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A MODEL OF SOLAR ENERGY INPUT TO THE SEA SURFACE

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Abstract

On the basis of the papers of Bird and Riordan (1986), Justus and Paris (1985), Krężel (1985, 1997) and Leckner (1978), a model of solar radiation energy input to the sea surface under real meteorological conditions has been developed. The model enables one to determine the flux or dose of total (direct + scattered) radiation within the whole visible light spectrum and any other spectrum interval in the range of 300–4000 nm. The initial data to the model are: atmospheric pressure and water vapour pressure at the sea surface and cloudiness. The seasonal mean long-term values of ozone and aerosol caused attenuation of light in the southern Baltic area were taken into account.

The calculations performed for Gdynia and Hel regions are in a good agreement with the actinometric data recorded in Gdynia. Therefore, the presented model could serve as a part of ecological model.

INTRODUCTION

The energy of solar radiation reaching the sea is one of the most important factors determining almost all processes in the marine environment. Its amount and temporal variability directly affect the occurrence and intensity of most of physical, chemical and biological processes. The process of thermal structure

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formation, flow fields in a given sea area, the value of the heat budget, photosynthesis intensity, primary production and phytoplankton bloom could be mentioned as examples. Thus, the energy of solar radiation is a component which must be included even in very simplified attempts of environment modelling.

The first stage in determination of the amount of radiation energy penetrating the sea, is to know its amount at the sea surface. This depends on astronomical factors and local ones that are related to the real atmospheric conditions. In the present state of knowledge, the former could be calculated with practically any accuracy, whereas the precise determination of such atmospheric parameters as concentration and quality of aerosols or amount and kind of cloudiness is still almost impossible. In this respect, satellite technique development may bring about a significant progress. Nevertheless, standard solutions in this field are still sought for.

The described model of solar energy input to the sea surface under real atmospheric conditions represents a traditional approach, *i.e.* parametrization of the process of attenuation of solar radiation in atmosphere by aerosols and cloudiness on the basis of data derived from traditional measurements or records carried out at meteorological stations. The model is based on the following papers: Bird and Riordan (1986), Justus and Paris (1985), Krężel (1985, 1997) and Leckner (1978) and allows (according to the needs of ecological model) the determination of density flux of solar radiation energy or its dose at the sea surface for any wavelength or radiation spectrum interval within the range from 300 to 4000 nm, with regard to direct and diffuse radiation in the case of cloudless sky as well as within visible part of solar spectrum (300–700 nm) in the presence of clouds. Thus, under real atmospheric conditions, the model enables one to evaluate solar energy totals in the entire spectrum at the sea surface.

MODEL

It is assumed that, for a given wavelength, the total solar radiation energy reaching the sea surface at a specified time period could be presented in the following form:

$$Q = \int_{t_1}^{t_2} (E_s \cos\vartheta + E_d) dt \cdot T_{Ch} \ , \tag{1}$$

where:

E_d, $E_s \cdot \cos\vartheta$, radiant flux density (irradiance) at the sea surface generated by direct and scattered in the atmosphere solar radiation, respectively; t, time; ϑ, solar zenith distance; T_{Ch}, function defining the effect of mean cloudiness on irradiance transmission at a time interval t_2–t_1.

Such a formula enables one to determine the amount of irradiance for a cloudless atmosphere and then, separately, to define the influence of cloudiness on the amount of irradiance.

ALGORITHMS FOR CALCULATING DIRECT SOLAR RADIATION

Considering the most important interactions of solar radiation passing to the sea surface with the atmosphere constituents, the direct irradiance of the area perpendicular to solar beam incidence (at the sea surface) could be expressed as:

$$E_s(\lambda) = \frac{F_s(\lambda)}{\beta^2} T_R(\lambda) \cdot T_a(\lambda) \cdot T_{wv}(\lambda) \cdot T_{O_3}(\lambda) \cdot T_G(\lambda)\,, \tag{2}$$

where:

λ, wavelength; $F_s(\lambda)$, spectral density of the solar constant; $\beta = R_s/R$, factor defining the annual variability of the distance between the Earth and the sun (R and R_s are actual and mean distances between the Earth and the sun, respectively); $T_R(\lambda)$,...,$T_G(\lambda)$, functions of light transmission describing irradiance attenuation in the processes of molecular scattering, scattering and absorption by aerosols and absorption by water vapour, ozone and the most important constant gaseous components of the atmosphere, respectively.

