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DAILY RADIATION BUDGET OF THE BALTIC SEA SURFACE FROM SATELLITE DATA

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ABSTRACT

Recently developed system for assessment of radiation budget for the Baltic Sea has been presented and verified. The system utilizes data from various sources: satellite, model and in situ measurements. It has been developed within the SatBałtyk project (Satellite Monitoring of the Baltic Sea Environment - www.satbaltyk.eu) where the energy radiation budget is one of the key element. The SatBałtyk system generates daily maps of the all components of radiation budget on every day basis. We show the scheme of making daily maps, applied algorithms and empirical data collection within the system. An empirical verification of the system has been carried out based on empirical data collected on the oil rig placed on the Baltic Sea. This verification concerned all the components of the surface radiation budget. The average daily NET products are estimated with statistical error ca. 13 Wm-2. The biggest absolute statistical error is for LWd component and equals 14 Wm-2. The relative error in relation to the average annual values for whole Baltic is the biggest for SWu and reaches 25%. All estimated components have correlation coefficient above 0.91.

Keywords: Surface radiation budget, satellite, Baltic Sea

INTRODUCTION

The exchange of radiative energy between the atmosphere and the sea surface plays an important role in shaping the climate of the Baltic Sea. Monitoring of the radiation budget components at the sea surface allows to assess possible changes in the Baltic Sea environment and its directions. The surface radiative budget *NET* consists of four fluxes: downward SW_d and upward SW_u shortwave (solar radiation range 0.3 µm - 4 µm), and downward LW_d and upward LW_u (atmospheric and sea surface thermal radiation range 4 µm - 100 µm) longwave radiation. The sum of all fluxes gives the surface radiation budget at surface *NET*. Details of these fluxes are shown on Fig.1.

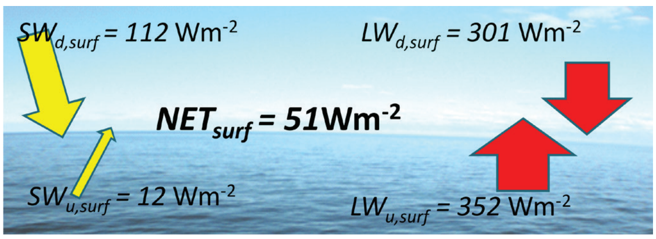


Fig. 1. Components of surface radiation budget with approximate values for the Baltic Sea estimated on the basis of data from SatBałtyk system

For the Baltic Sea seasonal changes of the radiation budget at sea surface are calculated mainly based on numerical models [1], [9] or from hydro-meteorological ship observations

[6]. The question of the energy budget of the Baltic Sea was developed within BALTEX (Baltic Sea Experiment [2], [3], [8], [12]). Depending on the model used, the final results are different [1], [9]. Due to the lack of direct measurements of the radiation fluxes at the sea, assessment of accuracy of such obtained data is very difficult. Therefore, other methods are desirable. Such a method commonly applied for many years is to assess radiative budget with the use of satellite observations. Satellite data allow the estimation of the surface radiation budget covering large areas at the one moment in time. Such estimations have been developed for many years by CM SAF (Climate Monitoring Satellite Application Facility on Ocean and Sea Ice) and OSI SAF (www.cmaf.eu, www.osi-saf.org). However, their study have a rather global character and possibilities of applying it to specific regions are often limited. In the SatBałtyk project [14], [15], local satellite algorithms have been used to create daily maps of radiation components. The algorithms were developed for the Baltic Sea [6], [16], [17] and improved within SatBałtyk project based on empirical data collected directly on the sea surface. The choice of satellite data source and appropriate algorithm determinates an accuracy of estimated values. In the case of a local area like the Baltic Sea, the space and time resolution of data used is also critical. It is important that the used algorithms have been developed specifically for this region. On the basis of these algorithms maps of radiation budget components are created every day and presented on the website http://satbaltyk.iopan.gda.pl/. The SatBałtyk project has launched actinometric stations along the Polish coast and one station on the oil rig placed around 70 km from shore. The data from the station at sea are very valuable and unique for the Baltic. The data enable to validate daily radiation budget components for real marine conditions for each day of the year. For the Baltic this type of analysis has not been conducted. Most of this type of validation was done on the basis of data from land stations or by indirect methods. The validations based on empirical data collected on the vessel have been made for instantaneous values [16].

