, is preferably supported by present-day data. Remote sensing OC data provide valuable information about bio-limnological and geochemical conditions of the water body under investigation. Within the paleoproject CONTINENT, the SeaWiFS data reveal the patterns of terrigenous input into Lake Baikal and the dynamics of phytoplankton biomass.

The optically visible water constituents that predominantly vary the light-penetration depths in the Lake Baikal water body are the SPM and CDOM. By MNF analyses, even the phytoplankton optical signal can be extracted from the fluvial influenced surface waters of Lake Baikal. PC time series of the SeaWiFS data set show semi-quantitatively the terrigenous input and phytoplankton distribution, which in turn reveals those influences on the CONTINENT coring sites.

After an enhanced SeaDAS atmospheric correction, combined with the MUMM tool, the derived OC4 Chl-a values in the pelagic zone are in good agreement not only with the CONTINENT ground truth data, but also with the long-term observation data values reported in literature (2,20) (0.5-1.5 µg/l Chl-a). For terrigenous influenced surface waters of Lake Baikal, the OC4 Chl-a values are considerably overestimated. As a solution, we will develop a look-up table approach, similar to the OC5 (21). In addition to the chlorophyll field cruise and sediment trap data, the SeaWiFS OC4 Chl-a pigment concentrations will be incorporated into the CONTINENT water column transfer model for Lake Baikal.

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