In the algorithms presented, $F_s(\lambda)$ values and the coefficients of light absorption by water vapour $a_{wv}(\lambda)$, ozone $a_{O_3}(\lambda)$ and constant gaseous components of the atmosphere $a_G(\lambda)$ for 122 wavelengths were taken from Neckel and Labs (1981). The algorithms allowing to determine value β and the solar zenith distance at a given place and time were taken from Krężel (1997).

To calculate the successive transmission functions one should know the so called relative optical atmospheric mass M. In the present calculations, the expression of Kasten (1966) taking into account the curvature of the atmosphere was applied:

$$M = [\cos\vartheta + 0.15 \cdot (93.835 - \vartheta)^{-1.253}]^{-1}\,, \tag{3}$$

where:

ϑ is expressed in [deg].

In the calculations of light transmission functions (2), the following algorithms were used:

a) molecular scattering (Kneizys *et al.* 1980):

$$T_r(\lambda) = \exp\left[\frac{-M'}{\lambda^4 \cdot (115.6406 - \frac{1.335}{\lambda^2})}\right], \tag{4}$$

where:
$M' = M \cdot (P/P_0)$; P, atmospheric pressure [hP]; P_0 = 1013 hP; wavelength λ is expressed in [μm].

b) light attenuation by aerosols:
taking into account slight dependence of attenuation by atmospheric aerosol on wavelength, the data presented by Krężel (1985) were used, *i.e.* the mean T_a values for four seasons of the year (Tab. 1). Because of the way these values were obtained (*i.e.* for the entire spectrum and for the sum of direct and diffuse solar radiation) their utilization in the model can be the source of difficult to estimate error. Nevertheless, the author believes that this error could be smaller then the one generated when the constant values of b_n and β_n coefficients in the classical formula of Angström (eq. 17) are used. Alternatively, if suitable data on horizontal visibility exist (*VIS*), the function describing attenuation could be determined from the expression (Kamada and Flocchini 1986):

$$T_a = (0.97 - 1.265 \cdot VIS^{-0.66}) \cdot M^{0.9}, \tag{5}$$

where:
5 km < *VIS* < 180 km

which is valid for the entire spectrum of solar radiation.
c) absorption by ozone is calculated from the formula:

$$T_0(\lambda) = \exp[-a_0(\lambda) \cdot O_3 \cdot M_0], \tag{6}$$

where the relative optical mass of atmospheric ozone M was defined after Iqbal (1983) as:

$$M_0 = \frac{(1 + \frac{h_0}{6370})}{(\cos^2 \vartheta + \frac{2 \cdot h_0}{6370})^{0.5}}, \tag{7}$$

and h_0 is the height at which maximum ozone concentration is found, accepted as 22 km. Because of relatively few measurement data, mean ten-year O_3 values defining ozone concentration in an atmospheric air column of the unit base area, for European latitudes 50°–60°N in individual months, were used (Tab. 2).
d) absorption by water vapour:
the expression presented by Leckner (1978) was used

$$T_w(\lambda) = \exp\left[\frac{-0.2385 \cdot a_w(\lambda) \cdot W \cdot M}{[1 + 20.07 \cdot a_w(\lambda) \cdot W \cdot M]^{0.45}}\right], \tag{8}$$

where W is the mass of water vapour in the atmospheric air column of the unit base area, calculated from the data on water vapour pressure e_0 at the sea level, according to the relation (Reitan 1960):

