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SatBałtyk – A Baltic environmental satellite remote sensing system – an ongoing project in Poland. Part 1: Assumptions, scope and operating range*

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Abstract

This article is the first of two papers on the remote sensing methods of monitoring the Baltic ecosystem, developed by a Polish team. The main aim of the five-year SatBałtyk (2010–2014) research project (Satellite Monitoring of the Baltic Sea Environment) is to prepare the technical infrastructure and set in motion operational procedures for the satellite monitoring of the Baltic environment. This system is to characterize on a routine basis the structural and functional properties of this sea on the basis of data supplied by the relevant satellites. The characterization and large-scale dissemination of the following properties of the Baltic is anticipated: the solar radiation influx to the sea's waters in various spectral intervals, energy balances of the short- and long-wave radiation at the Baltic Sea surface and in the upper layers of the atmosphere over the Baltic, sea surface temperature distribution, dynamic states of the water surface, concentrations of chlorophyll *a* and other phytoplankton pigments in the Baltic water, distributions of algal blooms, the occurrence of upwelling events, and the characteristics of primary organic matter production and photosynthetically released oxygen in the water. It is also intended to develop and, where feasible, to implement satellite techniques for detecting slicks of petroleum derivatives and other compounds, evaluating the state of the sea's ice cover, and forecasting the hazards from current and future storms and providing evidence of their effects in the Baltic coastal zone. The ultimate objective of the project is to implement an operational system for the routine determination and dissemination on the Internet of the above-mentioned features of the Baltic in the form of distribution maps as well as plots, tables and descriptions characterizing the state of the various elements of the Baltic environment. The main sources of input data for this system will be the results of systematic recording by environmental satellites and also special-purpose ones such as TIROS N/NOAA, MSG (currently Meteosat 9), EOS/AQUA and ENVISAT. The final effects of the SatBałtyk project are to be achieved by the end of 2014, i.e. during a period of 60 months. These two papers present the results obtained during the first 15 months of the project. Part 1 of this series of articles contains the assumptions, objectives and a description of the most important stages in the history of our research, which constitute the foundation of the current project. It also discusses the way in which SatBałtyk functions and the scheme of its overall operations system. The second article (Part 2), will discuss some aspects of its practical applicability in the satellite monitoring of the Baltic ecosystem (see Woźniak et al. (2011) in this issue).

1. Introduction

The ongoing transformation of the Earth's natural environment worldwide is persuading researchers to intensify their studies and forecasts of the effects of these changes (e.g. Chen et al. (eds.) 2011), in which a highly significant part is being played by processes taking place in marine ecosystems (e.g. Barange et al. (eds.) 2010), in particular the photosynthesis of organic matter and the accompanying release of oxygen by phytoplankton (Odum 1971, Steemann-Nielsen 1975, Lieth & Whittaker

1975, Falkowski & Knoll (eds.) 2007). Marine photosynthesis is one of the main factors shaping the Earth's climate (Glantz (ed.) 1988, Trenberth (ed.) 1992, Houghton 1997, Houghton 2005). These facts are sufficient to justify the constant monitoring of the state and productivity of marine ecosystems. For many years now, various environment state parameters, measured at sea using traditional in situ methods from on board research vessels, have provided relevant information. But such monitoring is not very effective, highly expensive, and by its very nature limited in time and space. It is therefore a highly unsatisfactory way of obtaining data for making reliable predictions of global changes. The great variability in the state of marine ecosystems in time and the vast expanses of the seas and oceans require a more systematic approach to their monitoring. One way of achieving this is by means of remote sensing techniques. Many attempts have already been made to use optical remote sensing methods with the aid of scanning radiometers mounted on board artificial satellites. Widely described in the literature (e.g. Gordon & Morel 1983, Sathyendranath et al. 2000, Burenkov et al. 2001a,b, Arts 2003, Robinson 2010), these methods are based on the recording and analysis of the spectral properties of the light emerging from the sea water in comparison with the sunlight incident on the sea surface. In other words, they are based on the analysis of the colour of the sea in daylight, which depends on the absorption and scattering of light by the constituents of sea water and is an indirect indicator of their concentrations (including chlorophyll and other phytoplankton pigments). These satellite observations, backed up by in situ test measurements in the sea, enable the efficient global monitoring of the state of the sea and the processes taking place in it, among them the photosynthesis of organic matter, the release of oxygen and eutrophication.

The use of remote sensing methods in studies of the sea is relatively simple only with respect to the waters of the central oceanic regions, i.e. Case 1 waters according to the optical classification (Morel & Prieur 1977). The great majority of substances affecting the colour of the sea in those regions are autogenic, that is, formed by the local ecosystem – photosynthesis by phytoplankton and the metabolism and decay of marine organisms. In consequence, the spectrum of the light emerging from these waters is correlated with the concentration of phytoplankton and its pigments, principally chlorophyll *a*, the commonest plant pigment. The concentration of chlorophyll *a* is therefore an index of phytoplankton concentration, water trophicity and other ecological characteristics of a marine basin.