The aim of this work is to show possibility of using satellite data to estimate the daily average of the surface radiation budget components for the Baltic Sea and to show accuracy of the presented methods. An empirical verification of the final products were carried out against empirical data from pyranometers and pyrgeometers placed on the oil rig [19]. The paper focuses on the overall scheme of modeling with emphasis on the type used input data and assessment of accuracy. Detailed information about the formulas used can be found in the cited papers [6], [16], [19] and in SatBałtyk project reports [18]. Most of them are still being modified and presented results should be treated as a preliminary.

METHODS AND INPUT DATA

Figure 2 shows the general block diagram for calculating components of the radiation budget. The input data come from the four independent sources: AVHRR (Advanced Very High Resolution Radiometer) radiometers working on board the American TIROS-N/NOAA meteorological satellites (NOAA 15, 16, 17), SEVIRI (Spinning Enhanced Visible and InfraRed Imager) radiometer working on board MSG (Meteosat Second Generation 9, 10) and from prognostic model UMPL and from ecohydrodynamic model 3D CEMBS [4] as auxiliary data. The data from these sources are generated by SatBałtyk service. The maps from each source were imported into a 1 km resolution format (1280×1408 pixels), in Lambert Azimuthal Equal Area projection. The final products have the same format. The main parameters determining the fluxes (sea surface temperature (SST), cloudiness) are defined based on satellite information. The SST were determined by using the split –window method for AVHRR thermal channels 10.8 µm and 12 µm [5]. The number of SST maps was from six to eight for a day. Most of the maps were empty or only partially completed due to the presence of clouds. The cloudiness parameter was estimated separately for SW_d and for LW_d algorithms. This is due to the different properties of the SW and LW radiation. In the case SW_d cloudiness coefficient was determined based on HRV (High Resolution Visible 0.4-1.1 µm) channel from SEVIRI [6]. In the case LW_d an impact of clouds on radiation reaching sea surface was determined by the functions of cloudiness different for night and daytime. For the daytime the function depends on HRV [18]. For the night the function is dependent on the cloud fraction parameter. Cloud fraction is determined based on thermal channels from SEVIRI [10].

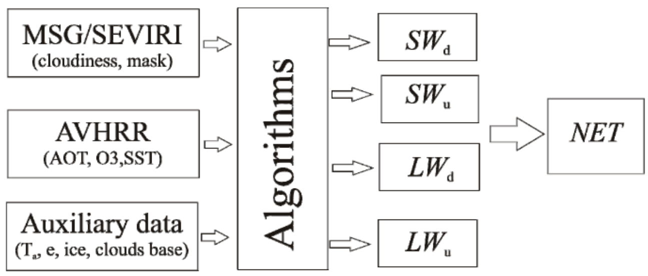


Fig. 2. Block diagram

The used models are described below. Most of them were developed or improved within the SatBałtyk project. The empirical data for satellite algorithms development were collected during cruises on s/y Oceania on the Baltic Sea in different seasons [16].

DOWNWARD SHORTWAVE RADIATION SW_D

The SW_d model described in detail by Krężel et al. [6] is a physical parametrization in which transmittances of the atmospheric column are computed separately for cloudless and cloudy situations. The model was developed within SatBałtyk project. For cloudless part $SW_{d,0}$ is computed by adding contributions from gaseous absorption, Rayleigh scattering and aerosols absorption and scattering. The model includes the absorption effect of the ozone (total ozone column daily from TOAST[1]/NOAA or OMI/Aura), the attenuation by aerosols (AOT - aerosol optical thickness of the atmosphere from AVHRR) and the water vapour content in the atmosphere (from UMPL model). The clouds transmission calculations is based on a cloudiness parameter from visible HRV channel from SEVIRI.

$$SW_d = SW_{d,0} T_{cloud} \tag{1}$$

where $SW_{d,0}$ - the irradiance for a cloudless atmosphere, T_{cloud} - cloud transmittance computed on the basis of satellite algorithm as a function of cloudiness coefficient.

