Papers

Solar radiation variability over the Baltic Sea due to weather conditions*

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Solar radiation
Baltic Sea

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Abstract

The variability of solar radiation flux reaching the South Baltic Sea surface is analysed. Fluctuations of various time scale, from milliseconds to years, are considered. Statistical characteristics of solar energy flux variability are given. The characteristics are based on meteorological and actinometric data, as well as on modelling of solar radiation transfer through the atmosphere.

1. Introduction

Solar energy flux reaching the sea varies in time. The time scale of these variations ranges from milliseconds to years (Hay and Hanson, 1985; Mullamaa, 1972; Schenck, 1957). The variability of solar radiation flux influences directly and indirectly the biological and hydrological processes in the sea. Time variations of the irradiance level affect primary production (Dera *et al.*, 1975; Frechette and Legendre, 1978; Steemann Nielsen, 1974; Walsh and Legendre, 1983; Woźniak *et al.*, 1988). Variations in the absorption of solar energy flux in the sea cause changes of water temperature (Czyszek, 1985; Keevallik, 1978). These effects are examples of the direct influence of radiation. Solar energy flux also has a strong indirect influence on most processes in the marine environment, *e.g.* it is one of the factors driving atmospheric circulation (Liou and Zheng, 1984), sea surface evaporation, water flows, *etc.*

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Solar energy flux fluctuations have been described for various time scales and regions of the Earth. Short period irradiance fluctuation in the upper sea layer caused by refraction of solar rays by the disturbed sea surface was described for the first time by Schenck (1957). Its analytical model was presented by Snyder and Dera (1970). Since then many papers have been published on this subject. Their synthesis is contained in the book by Ivanov (1975), as well as the paper by Dera and Stramski (1986). The influence of clouds on solar energy fluctuation over a day has been presented, for example, in books by Mullamaa (1972) and Feygelson (1981), as well as papers by Rozwadowska (1988) and Suehrcke and McCormick (1988), whereas papers of *e.g.* Amato *et al.* (1986), Baldasano *et al.* (1988), Olseth and Skartveit (1984), deal with variations of daily totals of solar irradiation over a month or a year. Variations of monthly irradiation totals over a year or years are presented in papers by Balling (1983), Czyszek *et al.* (1979), Krężel (1985) and Podogrodzki (1969). In spite of such a great number of papers dealing with solar radiation flux variability this phenomenon over and in the Baltic has not been fully investigated. The existing papers concern either land or seas other than the Baltic (Amato *et al.*, 1986; Balling, 1983; Hay and Hanson, 1985), or are based only on coastal data (Czyszek *et al.*, 1979; Krężel, 1985). There is also a shortage of papers having a global approach to the variability of solar radiation flux reaching the Baltic Sea surface.

The aim of this paper is a presentation of the real variability characteristics of the solar energy flux reaching the south-east Baltic. Time scale of the considered variations ranges from milliseconds to over 49 years. The characteristics presented herein are based on the results of long-term empirical and theoretical study carried out by the hydrooptical group at the Institute of Oceanology, Sopot. Actinometric and meteorological data published by the Institute of Meteorology and Water Management are also applied. Sources of data and descriptions of research methods are given in the cited papers.

2. Short period irradiance fluctuations in the upper sea layer due to refraction of sun rays by the disturbed sea surface

Considerably energetic fluctuations of downward irradiance are caused mainly by solar rays focused by the crests of surface waves. Thus in the top layer of water basins (from 1 to 10 meters, depending on water transparency) specific light conditions occur, found nowhere else in nature. On a sunny day, when direct sun rays can reach the sea surface, momentary irradiance can fluctuate by an order of magnitude. It can increase by a factor of 2, 3 or more, in relation to its mean value, during milliseconds. A typical example of such fluctuations at the standard depth

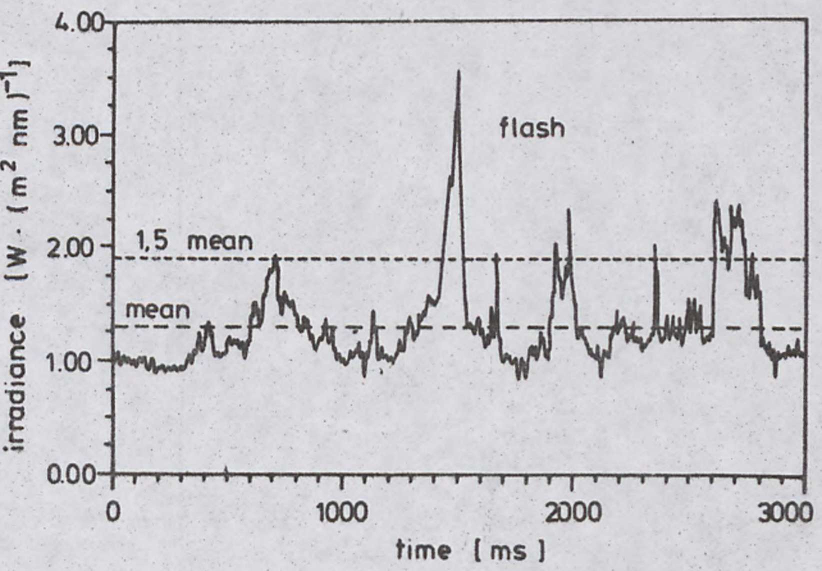

Fig. 1. A typical example of downward irradiance fluctuations due to refraction of solar rays on wind disturbed sea surface. Wavelenght = 525 nm, depth = 1 m

of 1 meter is demonstrated in Figure 1. Momentary increases of irradiance exceeding the mean value at the examined point by a factor of more than 1.5 (150% of the average level), are called light *flashes* (Dera and Stramski, 1986). They are recorded by a small (2.5 cm in diameter) collector of the irradiance meter. Their heights (local maxima on the irradiance records) are called *flash intensities*. An example of the frequency distribution of momentary irradiance is shown in Figure 2. This distribution forms a ridged line, which means that certain irradiance levels are much more probable than neighbouring values (notice the logarithmic scale of frequency). Very high levels, though of low probability, are also clearly visible.

