Development of a satellite method for Baltic ecosystem monitoring (DESAMBEM) – an ongoing project in Poland*

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Abstract

A large national project: Development of a satellite method for Baltic ecosystem monitoring (DESAMBEM) for creating mathematical models and a complex algorithm for the remote sensing of the Baltic ecosystem and its primary production is described. The final aim of the project is the development of a routine remote sensing methodology for determining characteristics of the Baltic ecosystem such as distribution maps of surface temperature, water transparency, upwelling currents, phytoplankton blooms, radiation balance, pigment concentrations and primary production. The progress of the study and examples of results are presented.

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1. Introduction

Baltic Sea waters are very different from those of open oceans, so the remote sensing of the characteristics of its ecosystem, in particular, pigments and primary production, demands an algorithm quite different from that applicable to oceans (Sathyendranath 2000, Darecki et al. 2003). A further aspect specific to the Baltic is the local atmosphere, for which the known algorithms for sea surface colour mapping (Ruddick et al. 2000) do not work properly and thus need alteration. On the other hand, the Baltic is of great importance to the countries surrounding it and its ecosystem is evolving as a result of human activities. This requires regular monitoring of environmental processes in the Baltic which, together with *in situ* analysis at selected sites and times, can only be effective with the implementation of remote sensing technology. In this regard, a comprehensive national project entitled Development of a satellite method for Baltic ecosystem monitoring (DESAMBEM, project number PBZ-KBN-056/P04/2001) for creating mathematical models and an algorithm for the remote sensing of the Baltic ecosystem and its primary production was inaugurated in the summer of 2002. It is being funded by the Polish Ministry of Scientific Research and Information Technology. Involved in this project are institutes with long experience, such as the Institute of Oceanology of the Polish Academy of Sciences in Sopot, the Institute of Oceanography of the University of Gdańsk, the Sea Fisheries Institute in Gdynia, and the Institute of Physics of the Pomeranian Pedagogical Academy in Słupsk.

The principal components of the project include: (i) remote sensing of solar energy inflow into the Baltic and its utilisation, (ii) remote sensing of sea surface colour and temperature, and (iii) models and algorithms applicable in the remote sensing of pigment distribution and primary production in the water.

To achieve these objectives, procedures for processing satellite data are to be applied. Although some of these procedures are already known (Antoine & Morel 1996), they need to be modified in accordance with the specific conditions of the waters and atmosphere in the Baltic region. The project makes provision for the adoption of completely new models and algorithms to describe a variety of phenomena in the sea. The most important of these models is a comprehensive bio-optical one that takes account of the relationships between the photosynthesis of marine algae and a whole range of biotic and abiotic factors in the sea (see Woźniak et al. 2003, http://www.iopan.gda.pl/oceanologia/45_2.html). The application of this model will considerably strengthen the diagnostic armoury for monitoring the state and functioning of the Baltic ecosystem.

The final aim of the project is the development of a routine methodology for determining the characteristics of the Baltic ecosystem. Following the implementation of these techniques, distribution maps of the following parameters will become available: surface temperature, water transparency, surface current structure, range of upwelled water in the surface layer, phytoplankton blooms, radiation balance, intensity of UV and PAR radiation at the sea surface, concentrations of chlorophyll and other pigments, and primary production. It will also be possible to supply essential information about the environment, for example, pollution and sea ice cover.

The project is in progress and will be continued. The present paper is a brief presentation of current results and examples of remotely-sensed pigment distributions, primary production, and other parameters.

2. Material and methods

The study problem embraces all elements related to the satellite monitoring of the Baltic ecosystem. It is a highly complex set of research tasks, a detailed description of which lies beyond the scope of this article. Here we present just a general outline of the research methods and the materials used, along with a few of the most essential details of the work. The key to this description is the simplified block scheme of the algorithm we have developed for determining the state of the ecosystem with the aid of *remote sensing* techniques (Fig. 1).

It consists of three sectors:

- **Input data** – the parameters describing the state of the air-sea system, which are essential for calculations and estimations: **Block D.1** – radiometric measurements performed by satellite sensors in the VIS, near-IR (IR_1) and thermal-IR (IR_2) ranges; **Block D.2** – further data on the state of the environment routinely available from the hydrological and meteorological services, or generated by operational meteorological models, e.g. atmospheric pressure, air humidity, wind speed and the wind direction.