The instantaneous maps are computed every 15 minutes. Map of dose is created based on these maps. Both products are in the SatBałtyk operational service. The average daily maps are computed from:

$$\overline{SW_d} = \frac{\sum_{t_{sunrise}}^{t_{sunset}} SW_d}{8640} \tag{2}$$

where 8640 – the number of seconds in a day.

UPWARD SHORTWAVE RADIATION SW_U

The SW_u flux is computed based on the function from Payne [11] modified by Rozwadowska [13] for Baltic Sea and developed in SatBałtyk project [19]:

$$SW_u = SW_d \begin{cases} A_{sea} & \text{for} \quad \text{water} \\ A_{ice} & \text{for} \quad \text{ice} \end{cases} \tag{3}$$

where A_{sea}, A_{ice} - sea and ice albedo dependent on the transmission of the atmosphere, solar zenith angle and ice thickness concentration.

The information about the ice concentration is taken from ecohydrodynamic model 3D CEMBS [4]. For ice areas albedo is calculated for melting ice, snow and pure ice.

The instantaneous SW_u maps are computed every 15 minutes and based on these maps, the daily average product is created:

$$\overline{SW_u} = \frac{\sum_{t_{sunrise}}^{t_{sunset}} SW_u}{8640} \tag{4}$$

DOWNWARD LONGWAVE RADIATION LW_D

The LW_d model described in detail by Zapadka et al. [16], [17] is a semi-empirical formula which depends on water vapour e concentration in the atmospheric column and greenhouse gases, air temperature at the sea surface and cloudiness. Air temperature T_a and water vapour e were taken from the UMPL model. Cloud parameters were calculated separately for daytime (cloudiness from visible HRV channel from SEVIRI) and for night (cloud fraction as a combination IR channels from SEVIRI).

$$LW_d = LW_{d,0} f(c_i) \tag{5}$$

where $LW_{d,0}$ - the longwave irradiance for a cloudless atmosphere, $f(c_i)$ - a satellite cloud function different for night and daytime. The instantaneous maps are computed every hour and based on these maps, the average daily product is created. The average daily downward longwave radiation is calculated based on:

$$\overline{LW_d} = \frac{\sum_{t=1}^{t=24} LW_{d,0}}{n} \tag{6}$$

where n – number of maps.

UPWARD LONGWAVE RADIATION LW_U

The LW_u flux is computed on the basis of sea surface temperature T_{SST} obtained as a combination of two IR channels from AVHRR [5] and ice surface temperature T_{ice}.

$$LW_u = \begin{cases} \varepsilon_w \sigma T_{SST}^4 \\ \varepsilon_{ice} \sigma T_{ice}^4 \end{cases} \tag{7}$$

where ε_w, ε_{ice} - emissivity of the sea and ice surfaces respectively, T_{SST} - sea surface temperature from AVHRR and T_{ice} - ice surface temperature from the model.

The daily maps are created on the basis of all available scenes from up to five days back.

$$\overline{LW_u} = \frac{\sum_{i=1}^{n} LW_u}{n} \tag{8}$$

where n – the number of cloudless pixels.

Almost 2/3 of a year the sky over Baltic Sea area is covered by clouds. Obtaining the momentary temperature map for the whole Baltic Sea is not easy and requires analysing satellite maps from wider time range. Creating a satellite daily map for whole Baltic Sea often was done by merging many momentary maps. Used methodology gives a possibility to fill upward radiation map in 90% for almost 300 days a year [19].