The frequency distribution of flash intensities largely depends on sea surface state expressed in terms of wind speed measured at the standard height of 10 meters (U_{10}) as well as cloud conditions, *i.e.* cloudiness and cloud type, and turbidity of the atmosphere described by daylight diffuseness parameter d_E. Examples of frequency distribution of flash intensity under various wind conditions for light of the wavelength band of 525 nm are shown in Figure 3. These distributions can be described by an exponential function:

$$N_E = N_0\, e^{-AE/<E>}, \tag{1}$$

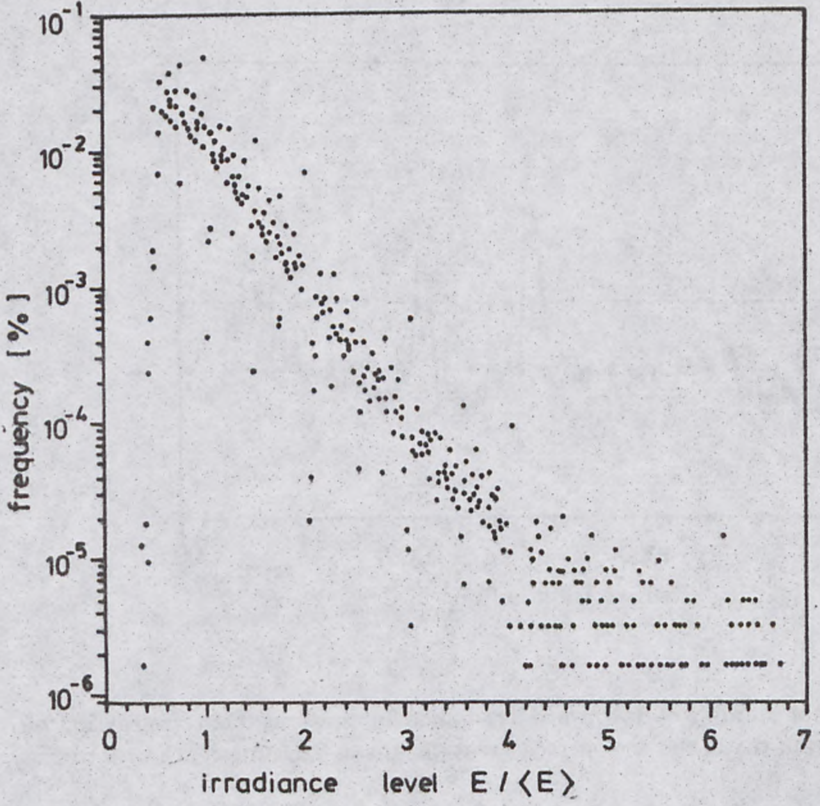

Fig. 2. Typical frequency distribution of downward irradiance under disturbed sea surface. $U_{10} = 1.8$ m/s, $d_E = 0.32$, depth = 1 m

where:
N_E – frequency of those flashes which exceed certain irradiance level E,
A – slope parameter describing the exponential decay rate of frequency N_E,
N_0 – parameter with no physical meaning,
$< E >$ – mean irradiance at the point of study.

The highest values of light flashes that we recorded in the sea during the years of study, reach the level of $6 < E >$, *i.e.* 600% of the mean irradiance at the standard depth of 1 m. These strongest flashes occur not more frequently than 1 per 10 minutes under a clear sky, high solar altitude ($h > 30°$) and wind speed ranging from 2 to 5 m/s. Assuming that with a clear atmosphere and solar altitude of 58°, the sea surface irradiance for wavelength $\lambda = 525$ nm is about 1.53 $\mathrm{W \cdot m^{-2} \cdot nm^{-1}}$ (Dera, 1983), the underwater flash intensities at the depth of 1 m can reach values of about 7.5 $\mathrm{W \cdot m^{-2} \cdot nm^{-1}}$, which is about 400% of the solar irradiance at the top of atmosphere.

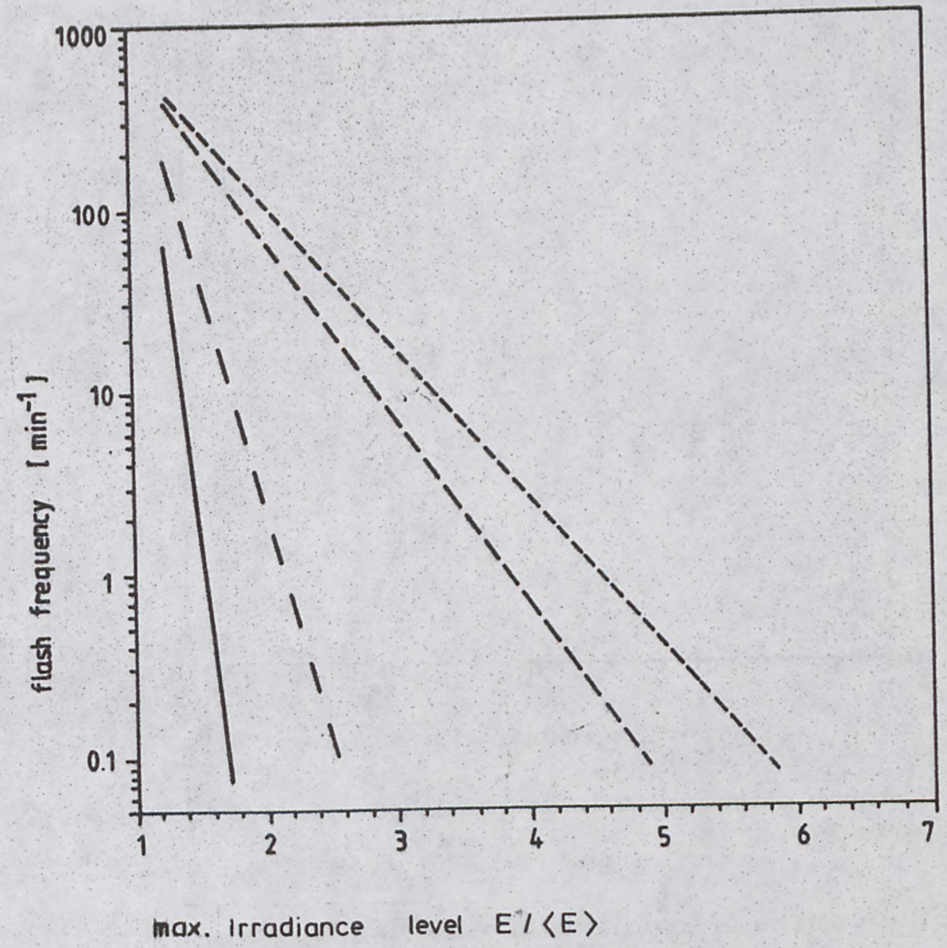

Fig. 3. Effect of wind speed on frequency distribution of flash intensities.
– – – – wind 2.6 m/s —— wind 3.4 m/s — — wind 4.6 m/s
——— wind 12.1 m/s; depth = 1 m

Figure 4 demonstrates the frequency of all flashes $(E/<E>) > 1.5$ versus wind speed. Under the most favourable weather conditions the total number of flashes per minute exceeds 300. Their duration times range from a few to several dozen milliseconds. Maximum flash frequency was recorded in light winds (2–5 m/s) indicating that light flashes are caused by small surface waves or high frequency components of the surface wave spectrum. The described light flashes are usually present in the surface water layer of a few meters during sunny weather (Dera, 1970; Stramski and Dera, 1988; Stramski, 1988a,b).