Table 1

Mean seasonal values of transmission function T_a in the Baltic Sea area

Area		Spring	Summer	Autumn	Winter
Longitude E	Latitude N				
10°-12°	54°-55°	0.88	0.83	0.80	0.83
10°-12°	55°-56°	0.88	0.83	0.80	0.86
10°-12°	56°-57°	0.89	0.83	0.83	0.87
10°-12°	57°-58°	0.90	0.85	0.85	0.89
10°-12°	58°-59°	0.90	0.86	0.88	0.90
12°-14°	54°-55°	0.88	0.84	0.80	0.82
12°-14°	55°-56°	0.88	0.84	0.80	0.85
12°-14°	56°-57°	0.89	0.84	0.82	0.87
12°-14°	57°-58°	0.90	0.85	0.84	0.88
14°-16°	54°-55°	0.88	0.86	0.81	0.80
14°-16°	55°-56°	0.88	0.86	0.82	0.83
14°-16°	56°-57°	0.89	0.86	0.82	0.85
16°-18°	54°-55°	0.88	0.86	0.81	0.79
16°-18°	55°-56°	0.89	0.87	0.82	0.81
16°-18°	56°-57°	0.90	0.87	0.82	0.85
16°-18°	57°-58°	0.90	0.87	0.83	0.88
16°-18°	58°-59°	0.90	0.88	0.85	0.89
18°-20°	54°-55°	0.88	0.87	0.80	0.77
18°-20°	55°-56°	0.88	0.87	0.81	0.79
18°-20°	56°-57°	0.89	0.87	0.82	0.82
18°-20°	57°-58°	0.90	0.87	0.83	0.87
18°-20°	58°-59°	0.90	0.88	0.84	0.89
18°-20°	59°-60°	0.90	0.90	0.87	0.90
20°-22°	54°-55°	0.87	0.87	0.79	0.76
20°-22°	55°-56°	0.88	0.87	0.80	0.78
20°-22°	56°-57°	0.89	0.87	0.81	0.79
20°-22°	57°-58°	0.90	0.88	0.82	0.84
20°-22°	58°-59°	0.90	0.88	0.83	0.88
20°-22°	59°-60°	0.90	0.90	0.86	0.90
22°-24°	57°-58°	0.89	0.88	0.81	0.82
22°-24°	58°-59°	0.90	0.88	0.82	0.87
22°-24°	59°-60°	0.90	0.89	0.83	0.89

$$W = (0.123 + 0.152 \cdot e_0)\frac{P}{1000}, \tag{9}$$

where:
e_0 and P are expressed in hP.

Table 2

Mean ozone concentration in the atmosphere in the Baltic Sea area

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
O_3 [cm]	0.378	0.424	0.441	0.432	0.398	0.354	0.331	0.310	0.312	0.318	0.321	0.351

e) absorption by other significant components of the atmosphere:
the expression from the paper by Leckner (1978) was applied

$$T_u(\lambda) = \exp\left[\frac{-1.41 \cdot a_u(\lambda) \cdot M'}{[1 + 118.3 \cdot a_u(\lambda) \cdot M']^{0.45}}\right]. \tag{10}$$

In the model for determination of irradiance generated by direct solar radiation at the sea level, algorithms (2) to (10) were used. The source of the biggest errors is undoubtedly the way of determination of solar radiation attenuation by aerosols. This error is greatest when the instantaneous illumination values are calculated and decreases with the extension of the averaging period.

ALGORITHMS FOR CALCULATING SCATTERED RADIATION

Algorithms presented in the paper of Bird and Riordan (1986) were used in the construction of the model.

It can be assumed that a scattered radiation incident on horizontal area is the total of three components:

$$E_d(\lambda) = E_{dR}(\lambda) + E_{da}(\lambda) + E_{dg}(\lambda), \tag{11}$$

first resulting from molecular scattering ($E_{dR}(\lambda)$), second resulting from aerosol attenuation ($E_{da}(\lambda)$) and third resulting from multiple reflections between the sea (land) surface and the atmosphere ($E_{dg}(\lambda)$).