EMPIRICAL MATERIAL

In this work we are presenting the verification of the mean daily values of every components. The verification was carried out against an empirical material collected in the years 2013 – 2014 on an actinometrical station located on the oil rig (PetroBaltic Platform on the Baltic Sea). The fluxes were measured using CG3, CGR4 pyrgeometers and CMP3 pyranometers (Kipp&Zonen) with one minute time resolution. Data were averaged for every day. The database contains 250 days from September 2013 to September 2014 without February, half March, half June, July 2014. Gaps in the data are connected with a break in the measurements. However,

[1] Total Ozone Analysis using SBUV/2 and TOVS

the range of values can be considered as representative for the Southern Baltic. SW_d changes from 6 to 370 Wm^{-2}, SW_u from 4 to 26 Wm^{-2}, LW_d from 255 to 392 Wm^{-2} and LW_u from 302 to 427 Wm^{-2}. In the Fig. 3 there is presented oil rig location on the background of exemplary *NET* map for 20th September 2014. This figure shows a print screen taken from SatBałtyk website where one can find analyzed products. The analysis concerns one pixel within which the actinometrical station occurs.

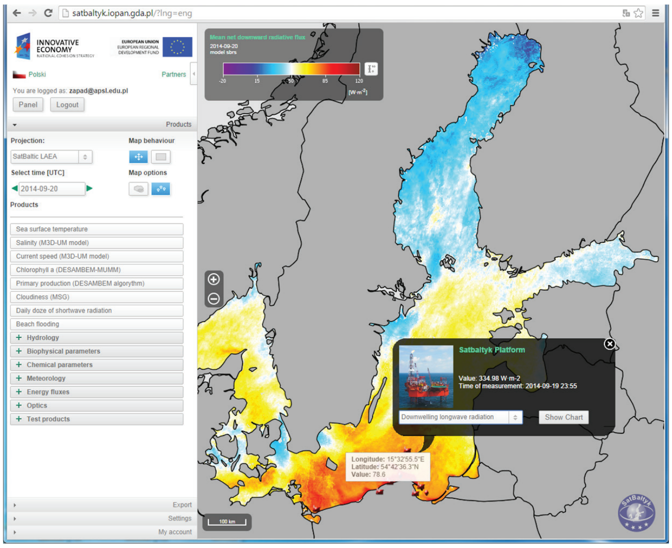


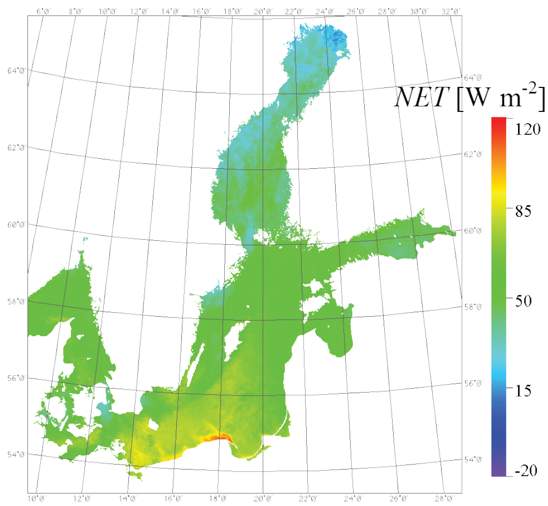
Fig. 3. Print screen from SatBałtyk website service with the oil rig localization

RESULTS

The methods described in paragraph 2 allow to create maps of each component of the radiation budget. The examples of daily average maps of SW_d, SW_u, LW_d, LW_u for a chosen day 20th September 2014 are shown in Fig. 4. As one can see in the case of shortwave products SW_d, SW_u distribution of values is similar but SW_u values are much smaller. It is because SW_u depends on SW_d. In the case of longwave radiation fluxes values, distribution differs and depends on many factors such as sea and atmosphere temperature, water vapour pressure and cloudiness. LW_u is usually smaller than LW_d. The daily map *NET* (Fig. 5a) for 20th September 2014 is a sum of four components where LW_u and SW_u are taken with the opposite sign. The smallest impact on the *NET* has SW_u but negligence of this variable could lead to big systematic errors especially in seasons of low sun position. The components are estimated with different accuracy. Comparisons between modelled and measured values of SW_d, SW_u, LW_d, LW_u respectively are presented in Fig. 4 on the right side. The first plot concerns SW_d. In this case, the correlation coefficient between the modeled and measured values is very high: r=0.99. Model works correctly in the whole range of values (for all seasons) with a slight underestimation of the value (systematic error - 2 Wm^{-2}). In the case of SW_u the model works correctly for values below 20 Wm^{-2}. It means that for high positions of the sun model overestimates. For LW_d the spread of values is the biggest and the statistical error reaches 14 Wm^{-2}. The main reason of so high error is wrong interpretation of cloudless and cloudy situations. Moreover, this version of model does not use information on the height of the clouds base. This is important in the case of used cloud fraction parameter especially for the night. The statistical error of LW_u reaching 7 Wm^2 is associated with underestimating mask of clouds. This error occurs for the edge of clouds. For instantaneous values specially selected for cloudless sky LW_u is estimated with statistical error of 4 Wm^{-2} [19].

