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CHLOROPHYLL $a$ CONTENT IN THE SURFACE LAYER OF THE GULF OF GDAŃSK IN THE AVHRR IMAGES

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Abstract

The satellite data in red and near infrared light (1st and 2nd channels of AVHRR) were processed and compared with chlorophyll $a$ concentration in the surface layer of the Gulf of Gdańsk. Taking into account Stumpf and Tyler (1988) proposal, quantitative relation between this concentration and the value of $Cij=R2/R1$ (where $R2$ and $R1$ denotes reflectance coefficients in AVHRR's channel 1 and 2 respectively) has been calculated.

INTRODUCTION

Review the chlorophyll concentration in the southern Baltic waters, against the analysis of opportunities of its calculation on the basis of the AVHRR data shows, that theoretically, it should be possible in some parts of the year, and within the Gulfs of Gdańsk and Pomeranian. Surface distributions of the chlorophyll $a$ in this region characterises great, both spatial and temporal variability (Nakonieczny et al. 1991). It means that obtaining reliable picture of the field of its concentration needs use of approximately dense measuring net. Taking into account the possibilities of traditional methods and lack of connections to the men’s economic activity, cost of such investigations should be difficult to accept. Therefore, such situation increases attraction of the remote sensing methods, and particularly the satellite ones.
THEORETICAL BASIS

Reference of the spectral distributions of reflectance, measured in the Southern Baltic by Olszewski et al. (1995) into spectral sensitivity of the AVHRR’s channel 1 showed, that the big quantitative differences of chlorophyll (frequently occurring during phytoplankton blooms) within the surface layer of the sea should be “shown” by this radiometer. Earlier, this kind of analysis was performed by Stumpf, Pennock and Tyler. Stumpf (1987) has worked out the method to use the AVHRR’s channels 1 and 2 for calculating the amount of chlorophyll in the surface layer of turbid estuarine waters (where its concentration exceeds 5 mg·m⁻³). According to this work (Stumpf and Tyler 1988), the ratio of reflectance in two optional spectral channels can be taken in form:

\[
C_y = \frac{R_y}{R_i} = \frac{b_{zi} s_j^* + a_{zi}}{s_j^* + a_{zi}}
\]

where:

\[
\begin{align*}
    s_j^*(\lambda) &= a_z^*(\lambda) + b_{zi}^*(\lambda) \\
    a_z(\lambda) &= a_w(\lambda) + a_{d}(\lambda)C_d + a_p^*(\lambda)C_p
\end{align*}
\]

where:

\[ C \] denotes concentration, \( a \) and \( b_z \) - absorption and backscatter coefficients respectively, subscripts: \( z, w, d \) and \( p \) - sediment, water, dissolved pigments and particulate pigments such as chlorophyll, respectively; * denote specific absorption or backscatter coefficients ([m⁻¹·(mg·m⁻³)⁻¹]·[m²·mg⁻¹]).

\( C_y \) can be considered the tangent of inclination angle of “water colour vector” (distance from the origin to the spectral point in the co-ordinate system where \( x \) and \( y \) axis are the reflectances of the AVHRR’s band 1 and 2 respectively). Stumpf and Tyler (1988) prove that because of logarithmic dependence of reflectance on \( C_z \), \( C_y \) can be treated as independent from \( C_z \) in the wide range of \( C_z \) variability. For \( C_z \) small (below 10 mg·m⁻³), the second fraction at the right side of (1) approaches \( a_z/a_{zi} \). As \( C_z \) becomes large, it approaches \( s_j^*/s_j^* \). Applying some simplifications and approximations, Stumpf (1987) has obtained relationship:
\[
\frac{a_{xj}}{a_{xj}} = G_s \cdot C_{ij}^{0.5}
\]

(3)

where:

\(G_s\) incorporates \(b_{se}^*\) and \(s^*\), thereby varying with sediment type,

or if the radiance measured from the „clear water” point is not equal 0 then:

\[
\frac{a_{xj}}{a_{xj}} = G_s \cdot C_{ij}^{0.5}
\]

(4)

Taking into account that in the area out of sun glitter, the radiance reaching radiometer, \(L_n\), equals (Robinson 1985):

\[
L_n = L_a + T_A \cdot L_w
\]

(5)

where:

\(L_a\) - atmospheric path radiance, \(L_w\) - water leaving radiance, \(T_A\) - atmospheric transmission coefficient

and equations (3) or (4), and assuming that in the vicinity of area under investigation variability of reflectance coefficient (or \(C_j\)) is not large, the dependence of chlorophyll concentration, \(C_p\), on \(C_{ij}\) coefficient can be expressed in a simple linear form:

\[
C_p = h \cdot C_{ij} + p
\]

or

\[
C_p = H \cdot C_{ij}^{0.5} + P
\]

(6)

where:

\(h, H, p, P\) - regression constant calculated empirically.