- **Model formulae** – mathematical models describing the links between: **Block M.1** – directly measured satellite data and selected hydrological and meteorological parameters of the atmosphere-sea system; **Block M.2** – parameters of the state of the atmosphere, its transmittance, and its other optical properties; **Block M.3** – various hydrometeorological parameters, and the state and optical properties of the sea surface; **Block M.4** – spectral values of the reflectance or albedo of the sea, and the concentrations of chlorophyll a and the

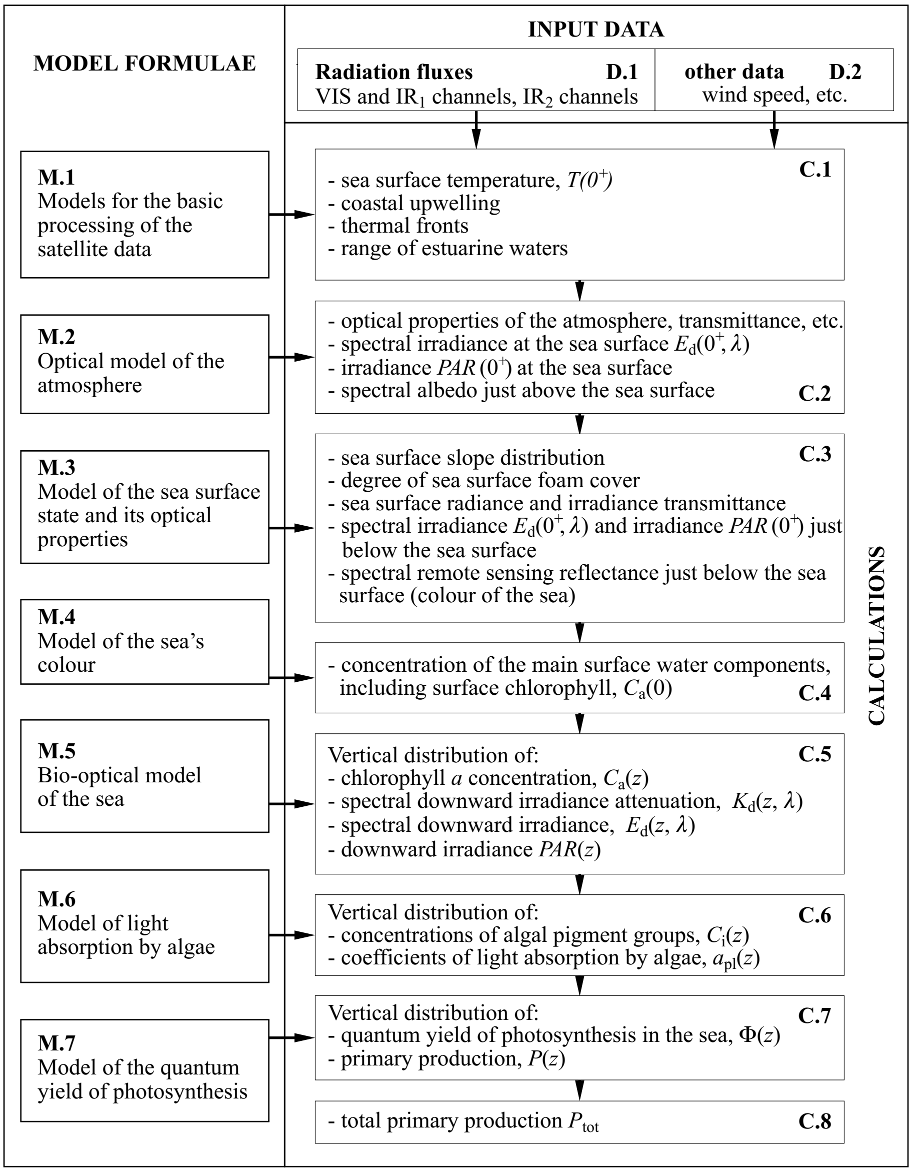

Fig. 1. Block diagram of the DESAMBEM algorithm

other principal components of sea surface water; **Block M.5** – the concentration of chlorophyll a at various depths, as well as diverse optical properties of sea water and parameters of the underwater irradiance field; **Block M.6** – parameters of the underwater irradiance field and coefficients of light absorption by algae; **Block M.7** – the underwater irradiance, temperature and light absorption by algae, as well as biotic and abiotic factors, and the quantum yield of photosynthesis and primary production in the sea.