Summarised results of empirical analysis are presented in Table I. The table contains statistical and systematic errors for each modelled component and correlation coefficients. Additional analysis was carried out for *NET* radiation balance. As one can see used model underestimates *NET*. Systematic error reaches value of -3 Wm^{-2}. The relative error in relation to the average annual values for the whole Baltic is the highest for SW_u and reaches 25% and the lowest for LW_u – 2%. In other cases for SW_d this error reaches 9% and for LW_d – 6%.

a)



b)

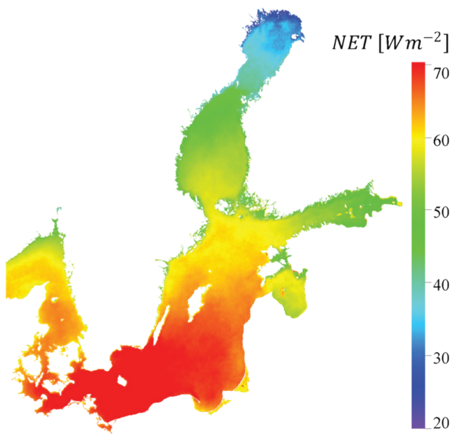


Fig. 5. The surface radiation budget NET for 20th September (a) and for 2013 year average annual (b)

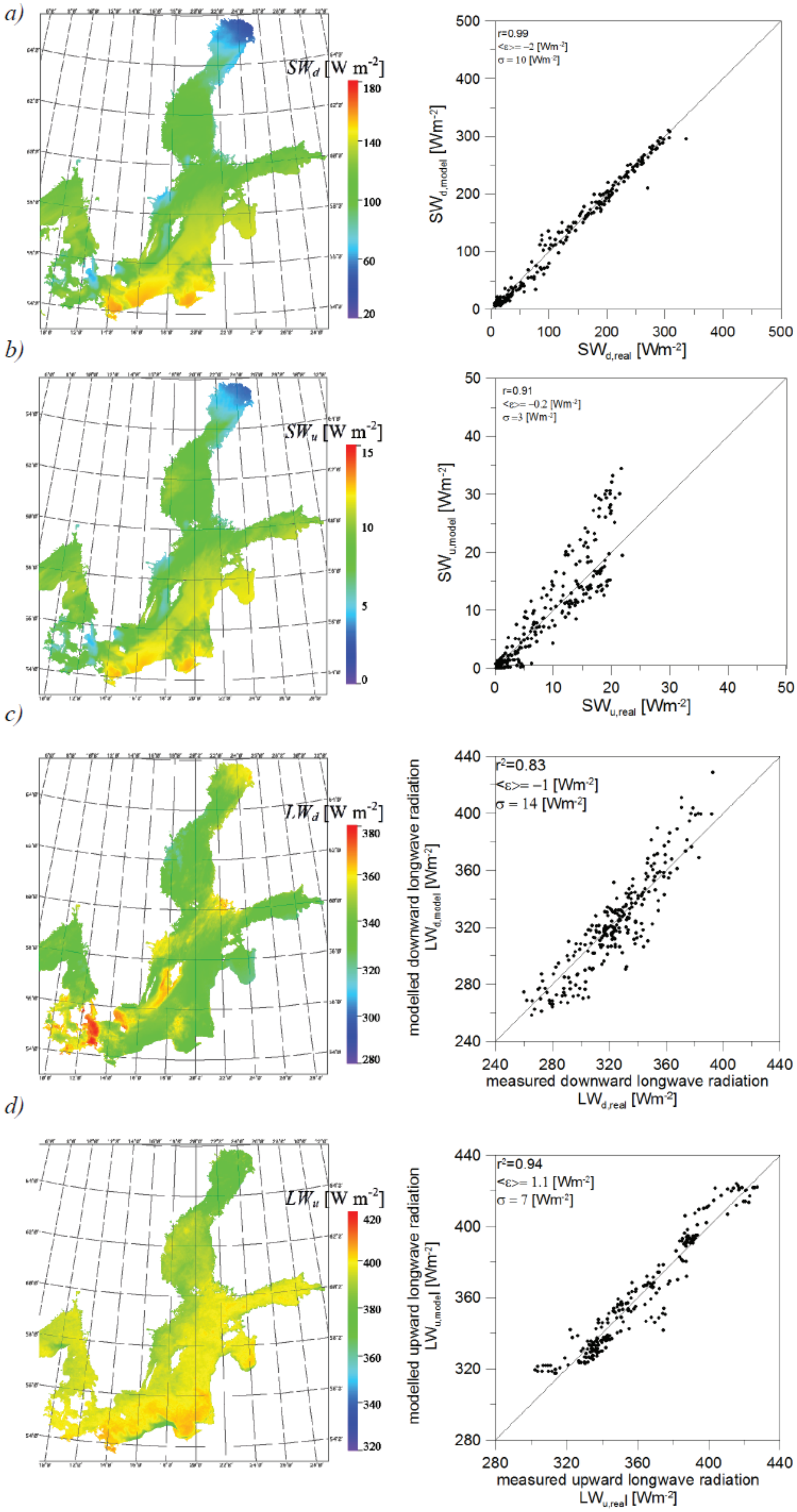


Fig 4. Daily average maps of SW_d a), SW_u b), LW_d c) LW_u d) for 20-09-2014 ,next to respectively for each flux comparisons between modelled and measured values

Table 1. Validation of the components of the radiation budget (Statistic error - standard deviation and Systematic error – BIAS, Mean – average values for all database)

flux	Mean	Syst. error [Wm^{-2}]	Stat. error [Wm^{-2}]	Correlation coefficient
SW_d	139	-1.8	10.0	0.99
SW_u	10	-0.2	3.1	0.91
LW_d	323	-1.3	14.2	0.91
LW_u	359	1.1	7.1	0.97
NET		-3.0	13.0	0.98

CONCLUSIONS

In presented work possibilities of estimating of the net radiation flux at the sea surface and its components SW_d, SW_u, LW_d, LW_u for Baltic Sea elaborated within SatBałtyk project have been shown. We presented the scheme of creating daily maps and used algorithms. Described methods allow operationally to create maps of SW_d, SW_u, LW_d, LW_u, NET for one day and any time period (Fig. 4; Fig. 5). The algorithms operate on the basis of input data from SatBałtyk system. To a large part, their development depends on additional input data generated by SatBałtyk system.

The validation was carried out for every component based on empirical data collected at sea surface on the oil rig (Fig. 3). Such data are unique to the Baltic and the Earth. The empirical verification showed that presented method allows with a high accuracy to estimate radiation budget for the southern Baltic Sea region (table 1). Unfortunately, the lack of empirical data for typical areas covered with ice, does not allow assessment of upward components for northern regions of the Baltic. We realize that some algorithms still require some improvement, for example, of LW_d and SW_u models. In the first place the presented model requires improvement of a cloudiness function. In the SW_u case the function of the solar elevation should be improved. LW_u dependence needs more correct mask of clouds.

The radiation budget at sea surface can be a key parameter for climate monitoring and analysis of the Baltic region. Satellite data allow estimation of the surface radiation budget with high spatial and time resolution. As shown, SatBałtyk system produce data which may be used to mentioned climate analysis. The daily map allows to analyse of spatial change of the surface radiation budget NET for every day in a year (Fig. 5a).The average annual map (Fig. 5b) shows the spatial distribution NET for the whole year.

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