These components have the following forms:

$$E_{da}(\lambda) = F_s(\lambda) \cdot \beta^{-2} \cdot \cos\vartheta \cdot T_{O_3}(\lambda) \cdot T_G(\lambda) \cdot T_{wv}(\lambda) \cdot T_{aa}(\lambda) \times \\ \times T_R(\lambda)^{1.5} \cdot [1 - T_{as}(\lambda)] \cdot F, \tag{12}$$

$$E_{dR}(\lambda) = F_s(\lambda)\cdot\beta^{-2}\cdot\cos\vartheta\cdot T_{O_3}(\lambda)\cdot T_G(\lambda)\cdot T_{WV}(\lambda)\cdot T_{aa}(\lambda)\times \times\left[1 - T_R(\lambda)^{0.95}\right]\cdot 0.5\,, \tag{13}$$

$$E_{dg}(\lambda) = \frac{[F_s(\lambda)\cos\vartheta + E_{dR} + E_{da}(\lambda)]\,r_s(\lambda)\,r_g(\lambda)}{1 - r_s(\lambda)\,r_g(\lambda)}\,. \tag{14}$$

$T_{aa}(\lambda)$ and $T_{as}(\lambda)$ are transmission functions describing light absorption by aerosol and due to scattering, respectively:

$$T_{aa}(\lambda) = \exp\{-[1 - \omega_0(\lambda)]\cdot\tau_a(\lambda)\cdot M\}\,, \tag{15}$$

$$T_{as}(\lambda) = \exp[-\omega_0(\lambda)\cdot\tau_a(\lambda)\cdot M]\,, \tag{16}$$

where:

$\omega_0(\lambda)$ is so called single scattering albedo (by definition $\omega_0 = \frac{b}{a+b}$); b and a are volume coefficients of scattering and absorption, respectively; $\tau_a(\lambda)$, optical thickness of the atmosphere resulting from aerosol occurrence, which is determined here from a classical formula of Angström (1963):

$$\tau_a(\lambda) = \beta_n\,\lambda^{-b_n}\,. \tag{17}$$

For the Baltic Sea area, the values of b_n and β_n coefficients, typical of the regions of relatively small atmosphere dustiness were applied, *i.e.* $\beta_n = 0.12$ and $b_n = 1.0274$ for $\lambda < 0.5$ μm and 1.2060 for $\lambda > 0.5$ μm.

It is assumed here that molecular scattering and scattering by aerosols are independent and, that half of irradiance is directed towards the lower hemisphere in the process of Rayleigh's scattering, regardless of actual direction of incident solar radiation.

The dependence of single scattering albedo on wavelength is expressed by the relation:

$$\omega_0(\lambda) = \omega_0(0.4\mu\mathrm{m})\cdot\exp[-\omega'(\ln\frac{\lambda}{0.4})^2]\,, \tag{18}$$

where:

ω_0 (0.4 μm), single scattering albedo for the wavelength of 0.4 μm; ω', coefficient.

In the regions of relatively small atmospheric turbidity, $\omega_0(0.4\ \mu\mathrm{m}) = 0.945$ and $\omega' = 0.095$. Coefficient $r_g(\lambda)$ represents surface albedo and is one of the input data necessary for calculations whereas atmosphere albedo could be expressed as:

$$r_s(\lambda) = T_{O_3'}(\lambda) \cdot T_{w'v}(\lambda) \cdot T_{a'a}(\lambda) \cdot \{0.5[1 - T_{R'}(\lambda)] + (1 - F') \cdot T_{R'}(\lambda) \times \\ \times [1 - T_{a's}(\lambda)]\}, \tag{19}$$

In the formula (13), F denotes the contribution of radiation scattered towards the lower hemisphere which could be assumed as 0.5 in the case of molecular scattering while attenuation by aerosol depends on solar zenith distance:

$$F = 1 - 0.5 \cdot \exp[(AFS + BFS \cdot \cos\vartheta) \cdot \cos\vartheta], \tag{20}$$