Presented algorithms were used for calculating of chlorophyll \(a\) concentration in the surface layer of the sea. Furthermore, it was assumed that the sea surface area,
identified previously as free of clouds, with the reflectance in AVHRR’s band 1 over 0.02 and below 0.04, and situated far from suspended sediment source was classified as the area of phytoplankton bloom.

RESULTS

From some time the AVHRR data are used in the Baltic Sea region for monitoring of the spatial extent of phytoplankton blooms (Kahru et al. 1994). A little bit further goes the program of Finnish researchers which uses the regular cruises of ferries between some Baltic ports for gathering information about phytoplankton concentration along its paths (Leppänen et al. 1991, 1995, Kononen 1992). In Fig. 1 we can see summary effect of phytoplankton concentration distribution analysis made on the basis of the AVHRR images taken in spring, summer and autumn 1995.

It is known that bloom in majority, is created by the cyanobacteria Nodularia spumigena. Nevertheless, variety of phytoplankton species¹ and still not big enough data base for comparison causes, that attempt to find more general relationship between chlorophyll concentration in the surface waters and the signal recorded by the AVHRR from the Earth orbit can be charged by the significant error.

It seems that a little bit easier is to use the remote sensing methods to conclude about character and spatial extent of phytoplankton bloom. Such investigations carried out by Kahru et al. 1994, for the period from 1982 to 1993 showed strong spatial and temporal variability of this phenomenon in the Baltic. Analysis of about 135 scenes recorded in the summer months enabled one following changes that ranges from the lack of phytoplankton bloom in 1987 and 1988 to its development up to 60 thousands km² in 1992. It is worth to stress that these investigation, in so great scale, were possible only with the satellite remote sensing methods. Particularly, because of the phenomenon more or less local character due to necessity of occurrence of optimal environmental conditions (water temperature over 16°C, enough amount of solar radiation, phosphorus content and strong vertical stratification in the surface layer). Nowadays, forecasting such conditions for purposes of planning traditional expeditions is rather impossible.

¹According to Finnish researchers in August in the southern part of the Baltic phytoplankton bloom is created by such species like Dinophysis norvegica, Prorocentrum minimum, Gymnodinium spp., Heterocapsa triquetra. In the same time they are not observed in the Gulf of Finland, where one can find for instance Plactothrix agardhii or Oscillatoria spp. which are not present in the southern part of the sea (Leppänen et al. 1995)
Fig. 1. The extent of the cyanobacterial blooms in the Baltic Sea in 1995. The image is based on satellite images, unattended ferry observations and reports given by the Finnish coast guard pilots. Bloom in the Riga Bay and in the sea area off the Poland coast are not confirmed by field observations. Bright-dark = less-heavy surface accumulations (Leppänen et al. 1995)

An instance in Fig. 2 shows typical pattern of spatial distribution of cyanobacterial bloom recorded by NOAA 12, in August 22, 1995 afternoon. In contrary to the opportunity to follow characteristic spatial features of phytoplankton distribution, information about the chlorophyll concentration is limited to the scale: small - medium - big. One of the reasons of it is that even the smallest heterogeneity of the atmosphere can have strong influence on the obtained chlorophyll concentration distribution. An example of such event is shown in Fig. 3. The linear structure crossing the Gulf of Gdańsk from Gdańsk city (the south-western end) to the Cape Taran results from thin strip of clouds. In the
inner part of the Gulf of Gdańsk (between Gdańsk and the end of Hel Penninsula) it can be easy misinterpreted as the area of increased concentration of chlorophyll.

**Gulf of Gdańsk**

Following the results of investigations of Latała (1982, 1985, 1993), Renk et al. (1976), Nakonieczny et al. (1991) and others, we can see that chlorophyll concentration in the surface layer of the Gulf of Gdańsk often reaches height that is high enough to make use of the AVHRR data for its calculation possible. Histograms of this concentration at several measuring stations in the Gulf, made on the
basis of every month measurements of Latala in 1986, 1987, 1992-1994 years (Fig. 4) show, that only in winter months, i.e. from December to March the values below 3 mg·m$^{-3}$ are predominant. During the rest part of the year, the values over 5 and sometimes even up to 200 mg·m$^{-3}$ are in majority. Measuring stations (except one) in the number of 25, were placed along profiles perpendicular to the coastline from the shore to the 50 m isobath i.e. within the strip from some to several kilometres wide (comp. Latala 1993). It means that it is the area where it is possible to get the AVHRR data undisturbed by the influence of land.

