Originally published as:

Heim, B., Oberhänsli, H., Fietz, S., Kaufmann, H. (2005): Variation in Lake Baikal's phytoplankton distribution and fluvial input assessed by SeaWiFS satellite data. - *Global and Planetary Change*, 46, 1-4, 9-27

DOI: 10.1016/j.gloplacha.2004.11.011.

Variation In Lake Baikal's Phytoplankton Distribution And Fluvial Input Assessed By
SeaWiFS Satellite Data

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ABSTRACT

The current behaviour of selected climate proxies in Lake Baikal was assessed by remote sensing analyses of 'Sea viewing Wide Field of view Sensor' (SeaWiFS) satellite data.

Suitable proxies include optically visible water constituents such as phytoplankton, suspended terrigenous matter and yellow substance. These limnological parameters reflect the present day climate bioproductivity and the river discharge in the catchment area.

A biological and geochemical ground truth data set for Lake Baikal was established with the help of members of the paleoclimate project CONTINENT. For processing the SeaWiFS satellite data, the atmospheric correction was adapted to the case of Lake Baikal. Chlorophyll as a proxy for phytoplankton was quantified using global NASA ocean colour algorithms OC2 and OC4. In cases of no optical interferences by terrigenous input, the calculated chlorophyll concentrations in clear pelagic waters were within $\pm 30\%$ accuracy with the CONTINENT cruise data during the summers of 2001 and 2002. Within this range of accuracy, the SeaWiFS time series will be able to show the seasonal variations of chlorophyll of specified bio-optical provinces of Lake Baikal and of CONTINENT sites. In this study, the suspended matter as a proxy for the terrigenous input was calculated according to an empirical algorithm using ground truth data in the time frame of flooding events in summer 2001. The approach chosen correlates the suspended matter concentration with the remotely sensed parameter of 'attenuation coefficient' to account for the organic-rich terrigenous input that originates from the swampy watersheds.

Seasonal and spatial information that is provided by the analyses of the SeaWiFS satellite data will assist paleoclimate researchers to interpret the autochthonous and allochthonous influences at the CONTINENT coring sites.

Key words: Lake Baikal, Remote Sensing, SeaWiFS, Chlorophyll, Suspended Matter

1. INTRODUCTION

Within the ‘High-resolution CONTINENTal paleoclimate record in Lake Baikal’ (CONTINENT) Project, funded by the European Union, sedimentary records from several locations in Lake Baikal are exploited for high-resolution paleoclimate studies. The record of the CONTINENT sediment cores (spanning potentially 150 000 years) at three sites within the lake (Charlet et al., this issue) and the multi proxy approach of the project provide unique opportunities to understand the Late Quaternary climate history of the Earth. However, in order to interpret the biogenic and silico-clastic records in the paleosediments more comprehensively, the present day formation of these climate proxies within Lake Baikal needs to be investigated. The interdisciplinary approach allows the examination of the present day bio-limnological and geochemical conditions of Lake Baikal, as well the processes occurring in the water column and the catchment. Sequential sediment trap data from the South and the North Basin, as well as field data provide information on the lake's phytoplankton and bioproductivity, on the terrigenous input into the lake and on the geochemistry.

The goal of this study is to show the potential of high spectral resolution satellite data to map the phytoplankton distribution and the terrigenous input into Lake Baikal.

Previous investigations on water clarity and suspended matter using operational satellite data were carried out e.g. by Bukata et al. (1974), Klemas et al. (1974), Munday (1974), Munday and Alfoeldi (1979), or Lillesand et al. (1983). They used Landsat-Multispectral Scanner (MSS) data, but their research was restricted to turbid, eutrophic lakes. The challenge then was to extract not only relative turbidity, but to estimate the main phytoplankton pigment (chlorophyll; (chl-a)) from the satellite data of the Landsat sensors MSS, TM and ETM+ (Yacobi et al. 1995, Mayo et al. 1995). While these land focused sensors provide high spatially resolved information, the limited radiometric and spectral resolution of these sensors

in the visible wavelength range are not suitable for analysing clear water bodies. The average errors of chlorophyll derivation in the case of land-focused sensors are high for existing algorithms, from $\pm 10 \mu\text{g l}^{-1}$ up to $\pm 20 \mu\text{g l}^{-1}$ chl-a (Burgess, 2003). In cases that use advanced techniques such as the spectral unmixing method in the Mecklenburg Lake district (Germany) (Thiemann and Kaufmann, 2000), the accuracy range is about $\pm 10 \mu\text{g l}^{-1}$ chlorophyll.

Due to the limited spatial resolution (1 km^2 per pixel) of the first Ocean Colour Sensor, the Coastal Zone Scanner (CZCS), launched in 1987 by NASA, water quality monitoring strategies for inland water bodies are mainly based on hyperspectral airborne scanner data. Hyperspectral approaches provide lake maps of water clarity, suspended matter concentration, chlorophyll and dissolved organic carbon (DOC) concentration (Dekker 1993, Heege 2000, George and Malthus 2001, Kallio et al. 2001, Keller 2001, Koponen et al. 2002, Thiemann and Kaufmann 2002, Kloiber et al. 2002). The chlorophyll algorithms for these generally eutrophic inland water bodies are principally based on the stable and significant reflectance features in the red and the near infrared wavelengths. In contrast, the water-leaving radiances of clear water bodies are naturally restricted to the blue and the green wavelength range due to the reduced contribution of scattering processes on particles (i.e. phytoplankton, detritus, minerogenic particles). The red to near infrared algorithms used for water quality investigations of eutrophic lake water bodies are therefore not applicable for clear water bodies, such as Lake Baikal.

The marine chlorophyll algorithm development for oligotrophic, pelagic waters (Morel and Gordon 1980, Gordon and Morel 1983, Stumpf and Tyler 1988, Gitelson et al. 1994) is performed with radiometrically highly resolved Ocean Colour satellite data, supported by high spectral resolution in the blue and green spectral regions. The chlorophyll algorithms were designed for clear pelagic 'case 1 waters' (Jerlov, 1978), in which the phytoplankton is the main optically relevant component, and other water constituents such as suspended matter and yellow substances are low in concentration and directly correlated with the chlorophyll

concentration. New powerful generations of high spectral resolution satellite sensors with a very high radiometric sensibility (SeaWiFS (NASA), MODIS (NASA), MERIS (ESA)) were launched in the late 1990s. Recent investigations (e.g. Ruddick et al. 2000, Koponen et al. 2002, Moore et al. 1999) focused on the optically more complex waters, ‘case 2 waters’ (Jerlov, 1978), in which the optically important water constituents may not be correlated, such as in coastal waters and semi-enclosed seas and large inland water bodies. So, while experimental algorithms for the calculation of chlorophyll and suspended matter concentrations are based on linear regression of spectral features according to field measurements (Kahru and Mitchell 1999, Froidefond et al. 1999, Froidefond et al. 2002), advanced techniques have been developed to separate the optically interfering and uncorrelated water constituents, such as analytical inverse modelling using neuronal network techniques (Doerffer and Fischer 1994, Hoogenboom et al. 1998, Schiller and Doerffer 1999, Heege and Fischer 2004) and principal component inversion (Neumann et al 1995, Krawczyk et al. 1996).