- **Calculations** – the abiotic and biotic parameters of the atmosphere-sea system, determined from the **Input data** with the aid of the **Model formulae**. The details of these estimated parameters are given in Fig. 1 (**Blocks C.1 to C.8**).

The development of this *remote sensing* algorithm for the Baltic involved a complex set of theoretical and empirical tasks. Some of these tasks, together with the results obtained so far, have already been published elsewhere (see citations). We now present only the most essential information characterising the progress of this modelling.

Block M.1. The primary purpose of this part of the algorithm is to utilise radiometric satellite data to compile maps of the sea surface temperature (SST). To this end earlier methods have been modified (Krężel 1997). Greater precision of recording SST distributions in the Baltic was obtained through the selection of an appropriate algorithm and the development of an original operational system: unsupervised geographic registration, geometric correction and AVHRR data processing (Kowalewski & Krężel, in press). Furthermore, over 20 algorithms for defining SST on the basis of data from the radiometer AVHRR/3 operating on satellites NOAA 15 and NOAA 16 were tested. This was done by comparing SSTs in the top c. 0.5 m layer of the sea measured *in situ* with those recorded remotely with the aid of these various algorithms. Some 800 of the c. 50 000 *in situ* measurement data obtained in the Baltic in 2002–2003 were used in these tests; they correspond to the flight times of the satellites across the region under favourable atmospheric conditions. On this basis the best **operational algorithm** was the non-linear algorithm (NLSST) with coefficients recommended by NOAA/NESDIS (Coast Watch SST product). To determine SST in cloud-covered areas, an interpolation procedure was developed on the basis of geostatic methods using consecutive maps in a time series.

Block M.2. The main aim of this block is to determine from satellite data the quantities of solar light energy reaching the sea surface. At present we are using an improved spectral model of the solar radiation inflow to the surface of the Baltic Sea (Krężel 2001). This improvement is based on the parameterisation of the effect of aerosols and cloudiness on the transmittance of radiation through the atmosphere. With respect to the aerosols, the mean long-term value of the transmittance function in the Baltic region was replaced by weekly mean values of the optical aerosol thickness of the atmosphere, determined in a 100×100 km grid from radiation data measured in AVHRR channels 1 and 2. Greater accuracy in assessing the influence of cloudiness on solar radiation inflow to the sea surface was achieved in that visual estimates of cloudiness by observers at shore stations were replaced by cloudiness data from channel 1 of the geostationary METEOSAT satellite.

Block M.3. The emphasis in this part of the algorithm is on determining the spectral irradiance $E_d(0^-, \lambda)$ and irradiance PAR (0^-) just below the sea surface from remotely recorded values of the spectral irradiance $E_d(0^+, \lambda)$ and irradiance PAR (0^+) at the sea surface (see block **M.2**). Hence, a model of light propagation across the sea surface was formulated to take into account wave motion, the partial covering of the surface by foam, and the angular distribution of light fluxes incident on these surfaces from the atmosphere and from under the water. Here we invoked the classic distribution of slopes on a wind-roughened sea surface (Cox & Munk 1954), now parameterised by instantaneous wind speed values and the wind direction over the water. Achievements in the modelling of light transmittance across a wind-roughened sea surface (see e.g. Woźniak 1996, 1997a, b) were also applied to the specific problems of remote sensing studies. Our model computations enabled us to formulate, for instance, a practicable method of determining mean daily coefficients of natural PAR irradiance transmittance across the sea surface. This method was implemented in the algorithm described here. In the future, the possibilities of employing this model for the 'surface correction' of the satellite signal will be explored.

Block M.4. The model of the sea's colour is intended to facilitate determination of the concentrations of the most significant optically active admixtures in sea water – the present version largely restricts this possibility to estimates of the chlorophyll a concentration $C_a(0)$ in the surface layer of the sea. The existing operational empirical algorithms for the SeaWiFS and MODIS satellite scanners have thus undergone refinement. With the aid of our long-term bio-optical data base, a critical assessment and validation was carried out for all the standard algorithms developed for the needs of the SeaWiFS (OC2v4 and OC4v4) and MODIS (MODIS CZCS_pigm, chlor_MODIS, chlor_a_2, chlor_a_3) scanners, for determining concentrations of chlorophylls a or chlorophyll a with phaeophytins, light absorption by yellow substances a_{CDOM} (400 nm), and the diffuse attenuation coefficient of downward irradiance K_d (490 nm) (Darecki & Stramski 2004, Darecki et al. in press). When the above algorithms were used to determine these parameters for the Baltic Sea, the latter turned out to be encumbered with large systematic errors. In an attempt to reduce these errors, new versions of these algorithms, adapted to Baltic conditions, were developed (Darecki et al. 2003). The best of them, used in this paper, was algorithm OC4vB, which is operational algorithm OC4v4 adapted to Baltic conditions. Work is in progress to further improve this algorithm, in particular to enhance the accuracy of the 'atmospheric correction', the imprecision of which is responsible for the greatest errors in estimates of chlorophyll concentrations and other parameters of this ecosystem.