In spite of a comparatively big amount of in situ measurements carried out within the southern Baltic region, calibration of method of its calculation on the basis of colour coefficient $C'$ (equation (1)) still brings serious troubles. The reason is work and time consumption of traditional method of chlorophyll $a$ analysis that causes its significant scattering in time. Thus, only part of them can be classified as so called undersatellite measurements and in consequence, finding appropriate amount of good quality satellite data is a serious problem.

In Fig. 5 there are the results of analysis of such data gathered in April 15, May 9, 14 and 21 1993, and April 16 1994 during expeditions of k/h Oceanograf

2 and r/v Oceania$^1$. Statistically significant dependence of colour index on chlorophyll $a$ concentration has been stated. It can be expressed by the equations (6) or:

$$C_p = A_1 + \exp(A_2 + A_3 \cdot C_y)$$

(7)

shown in Fig. 5 as curves B and A respectively. The result is similar to that achieved by Stumpf (1987) for Chesapeake Bay. However, as one can see, the dependence is rather weak (comparatively low correlation coefficient) and at most can be used for estimation of chlorophyll $a$ in the sea surface layer if its concen-

$^1$Data from Ms. Mirosława Ostrowska (Institute of Oceanology, Polish Academy of Sciences in Sopot)
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\[ A \; C_p = -19.77 + \exp(2.58 + 1.86 \; C_{ij}) \]
\[ N=45; \; R=0.72 \]

\[ B \; C_p = 92 \cdot C_{ij} - 32 \]
\[ N=45; \; R=0.67 \]

**Fig. 5.** Dependence of the colour index, $C_p$ on chlorophyll $a$ concentration in the surface layer of the Gdańsk Basin region; $N$ - number of observations, $R$ - correlation coefficient

...tration is big enough. In other words, obtained results should be treated rather as confirmation of concept then operational recipe for quantitative determination of this concentration from the satellite level.

The examples of using of algorithm (7) with the regression coefficients $A_1=-19.8$, $A_2=2.58$ and $A_3=1.86$ are presented in figs. 6 and 8. At the background of remotely sensed distribution there are chlorophyll $a$ concentrations determined in traditional way. The time gap between satellite pass and picking up water samples did not exceed ±6 hours.

In the first instance (Fig. 6), the values obtained with the use of both methods are similar. But the strength of this test can be easily weaken if one takes into account that the time gap between the first and last measurement exceeded 8 hours and that the field had characteristic “patchy” appearance. Another questionable feature of the obtained distribution is a linear structure of higher concentrations, parallel to the coast eastwardly to the Vistula river mouth, some kilometres from the coastline. It suspiciously follows the edge of higher concentrations of suspended matter (Fig. 7). So it is not quite clear whether it illustrates the real chlorophyll distribution or the suspended matter concentration changes in the area...
Fig. 6. Chlorophyll a concentration in the surface layer of the Gulf of Gdańsk calculated on the basis of AVHRR data with the use of equation (7). '+' denotes the water sampling sites and the values obtained with the laboratory method.

Fig. 7. Distribution of suspended matter concentration in the surface layer of the Gulf of Gdańsk calculated on the basis of AVHRR data.
are too big for the used method (as it was pointed out, one of the limiting assumptions that should be fulfilled is that the variability of reflectance in the area of investigation are small).

In the second instance (Fig. 8), the field is much more smooth. One of the reasons of this is because it was calculated for the edge area of the scene. It means that the real spatial resolution was significantly lower then previously, i.e. every pixel had been created in the area several times greater. Another disadvantages of it is that the regions close to the coastline (up to 4 km) must be excluded from analysis. In conclusion, only small part of undersatellite measurements can be it is that the regions close to the coastline (up to 4 km) must be excluded from used for comparison with the satellite data. As we can see in Fig. 8, only six, among remaining in situ measurements, correspond with the remotely calculated, and four of them don’t.

CONCLUSIONS

Taking into account all presented results it appears that the use of AVHRR data for quantitative determination of chlorophyll concentration in the coastal surface waters seems to be very problematic without further, strict calibration against in situ measurements. Pointwiseness of field measurements and patchiness of chlorophyll distribution cause such measurements very difficult. They must be carried out in, at least, several places in the same time, synchronized with the satellite
pass and cloudless weather. The satellite data can’t be taken from the edge of registered scenes. It is crucial to make very precise atmospheric correction and cloud masking.

A serious limitations arises from high variability of suspended matter concentration that often takes place in the vicinity of its land sources.

If it is possible to fulfill all above expressed conditions, the distribution of chlorophyll $a$ in the surface layer of coastal regions with the high values of its concentration can be estimated from the AVHRR data. The quantitative dependence between these data can be expressed by the formula (6) or (7).

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