$$AFS = ALG \cdot [1.459 + ALG \cdot (0.1595 + ALG \cdot 0.4129)], \tag{21}$$

$$ALG = \ln(1 - \cos < \theta >), \tag{22}$$

$$BFS = ALG \cdot [0.0783 + ALG \cdot (-0.3824 - ALG \cdot 0.5874)] . \tag{23}$$

Taking into account that the model should be valid for the Gulf of Gdańsk area where the atmosphere is under strong influence of land sources of aerosol, asymmetry factor $<\cos\theta>$ was included into the, so called, rural atmosphere model (0.65). In relation (19), the primed parameters were calculated applying $M = 1.8$. In the formula defining F, $\cos\vartheta$ equals $\frac{1}{1.8}$. Finally, the obtained expression $E_d(\lambda)$ is multiplied by coefficient C:

$$C = \begin{cases} (\lambda + 0.55)^{0.8} & \text{for } \lambda \le 0.45\ \mu\text{m} \\ 1.0 & \text{for } \lambda > 0.45\ \mu\text{m} \end{cases} . \tag{24}$$

Recapitulating, the determination of illumination or radiation dose at the sea level by means of the presented algorithms requires the knowledge of only two parameters of atmospheric conditions: atmospheric pressure and water vapour pressure, routinely registered at the sea level at meteorological stations. Albedo of the sea area was assumed constant and equal to 0.06.

CLOUDINESS

In the southern Baltic area the effect of cloudiness on the amount of solar radiation energy reaching the sea surface was evaluated by means of the algorithm given by Krężel (1985):

$$Q = Q_c \cdot T_{ch} = Q_c \cdot (1 - 0.33 \cdot c - 0.37 \cdot c^2) \quad \text{for } \varphi < 57°\text{N}, \tag{25}$$

where:
Q_c, energy dose reaching the sea surface in the case of cloudless atmosphere, regardless of cloudiness; c, cloudiness in fractional form (fraction of cloud cover).

RESULTS

Having accepted the assumptions described in Introduction, a computer program applying the presented algorithms has been developed. The program allows the determination of the flux density of solar radiation energy (illumination) or its dose at the sea surface, with regard to direct and diffuse radiation, for any wavelength or radiation spectrum interval in the range of 300–4000 nm. The results of calculations performed by means of the program were compared with actinometric measurements carried on a deck of r/v "Oceania" and at IMGW (Institute of Meteorology and Water Management) actinometric station in Gdynia.

Fig. 1 illustrates the daily illumination course at the sea surface registered from on board r/v "Oceania" and, against this background, presents the calculation results of the model part for cloudless sky. When the sky is cloudless, the values of modelled and measured parameters are in a good agreement. An attention should be drawn to the periods with clouds of *cumulus* type. When the sun's disk was covered by a cloud, the illumination decreased by over two times. However, just before the covering it increased by more than ten or sometimes even tens per cent due to the direct solar radiation reflected from side edges of the clouds. This phenomenon has certainly an influence on underestimation of irradiance amount in those models which take into account the effect of cloudiness, *i.e.* the degree of sky covering by clouds. Any of those models admit the possibility of simultaneous increase in irradiance and cloudiness, which could take place, as shown in Fig. 1.

The successive figures present hourly (Fig. 2) and daily totals (Fig. 3) generated by the model against the background of actinometric measurements registered in Gdynia. One of the input parameters, the cloudiness course, registered 3 times a day in Gdynia and histograms of differences between modelled data and observational ones are included. Statistical parameters describing these processes were evaluated for the whole comparable series, *i.e.* for 540 cases of hourly totals (June 1996) and 366 cases of daily totals (1966).

In the case of hourly totals (June 1996), the energy total estimated from the model was about 12 % lower than the measured one. This discrepancy is relatively big, although the differences (Fig. 2) show a quite regular distribution around 0. Considering the possibility of simultaneous increase in energy inflow and some kinds of cloudiness (often in summer months) and small frequency of cloudiness observations, such a big difference should not be surprising. Fig. 2, illustrating a part of the daily course of variability of irradiance, expressed in hourly totals, shows that in particular cases the difference between modelled and measured data could reach even 300 % (morning hours, 03.06.1996). This phenomenon is always connected with the method of cloudiness evaluation which does not contain information if the sun's disk was covered by clouds or not. If the sky was covered by clouds to a high degree and at a given place the sun was uncovered for a relatively long time, then the differences between modelled and measured values could be very big. The method of handling cloudiness used in the present model does not consider such situations.