Most of the algorithms now in common use for characterizing the state and functioning of marine ecosystems on the basis of remote sensing data are thus applicable to these waters: they utilize the correlations of their optical properties with the chlorophyll *a* concentration in surface waters and the correlation of this concentration with other properties of the aquatic environment (e.g. Platt et al. 1988, 1995, Sathyendranath et al. 1989, Platt & Sathyendranath 1993a,b, Antoine & Morel 1996, Antoine et al. 1996, Woźniak et al. 2003, Ficek et al. 2003, and the collective work by Campbell et al. 2002 and Carr et al. 2006). In contrast, the construction of analogous algorithms for Case 2 waters (Morel & Prieur 1977), which include the Baltic Sea basin, is much more complicated. Apart from chlorophyll and other products of the local ecosystem, such waters contain many substances entering it from the exterior (from rivers, the land, the atmosphere, the sea bed and shores), which have complex optical properties, not directly correlated with the chlorophyll *a* concentration (Woźniak & Dera 2007, Jonasz & Fournier 2007). These allogenic substances contained in the water modify its colour in a more complex manner, characteristic of a given sea region. The use of remote sensing techniques to monitor such waters requires the application of separate, complex algorithms, purpose-designed for a particular sea region. A serious problem hampering the design and use of these algorithms is also the dynamic variability of atmospheric states, which distort the light spectrum bearing information from the sea to the satellite. Work on the development of suitable algorithms for the Baltic Sea has been going on in Poland for the last 20 years by the teams of researchers represented by the authors of this paper. This work, conducted before the SatBałtyk project was embarked upon and described below in section 2, has provided the scientific foundation and inspired the implementation of this large-scale Project.

2. An outline history of Polish research forming the basis of the remote sensing of the Baltic Sea

The beginnings of the remote sensing of the Baltic Sea by Polish scientists go back to the early 1990s. This pioneering work was done at the Institute of Oceanology of the Polish Academy of Sciences (IO PAN), where marine optics, including optical studies of the Baltic Sea, has been a leading discipline since the early 1960s, and which nowadays is of fundamental importance for the satellite monitoring of this sea's environment. The first studies investigated the optical properties of Baltic water constituents, their effect on underwater visibility and the structure of the underwater light field (Dera 1963a,b, 1967, 1971, Dera & Olszewski 1969, Olszewski 1973, Woźniak 1973). Subsequently, these optical studies were extended to cover different processes in the sea stimulated by sunlight, including the photosynthesis of organic matter in marine algae (Dera et al. 1975, Woźniak et al. 1980, 1989, Woźniak 1990). In the 1990s this provided the impetus on the one hand to develop the modelling of bio-optical phenomena taking place in the sea (Woźniak & Ostrowska 1990a,b, Woźniak & Pelevin 1991, Dera 1995, Woźniak & Dera 2000, Ostrowska et al. 2000a,b), and on the other to devise remote optical methods for studying the functioning of marine ecosystems, in particular techniques based on satellite observations (Pelevin et al. 1991, Darecki et al. 1993, 2005, Olszewski (ed.) 1995, Woźniak et al. 1995, 1997a, Rozwadowska & Isemer 1998, Antal et al. 1999, 2001, Darecki & Stramski 2004, Rozwadowska 2007, Kowalczuk et al. 2010).

Three other Polish institutes have made significant contributions to the satellite remote sensing of the Baltic: the Institute of Oceanography of the University of Gdańsk (IO UG), the Institute of Physics of the Pomeranian University in Słupsk (IF PUinS) and the Institute of Marine Sciences at the University of Szczecin (IMCS US).

At IO UG cooperation with Interkosmos[1] was well in hand already during the 1980s, with its participation in so-called sub-satellite cruises in the Black Sea and Atlantic Ocean[2]. IO UG was also conducting research into the optical properties of the atmosphere over the Baltic, particularly the propagation of solar radiation in the atmosphere (Krężel 1985, 1992, Kowalewska & Krężel 1991). This provided the basis, in the 1990s, for constructing remote-sensing algorithms for determining the intensity of the solar radiation passing through the atmosphere to reach the surface of the Baltic (see the review by Dera & Woźniak 2010). In the year 2000 the implementation at IO UG of a satellite data receiver (AVHRR/NOAA)[3] supplying continuous information (standard – HRPT[4]) in the visible and infrared spectral bands enabled investigations to be undertaken on processes for which variability in sea surface temperature (SST) is crucial. As is well

[1]The Soviet space programme of the late 1960s and early 1970s.

[2]– The International seminar 'Black Sea 85', Szczecin, 10–15 November 1986; paper: Krężel A., Furmańczyk K., Targoński L., Trumpakaj Z., *Primary results of measurements carried out with the use of spectroalbedometer during experiment 'Black Sea 85'* (in Russian);

– The International symposium 'Interkosmos – World Ocean, Atlantic Experiment 87', Yalta, USSR, September 1988; paper: Krężel A., Targoński L., Furmańczyk K., *Reflectance coefficient and other optical properties of waters in the western part of Tropical Atlantic during experiment 'Atlantic 87'* (in Russian).

[3]The principal abbreviations and symbols used can be found in Annexes 1 and 2 in Part 2 of this series of articles (Woźniak et al. 2011 – this issue).

[4]High Resolution Picture Transmission.

known, SST data can be used to compile distributions/maps of hydrological fronts, which are ultimately useful for identifying and characterizing upwelling events, zones of phytoplankton blooms and the extent of spread of terrestrial waters (Kręźel et al. 2005a,b, Myrberg et al. 2008, Bradtke et al. 2010).

At IF PUinS, biophysical studies, especially the mathematical modelling of the bioenergetics of marine photosynthesis, have been carried out jointly with IO PAN in Sopot since the mid-1990s (Woźniak et al. 1997b, 1999, 2000a,b, 2002, Ficek 2001). Developed at IF PUinS, the models of the adaptation of the sets of phytoplankton pigments to ambient environmental conditions (Majchrowski & Ostrowska 1999, 2000, Majchrowski et al. 2000, Majchrowski 2001) and the model of the quantum efficiency of photosynthesis in the sea (Ficek et al. 2000a,b) are today used, inter alia, in algorithms for determining the primary production of organic matter and photosynthetically released O_2 in Baltic Sea water. In the last decade extensive research has also been carried out at IF PUinS into the balance of the long-wave radiation emitted by the sea surface using, for example, remote sensing methods (Zapadka et al. 2001, 2007, 2008); this work is of fundamental significance for climate studies.