Perhaps one of the most important, yet complex tasks refers to the atmospheric correction of satellite data. Normally in the case of clear water-body targets, more than 99 % of the radiometric signal that is scanned by the satellite sensor originates solely from the atmospheric contribution and specular reflection of sky radiance at the air-water interface. Therefore, the quality of the extraction of limnological parameters from satellite data is highly dependant on the atmospheric correction process. Defined standard atmospheric correction methods exist for the marine environment such as in the ‘SeaWiFS data analysis system’ SeaDAS (McClain et al., 2000). Recently, Knobelspiesse et al. (2000) developed a tool within SeaDAS for atmospheric correction over inland water bodies (Lake Superior (USA)). Knobelspiesse et al. (*ibid.*) extrapolated atmospheric parameters that were calculated above clear water areas towards turbid lake areas. The atmospheric correction method proved to be successful in the green wavelength range ($\pm 5\%$ for SeaWiFS bands 3 to 6), but still failed for the important blue wavelength range (SeaWiFS bands 1 and 2). An Ocean Colour data

processing for continental inland water bodies, which will be used as satellite data standard processing (i.e. for MERIS data), was accomplished by Vidot and Santer (2003) using Lake Balaton (Hungary) and Lake Constance (Germany) as test sites.

For Lake Baikal, the first remote sensing studies used information from ‘Advanced Very High Resolution Radiometer’ (AVHRR) satellite data in the thermal wavelength range (3.6-3.9 μm ; 10.3-11.3 μm ; 11.5-12.5 μm) (Gitel’zon et al., 1991; Bolgrien et al., 1992; Evans et al., 1992; Bolgrien et al., 1995; Semowski et al., 1998; Semowski et al., 2001) and radar data sets (ERS-1) for water body circulation studies (Semowski et al., 1999c). For optical remote sensing studies of lake ice cover and ice types, AVHRR data (Mogilev et al., 1999; Semowski et al., 2000) and satellite data of the ‘Along Track Scanning Radiometer’ (ATSR) (Lawrence et al., 2000) have been used. Physical investigations of optical properties of Lake Baikal by Russian authors (e.g. Sherstyankin 1975), including the spectral composition of upwelling and downwelling irradiance, concentrated on studies of the under-water light field under ice and snow cover and on specific optical properties of deep water layers. Semowski (1999a) first conducted remote sensing studies of Lake Baikal’s water constituents with satellite data in the visible wavelength range. His study on the visible bands of the AVHRR was limited by a land surface adapted atmospheric correction approach, which did not result in an applicable remote sensing chlorophyll algorithm. Instead, Semowski (1999b) was the first to define the bio-optical parameters for Lake Baikal to simulate the underwater light-field. This bio-optical model for Lake Baikal performs well in simulating the vertical optical structure, which was validated with in situ attenuation depth profiles of Sherstyankin in the South Basin of Lake Baikal (Semowski 1999b). Semowski further concluded that bio-optical modelling in the South Basin of Lake Baikal has to account for its ‘yellow substance’ content.

‘Yellow substance’ is a limnological term that is applied to a variable mixture of different groups of absorbing and fluorescing water constituents, after the concept of ‘Gelbstoff’, first introduced by Kalle (1949). Humic, fulvic and some hydrophilic acids are the main coloured constituents of dissolved organic carbons. However, the bio-optical properties of dissolved

and particulate organic matter in the natural aquatic environment are not yet well understood (e.g. Yacobi et al., 2003).

This paper presents the first remote sensing study of Lake Baikal's surface waters using optical satellite data with high spectral resolution. The SeaWiFS satellite data show the seasonal distribution pattern and intensity of terrigenous input and the spatial and seasonal variations of phytoplankton. The results are then related to the autochthonous and allochthonous influences with regard to the coring sites 'Continent', 'Posolsky', 'Vydrino' (Charlet et al., this issue).

2. Lake Baikal

Lake Baikal located in south-eastern Siberia (51-56° N, 104-110° E) and is the most voluminous inland water body on earth (Shimaraev et al., 1994). The lake is oligotrophic and has a mean chlorophyll pigment concentration in summer from about 0.5 to 2.5 $\mu\text{g l}^{-1}$ chl-a (Kozhova and Izmeteva, 1998). Within bays, along the coast, and near the Selenga Delta the water may carry up to 5 $\mu\text{g l}^{-1}$ chl-a in late summer. Baikal water is extremely transparent, with Secchi depth measurements in pelagic waters showing values up to 40 m in June and still up to 20 m in July when phytoplankton is more abundant. The main phytoplankton blooms (up to 10 $\mu\text{g l}^{-1}$ chl-a) develop in early spring in turbulent waters under the ice cover (Kozhova and Izmeteva, 1998). In the South Basin, the ice usually establishes in early January and breaks up in May, although the break-up time for the North Basin can be as late as in June.

River discharge and shore erosion, aeolic and ice transport result in a horizontally heterogeneous pattern of dissolved and particulate terrigenous matter in Lake Baikal. 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 (Figure 1). The Barguzin River discharges into the Central Basin while the Upper Angara River feeds into the very north of the North Basin. The seasonally controlled input of humic substances into the lake can be high, e.g., 200 to 500

$\mu\text{M C}$ (2.4 to 6 mg l^{-1}) DOC, and 100 $\mu\text{M C}$ (1.2 mg l^{-1}) POC (particulate organic matter) downstream from the Selenga and the Barguzin rivers (Yoshioka et al., 2002). During periods of high terrigenous input, Lake Baikal may be seasonally and locally assigned to ‘case 2 waters’ according to the classification of Jerlov (1978) due to the significant optical contribution of non-correlated terrestrial matter. The dissolved and particulate organic matter originates from swampy areas and bogs within the Lake Baikal watershed. Yoshioka et al. concluded that the main origin of DOC in Lake Baikal, even in pelagic waters, seems to be terrestrial because the $\delta^{13}\text{C}$ values of DOM in the lake and in the tributaries are comparable.

3. MATERIAL AND METHODS

3.1. GROUND TRUTH DATA

3.1.1 *Field Expedition*

Data collection during field expeditions were planned to take place in June and July when wind conditions across Lake Baikal are moderate. However, these months have one drawback for remote sensing applications because of frequent cloudy, foggy, and rainy weather conditions. Despite weather limitations, a set of ground truth data has been collected during the CONTINENT ship cruises in summers 2001, 2002 (Table 1), and 2003 in the Southern, Central, and North Basins (Figure 1). Special attention was paid to the lake regions most influenced by terrigenous matter input by establishing transects from the vicinity of the large tributaries, such as the Barguzin and the Selenga River inflows, into the pelagic regions of the lake. Investigations were also made in the catchment area of the Selenga river: surface water (from 0.5 m depth) was sampled from the Mongolian border along the course of the river through the Khamer Daban mountain range towards the Selenga Delta (Figure 1).