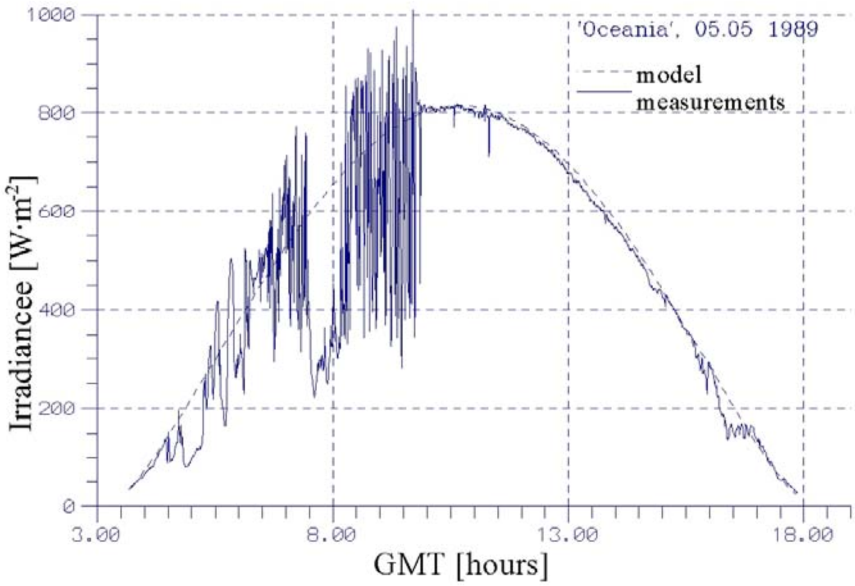

Fig. 1. Representative course of daily variability in illumination measured by an actinometer and calculated by means of the numerical model

With the increase in an averaging period, the results of measurements and modelling should approach each other. Such a proposition could be put forward considering the fact that algorithm (25) was developed on the basis of daily solar radiation totals and on daily cloudiness means, and the data not only from the station in Gdynia but from 4 actinometric stations in the southern Baltic area. The differences between modelled and measured daily totals are at a first glance lower than in the case of the hourly totals. During 1996 the difference between them was somewhat above 8 % which is still a significant discrepancy. A distinct relationship between the amount of irradiance at the sea surface and cloudiness was also found. This indicates that the attempts to improve the model should concentrate mainly on the method of handling cloudiness.