At IMCS US remote sensing techniques have been in use since the 1980s. The scientists at this institute had a portable APT/HRPT station at their disposal for receiving images from NOAA satellites. Among other things, they attempted to apply remote thermal images to the analysis of the spatial distributions of SST mainly in the Bering and Baltic Seas and ice phenomena in the Weddell and Bellingshausen Seas. This team also addressed the problem of defining bathymetry on the basis of aerial photographs and took part in the undersatellite research of the Interkosmos program (Furmańczyk 1985, Hus & Furmańczyk 1985). At present this team is participating in the SatBałtyk project, focusing on the dynamics of Baltic shoreline changes (see e.g. Furmańczyk 1994, Schwarzer et al. 2003, Dudzińska-Nowak 2006, Furmańczyk & Dudzińska-Nowak 2009, Furmańczyk et al. 2011).

But the greatest Polish achievements in satellite remote sensing of sea came with the advent of the 21st century, when cooperation between the first three of the four institutes mentioned earlier was established and generously subsidised by the Polish state. In 2001–2005 IO PAN, together with IO UG and IF PUinS, worked on a project commissioned by the Polish National Committee for Scientific Research entitled *The Development of a Satellite Method for Baltic Ecosystem Monitoring* (project No. PBZ-KBN 056/P04/2001). The first major result of this cooperation was the derivation of the first version of the DESAMBEM algorithm (the name is taken from the project's acronym)[5] and its application to remote sensing data recorded on 8 May 2001, which yielded a set of distribution maps of four significant characteristics of the Baltic Sea, namely, sea surface PAR[6] irradiation, sea surface temperature, surface chlorophyll *a* concentration and total primary production in the water column (Woźniak et al. 2004). This historically important result is presented in Figure 1. Cooperation between the three institutes continued within the framework of the Inter-Institute Team for Satellite Observations of the Marine Environment, partly funded by the Ministry of Science and Higher Education, (MNiSW Decision No. 31/E-45/BWSN-0105/2008). The main aim of these activities was to establish the scientific foundations and methodology for employing remote sensing techniques to monitor the Baltic as an inland sea with a high biological productivity yet under serious threat from the effects of economic development. From this work there emerged a number of detailed models of different physical, chemical and biological phenomena taking place in the Baltic and in the atmosphere above it, enabling numerous parameters characterizing the state and functioning of the Baltic ecosystem to be determined from remote sensing data (see, for example: Woźniak et al. 1992a,b, 1995, 1997a,b, 2000, 2002a,b, 2003, 2004, 2007a,b, Dera 1995, Kaczmarek & Woźniak 1995, Krężel 1997, Majchrowski & Ostrowska 1999, 2000, Majchrowski et al. 2000, 2001, Ostrowska et al. 2000a,b, 2007, Ficek et al. 2000a,b, 2003, 2004, Ficek 2001, Majchrowski 2001, Ostrowska 2001, Darecki & Stramski 2004, Kowalewski & Krężel 2004, Darecki et al. 2005, Krężel et al. 2005a,b, 2008). Synthesis of these detailed models yielded a more ramified and more precise version of the comprehensive DESAMBEM algorithm (version 2008) consisting of many subalgorithms (Woźniak et al. 2008). Tests on the Baltic showed this algorithm to be an effective tool for estimating many properties of this sea on the basis of satellite data from systems like AVHRR/TirosN/NOAA, SEVIRI/Meteosat, SeaWiFS/OrbView 2 and MODIS/Aqua. These properties include SST distributions, concentrations of chlorophyll and other phytoplankton pigments in the surface layer and at various depths in Baltic waters, the solar irradiance distribution at the Baltic Sea surface, vertical profiles of selected optical properties of the sea, spectral distributions of the light energy available for photosynthesis and of the energy absorbed by phytoplankton at different depths, vertical distributions of the quantum efficiency of photosynthesis, of the primary

[5]DESAMBEM – DEvelopment of a SAtellite Method for Baltic Ecosystem Monitoring; the previous project (Woźniak et al. 2008, Darecki et al. 2008).

[6]PAR – Photosynthetic Available Radiation (∼ 400–700 nm).