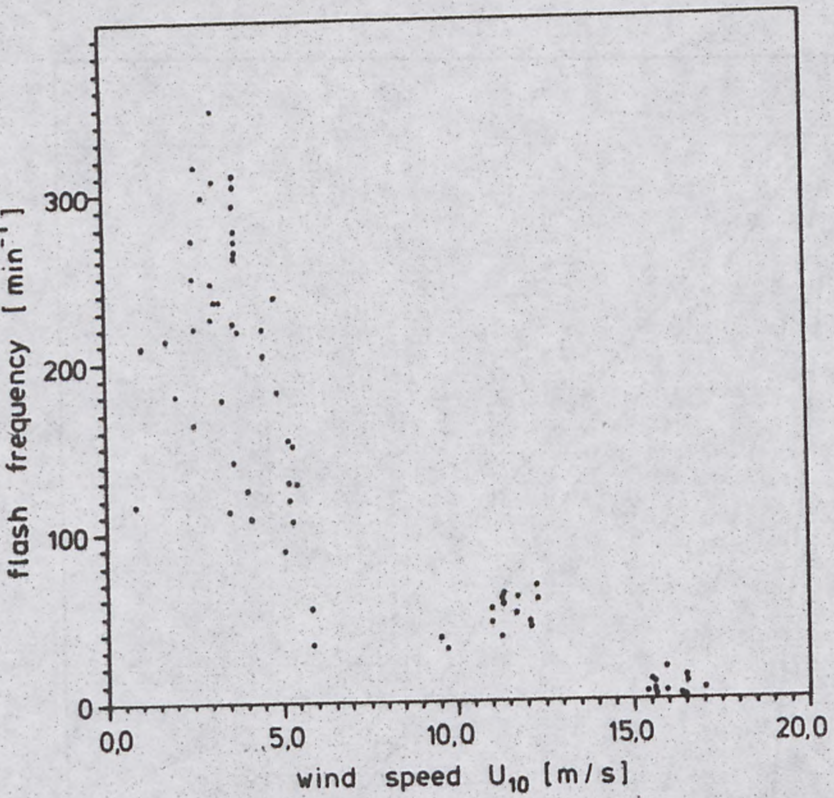

Fig. 4. Frequency of underwater flashes as a function of wind speed. Depth = 1 m, $E > 1.5 < E >$

3. Fluctuations of irradiance due to clouds

The amount of solar energy reaching the sea surface depends on two basic factors: solar altitude above the horizon and the state of the atmosphere including cloudiness, cloud type, amount and composition of atmospherical aerosols, amount of water vapour, carbon dioxide and ozone. About 99% of the solar energy reaching the sea surface is contained in the spectral range 0.3 to 3.0 μm (Dera, 1983). All solar energy data and relations presented in the following part concern global solar radiation approximately in this part of the solar spectrum (the limits of the spectral interval depend on the spectral sensitivity of typical pyranometers).

Irradiance at the sea surface at time t can be computed accurately only for a cloudless sky and the standard clear atmosphere. Many algorithms for irradiance computing at the Earth surface, based on mathematical models and empirical approximations, have been developed so far (for example:

Braslau and Dave, 1973; Frouin *et al.*, 1989; Paltridge and Platt, 1976; Timofeyev, 1983). One practically useful formula is the expression for downward irradiance at the sea surface:

$$E(0) = T_E(h)\, f\, S\, \sin(h), \tag{2}$$

where:

T_E – *irradiance transmittance* through the atmosphere under a cloudless sky with the assumption that the state of the atmosphere is stable in time and $T_E(h)$ depends only on solar altitude h,

f – formula expressing changes of downward irradiance at the outer limits of the atmosphere due to variations in the distance from the Sun to the Earth over a year (Exell, 1981):

$$f = 1 - 0.0335 \sin\left[\frac{360(N_d - 94)}{365}\right], \tag{3}$$

where:

N_d = 1, 2, ..., 365, and denotes the respective days of the year,

S – the assumed solar constant 1368 $\mathrm{W \cdot m^{-2}}$ (Willson, 1984),

h – solar altitude above the horizon in degrees.

Irradiance transmittance of the atmosphere is described as a ratio of the downward irradiance at the sea surface $E(0)$ to the downward irradiance at the outer limits of the atmosphere $E(\infty)$:

$$T_E = \frac{E(0)}{E(\infty)}. \tag{4}$$

The investigations carried out by our group showed that the solar irradiance transmittance of the clear atmosphere over the Baltic can be approximated by the empirical formula:

$$T_E(h) = 0.7650\,(\sin h)^{0.13}, \tag{5}$$

developed for the atmosphere over the North Atlantic with atmospherical transparency coefficient $t_2 = 0.75$ by Jegorov and Kirillova (1973).

Figure 5 shows the variations of the downward irradiance at the southern Baltic surface on chosen days when the atmosphere was clear, calculated from the relations (2) and (5). The curves represent practically the maximum irradiances which may occur at a certain place and time on given days. Since the highest and lowest solar altitudes at noon are observed respectively on June 22nd and December 21st Figure 5 also illustrates the difference between the extreme variations of irradiance on a clear day during the year. The downward irradiance under clear sky at the southern Baltic surface at noon in June is about 5 times higher than in December. In the following section we will use diagrams based on formulas (2) and (5) as a background for the presented real irradiance fluctuations under various sky conditions.

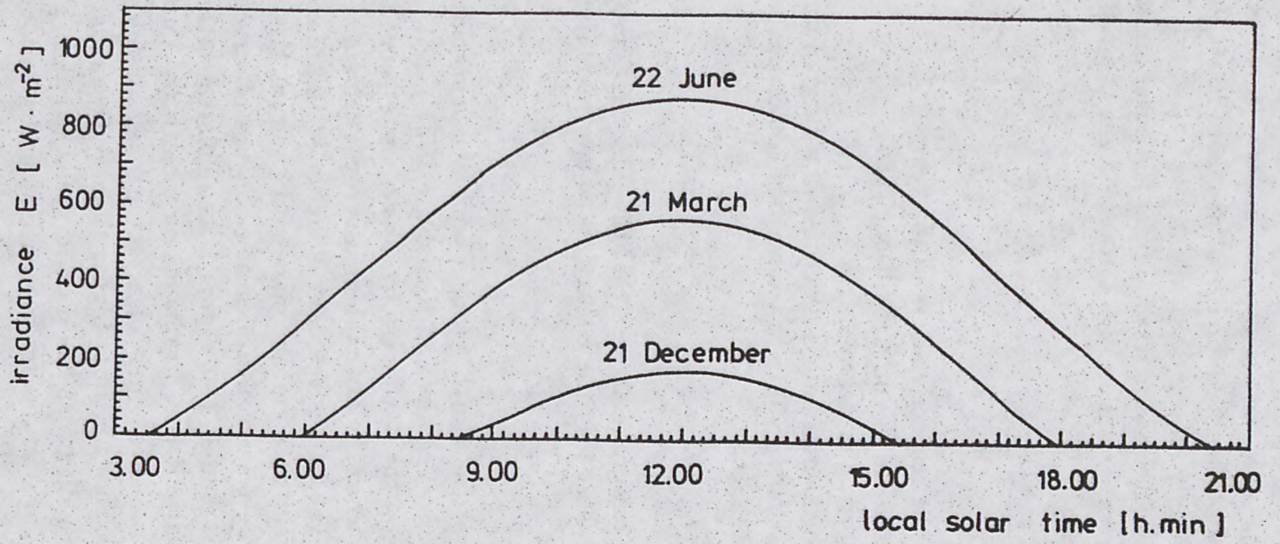

Fig. 5. Modelled daily global irradiance variations at the southern part of the Baltic surface due to solar altitude changes under typical clear sky conditions. Coordinates of the Station: $\phi = 54°27'$N, $\lambda = 18°34'$E

In reality it is rare to find clear, cloudless atmospheric conditions which last throughout the day. The sky is usually at least partly covered with clouds, or haze, turbidity or fog can occur. Apart from the solar altitude, the shading of the sun by clouds, as well as variation in cloudiness and cloud type are the main factors influencing the variability of solar radiation during a day.