Limnological parameters that are of interest for remote sensing studies were derived by analysis of phytoplankton composition and pigment concentration of chlorophylls and carotenoids, (Fietz and Niklisch, 2004; Fietz et al., this issue), on DOC (pers. Rosell-Melé,

2003; pers. Borovec, 2004), and on suspended matter concentration. The water samples were taken from 1 m, 5 m, and 30 m depths, plus additional depths if the fluorescence probe measurements indicated phytoplankton subsurface maxima at these depths. The sampled waters were immediately filtered on board the ship for the pigment and the DOC analyses, and for the yellow substance absorption measurements. The samples for analysis of pigment concentration were filtered on 0.7 µm pore Whatman GF/F-filters and were analysed using HPLC (Fietz and Niklisch, 2004). Phytoplankton and autotrophic picoplankton were counted under light and epifluorescence microscopes (Fietz and Niklisch, 2004). The samples that were filtered on a 0.2 µm pore cellulose acetate filters were analysed for DOC (pers. Rosell-Melé, 2003) using the high temperature catalytic oxidation method. Suspended particulate matter (SPM) concentration was determined using the gravimetric method: the samples were filtered on board ship on preweighed, predried (95° C) cellulose-acetate filters and dried before storage. Yellow substance absorption was measured relatively to pure water after filtration through 0.7 µm pore Whatmann glass fibre filters in a 5 cm cuvet, using a Spectroquant NOVA60 (Merck).

Information on the under-water light field was acquired spectrometrically using field spectrometer measurements (GER 1500, Geophysical & Environmental Research Corporation, New York, USA) that were performed at approx. 25 stations during each ship cruise in 2001, 2002, and 2003 (Heim et al., 2003). The underwater light field was measured within a depth range of 1 to 5 meters based on the Smith and Baker (1983) method; simultaneously, the down-welling incident irradiances $E_{\text{down}}(?) [0+]$ were measured onboard ship. These irradiance values were transferred below the water surface after Gordon et al. (1988a) using:

$$E_{\text{down}}(?) [0-] = E_{\text{down}}(?) [0+] * 0.96 \quad (1)$$

where the retrieved water volume reflectance, $R_{\text{vol}}(?)$, is the diffuse reflectance $E_{\text{up}}(?) [0-] / E_{\text{down}}(?) [0-]$ directly at the air/water interface. Another standard parameter, the Remote Sensing Reflectance, $R_{\text{RS}}(?)$, was calculated by:

$$R_{RS}(?)[0+] = (E_{up}(?)[0-] * 0.52 / E_{down}(?)[0+]) / Q \quad (2)$$

where Q (the ratio between upwelling radiance and upwelling irradiance) is assumed to be equal to 5 (Mueller and Austin, 1995), and the ratio between below and above water radiance is assumed to be equal to 0.52 (Gordon et al., 1988a).

3.1.2 Geo-Biolimnological Data Set

Fietz and Niklisch (2004) assessed phytoplankton pigment composition of the water samples and phytoplankton assemblages for unstratified and stratified conditions. Chlorophyll concentrations in the pelagial waters ranged from 0.3 to 3.5 $\mu\text{g l}^{-1}$ chl-a, with average concentrations for the central part of the North Basin of 0.4 to 0.7 $\mu\text{g l}^{-1}$ chl-a, for the Central Basin of around 0.8 $\mu\text{g l}^{-1}$ chl-a, for the South Basin of around 1.2 $\mu\text{g l}^{-1}$ chl-a, and for the areas influenced by the Selenga input to around 2 $\mu\text{g l}^{-1}$ chl-a (pers. Fietz, 2001, 2002, 2003). The dominant groups incorporated Bacillariophyceae plus Chrysophyceae, Chlorophyta, cyanobacterial picoplankton, and Eustigmatophyceae (Fietz et al., this issue). This phytoplankton composition varied within the Lake Baikal water body depending on latitude (Fietz and Niklisch, 2004). As the remote sensing reference, chl-a values of each sampling point have been averaged over a depth up to 30 m, equivalent to the extent of Secchi depths in Lake Baikal.

The Selenga River carried a mean suspended matter load of approx. 15 mg l^{-1} along its course in June/July 2001, while up to ca. 22 mg l^{-1} SPM river load reached the Selenga Delta area. Data collected during the 2001 ship cruise exhibited the widest SPM concentration range due to flooding events in the Lake Baikal area and served as the calibration database for the SPM algorithm development. SPM concentrations in 2001 varied from 0.2 mg l^{-1} for the central region of the North Basin, to average concentrations from 0.4 to 1 mg l^{-1} for the Central and the South Basins and up to 5 mg l^{-1} around the shallow waters of the Selenga Delta. In summer 2002 and 2003, the hydrological conditions were unexceptional (unlike the flooding which occurred in summer 2001) and there was no influence of terrigenous input in the

pelagic areas. Table 1 gives an overview of the range of chlorophyll and SPM measured during the CONTINENT Cruises 2001 and 2002.

In summer 2002, DOC measurements (0.2 μm filter pore size) for the pelagic waters showed values lower than 0.5 mg l^{-1} for the Northern and Central Basins in 2002, but were up to 2 mg l^{-1} DOC in several regions of the South Basin (pers. Rosell-Melé, 2003). In July 2003, DOC concentrations were on average 1.2 to 1.4 mg l^{-1} (0.4 μm filter pore size) in the pelagic waters of the Southern and the Central Basin (pers. Borovec, 2004). The yellow substance absorption measurements of the cruise in 2002 served as an estimate of the absorption at 440 nm. However, the quality of the spectral laboratory measurements on board the ship was not good enough to evaluate slope and exponent values.

3.2. SATELLITE DATA

3.2.1 *SeaWiFS*

The SeaWiFS instrument is on board the Orbimage2 satellite on a 705 km circular orbit with a revisit time of one to two days. The optical scanner records the reflected radiances from the atmosphere and the earth's surface in eight spectral bands (Table 2). The transmitted High Resolution Picture Transmission (HRPT) satellite data have a spatial resolution of a nominal pixel size of 1.3 km^2 at nadir. From June 2001, the SeaWiFS receiving station in Ulaanbaatar (Mongolia) provided us with HRPT data of SeaWiFS, which were processed using the SeaDAS (NASA) software (McClain et al., 2000). The HRPT Level 1A (unprocessed) SeaWiFS data from Ulaanbaatar were transferred to Level 1B (radiometrically converted) products, the reflectances at the top of the atmosphere, R_{toa} . Table 2 gives an overview on the SeaWiFS acquisition data that were used in this study.

3.2.2 *Atmospheric Correction*

The radiances measured at the sensor are typically an order of magnitude larger than the water-leaving radiances carrying the optical information of the upper water column. This is due to the scattering of solar radiation and reflected radiation by air molecules, aerosols, and by the lake's surface itself. The removal of these atmospheric and surface effects is called atmospheric correction. The reflectances R_{TOA} have at first to be corrected for the atmospheric molecular contribution of Rayleigh scattering and the ozone and oxygen absorption. Then, Mie scattering by specific aerosol assemblages and the multiple scattering between aerosols and air molecules have to be corrected according to established aerosol climatologies. With this kind of atmospheric correction, new geophysical output parameters of Level 2, the remote sensing reflectances R_{RS} , are produced, and in the case of water remote sensing, these are the water-leaving reflectances. Without a highly accurate atmospheric correction, it is not possible to derive chlorophyll and suspended matter values within realistic concentration ranges in the case of clear water bodies. This problem is well known, especially over inland and coastal water bodies (e.g. Ruddick et al., 2000; Jørgensen, 2004) due to complex atmospheric composition and areas of non-zero water leaving radiances in the near-infrared.