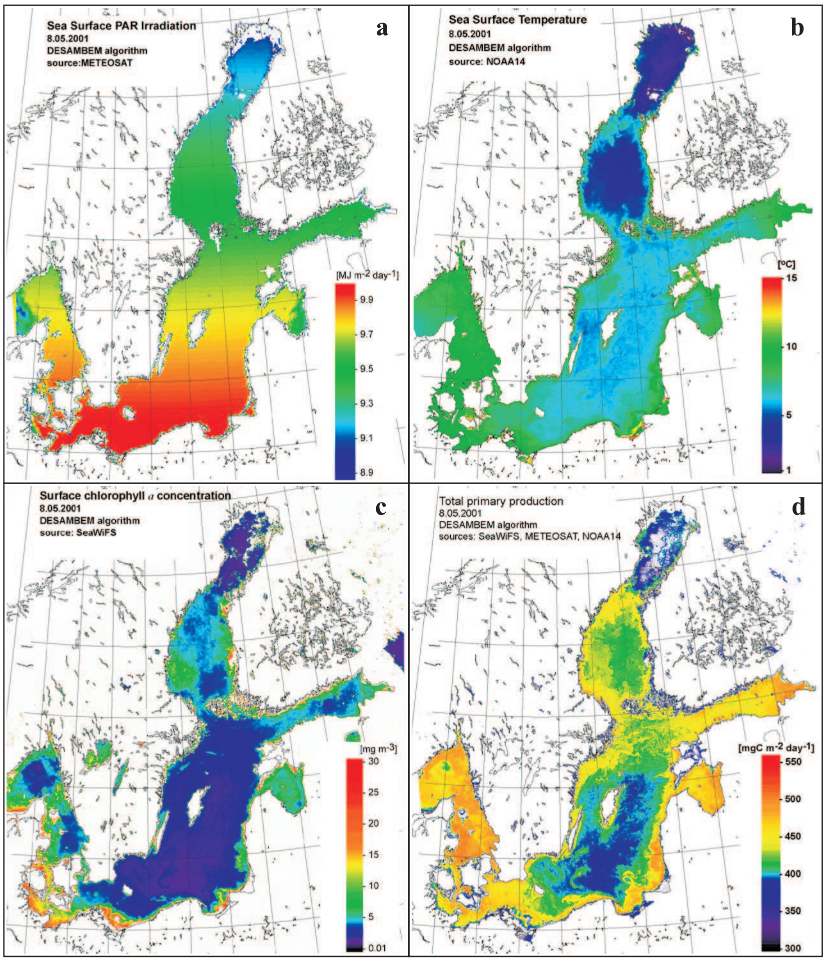

Figure 1. The first satellite maps, co-produced by IO PAN in Sopot, IO UG in Gdynia and IF PUinS in Słupsk, showing examples of the remotely sensed distributions of 4 parameters of the Baltic ecosystem on 8 May 2001: a) Sea surface PAR irradiation, calculated from METEOSAT and AVHRR data; b) Sea surface temperature, calculated from AVHRR (NOAA 14) data; c) Surface chlorophyll *a* concentration, calculated from SeaWiFS data; d) Total primary production in the water column, calculated from SeaWiFS, METEOSAT and AVHRR (NOAA 14) data (after Woźniak et al. 2004)

production of organic matter, and of the total primary production (under unit area of sea surface).

The estimates of all these quantities obtained from satellite data processed using the DESAMBEM algorithm v. 2008 were validated by comparing them with in situ measurements. The results of this empirical validation are discussed in detail in Darecki et al. (2008). The accuracy of the estimated parameters is very close to or only slightly less than that of the measurements made in the sea. The effectiveness of satellite estimates is incomparably greater than that of traditional measurements made from on board ships and other research platforms: a very much larger number of temporal and spatial sea surface pixels can be covered by satellite monitoring than by the existing numbers of measurement stations using ships, buoys and the like. Moreover, the costs of satellite monitoring are insignificant compared with those of traditional oceanographic methods. We, like our funding agencies, therefore consider that the results of the successfully concluded DESAMBEM project, generously financed by the Committee for Scientific Research, should be implemented in the interests of the efficient and systematic monitoring of the state of the Baltic environment and the forecasting of the changes taking place in it. This imposes the duty of conserving the natural environment of the Baltic in accordance with international conventions and legal regulations, such as the Helsinki Convention, the EU's New Water Directive and the GMES programme. The implementation of remote sensing methods has become possible thanks to the acceptance of the SatBałtyk project by the Ministries of Science and Higher Education, and of Regional Development. Thus came into being project No. POIG.01.01.02-22-011/09-00 entitled 'The satellite monitoring of the Baltic Sea environment' (acronym SatBałtyk). A period of five years (2010–2014) are envisaged for the project's realization. It is being implemented within the framework of the Innovative Economy Operational Programme[7], financed from EU funds. The beneficiary appointed to see the project through is the SatBałtyk Scientific Consortium, consisting of four scientific institutions located on the Polish coast. They are the three institutes that have been cooperating for many years, i.e. IO PAN (coordinator), IO UG and IF PUinS, and additionally IMCS US, which is also highly qualified to undertake the satellite monitoring of the Baltic environment. More detailed information on the organization of this project are given in Dera (2010). The aims of the project and the expected range of work will be briefly outlined in section 3.

3. The objectives and scope of the SatBałtyk project

The prime objective of the SatBałtyk project is the preparation and implementation of the technical infrastructure and practical operational procedures enabling the efficient routine determination of the states of

[7]Priority axis 1: Research and development of modern technologies, Action 1.1: Support for scientific research for establishment of a knowledge-based economy.

the Baltic environment, i.e. the production of maps of its structural and functional characteristics. These include the influx and characteristics of solar radiation energy (PAR, UV, IR[8]), the short- and long-wave radiation budget at the sea surface and in the upper layers of the atmosphere, temperature distributions, the dynamic state of the sea surface, concentrations of chlorophyll and other phytoplankton pigments in the water, algal blooms, the occurrence of upwelling events, and the characteristics of the production of organic matter and photosynthetically released oxygen O_2 in the water. Also envisaged are the development and, if possible, the implementation of remote sensing methods for assessing the state of sea surface ice cover and slicks due to petroleum-derived pollutants, and for recording the effects and forecasting threats in the sea's littoral zones resulting from current and anticipated storm states. The ultimate aim of the project is to put in place an operational system for the rapid and effective determination of all the above-mentioned characteristics of the Baltic Sea in the form of maps of their distribution within the sea's area; in other words, the main aim of the project is to develop and implement a system based on remote sensing data for the efficient, routine monitoring of the Baltic Sea.

The SatBałtyk Operational System is based on the most efficient of the available modern algorithms applicable to the Baltic Sea, i.e. the above-mentioned DESAMBEM v. 2008. However, this algorithm requires further modification and improvement, and its implementation in routine monitoring practice is a very complex IT problem. Thus, in order to achieve the project's principal objective, formulated above, a whole range of difficult partial objectives (tasks) have to be realized. In brief, they can be stated as follows:

- Refinement of the theoretical models upon which the DESAMBEM v. 2008 algorithm is founded. This will involve investigating aerosols in order to refine the model of solar radiation transfer through the atmosphere over the Baltic, to improve the model of solar radiation influx to the Baltic Sea surface and the so-called 'atmospheric correction' of signals recorded by satellites, and to update the optical models of the sea, the light-photosynthesis model and others. We also envisage extensive studies of the links between the taxonomic composition of Baltic plant communities and the compositions of phytoplankton pigments in the various conditions prevailing in this sea; this will enable an approximate method to be devised for estimating the concentrations of different phytoplankton taxa from their remotely determined pigment compositions.