Block M.5. The purpose of the bio-optical model of the sea is to be able to employ surface chlorophyll concentrations $C_a(0)$ and irradiances just below the sea surface $E_d(0^-, \lambda)$ and $PAR(0^-)$, determined in earlier blocks of the algorithm, for estimating the vertical distributions of chlorophyll $C_a(z)$ and of various inherent and apparent optical properties of the sea, and also the underwater light fields $E_d(z, \lambda)$ and $PAR(z)$. The present version of this algorithm makes use of two statistical descriptions to determine the vertical distributions of these parameters: (i) the statistical model of vertical distributions of chlorophyll concentrations in Baltic basins, developed by Woźniak et al. (1995), enabling $C_a(z)$ distributions to be estimated from known surface concentrations of chlorophyll $C_a(0)$ for a given season (defined by the day number of the year); (ii) the so-called optical classification of sea waters, which permits spectral coefficients of attenuation of downward irradiance (and hence also of the irradiance fields $E_d(z, \lambda)$ and $PAR(z)$) to be determined from known concentrations of chlorophyll a in the sea. This classification was initially developed for oceanic waters (Woźniak et al. 1992); later a preliminary modification for the Baltic was developed (Woźniak et al. 2003). Further improvements to both of these statistical descriptions are planned.

Block M.6. This part of the algorithm, a model of light absorption by marine algae, had been developed earlier for oceanic conditions (Majchrowski et al. 2000, Woźniak et al. 2000); it is one of the two most original biophysical models developed by our team (the other is the model of the quantum yield of photosynthesis). Describing the processes occurring in algae stimulated by sunlight, it takes e.g. photo- and chromatoacclimation into account (see Majchrowski & Ostrowska 2000). The model thus permits the absorption properties of phytoplankton and the quantity of light energy absorbed by its photosynthetic apparatus to be estimated at various depths in the sea from the values of $C_a(0)$, $C_a(z)$, $PAR(z)$ determined in blocks **M.4** and **M.5.** Tests of this part of the algorithm showed that the oceanic version of the model of light absorption by algae also yields good results in Baltic basins. Nevertheless, we are working to produce a version that is even better adapted to conditions in the Baltic.

Fig. 2. Example of the remotely sensed distribution of 4 selected parameters of the Baltic ecosystem on May 8, 2001: (a) Sea surface PAR irradiation; calculated with METEOSAT data and the DESAMBEM algorithm; (b) Sea surface temperature; calculated with AVHRR (NOAA 14) data and the DESAMBEM algorithm; (c) Surface chlorophyll *a* concentration; calculated with SeaWiFS data and the DESAMBEM algorithm; (d) Total primary production in the water column; calculated with SeaWiFS, METEOSAT and AVHRR (NOAA 14) data and the DESAMBEM algorithm

Block M.7. The model of the quantum yield of photosynthesis by algae under natural conditions in the sea plays a key part in this algorithm. The aim here is to determine this yield, and hence the primary production of algae, on the basis of biotic and abiotic parameters as well as the quantity of energy absorbed by phytoplankton, all of which will have been determined in the earlier blocks of the algorithm (**M.1**–**M.6**). Testing this algorithm involved investigating the applicability of three unique models of the quantum yield of photosynthesis to the Baltic: the French model (Morel 1991, Antoine & Morel 1996, Antoine et al. 1996), our 'Baltic' model (Woźniak et al. 1992, 1995, Dera 1995), and our latest 'oceanic' model (Woźniak et al. 2002, 2003, Ficek et al. 2003). The best one turned out to be the last-mentioned, 'oceanic' model, which is being implemented at present. At the same time, work is in progress to adapt it better to Baltic conditions.