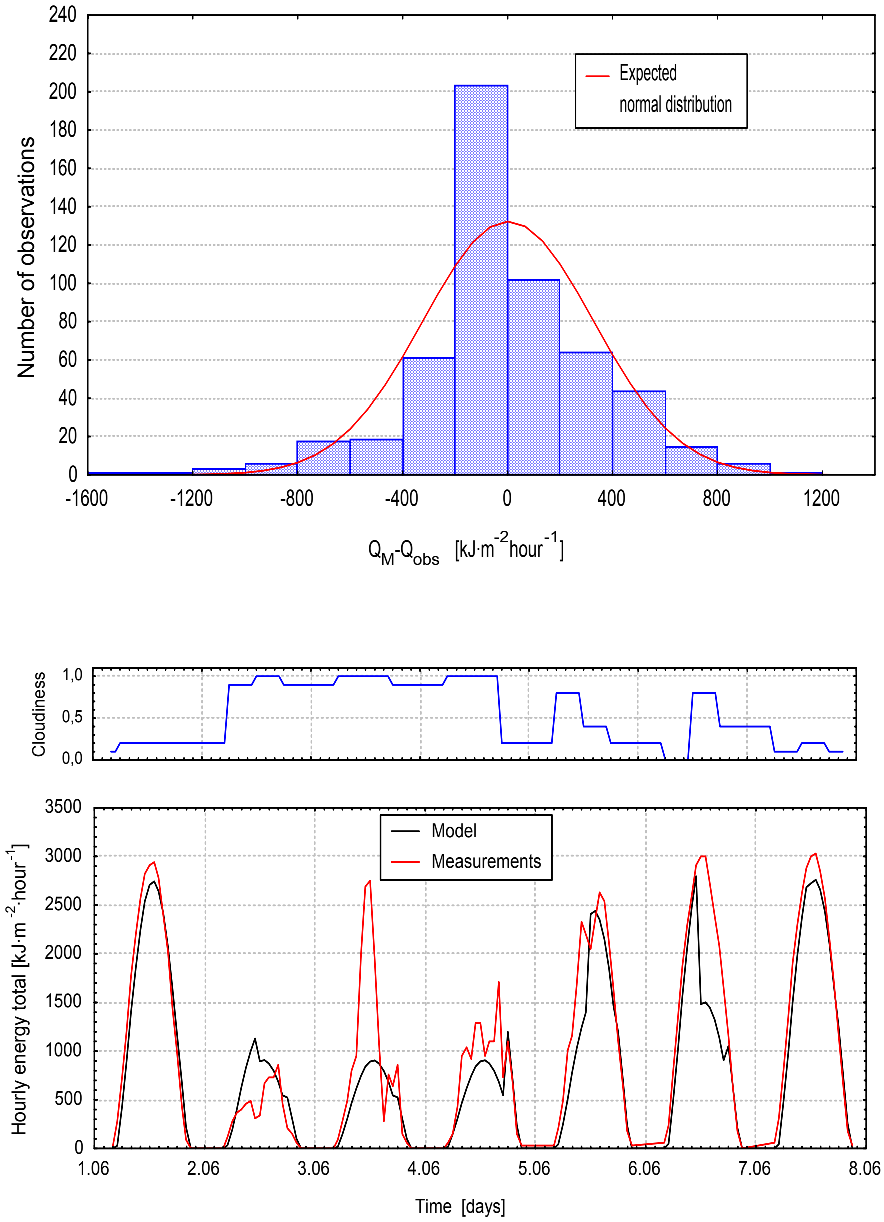

Fig. 2. The exemplary measured and modelled course of hourly solar radiation totals in Gdynia in an indicated period of 1996, and the histogram of differences between them during the whole month; the course of cloudiness applied in the model as input data was enclosed for comparison