The character of the fluctuations caused by moving clouds depends on cloudiness and the type of predominant clouds in the sky.

Our empirical study on this question was carried out from 1984 to 1986 on the beach of Sopot. Global solar irradiance was measured with the Yanishevsky pyranometer (Rozwadowska, 1988). Examples of the recorded global irradiance fluctuations under different cloud conditions are demonstrated in Figures 6–10. Figures 6–8 show the situations when cumulous clouds (Cumulus or Cumulonimbus) are predominant, while Figures 9 and 10 illustrate fluctuations under layer cloud regimes.

For quantitative statistical description of fluctuations caused by clouds, solar irradiance is expressed in terms of *irradiance transmittance* (that is the relative irradiance according to equation (4)), so as to remove the influence of solar altitude variation over a day. The average frequency distributions of irradiance transmittance through the atmosphere under different cloud conditions (the examples of the irradiance records were demonstrated in Figures 6–10) are shown in Figures 11 and 12.

Under cumulous clouds (Fig. 11) the frequency distributions of irradiance transmittance are bimodal. The lower mode is the most probable value of irradiance transmittance for the clouds when the sun is covered *i.e.* not visible at the point of the observation. The higher one is the most probable value of atmospheric transmittance when the sun is unobscured. With increasing cloudiness both the probability of the sun being shaded by cloud and the mean thickness of clouds increase. Moreover, with increasing cloudiness the 'reflection' of solar rays by cloud edges (sides) towards the sea surface, when the sun is visible, becomes more effective. The result is an increase of the maximum value of the difference between the maximum and minimum momentary transmittances (from 65% for cloudiness 0.1–0.3 to 85% for cloudiness 0.7–0.9). On average, however, with increasing cloud amount the mean transmittance of the atmosphere decreases from 72% for cloudiness 0.1–0.3 to 43% for cloudiness 0.7–0.9. It can be assumed that when the irradiance transmittance is approaching the higher mode value, the underwater fluctuations mentioned in section 2 caused by refraction of solar rays on the sea surface may occur. The transmittance standard deviation σ_{T_E}, which can be treated as a characteristic of fluctuation amplitude, reaches its maximum value of 25% with cloudines $n = 0.7$ (Rozwadowska, 1988).

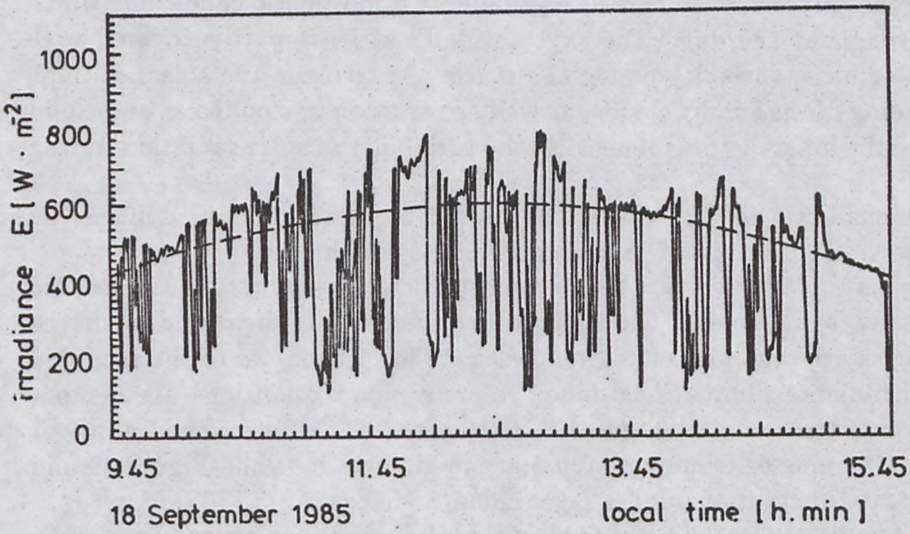

Fig. 6. Example of global solar irradiance fluctuations at the sea surface due to clouds. Cloudiness and predominant cloud types: 0.5 Cu med. Coordinates of the Station: $\phi = 54°27'$N, $\lambda = 18°34'$E. Dashed line shows modeled clear sky irradiance on that day

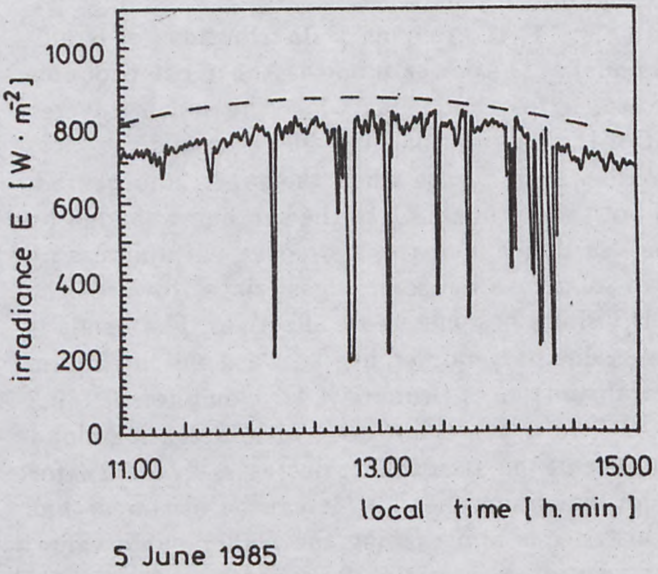

Fig. 7. Example of global solar irradiance fluctuations at the sea surface due to clouds. Cloudiness and predominant cloud types: 0.1–0.3 Cu. Coordinates of the Station: $\phi = 54°27'$N, $\lambda = 18°34'$E. Dashed line shows modelled clear sky irradiance on that day