The average barometric pressure values of the respective summer months were applied, to account for the continental air pressure oscillation in Southern Siberia. Changes in air pressure are related to changes in concentration of air molecules (nitrogen, oxygen, etc.). The discrepancy between the actual low-pressure values in July to the barometric pressure calculated using a digital elevation model (approx. 10 mbar) accounts e.g. for $-0.05 \text{ W m}^{-2} \text{ nm}^{-1} \text{ sr}^{-1}$ in the Rayleigh radiances in SeaWiFS band 1 (412 nm).

The atmosphere over Lake Baikal is very transparent with low aerosol concentrations over the Central and the North Basins (van Molderen et al., 1996). The volume fraction of large biogenic aerosols ($> 2\mu\text{m}$) covers ca. 30 % in the summer aerosol assemblage (Matthias-Maser et al., 2000). The atmospheric processes of cyclonic and anticyclonic air circulation forces upwelling in the centre of the lake basins, and this in turn is accompanied by wide areas of high humidity (90 %), humidifying of aerosols, or even by advective fogs (Balin et

al., 2003). The atmospheric conditions do not reflect standard continental atmospheric conditions, which generally have a low humidity and relatively high amount of small sized aerosols.

The results of SeaDAS standard atmospheric correction were tested on HRPT SeaWiFS summer data of 2001 and 2002 using different aerosol models. The ratio of two Rayleigh corrected spectral bands ($i:j$) is indicative for the aerosol composition. This is termed the ratio $e^{(i,j)}$ of single-scattering aerosol reflectances. In SeaDAS, the ratio $e^{(7,8)}$ of the Rayleigh-corrected reflectance in SeaWiFS band 7 against the Rayleigh-corrected reflectance in band 8 is used to choose the aerosol model. An e value of approx. one refers to a so called white spectral behaviour which is caused by relatively large particles (e.g. aerosol size distribution in marine atmospheres). Large e values point at an aerosol composition typically with a dominance of small particles (e.g. aerosol size distribution in urban and rural atmospheres). Unusual large e values ($e > 1.35$) may be indicative of non-zero water leaving radiances in the near-infrared (e.g. Ruddick et al. 2000) and can be excluded since the development of SeaDAS version 4.4. The majority of SeaDAS aerosol models (coastal with different humidities; tropospheric, etc.) failed during the processing, which corrects for the Mie scattering. The SeaWiFS data in this study could be successfully processed with the parameter choice of e around 1, representing an atmosphere containing large particles.

3.2.3 Satellite Data Analyses

The atmospherically corrected satellite data were geo-referenced with the software ERDAS Imagine (ESRI). Image processing included spectral analyses, which were conducted with the image analysing software ENVI (RSI). Furthermore, using mathematical combinations of the atmospherically corrected visible SeaWiFS bands (b1, b2, b3, b4, b5, b6), it was possible to combine their multi-spectral information on an experimental basis with field data, respectively with global ground truth data sets as described below.

The phytoplankton's main photosynthetic pigment, chl-a, is generally estimated in oligotrophic water by its absorption maximum in the blue wavelength region around 440 nm. Additionally, the phytoplankton pigment groups of carotenoids and phycobillins vary the spectral shape of the radiances leaving water. Therefore, chlorophyll algorithms that are suitable for oligotrophic waters also take into account the spectral green range, using different ratio algorithms. In oligotrophic waters, there is no water-leaving signal in the red and near-infrared region, which could be evaluated for chlorophyll quantification. This is, why we have proceeded with marine algorithms for oligotrophic systems, and not with the common red/near-infrared algorithms for limnic and coastal systems. Phytoplankton composition and its pigment configuration and morphology are variable on a regional and seasonal scale, which is a major reason for discrepancies in chlorophyll calculation.

The best known and globally used NASA chlorophyll algorithms OC2 and OC4 (O'Reilly et al., 1998, 2000) have been established by linear regression analyses between the logarithm of chlorophyll concentration (global ground truth data set) and the logarithm of the ratio of two bands in the blue-green spectral range (table 4). These global band ratio algorithms achieve accuracies of $\pm 35\%$ in case 1 conditions (O'Reilly et al., 2000). Iluz et al. (2003) list a set of best-fit functions of the reflectance ratio R_{Rs443}/R_{Rs555} that have been used by different authors for studies in oligotrophic waters. Their own empirical coefficients in their SeaWiFS satellite data investigations of the oligotrophic Gulf of Eilat (Red Sea) showed different values each year during three successive years. We calculated chlorophyll concentrations using OC2 and OC4 chlorophyll algorithms. Additionally, we tested coefficients for eleven ratio algorithms from several sources, which are described in Iluz et al. (2003) as well as a ratio algorithm derived from the ground truth data set in 2002 ($n = 12$) (table 4).

The physically accepted principle for standard empirical SPM algorithms (e.g. Tassan, 1994; Peters et al., 1999) holds that for increasing concentrations of suspended matter the reflectance increases in the visible and near infrared spectrum. Commonly, SPM algorithms are derived from a linear regression between the peak of the water-leaving reflectances and

the *in situ* SPM data set (e.g., Jørgensen, 2000; Binding et al., 2003), while the height of the peak may be normalized using band 8 (850 nm) (Doxaran et al., 2002). In terms of empirical algorithms, the red to green reflectance ratio band 5 (555 nm) / band 6 (650 nm) is expected to perform for SPM algorithms, reflecting the shift of the peak in the reflectance spectra from green to red with increasing SPM concentrations (Mitchelson-Jacob, 1999, Froidefond et al., 2002). The reason is that the change in height of the water-leaving reflectance in the green wavelength range plateaus to match a logarithmic distribution above a given turbidity (e.g. in case of SPM higher than 5 mg l⁻¹ (Froidefond et al. 2002) while similar results were also found by Stumpf and Pennock (1989); Ritchie et al. (1990); Moore et al. (1999). Above this turbidity threshold, the height of reflectances, first in the red, then in the near infrared wavelength range, rises with increasing SPM concentrations. Commonly, all these empirical SPM algorithms, which are based on the principle of rising reflectances in field spectrometer measurements and satellite data, originate from coastal areas of the Mediterranean, Atlantic Ocean, and the North Sea.

There still exists a large uncertainty from the optical properties of the *in-situ* state of suspended matter (due in part to a lack of detailed field observations to derive accurate parameterizations of processes such as flocculation, re-suspension, etc). Results of investigations in optical turbidity measurements include findings that optical variations (of measurements of attenuation, scattering, reflection) depend not only on the concentration, but significantly as well on the shape, size and composition of suspended particles (Clifford et al. 1995; Gippel, 1988) as on the coloured dissolved matter content (Malcolm, 1985). Therefore, the optical relationships may be assessed *in situ* as trends of different water bodies (e.g. Packman et al. 1999).