[8]UV – ultraviolet radiation, IR – infrared radiation.

- Extending the list of properties of the marine environment remotely determined on the basis of the DESAMBEM v. 2008 algorithm to include, inter alia, the radiation budget between the sea surface and the upper layers of the atmosphere, the intensity of UV radiation over the sea and in coastal areas, the concentrations of some other constituents in the sea water, and estimates of the amount of photosynthetically released oxygen, of the extent of any oil-based pollution, surface wave parameters, ice cover and changes in sea-shore structure.
- The development and implementation of a packet of prognostic models together with procedures for the assimilation of the satellite data and data obtained with the aid of DESAMBEM's diagnostic subalgorithms. This is essential in view of the frequent cloudiness over the Baltic, which partially or wholly precludes the use of satellite sensors for the observation and immediate diagnosis using the DESAMBEM algorithm of phenomena taking place in the sea. In such cases interpolation (between points in space-time) of measurements obtained remotely in cloud-free areas is applied. The most intelligent means of interpolation is to use data generated by prognostic ecohydrodynamic models. The use of these mathematical models provides a far better interpolation of data than statistical methods can, because such models take into account the physical and other laws shaping the spatial distributions of the parameters in question.
- The development and implementation of methods for the continuous calibration of the SatBałtyk system (measurements from research vessels, platforms and sea buoys, shore stations).
- The preparation of the technological resources for the SatBałtyk Operational System and its routine implementation for the solving of technical and informational problems arising out of the gathering, processing, accumulation and dissemination of data about the marine environment estimated using this System.

Only when the above-mentioned partial objectives have been achieved will it be possible to launch the complete SatBałtyk Operational System, equipped with appropriate procedures for the continuous spatial and temporal monitoring of the main structural and functional characteristics of the entire Baltic Sea, and not just of instantaneous and local situations from the very restricted study areas accessible from ships or buoys. The main source of the satellite input data for this system will be the ongoing systematic measurements made by meteorological, environmental and special-purpose satellites: TIROS N/NOAA, MSG (currently Meteosat 9), EOS/AQUA, DMSP, ENVISAT and others. This monitoring and the running analyses of its results will enable the production of maps, graphs, tables and descriptions characterizing the state of various aspects of the Baltic environment. This should be achievable in about 3–4 years' time. The two articles in the present series of publications on the SatBałtyk project can be considered as a 'first quarter' summary (March 2011 was the fifteenth month of the project, its total duration being 5 years, i.e. 60 months). In the remainder of this article (Part 1), we give a fairly detailed description of the main components of the SatBałtyk Operational System as we see it at present, and a brief outline of how it should eventually function. In Part 2 (see Woźniak et al. 2011 in this issue) we shall mainly present in map form the preliminary results obtained during the first 15 months of the SatBałtyk project.

4. The way in which SatBałtyk functions and the scheme of its overall operational system

The development of the SatBałtyk Operational System has 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 characterizing the progress of this modelling.

Figure 2 illustrates the main components of the SatBałtyk Operational System and a simplified general block diagram of how it is ultimately expected to function. This system consists of two independent but coordinating subsystems: the DESAMBEM Diagnostic System and the BALTFOS[9] Forecasting System. They contain sets of algorithms enabling current or anticipated sea states to be diagnosed on the basis of appropriate input data, the sources of which are principally satellite radiometers and/or hydrometeorological data supplied by specialized routine services.

The DESAMBEM Diagnostic System, upon which the entire SatBałtyk Operational System is founded, enables current structural and functional parameters of the marine environment to be determined on the basis of the relevant calculations, for which the input data are the results of current remote sensing registrations. In view of the sequence of the calculations to be carried out and their complexity, five blocks of algorithms can be distinguished:

- **Block D0 (INITIAL PROCESSING)** contains a set of preliminary, mostly routine, algorithms and procedures for processing

[9]BALTFOS – BALTic FOrecasting System.