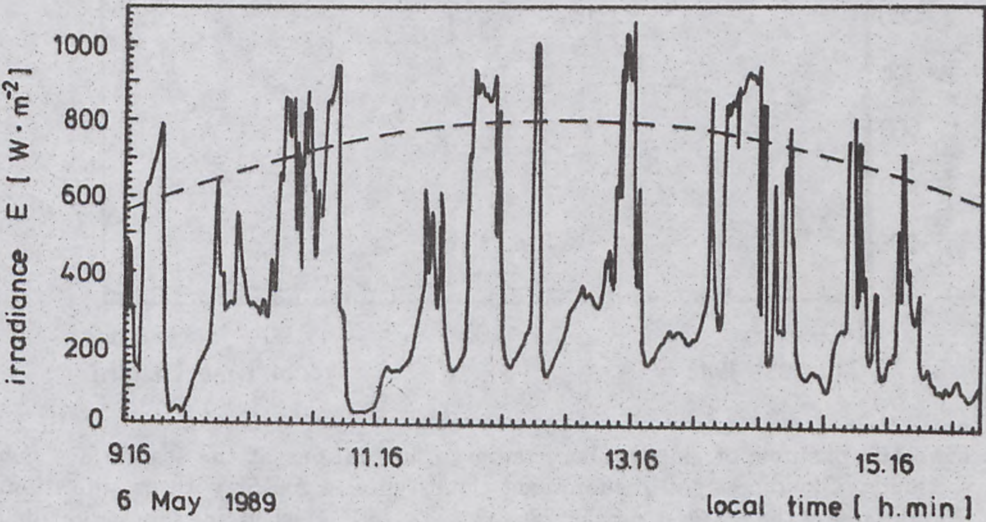

Fig. 8. Example of global solar irradiance fluctuations at the sea surface due to clouds. Cloudiness and predominant cloud types: 0.7–0.9 Cb, Cu con. Coordinates of the Station: $\phi = 54°27'N$, $\lambda = 18°34'E$. Dashed line shows modelled clear sky irradiance on that day

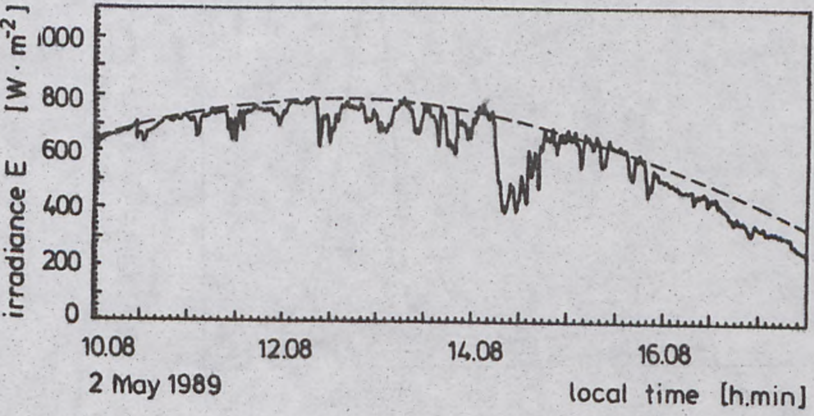

Fig. 9. Example of global solar irradiance fluctuations at the sea surface due to clouds. Cloudiness and predominant cloud types: 0.5–0.9 Ci, Cc. Coordinates of the Station: $\phi = 54°27'N$, $\lambda = 18°34'E$. Dashed line shows modelled clear sky irradiance on that day

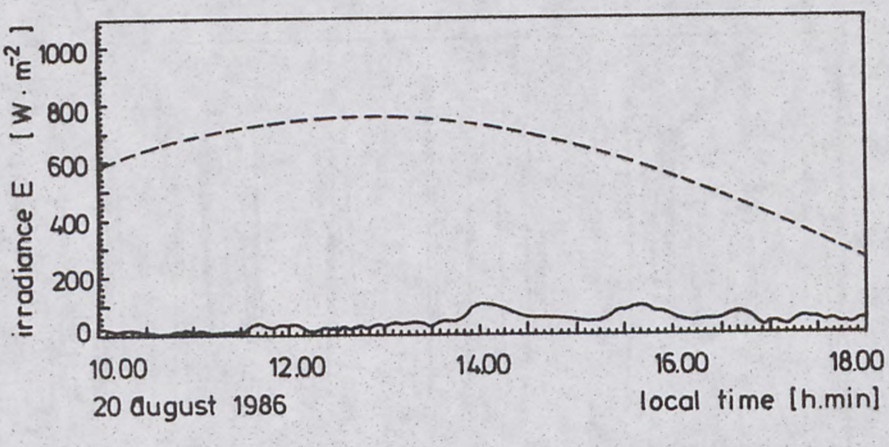

Fig. 10. Example of global solar irradiance fluctuations at the sea surface due to clouds. Cloudiness and predominant cloud types: 1 As, Sc with precipitation. Coordinates of the Station: $\phi = 54°27'N$, $\lambda = 18°34'E$. Dashed line shows modelled clear sky irradiance on that day

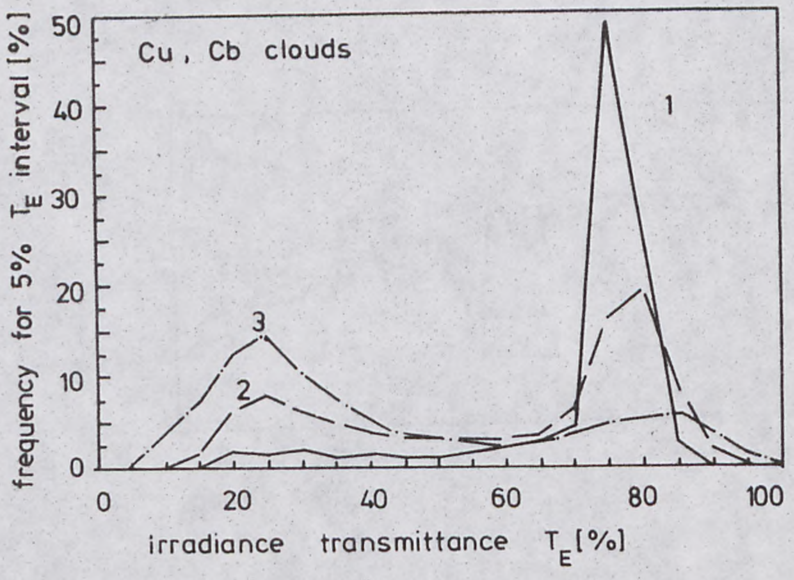

Fig. 11. Frequency distribution of irradiance transmittance through the atmosphere over the southern part of the Baltic under various cloud conditions (sun altitude > 32°): 0.1–0.3 Cu (1), 0.4–0.6 Cu (2), 0.7–0.9 Cu with or without Cb or Sc (3)

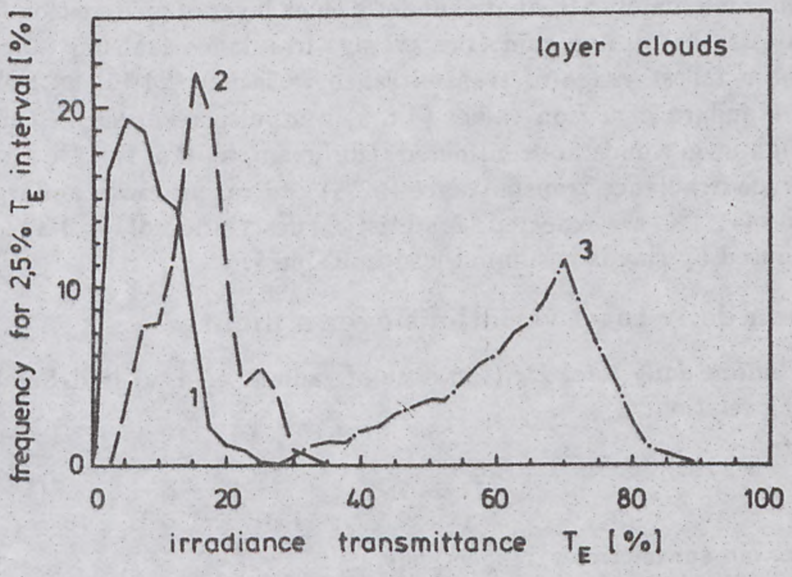

Fig. 12. Frequency distribution of irradiance transmittance through the atmosphere over the southern part of the Baltic under various cloud conditions (solar altitude > 32°): 1.0 opaque clouds with precipitation: Ns, St, Sc, As (1), 1.0 opaque clouds without precipitation: Ns, St, Sc, As, Ac (2), 0.5–1.0 Ci, Cc, Cs (3)