In this study, we involved the optical parameter ‘diffuse attenuation coefficient’ as a sensible optical coefficient, which combines the absorbing and scattering processes (Kirk, 1976). The algorithm of the diffuse attenuation coefficient at 490 nm (K₄₉₀) is based on calculations on empirical coefficients from a global data set (O’Reilly et al, 2000):

$$K_{490} = K_{w490} + 0.15645 \times ([\text{band 4}] / [\text{band 5}])^{-1.5401} \text{ in } [\text{m}^{-1}] \quad (3)$$

where K_{w490} is the diffuse attenuation coefficient for pure water, while the SeaWiFS band input data band 4 (510 nm) and band 5 (555 nm) are the atmospherically corrected water-leaving radiances. This remotely sensed parameter was related to a limited set of CONTINENT ground truth samples representing terrigenous influence.

4. RESULTS

4.1. SEAWIFS DATA ANALYSES

4.1.1 *Quantitative Results*

Lake Baikal is not influenced by strong surface currents, as is the case for marine coastal waters. Therefore, we used the ground truth data set of chlorophyll and suspended matter concentrations that originate from a storm-free cruising period between 17/07/2001 to 24/07/2001 as the validation data set for the cloud-free parts of SeaWiFS acquisitions on the 02/07, 04/07, 16/07, 18/07, 19/07 (19/07 as the only acquisition with less than 30 % cloud cover), 21/07, and 26/07/2001. In 2002, despite foggy and high rainfall weather conditions, the ground truth data between 05/07 to 15/07/2002 were used to evaluate the cloud-free parts of the SeaWiFS acquisition dates 02/07, 12/07, 13/07, 20/07, 22/07, 24/07, and 25/07/2002.

The self established empirical chlorophyll algorithm ($n = 12$) of the SeaWiFS data set from 2002 ($r^2 = 0.86$) seems not to be suitable for the data sets in 2001 ($r^2 = 0.55$), and is therefore not examined any further. One possible reason are significant differences in horizontal phytoplankton distribution (Fietz and Niklisch 2004), considering that the large water body of Lake Baikal stretches over three latitudes and therefore is regionally influenced by different meteorological and hydro-physical factors. Additionally, factors influencing the quality of OC2 and OC4 algorithms such as the carotenoid/chlorophyll ratio varied within the bio-optical provinces of Lake Baikal and showed a different average value for summer 2003 compared to the summers 2001 and 2002 (person., Fietz 2004).

Therefore, a global chl-a algorithm, which is based on a large ground truth data set, was considered to be more robust and more suitable for this study. The results in Table 5 a-c show the best collective performance for OC2 and OC4 chlorophyll algorithms in case 1 water areas, which are not influenced by terrigenous input. The calculated chlorophyll OC2 and OC4 concentrations are within an estimation error of $\pm 32 \%$ for 2001 and $\pm 27 \%$ for 2002 (when in 2001, only the cases of clear pelagic waters is considered). The best of the set of eleven fitting coefficients for case 1 waters listed in Iluz et al. (2003) was found in the coefficients of Gordon et al. (1983) (Table 4 and 5 c). Tables 5 a and b show the accuracy and average deviation for the calculated chlorophyll concentrations of SeaWiFS acquisitions in the time frame of the CONTINENT cruises in 2001 and 2002. Figure 2 shows the scattergram of calculated OC2 chlorophyll (case 1) against the ground-truth pigment concentrations for 2001 and 2002.

Despite the high quality for the data sets in 2002, the comparison of ground truth data with calculated chlorophyll data shows that there is considerable chlorophyll overestimation for several data points in 2001 (Table 4 a). These are the samples in terrigenously influenced areas of the lake, where there is considerable absorption in the blue-wavelength range by yellow substances (e.g. around the Selenga Delta and Barguzin Bay). In the case of high organic fluvial terrigenous input, the absorption in the blue to green spectral wavelength range is caused by yellow substance and by phytoplankton. Because the standard chlorophyll algorithms do not have the capability to distinguish between yellow substance and phytoplankton absorption, they overestimate chlorophyll concentrations in these waters considerably. In contrast to clear pelagic waters, the chl-a output for fluvial influenced areas seems to be amplified by a factor of 3 to 5. Pozdnyakov et al. (2003) reported similar findings in a study on coastal waters of the White Sea. They estimated a three-fold chlorophyll-model overestimation that is caused by the optical interactions of high organic terrestrial input.

Considering that there are regional and seasonal changes in pigment composition in Lake Baikal, as described above, we decided to rely on the robust global OC2 chlorophyll

algorithm for processing the SeaWiFS acquisitions in the months of June, August and September 2001 and 2002. To exclude wrong processing in case 2 type waters, a ‘mask of terrigenous input’ is applied which is described in the following section. Due to case 2 conditions, i.e. widespread terrigenous influence during the snow melting season, acquisitions of the SeaWiFS time series in May were not evaluated for chlorophyll concentration.

According to ground truth and SeaWiFS spectra for 2001 to 2002, the green peak of the highly transparent waters of Lake Baikal is commonly located at SeaWiFS band 4 (510 nm). However, the absorbing and scattering optical activities in the presence of the terrigenous input shift the peak position towards SeaWiFS band 5 (555 nm). The waters in the observable cloud-free parts of the SeaWiFS acquisitions are not as turbid, so there does not occur a spectral shift in the peak position of the SeaWiFS spectra from SeaWiFS band 5 (555 nm) to band 6 (650 nm). This observed spectral behaviour of the peak shifting from 510 nm to 555 nm in the 2001 to 2002 SeaWiFS data sets of Lake Baikal can be simulated and reproduced using the bio-optical software ‘Water Colour Simulator’ (WASI) (Gege, 2004). This described spectral behaviour has been similarly shown from previous historical limnological studies. For example, Thomson and Jerome (1975) stated that clear waters of Lakes Ontario and Superior (USA) had a dominant wavelength of 490-530 nm, biologically more productive waters had a dominant wavelength of 550-560 nm, and waters with heavy sediment loadings had a dominant wavelength of > 565 nm.

This spectral shift is regarded as an indicator for the terrigenous input and can be used by applying a ‘mask of terrigenous input’ on the atmospherically corrected SeaWiFS data defined by reflectance ratio values of R_{RS510}/R_{RS555} below 0.9. This is in accordance to the SeaWiFS study done by Froidefond et al. (2002) in the Bay of Biscay, who observed chlorophyll overestimation (due to terrigenous input) in cases of R_{RS490}/R_{RS555} below 1.

When calculating standard suspended matter products (Jørgensen, 2000; Binding et al., 2003), the high organic fluvial input in Barguzinski Bay and local fluvial input into the South Basin shows inverse grading with lowest calculated SPM concentrations towards the river inlets.

Field spectrometer measurements and ground truth data show that, for several bio-optical provinces of Lake Baikal, the assumption that the suspended matter concentration correlates with the height of the reflectance peak is not appropriate (Figure 3). This may be because absorption processes become dominant in highly organic waters and can reduce the water-leaving reflectance sufficiently to mask scattering by even relatively high quantities of suspended particles.