3. Results and discussion

In map form (Fig. 2), we present some preliminary results of applying this satellite algorithm to the estimation of a number of parameters describing the state of the Baltic ecosystem. Preliminary results of the empirical validation of the entire algorithm are also given. To this end, the magnitudes of ecosystem parameters determined using the algorithm from NOAA (AVHRR), METEOSAT and OrbView 2 (SeaWiFS) satellite data are compared with the magnitudes of the same parameters recorded at 21 Baltic measurement stations from on board r/v 'Oceania' in 2000–2002. The relevant errors have been calculated from these comparisons in accordance with arithmetic and logarithmic statistics (see Table 1). At the current stage of development of this satellite algorithm for the Baltic, these errors, typical of remote, spatial estimates, can be regarded as fairly satisfactory. Nevertheless, in order to reduce them, improvement of all the components of this complex algorithm will continue.

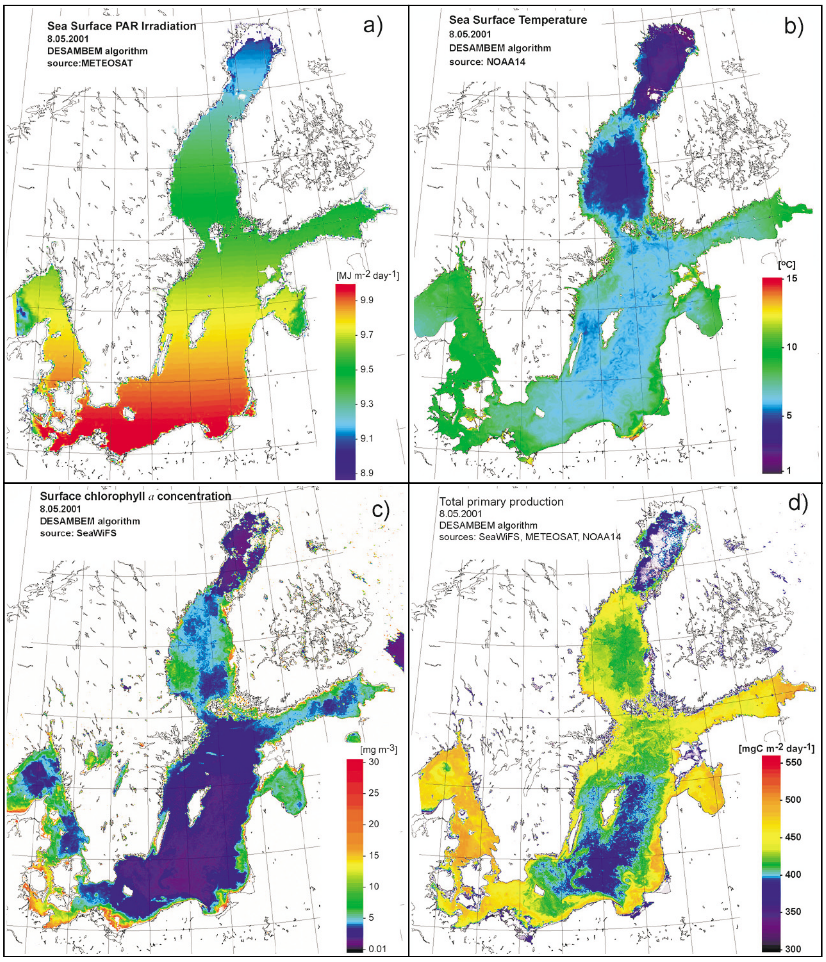

Table 1. Errors in the estimation of selected quantities with the algorithm at its present stage

Quantity	Arithmetic statistics		Logarithmic statistics			
	systematic error	statistical error	systematic error	standard error factor	statistical error	
	$\langle\varepsilon\rangle$ [%]	σ_ε [%]	$\langle\varepsilon\rangle_g$ [%]	x	σ_- [%]	σ_+ [%]
dose $PAR(0)$	–21.3	± 15.0	–22.7	1.22	–18.1	22.0
Chl a	77.8	± 124	42.0	2.12	–52.9	112
$a_{pl}(0)$	–31.0	± 18.6	–33.1	1.30	–22.8	29.6
P_{tot}	–28.4	± 24.9	–31.6	1.39	–27.9	38.6
	Arithmetic statistics					
SST	Systematic error Δt [°C] = 0.99		Statistical error σ [°C] = ± 1.05			

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