Table 1. Mean value, standard deviation and extreme values of irradiance transmittance through the atmosphere over the southern part of the Baltic under various cloud conditions

Type of clouds	Cloudiness	Irradiance transmittance T_E [%]			
		$< T_E >$	σ_{T_E}	$T_{E_{min}}$	$T_{E_{max}}$
Cu	0.1–0.3	72	13.7	20	85
Cu	0.4–0.6	60	23.1	15	90
Cu with or without Cb, Sc	0.7–0.9	43	25.2	10	95
Ns, St, Sc, As with precipitation	1.0	8.4	4.8	1	25
Ns, St, Sc, As, Ac without precipitation	1.0	16	5.6	5	30
Ci, Cc, Cs	0.5–1.0	62	12.1	30	85

In the case of layer clouds the frequency distributions are unimodal. Solar radiation is maximally attenuated under a thick layer of opaque clouds (mainly Nimbostratus) during rain (the average irradiance transmittance is 8.4%). The smallest range of transmittance variation (24%), as well as the lowest standard deviation values (4.8%) were also recorded in this case. When high level clouds are considered (for example 0.5–1.0 Ci, Cc, Cs), high average irradiance transmittance (62%) and rather low standard deviation values (12.1%) are expected. A statistical description of irradiance fluctuations caused by clouds is summarized in Table 1.

4. Irradiation daily total variations over a month

Solar *irradiation daily total* D_d (the dose of radiant energy) is defined by the following relation:

$$D_d = \int_{t_r}^{t_s} E(t)\, dt, \tag{6}$$

where:

t_r, t_s – sunrise and sunset times, respectively,

$E(t)$ – irradiance at the sea surface at time t.

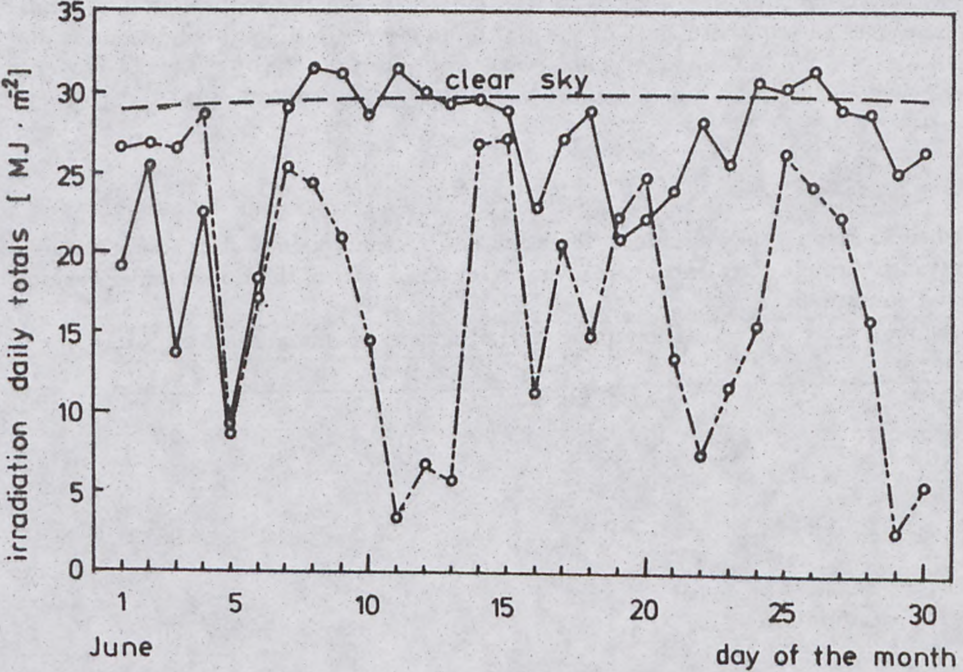

Fig. 13. Variability of solar irradiation daily totals in June of 1969 (———) and 1971 (— - - —) in Gdynia, based on data from *Promieniowanie słoneczne, 1965–1977*

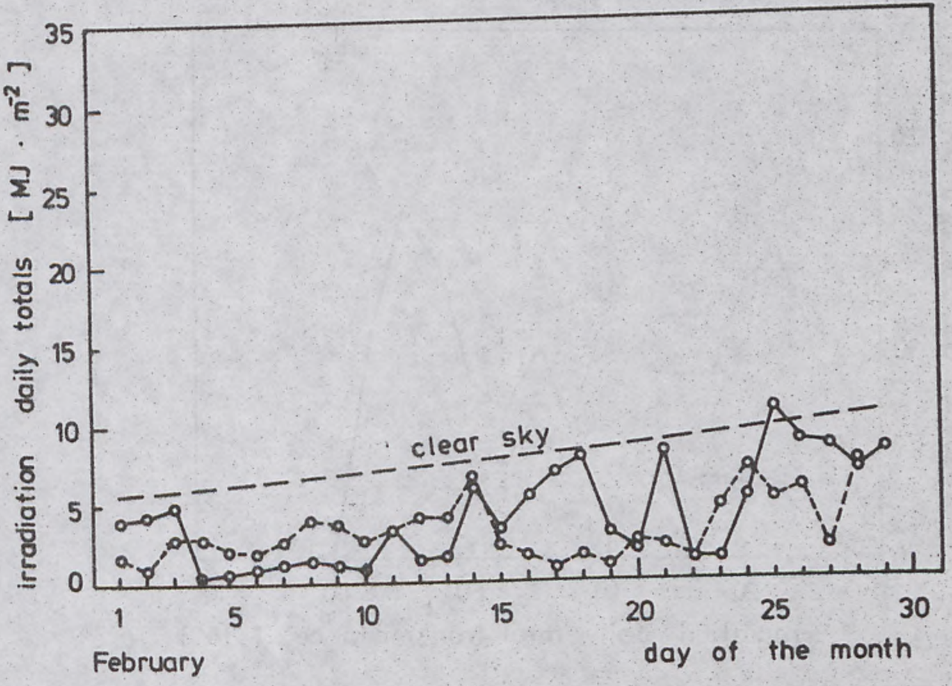

Fig. 14. Variability of solar irradiation daily totals in February of 1968 (——) and 1973 (– – – –) in Gdynia, based on data from *Promieniowanie słoneczne, 1965–1977*

Figure 5 indicates that irradiation daily totals in various seasons of the year can vary considerably even in the case of a cloudless and clear atmosphere. The ratio of maximum values of irradiation daily totals (*i.e.* the totals for a clear sky) for the southern part of the Baltic for June and December is about 10.