The approach chosen in this study quantifies the SPM concentration with the attenuation coefficient value instead of the water-leaving reflectance value. The limited set of in situ terrigenous particulate samples ($n = 6$ in 2001) was linked to SeaWiFS K490 data by linear regression, leading to:

$$\text{SPM} = 9.4502 \times (0.016 + 0.15645 \times ([b4] / [b5])^{-1.5401}) - 0.6111 \text{ in } [\text{mg l}^{-1}] \quad (r^2 = 0.71) \quad (4)$$

Here, due to the very limited ground truth data set of water samples, which were influenced by terrigenous input, this is a very preliminary calculation. Nevertheless, this approach demonstrates its potential to get an adequate representation of the high organic terrigenous input in the case of Lake Baikal.

Figure 4 represents the result as concentrations of SPM (mg l^{-1}) of the 19/07/2001 acquisition. The calculated SPM concentrations correctly highlight the Selenga River and other local river distributions. The data sets in July 2001 show considerable terrigenous input especially in the South Basin and represent exceptional hydrological conditions, due to catastrophic flooding events in early July in the Northern Mongolian and the Irkutsk region.

4.2.2 SeaWiFS time series

The limnological and geochemical field data enable the bio-optical classification of water types according to which constituents (phytoplankton pigments, suspended matter, yellow substance) mainly influence the water-leaving spectral signal. Important bio-optical provinces for Lake Baikal are the pelagic clear waters, the maximal oligotrophic gyres in the North

Basin, the suspended matter-dominated Selenga river input, and the organic-matter dominated Barguzin river input.

The spatial overview of satellite data enables the interpretation of the CONTINENT sites in relation to discrete field data. In May, the North Basin is still under ice cover, while the Central and South Basins are influenced by substantial fluvial input from the Selenga and local mountain rivers. During this season, the Selenga River inflow is mainly distributed towards the South Basin along the Western coastlines and there is reduced terrigenous input into the Central Basin. Figure 5 shows the typical situation of heavy terrigenous input in times of the ice break up and snow-melt season during the month of May (2002). The terrigenous input firstly increased after the break-up of ice on the lake. Then, signals of the suspended and dissolved terrigenous material vanished quickly by the end of May/beginning of June, as the calculated SPM concentrations in the South Basin decline to levels below 1 mg l^{-1} again.

In late July and August 2001 and 2002 strong horizontal heterogeneity develops with eddy formation and phytoplankton development. There is also much less fluvial input coming into the lake from the rivers. This is associated with a change in the circulation patterns, where the relatively low fluvial inputs from the Selenga and Barguzin Rivers flow into the Central Basin.

According to the satellite data time series, the coring site 'Posolsky' is inter- and intra-annually highly influenced by the Selenga River input. Whereas, according to the distribution pattern on the calculated SeaWiFS SPM maps, the coring site 'Vydrino' is strongly influenced by the discharge from local mountain rivers, which is in accordance to the findings of Charlet et al. (this issue). At Vydrino, pollen (pers. Heumann and Demske, 2004) and heavy mineral analyses (pers. Thamó-Bozsò, 2004) of core sediments further indicate that local influences are likely to have been present on the 'Vydrino' even during early Holocene. These findings are important as biological indicators from the shallow waters of the Selenga Delta and other regions in the South Basin are different, and will have implications for how to interpret sedimentary records in these two regions.

Within the central eddies of the North Basin, the trophic state is very low, representing very oligotrophic waters. In contrast, the satellite data highlight that the east coast of the North Basin (in the region of the coring site ‘Continent’) consistently has (inter- and intra-annually) more phytoplankton in patchy and heterogeneous patterns. Again, this demonstrates that coring locations are important when considering how proxy material is distributed around the lake, before settling into the sediment archive. Data from this core form the basis for the reconstruction of paleoclimatic conditions for the North Basin. Thus, as a result of the remote sensing investigation, the correlation between the core records and the findings from the sediment-traps in respect e.g. to bio-markers and bioproductivity have to be done with great care.

In summer 2001, exceptional storm events occurred that led to catastrophic floods, manifested as high fluvial discharge signals from Selenga and local mountain rivers into Lake Baikal (see also Figure 4). Because of these floods, the optical signal of yellow substance expressed itself in wider range around the lake, with a considerable absorption in the blue and green wavelength range. This optical signal can be distinguished by the ‘mask of terrigenous input’, and persisted for a minimum of two weeks in the SeaWiFS time series. This event shows how storm conditions may influence the terrigenous signals in the sediment cores.

5. CONCLUSIONS AND OUTLOOK

For paleoclimate studies, the interpretation of selected climate proxies, such as diatoms, pigments, biomarkers, carbon, and clay material in marine and limnic sediment cores, may be validated with present-day data. The aim of this remote sensing study is to provide a spatial and temporal overview of limnological parameters such as the dynamics of phytoplankton and the allochthonous input. Global and empirical SeaWiFS algorithms have been applied to the atmospherically corrected satellite data for an estimation of chlorophyll and terrigenous suspended matter.

The calculated chlorophyll values are in good agreement not only with the CONTINENT ground truth data ($\pm 30\%$, meeting the NASA quality standard), but also with the long-term observation data values reported in literature (Kozhova and Izmeteva, 1998). For terrigenous influenced surface waters of Lake Baikal, the OC2 chlorophyll values are 3 to 5 fold overestimated. As a method for quantifying terrigenous suspended matter from the SeaWiFS satellite data, we initially found the best solution was to link our ground truth data (6 selected samples during the flooding event in 2001) to the 'diffuse attenuation coefficient' calculated from the SeaWiFS data.

The results of this paper demonstrate that it is possible to map the fluvial input and phytoplankton pigments of Lake Baikal using high spectral resolution satellite data. The actuo-sediment flux into Lake Baikal varies regionally and seasonally. The SeaWiFS SPM maps provide spatial distribution information for overview, especially in times of maximal terrigenous input during the snow-melting season, additional to the discrete cruise data that are less conclusive and restricted to the time window of the cruise.

The SeaWiFS chlorophyll time series will be combined with information on pigments (Fietz et al., this issue) and biomarkers (Russel and Rosell-Melé, this issue) to assist the interpretation of sediment trap data and develop realistic seasonal input parameters for the CONTINENT water column transfer model. The information on spatial variation will also complement other investigations, such as the primary production of Lake Baikal of Straskrbova et al. (this issue).

6. ACKNOWLEDGMENTS

We would like to thank the SeaWiFS project and the HRPT station in Ulaanbaatar, Mongolia, for the processing and providing the satellite data used in this study. This research was conducted within the project CONTINENT (supported by the European Commission under contract EVK2-CT-2000-00057). Particular acknowledgement is made to S. Fietz from the

Leibniz Institute of Freshwater Ecology and Inland Fisheries (IGB), Berlin, Germany, and to A. Rosell-Mele from the Institute of Environmental Science and Technology (ICTA), Autonomic University of Barcelona, Spain, for major assistance in the field, and for performing quantitative analyses of pigments, phytoplankton composition, and DOC. Thanks are also given to A. Nicklisch from the Humboldt University, Berlin, Germany, to V. Straskrabova and J. Borovec from the Hydrobiological Institute (HUB), Academy of Sciences of the Czech Republic, for setting up of the monitoring projects, for consultation, and for providing important data-sets. Thanks are due to A.W. Mackay, D.W. Morley, and P. Rioual from University College London (UCL), UK, for provision of data sets. Finally, many thanks are given to D. Jewson and to two anonymous referees, whose comments helped to considerably improve this paper.