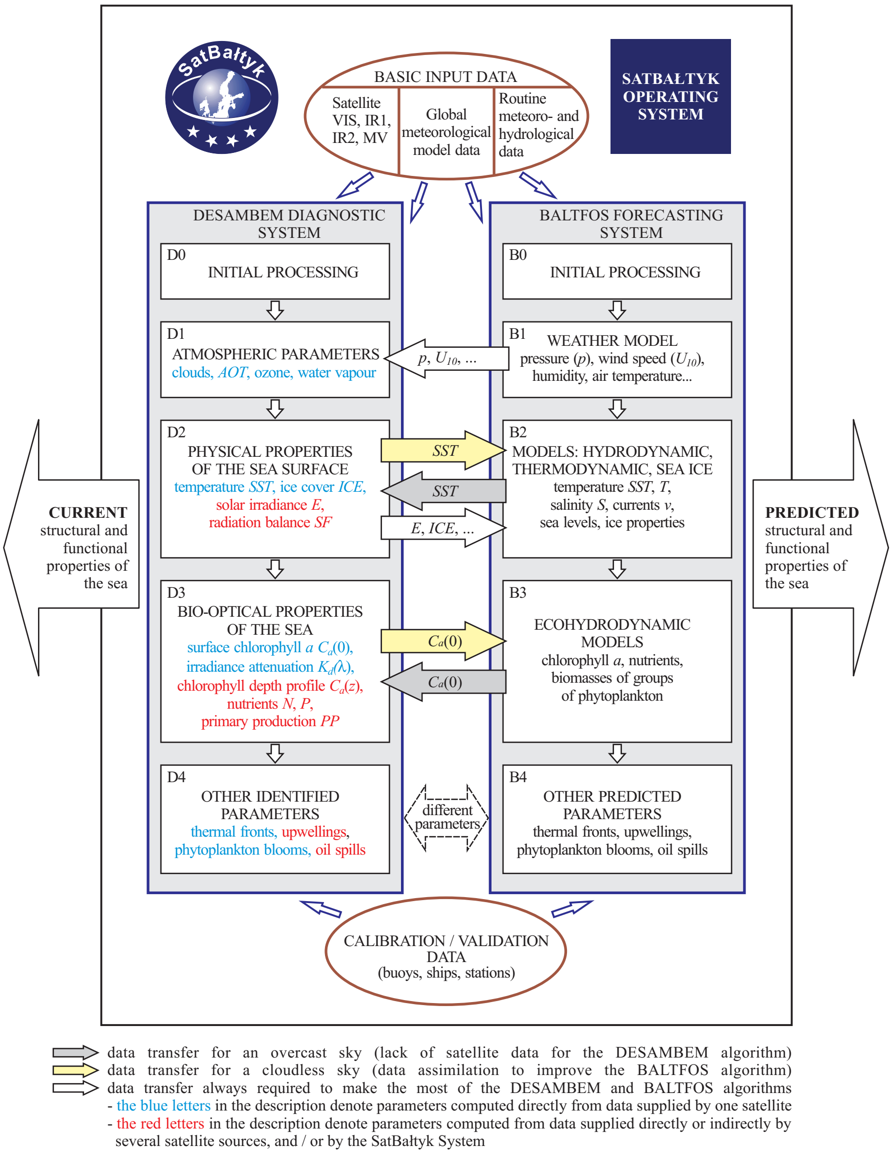

Figure 2. Block diagram of the SatBałtyk Operational System

satellite data (formatting, geographical registration, instrumental correction, geometric correction etc.) (Kowalewski & Krężel 2004).

- **Block D1 (ATMOSPHERIC PARAMETERS)** contains algorithms for determining various parameters of the state of the atmosphere, significant for the transmission of radiation, like cloud cover and transmission, aerosol optical thickness, water vapour and ozone content, which can usually be determined directly on the basis of the radiometric data from one satellite (Krężel et al. 2008, Krężel & Paszkuta 2011).

- **Block D2 (PHYSICAL PROPERTIES OF THE SEA SURFACE)** contains algorithms for determining various physical parameters of the sea surface and contiguous water layers. Some of them, like sea surface temperature (SST), ice cover (ICE) and a few others, are defined directly – as above – on the basis of radiometric data from one satellite (Krężel et al. 2005b, Sandven & Johannesen 2006, Woźniak & Krężel 2010). Others, like the sea surface irradiance E, the sea surface radiation balance NET and its components, are parameters whose determination requires calculations based on data supplied directly or indirectly by several satellite sources (Zapadka et al. 2008).
- **Block D3 (BIO-OPTICAL PROPERTIES OF THE SEA)** contains algorithms for determining the bio-optical parameters of both the surface waters of the sea, and of the water masses at various depths. They include surface chlorophyll a concentration $C_a(0)$, downward irradiance attenuation coefficient $K_d(\lambda)$ and other inherent (IOPs) and apparent (AOPs) optical properties of the basin, carrying information about the concentrations of the optically significant constituents of sea water occurring there, inter alia, the vertical distributions of chlorophyll a and other pigments ($C_a(z)$, $C_i(z)$), and nutrients (N, P,...), various characteristics of the photosynthesis of marine phytoplankton, primary production PP and oxygen released during photosynthesis (O_2). Some of these magnitudes are determined relatively simply from the radiometric data provided by one satellite. Most, however, require the use of complex mathematical models of the optical and biophysical processes occurring in the sea and calculations from data supplied directly or indirectly by several satellite sources (Darecki et al. 2008, Woźniak et al. 2008).
- **Block D4 (OTHER IDENTIFIED PARAMETERS)** contains additional algorithms for identifying various complex phenomena, such as thermal fronts, upwelling events, phytoplankton blooms, oil spills, etc., which are determined from some of the above-mentioned remotely sensed sea state parameters (Krężel et al. 2005a,b Brekke & Solberg 2005, Kostianoy et al. 2006, Belkin & O'Reilly 2009).

The operation of the DESAMBEM diagnostic system is subject to certain constraints, however. The frequent completely overcast skies in the Baltic region prevent some of the optical sensors on board satellites from gaining a direct view of the water surface, so under these conditions remote sensing using the DESAMBEM algorithm alone is impossible. This applies in particular to satellite scanners, operating in the visible and infrared ranges, used to determine, for example, the surface concentration of chlorophyll *a* $C_a(0)$ and the sea surface temperature (SST). Nevertheless, values of $C_a(0)$ and SST are indispensable as input data for calculating optical properties and the characteristics and state of marine ecosystems, including primary production in the sea, if we wish to use the algorithm in Blocks D2–D4 for this purpose. Under such conditions, we can use values of $C_a(0)$ and SST, respectively interpolated on the basis of their values remotely sensed on cloudless days, that is, for spatio-temporal points when the sky was not overcast. After many attempts at using different methods of this interpolation (e.g. 'kriging' and 'cokriging' – see e.g. Abramowitz & Stegun 1972, David 1988), we decided that the best way of solving this problem would be to use a packet of prognostic hydrodynamic and ecological models enabling the assimilation of satellite data processed by the DESAMBEM system (see Figure 3 and its discussion). This packet is the **BALTFOS Forecasting System**, mentioned earlier. It is based on models that we developed earlier (Kowalewski 1997, Ołdakowski et al. 2005, Dzierzbicka-Głowacka 2005, 2006), which are now being expanded and adapted to the objectives of the SatBałtyk project (Dzierzbicka-Głowacka et al. 2011). The BALTFOS system consists of the five blocks described below:

- **Block B0 (INITIAL PROCESSING)**, which contains a set of procedures for obtaining and initially processing input data from global operational weather models as well as routine meteorological and hydrological measurements from buoys or shore stations. Data from the global models will serve to prepare the initial and boundary conditions for local weather models and ecohydrodynamic models, whereas the measurement data will be assimilated in these models.
- **Block B1 (WEATHER MODEL)** includes local weather models facilitating the forecasting of meteorological parameters obtaining in the Baltic region, in particular, wind conditions, atmospheric pressure, air temperature and air humidity, and cloudiness. These parameters are indispensable for other prognostic models, and some of them constitute complementary information in the DESAMBEM Diagnostic System (Block D1). The first stage of the project will use operational data from the UM model operating at ICM (Herman-Iżycki et al. 2002). In subsequent stages it is planned to implement local applications of the WRF model (Skamarock et al. 2008) especially for the requirements of the SatBałtyk project.

- **Block B2 (HYDRODYNAMIC, THERMODYNAMIC AND SEA ICE MODELS)** contains numerical models with which hydrodynamic parameters of the sea (temperature, salinity, sea level, currents) and of sea ice (concentration, thickness, direction and speed of drift) can be forecast. The use of these models will enable the assimilation of remotely sensed SST (Block D2), and these values can then be used to fill the gaps in satellite maps of SST in overcast areas. It is anticipated that two different hydrodynamic models integrated with the CICE sea ice model will be used (Hunke & Lipscomb 2010), the former based on the POM model (Blumberg & Mellor 1987), the latter on the POP model (Bryan 1969, Semtner 1974, Cox 1984, Smith & Gent 2004). Both models have been adapted to the Baltic Sea (Kowalewski 1997, Dzierzbicka-Głowacka et al. 2011); CICE will be adapted to Baltic conditions within SatBałtyk.
- **Block B3 (ECOHYDRODYNAMIC MODELS)** covers numerical ecological models integrated with the hydrodynamic model, which will allow the biomasses of groups of phytoplankton, primary production, and the concentrations of nutrients, chlorophyll a and dissolved oxygen to be forecast. The ecohydrodynamic models will supply information on chlorophyll a for periods of overcast weather. Within SatBałtyk it is planned to develop a new model (EcoSat), enabling the assimilation of remotely determined distributions of surface chlorophyll a. This new model will be based on existing models developed for the Baltic: ProDeMo (Ołdakowski et al. 2005) and 3DCEMBS (Dzierzbicka-Głowacka 2005, 2006, Dzierzbicka-Głowacka et al. 2011).
- **Block B4 (OTHER PREDICTED PARAMETERS)** contains models and algorithms for forecasting complex phenomena taking place in the basin, such as thermal fronts, upwelling events and phytoplankton blooms. This block will also include models enabling the effects of and possible threats to the coastal zone of storms (rip currents, risk of beach inundation, the amount of material eroded from the shore and the amount of material suspended in the water). This will be an extension of the existing early-warning system for storms, developed within the international MICORE 7 Framework Programme (http://www.micore.eu).

As shown earlier, the two cooperating data processing subsystems DESAMBEM and BALTFOS are complementary within the framework of the SatBałtyk Operational System. So, for example, if direct remote sensing of the sea is not possible because the sky is overcast, especially if the sea surface temperature (SST) and the surface chlorophyll a concentration

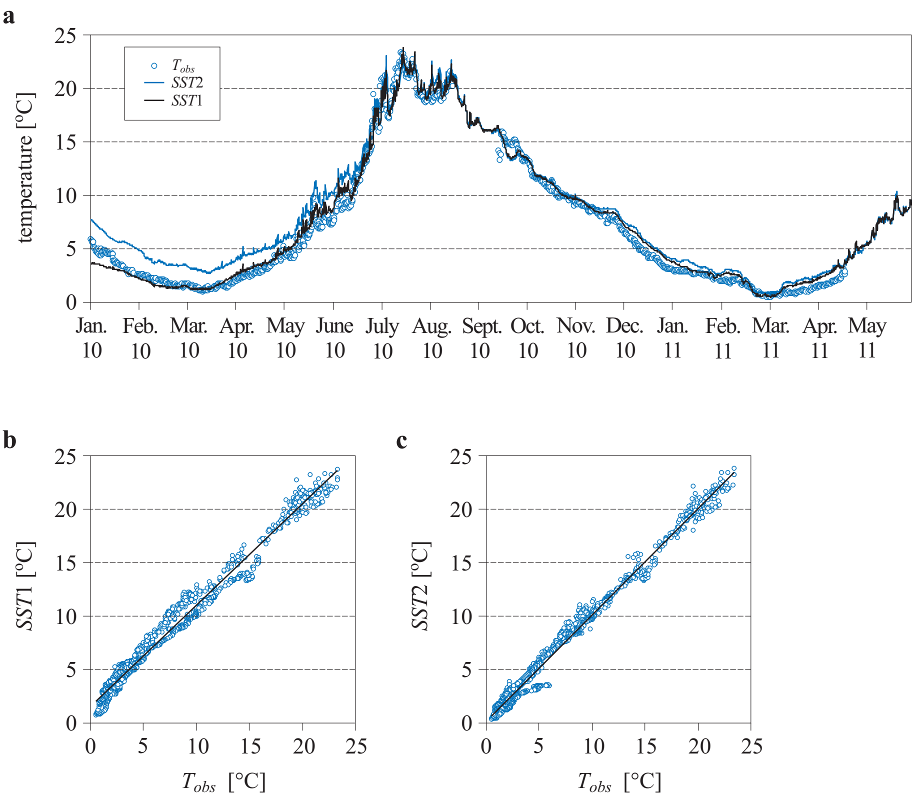

Figure 3. Examples of seasonal changes in sea surface temperature at a station in the southern Baltic (18.78°E, 55.92°N): measured between January 2010 and June 2011 – T_{obs}, modelled by assimilating SST satellite maps – $SST2$, and modelled without this assimilation – $SST1$ (a); comparison of sea surface temperature measured at stations in the southern Baltic – T_{obs} with forecast SSTs modelled without the assimilation of satellite maps of SST – $SST1$ (b); comparison of sea surface temperature measured at stations in the southern Baltic – T_{obs} with forecast SSTs modelled with the assimilation of satellite maps of SST – $SST2$ (c)