As has been shown previously, clouds can considerably decrease the sea surface irradiance during a day. Cloudiness and cloud type are associated with the synoptic situation over the considered area. For example, a cyclone with a system of atmospheric fronts causes high levels of cloudiness (largely in the form of layer clouds), whereas an anticyclone usually guarantees cloudless skies or the occurrence of high semitransparent clouds (Kwiecień, 1968). In the coastal zone the general circulation can be modified by breeze circulation. Cyclones and anticyclones appearing over a certain point, accompanied by various cloud types, as well as cloud amounts, cause additional fluctuations that overlap the variation of the radiant flux due to astronomical factors, *i.e.* the length of the day and culmination altitude of the sun. To eliminate these factors in the description we will use solar *irradiation daily total transmittance*, which is defined as follows:

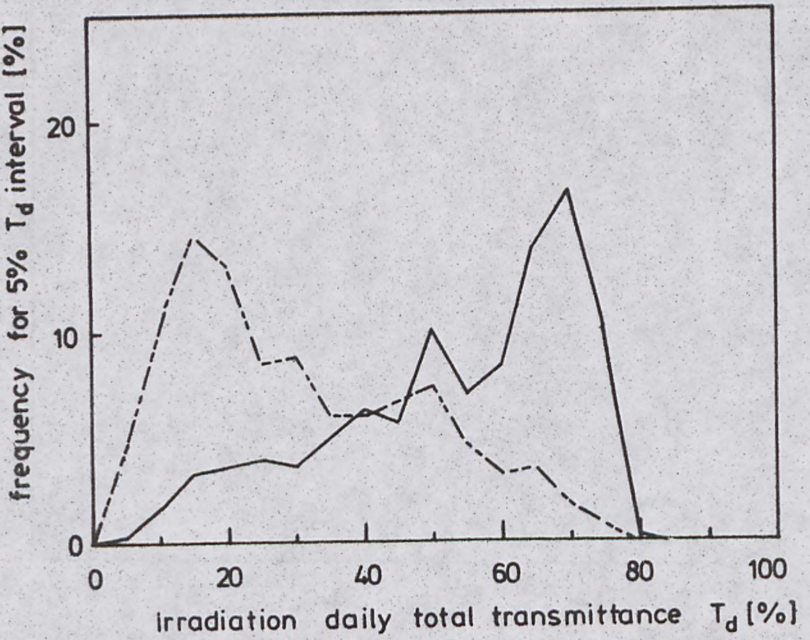

Fig. 15. Frequency diagrams of irradiation daily total transmittance in Gdynia for June and February based on ten-year data (1965–1974) from *Promieniowanie słoneczne, 1965–1977*. – – —— February, ——— June

$$T_d = \frac{D_d(0)}{D_d(\infty)}, \tag{7}$$

where:

$D_d(0)$ – irradiation daily total at the sea surface,

$D_d(\infty)$ – irradiation daily total outside the atmosphere.

Two examples of irradiation daily total variability in June and February are demonstrated in Figures 13 and 14. The dashed lines represent modelled irradiation totals (according to relations (2), (5) and (6)) over a month, in the case of clear skies. These Figures show a considerable variation of solar irradiation daily totals at the sea surface from day to day. They reveal two regularities: continuous periods of low atmospheric transmittance (very cloudy conditions) are shorter in June, *i.e.* in the warm half of the year, than in February, representing the cold half, and the records of irradiation daily totals over a certain month in various years may differ considerably.

The irradiation daily total transmittance distributions of 4 selected months, (February, April, June and October), averaged for the 10 years 1965–1974, are presented in Figures 15 and 16. Because of the lack of regular solar energy measurements at sea, the data from the coastal actinometric

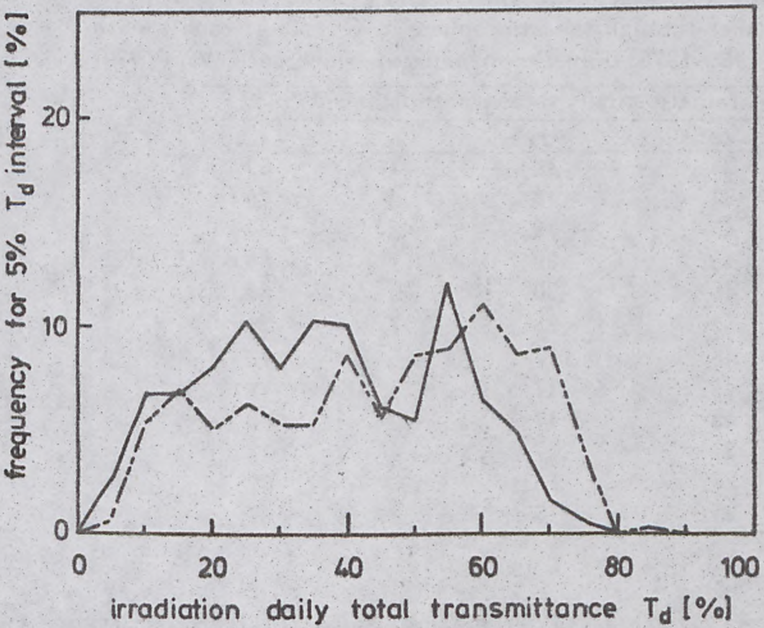

Fig. 16. Frequency diagrams of irradiation daily total transmittance in Gdynia for October and April based on ten-year data (1965–1974) from *Promieniowanie słoneczne, 1965–1977.* ——— October, —·— -- April

station in Gdynia (*Promieniowanie słoneczne, 1965–1977*) was applied in this section. Frequency distributions of irradiation daily total transmittance for various months take different shapes. The distributions of both February and June have a relevant maximum. In February, days with a daily total transmittance of about 15% are most probable and the ten-year mean value of the daily total transmittance is 31%. A similar shape of distribution is characteristic of all months from November to February. The lowest value of mean transmittance was observed in December ($< T_d >= 25\%$).

In June days with a daily total transmittance of about 75% are the most probable and the ten-year mean value of this transmittance is 53%. June is the most sunny month in Gdynia, but a similar type of frequency distribution is observed from June to August. The presence of cold water stabilizing the atmosphere fosters the relatively high number of sunny days in spring and at the beginning of summer (Kwiecień, 1987). In spring and autumn the probability of the occurence of high and low values of daily total transmittances is more similar, *i.e.* distributions are flatter, and the mean transmittances range from summer values of, for example $< T_d >= 45\%$ (April) to winter values of, for example $< T_d >= 37\%$ (October).