APPENDIX A

Frequently Used Symbols

chl-a	chlorophyll a concentration in $\mu\text{g l}^{-1}$
d	isotopic delta value
$e^{(i,j)}$	theoretical single-scattering aerosol reflectance ratio, bands $i:j$
$e^{(7,8)}$	imposed multiple-scattering aerosol reflectance ratio, bands 7:8,
K490	diffuse attenuation coefficient at 490 nm in m^{-1}
$L(?)$	spectral radiance in $\text{W m}^{-2} \text{nm}^{-1} \text{sr}^{-1}$
n	number
r^2	R-square/coefficient of determination
$R(?)$	spectral reflectance. Frequently used variants are:
· $R_{\text{toa}}(?)$	reflectance, top of atmosphere (sr^{-1})
· $R_{\text{RS}}(?)$	remote sensing reflectance (sr^{-1})
· $R_{\text{vol}}(?)$	water volume reflectance (sr^{-1})

APPENDIX B

Frequently Used Acronyms

ATSR	Along Track Scanning Radiometer
AVHRR	Advanced Very High Resolution Radiometer
CZSC	Coastal Zone SCanner
DOC, DOM	Dissolved Organic Carbon/Matter

ENVI	Environment for Visualizing Images, software
ERDAS	Earth Resources Data Analysis System Imagine, software
ESA	European Space Agency
GER	Geophysical and Environmental Research field spectrometer
GFZ	GeoResearchCenter Potsdam, Germany
HPLC	High Performance Liquid Chromatography
HRPT	High Resolution Picture Transmission
IGB	Leibniz Institute of Freshwater Ecology and Inland Fisheries, Berlin, Germany
ICTA	Institute of Environmental Science and Technology, Barcelona, Spain
L 1A	Level 1A data, unprocessed satellite data
L 1B	Level 1B data, calibrated radiances
L 2	Level 2 data, geophysical output parameters
MERIS	Medium Resolution Imaging Spectrometer
MODIS	MODerate resolution Imaging Spectrometer
NASA	National Aeronautics and Space Administration
NOVA60	Merck photometer
SeaDAS	SeaWiFS Data Analysis System
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SPM	Suspended Particulate Matter
TM/ETM+	Thematic Mapper/Enhanced Thematic Mapper

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Table 1. Value span of ground truth data sets (CONTINENT field expeditions in 2001, 2002, and 2003)

	<i>years</i>	<i>n</i>	<i>mean</i>	<i>min</i>	<i>max</i>
chl-a [$\mu\text{g l}^{-1}$] all samples *	2001, 2002, 2003	214	1.42	0.29	4.87
chl-al [$\mu\text{g l}^{-1}$] type: pelagial *	2001, 2002, 2003	142	1.07	0.29	3.5
SPM [mg l^{-1}] type: pelagial	2001, 2002, 2003	24	0.8	0.2	1.6
SPM [mg l^{-1}] type: fluvial input	2001	6	2.8	0.5	5.1

* analysis undertaken by S. Fietz, 2004

Table 2. Sensor characteristics of SeaWiFS onboard SeaSTAR (NASA): HRPT format.

Mission (launch)	SeaWiFS (1997)
resolution [km] (area coverage format)	1.1 (HRPT)
swath [km] (area coverage format)	2801 (HRPT)
visible band numbers	1, 2, 3, 4, 5, 6
central visible wavelengths [nm]	412, 443, 490, 510, 555, 670
NIR band numbers	7,8
central NIR wavelengths [nm]	765, 865
Orbit node (inclination)	12:00 noon + 20 min (descending)
Orbit type (height [km])	Sunsynchronous (705)
Onboard calibration	Solar diffuser, lunar imaging

Table 3. HRPT SeaWiFS acquisitions and dates of CONTINENT cruises

	April	May	June	July	August	September
HRPT 2001			25,27,30	2,4,16,18,19, 21,26,30	6,7,8,20,25, 28,29,31	7,17,28
(< 30 % clouds)			(25)	(19)	(6,8,28)	
Cruise 2001				15 to 25		
HRPT 2002	30	6,8,9,10,12, 14,18,22,23,25	11,12,14,22,29	2,12,13,20, 22,24,25,26	1,2,6,9,11, 17,24,30	1,7
(< 30 % clouds)	(30)	(6,8,14,23,25)		(20,24,25,26)	(9)	
Cruise 2002				5 to 15		

Table 4. Comparison of the best-fit chl-a algorithms tested in this study. This table shows the parameters of chl-a algorithm, and as an example, the performance using atmospherically corrected SeaWiFS data from 2002/07/20. In each case, the determination coefficient (r^2) of chl-a measured (ground truth data set of Lake Baikal in 2002) and chl-a calculated from 2002/07/20 is specified. Values of measured chlorophyll are the mean concentrations of all samples from 5 to 30 m at one sampling point.

<i>source</i>	$x = Ri/Rj$ ($R = L_{up}/E_{down}$)	<i>chl-a algorithm</i>	r^2
A OC2 global chl-a O'Reilly et al. (2000)	$x = \log_{10}$ {R490/R555}	$10^{\{0.319 - (-2.336 x) + 0.879 (x^2) - 0.135 (x^3) - 0.071 (x^4)\}}$	0.74
B OC4 global chl-a O'Reilly et al. (2000)	$x = \log_{10}$ {R443/R555}, {R490/R555}, {R512/R555} (max. ratio: MAX)	$10^{\{0.366 - (-3.067 x \text{ MAX}) + 1.93 (x \text{ MAX}^2) + 0.649 (x \text{ MAX}^3) + 1.532 (x \text{ MAX}^4)\}}$	0.74
C empirical chl-a this study, Lake Baikal (RU), July 2002	$x = R490/R550$	$1.94 x^{-2.81}$	0.73
D empirical chl-a this study, Lake Baikal (RU), July 2001 + 2002	$x = R490/R550$	$1.43 x^{-1.8}$	0.72
E empirical chl-a this study, Lake Baikal (RU), July 2002	$x = R443/R550$	$1.82 x^{-2.47}$	0.73
F Iluz et al. (2003), Gulf of Eilat (Red Sea), years 1994 + 1995 + 1996, all seasons	$x = R443/R550$	$0.7 x^{-0.98}$	0.74
G Iluz et al. (2003), Gulf of Eilat (Red Sea), year 1996, all seasons,	$x = R443/R550$	$1.27 x^{-1.38}$	0.74
H Gordon et al. <i>case 1</i> (1983) (in Iluz et al., 2003)	$x = R443/R550$	$1.13 x^{-1.71}$	0.74

Table 5a. Comparison between chl-a measured and chl-a calculated from SeaWiFS data in July 2001. Values of measured chlorophyll are the mean concentrations of each sampling point in July 2001 (personal. com., S. Fietz) from 5 to 30 m depth. Only the cloud-free parts of SeaWiFS data (2001/07/16-26) could be chosen, and the most cloud free acquisition was obtained on the 2001/07/19. Note, that the accuracy of the complete calculated chl-a data set is reduced by the influences of terrigenous input.