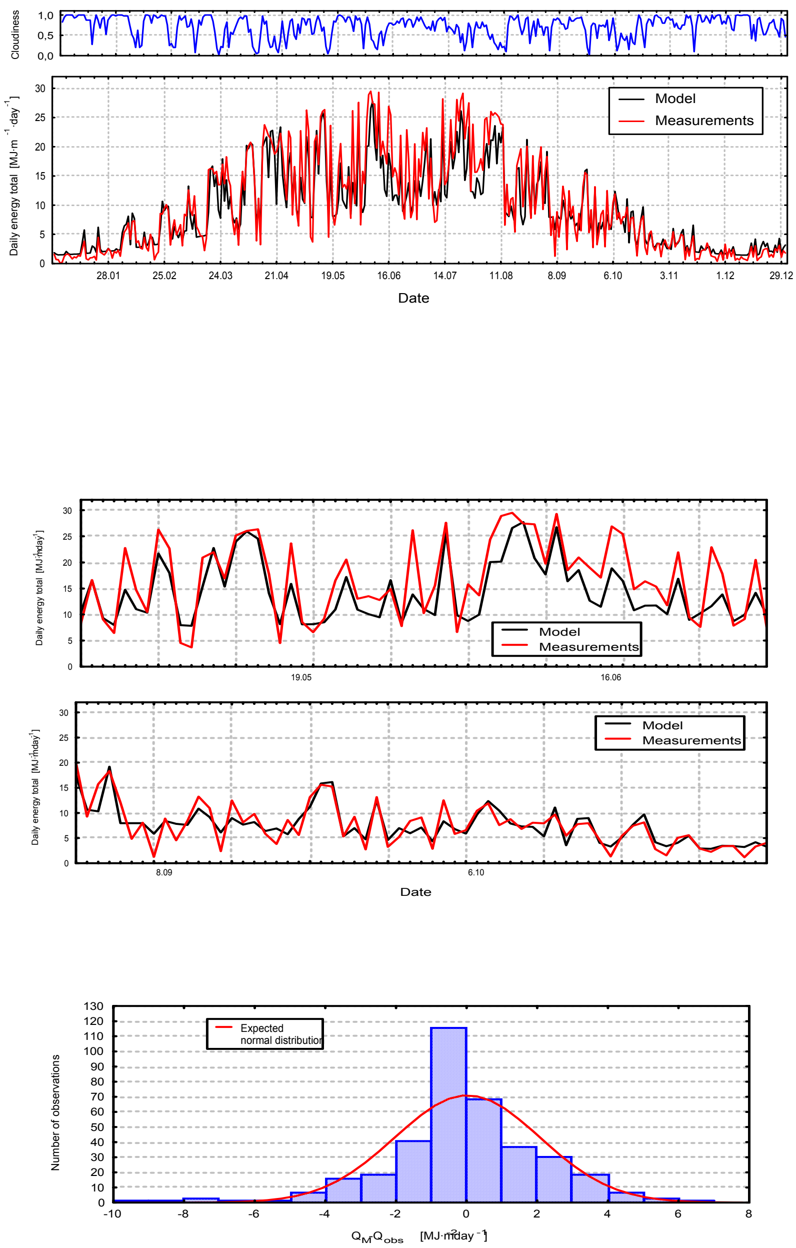

Fig. 3. The measured and modelled variability in daily totals of solar energy in Gdynia in 1966 and in selected periods and the histogram of differences between them

CONCLUSIONS

The presented examples show that in the case of short time periods the modelled totals of solar energy at the sea surface can significantly differ from the real values. In the case of some processes which depend on the solar energy (like photosynthesis) this can result in serious quantitative errors. Cloudiness is the factor responsible for these discrepancies. When the time interval of calculations decreases, even more important becomes the information whether and for how long the sun was covered by clouds. Thus, providing such information is very important for improving accuracy of the calculations. Cloudiness is measured at some meteorological stations as sunshine duration. It can also be determined with the use of satellite data.

When satellite data are used, information about cloudiness usually concerns a large portion of the sea, and if delivered by geostationary[1] satellites it can be obtained every half an hour. An example of such data is shown in Fig. 4. Even rather poor spatial resolution at high longitudes (about 40 km) does not deny the supremacy of this kind of information over routine observations at meteorological coastal stations. During further development of the model, it is planned to incorporate into it the data collected by visible channel of the METEOSAT 5 satellite.

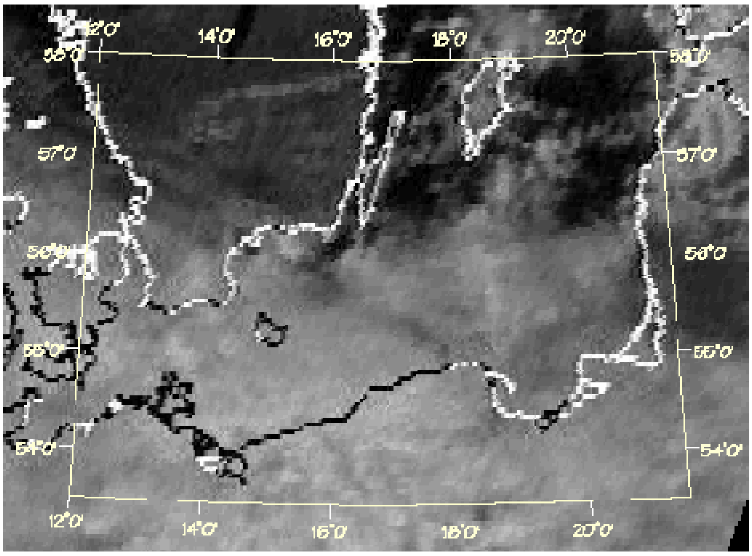

Fig. 4. Satellite image of the southern Baltic area; satellite visible channel, colour scale from black to white is proportional to increasing cloudiness

[1] The Baltic Sea area is scanned by METEOSAT satellite (at present METEOSAT 5)

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