$C_a(0)$ cannot be measured, the values of these data in the DESAMBEM subsystem serving to determine various current values of marine ecosystem parameters based on SST and $C_a(0)$ data are based on forecasts made by the BALTFOS subsystem (see the horizontal arrows from right to left between the subsystems on Figure 2). On the other hand, the forecast values of parameters determined by the component algorithms of the BALTFOS subsystem can be verified (calibrated) by the assimilation of the actual values of these parameters determined by the DESAMBEM algorithm (see the horizontal arrows from left to right between the subsystems on Figure 2).

Table 1. Absolute errors of estimates of sea surface temperatures, forecast using BALTFOS algorithms: $SST1$ – calculated without the assimilation of satellite data; $SST2$ – calculated with the assimilation of satellite data

	Arithmetic statistics	
Quantity	Systematic error $< \varepsilon >$ [°C]	Statistical error σ_ε [°C]
$SST1$	1.17	±0.89
$SST2$	0.47	±0.55

As a result, the accuracy of the current structural and functional parameters of the sea estimated by both subsystems is far greater than would be the case if these estimates were made separately, that is without the cooperation of both systems. This improvement in accuracy is illustrated in Figure 3, on which SSTs forecast using the hydrodynamic model (Kowalewski, 1997, Kowalewski & Kowalewska-Kalkowska 2011) are compared with the corresponding values from a measurement buoy in the southern Baltic (18.78°E, 55.92°N). The data from this buoy were obtained from SMHI (Swedish Meteorological and Hydrological Institute) within the framework of BOOS (Baltic Operational Oceanographic System). Figure 3a shows temperature changes from January 2010 to June 2011 measured directly at this station and those simulated with and without the assimilation of remotely sensed SSTs. The figure shows that the temperatures forecast using assimilated remotely sensed SSTs are far closer to the real values than is the case with forecasts done without such assimilation. This is made clear in Figures 3b and 3c, which present a comparison of both these forecast temperatures with measured temperatures and the estimated errors for both cases set out in Table 1. In the case of estimation using assimilated measurement data both the statistical and the systematic errors in the determined SSTs are around half those errors determined without that assimilation and are relatively small, ca half a degree. Therefore, assimilation by the BALTFOS subsystem of remotely sensed SST data supplied relatively frequently by the DESAMBEM subsystem is highly desirable. On the other hand, using SST data forecast by BALTFOS for calculating current values of those parameters of the sea determined by the DESAMBEM algorithm for high degrees of cloudiness is preferable to interpolating SST by 'kriging' and 'cokriging'. This is because, in our opinion, these latter methods of interpolating SST, even for brief episodes of cloudiness affecting small areas, can give rise to errors of the order of one to several degrees.

To be fair, however, we must add one more important comment. The above arguments, corroborated by the quoted values of the relevant errors of estimated current and/or forecast sea states and confirming the usefulness of coupling the two complementary subsystems DESAMBEM and BALTFOS in the SatBałtyk Operational System, relate directly only to SST. At the present time we still do not have appropriate numerical data characterizing the accuracy of current and/or forecast estimates of other structural and functional parameters of marine ecosystems, in particular the concentration of chlorophyll *a*, which would support the usefulness of such coupling. Even so, this usefulness is being confirmed by the preliminary results of analyses, the results of which will be published at a later date.

5. Final remarks

The work done so far in the SatBałtyk project confirms the usefulness of satellite systems for the comprehensive and effective monitoring of the current state of the marine environment, and also to a large degree for the forecasting of a whole range of natural phenomena taking place in Baltic waters and in the atmosphere above, including the monitoring of the water's purity and the extent of its eutrophication. These satellite systems enable the production of maps of spatial distributions of many state parameters of this environment, as well as certain state parameters and optical properties of the atmosphere, surface temperatures in different basins and hence surface currents and upwelling events, the range and direct spread of river waters in the Baltic, water transparency and the optical properties of the sea, the depth of the euphotic zone, the radiation balance at the sea surface and in the upper layers of the atmosphere, the intensity of UV radiation over the sea and coastal areas, the distributions of irradiance energy useful for photosynthesis PAR, the concentration of chlorophyll and other pigments in the water, the primary production of organic matter and the photosynthetically released oxygen in the sea, as well as the extents of phytoplankton blooms (including toxic cyanobacteria). It is also possible to determine a range of biological parameters characterizing, among other things, the condition of marine life, in particular algae and their physiological and phytophysiological parameters like the maximum assimilation number, the factor of non-photosynthetic pigments, the efficiency of photosynthesis at different depths, and the maximum quantum yield of photosynthesis in water of a given trophicity. Specific examples of many of these physical, chemical and biological parameters characterizing the sea-atmosphere system and marine ecosystems and the processes taking place in them will be described and discussed in Part 2 of this series of articles (see Woźniak et al. (2011) in this issue). This will show distribution maps of some of these parameters in the Baltic Sea, produced using the algorithms of the SatBałtyk Operational

System. These examples provide an ample illustration of the merits and potential uses of these algorithms.

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