<i>2001</i>		<i>HPLC *</i>	<i>OC4 07/16-26</i>	<i>OC4 07/19</i>	<i>OC2 07/16-26</i>	<i>OC2 07/19</i>
n	chl-a -all-	12	4	12	4	12
n	chl-a case1		4	8	4	8
mean	[$\mu\text{g l}^{-1}$]	1.7	1.7	2.6	1.5	2.4
median	[$\mu\text{g l}^{-1}$]	1.2	1.0	1.9	1.0	1.8
stdev	[$\mu\text{g l}^{-1}$]	1	1.1	1.9	0.85	1.7
acc. -all-	[$\mu\text{g l}^{-1}$]		± 0.4	± 1.4	± 0.4	± 1.2
			$\pm 24 \%$	$\pm 90 \%$	$\pm 22 \%$	$\pm 85 \%$
acc. Case1	[$\mu\text{g l}^{-1}$]			± 0.6		± 0.5
				$\pm 32 \%$		$\pm 30 \%$

* analysis undertaken by S. Fietz, 2004

Table 5b. Comparison between chl-a measured and chl-a calculated from SeaWiFS data in July 2002. Values of measured chlorophyll are the mean concentrations of each sampling point in July 2002 (personal. com., S. Fietz) from 5 to 30 m depth. Only the cloud-free parts of SeaWiFS data (2002/07/02-13) could be chosen, and the most cloud free acquisition was obtained on the 2002/07/20. Note, that the contributions of sampling points vary between the data sets of 2002/07/02-13 and 2002/07/20 due to different cloud coverage.

<i>2002</i>		<i>HPLC*</i>	<i>OC4 07/02-13</i>	<i>OC4 07/20</i>	<i>OC2 07/02-13</i>	<i>OC2 07/20</i>
n	chl-a -all-	22	18	17	18	17
n	chl-a case1		18	17	18	17
mean	[$\mu\text{g l}^{-1}$]	1.6	1.6	1.35	1.45	1.3
median	[$\mu\text{g l}^{-1}$]	1.55	1.2	1.25	1.15	1.3
stdev	[$\mu\text{g l}^{-1}$]	0.8	0.9	0.5	0.8	0.4
acc. -all-	[$\mu\text{g l}^{-1}$]		± 0.33	± 0.35	± 0.3	± 0.3
			$\pm 20 \%$	$\pm 27 \%$	$\pm 18 \%$	$\pm 24 \%$

* analysis undertaken by S. Fietz, 2004

Table 6. Overview on accuracies of chl-a algorithms (see also table 4) applied on SeaWiFS data in July 2002 (07/20). Chl-a algorithms are OC2 (**A**, table 4), and OC4 (**B**, table 4), empirical chl-a algorithm (**D**, table 4) from ground truth data set of Lake Baikal in 2001 and 2002 (this study), chl-a algorithms from Iluz et al. (2003): coefficient of studies from 1994 to 1996 (**F**, table 4), coefficient of 1996 separately (**G**, table 4), and case 1, Gordon et al. (1983) (**H**, table 4).

2002/07/20		HPLC*	OC4	OC2	this study, July 2001+2002
n	chl-a -all-	22	17	17	17
n	chl-a case1		17	17	17
mean	[$\mu\text{g l}^{-1}$]	1.6	1.35	1.3	0.85
median	[$\mu\text{g l}^{-1}$]	1.55	1.25	1.3	0.8
stdev	[$\mu\text{g l}^{-1}$]	0.8	0.5	0.4	0.25
acc. -all-	[$\mu\text{g l}^{-1}$]		± 0.35	± 0.3	± 0.38
			$\pm 27 \%$	$\pm 24 \%$	$\pm 27 \%$

2002/07/20		HPLC*	Iluz et al.(2003) years 1994-1996	Iluz et al. (2003), year 1996	Gordon et al. case1 (1983)
n	chl-a -all-	22	17	17	17
n	chl-a case1		17	17	17
mean	[$\mu\text{g l}^{-1}$]	1.6	0.6	1	0.85
median	[$\mu\text{g l}^{-1}$]	1.55	0.6	0.94	0.8
stdev	[$\mu\text{g l}^{-1}$]	0.8	0.1	0.4	0.25
acc. -all-	[$\mu\text{g l}^{-1}$]		± 0.6	± 0.41	± 0.45
			$\pm 54 \%$	$\pm 27 \%$	$\pm 27 \%$

* analysis undertaken by S. Fietz, 2004

Figure legends

Figure 1

Landsat TM-MOSAIC RGB742 (UTM 48), source: Baikal Online-GIS: <http://dc108.gfz-potsdam.de/website/>. The satellite map shows the Lake Baikal area, 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). Additionally, note the transect sampling at B1, B2, B3, in Barguzin Bay.

Figure 2

The scattergram shows the relationship between concentrations of chl-a calculated from SeaWiFS OC2 and chl-a calculated determined from ground truth measurements during field expeditions in Lake Baikal during 2001 and 2002. Values of measured chlorophyll *a* (HPLC) are the mean concentrations of each sampling point from 5 to 30 m depth. For the OC2 chl-a calculations, the most cloud free acquisitions in 2001 (2001/07/19) and 2002 (2002/07/20) were chosen. Note the considerable chl-a overestimation caused by the influences of terrigenous input in case 2 waters. (Data available at: doi:10.1594/GFZ/ICDP/CON/2004....) * analysis undertaken by S. Fietz, 2004

Figure 3

Barguzin transect 2002/07/11, Variation of volume reflectance data (GER 1500).

B1: 0.9 km from Barguzin mouth: 4 mg l⁻¹, 3.9 mg l⁻¹, 1.9 µg l⁻¹ (DOC**, SPM, chl-a*);

B2: 11.2 km from Barguzin mouth: 1.4 mg l⁻¹, 1.3 mg l⁻¹, 1.8 µg l⁻¹ (DOC**, SPM, chl-a*);

B3: 19.2 km from Barguzin mouth: 0.5 mg l⁻¹, 0.8 mg l⁻¹, 2 µg l⁻¹ (DOC**, SPM, chl-a*).

(Data available at: doi:10.1594/GFZ/ICDP/CON/2004....)

* analysis undertaken by S. Fietz, 2004 ** analysis undertaken by A. Rosell, 2004

Figure 4

SeaWiFS SPM map, 2001/07/19. SPM concentrations are in mg l^{-1} . This figure shows intense fluvial input by the Selenga River, the Barguzin River and local mountain rivers due to storm events that happened two weeks previously. (Data available at: doi:10.1594/GFZ/ICDP/CON/2004....)

Figure 5

SeaWiFS colour coded SPM maps, May 2002. SPM concentrations are in mg l^{-1} . The time series shows the increase of the fluvial input during the snow melting season. Note the high input from 2002/05/14 to 2002/05/23 by the Selenga River and local mountain rivers into the Southern Basin. (Data available at: doi:10.1594/GFZ/ICDP/CON/2004....)

- 2002
- 2001 case 1
- 2001 case 2

11/07/2002, Barguzin Transect

a) 06/05/2002

b) 14/05/2002

c) 23/05/2002