Table 2. Mean value, standard deviation and extreme values of irradiance daily total transmittance through the atmosphere in Gdynia of each month, based on ten-year data (1965–1975) from *Promieniowanie słoneczne, 1965–1977*

Months	Irradiation daily total transmittance T_d [%]			
	$< T_d >$	σ_{T_d}	$T_{d_{min}}$	$T_{d_{max}}$
January	27	16	1	69
February	31	18	4	75
March	43	19	2	84
April	45	20	7	84
May	48	20	6	81
June	53	18	7	79
July	48	17	6	78
August	48	17	4	78
September	43	17	9	73
October	37	17	4	75
November	27	16	1	67
December	25	15	2	67

The highest variations of irradiation daily total transmittance over a month were observed for March ($\sigma_{T_d} = 19\%$), April ($\sigma_{T_d} = 20\%$) and May ($\sigma_{T_d} = 20\%$), the lowest variations for November ($\sigma_{T_d} = 16\%$), December ($\sigma_{T_d} = 15\%$) and January ($\sigma_{T_d} = 16\%$). The minimum observed values of daily total transmittance ranged from 1% to 4% for the months from October to March and from 4% to 9% for the months from April to September. In November and December the daily total transmittance values did not exceed 67%, whereas in March, April and May transmittances of over 80% occured. Such high values of maximum transmittances in spring and summer are caused by advections of clear and usually dry air masses from the North and the North-East, as well as relatively high daily mean values of solar altitude (Rafałowski *et al.*, 1955). The presence of Cumulus clouds near the sun, which do not cover it, but reflect an additional amount of solar energy toward the station, may also contribute to the high values of daily total transmittance (Podogrodzki, 1969). These findings are summarized in Table 2.

5. Variations of irradiation monthly totals

Frequency distributions of irradiation daily totals presented in the previous section show the average situation. As is demonstrated by Figures 13 and 14, monthly records of daily totals for certain months in various years may differ considerably. This feature involves the variability of the *irradiation monthly totals*:

$$D_M = \sum_{i=1}^{M} D_{d_i}, \tag{8}$$

where:

D_{d_i} – irradiation daily total on i-th day of a month,
M – number of days in the month.

The following the irradiation *monthly total transmittance* will be applied in the further part of the description:

$$T_M = \frac{D_M(0)}{D_M(\infty)}, \tag{9}$$

where:

$D_M(0)$ – irradiation monthly total at the sea surface,
$D_M(\infty)$ – irradiation monthly total at the top of the atmosphere.

A semi-empirical model of solar energy monthly totals at the sea surface was developed in Sopot. The model was based on an idea of Krężel (1985). In the model an assumption is made that the variabilities of cloud type and amount are the main meteorological factors influencing solar flux variations. All the possible cloud type combinations are divided into two classes:

1 – middle level clouds, semitransparent or opaque for sunlight, or low level clouds are predominant,

2 – high level clouds or middle level clouds transparent for sunlight are predominant.

Moreover, it has been assumed that the occurrences of certain cloudiness n and certain cloud class cc are statistically independent. Thus the long-term mean monthly total of solar irradiance D_M may be expressed as:

$$< D_M >= \sum_{i=0}^{10} \sum_{cc=1}^{2} p(n = 0.1\, i)\, p(cc)\, D_M\,(n = 0.1\, i, cc), \tag{10}$$

where:

$p(n = 0.1\, i)$ – probability of occurrence of cloudiness n in the considered month,
$p(cc)$ – probability of occurrence of cloud class cc in that month,
$D_M(n = 0.1\, i, cc)$ – irradiation monthly total for cloudiness n, cloud type cc and long-term monthly mean values of atmospheric pressure, water vapour pressure and irradiance transmittance for atmospheric aerosols, and:

$$D_M(n, cc) = \sum_{j=1}^{M} \int_{trj}^{tsj} \frac{S f \sin(h(t)) T_0(h(t)) T_{cl}(n, cc, h(t))}{1 - A_{sk}(n, cc, h(t)) A_s(n, cc, h(t))} dt, \tag{11}$$

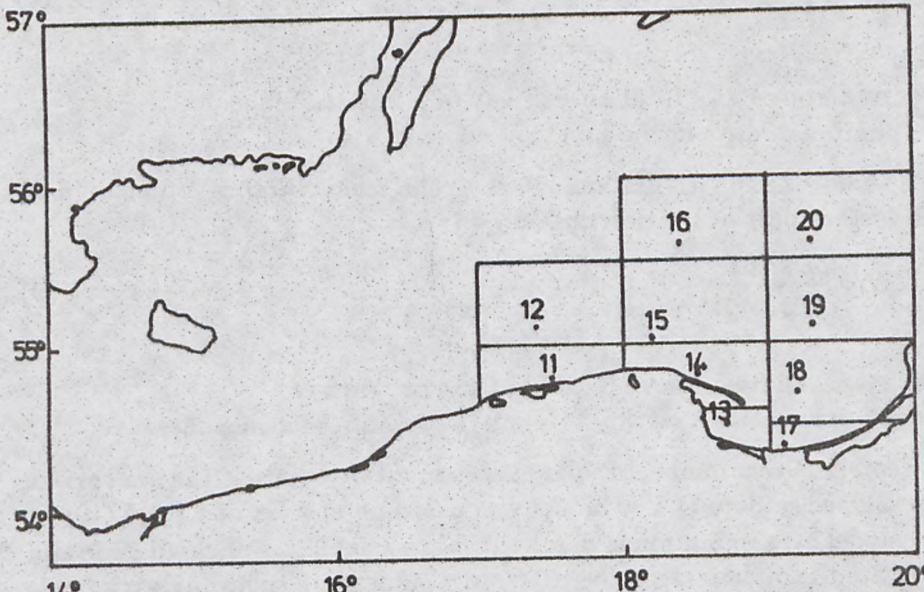

Fig. 17. The south-east Baltic divided into rectangles. Dots denote stations for which model computations were made

where:

$T_0(h(t))$ – irradiance transmittance of cloudless atmosphere dependent on water vapour pressure, atmospheric pressure, irradiance transmittance for atmospheric aerosols and solar altitude h at the time t,
$T_{cl}(n, cc, h)$ – irradiance transmittance function for clouds,
$A_{sk}(n, cc, h)$ – sky albedo,
$A_s(n, cc, h)$ – sea surface albedo,
tsj, trj – sun set and sun rise times, respectively,
M – number of days in the month.

For a detailed description of the model see Rozwadowska (1990).

Nineteen-year (1961–1980) monthly mean values of meteorological parameters, like atmospheric pressure, water vapour pressure, cloudiness, cloudiness frequency distribution (ship data (Augustyn, 1985)), as well as ten-year 1965–1974) monthly mean aerosol transmittance (seashore data (Krężel, 1982)) were applied as the input parameters in our model. The south-east Baltic was divided into 10 rectangles presented in Figure 17. Model computations were made for stations whose coordinates are mean values of the coordinates of all the real stations belonging to a certain

Table 3. Numbers of meteorological observations used in the model computations. Positions of stations are presented in Figure 17

Station number	Months											
	1	2	3	4	5	6	7	8	9	10	11	12
11	–	–	–	75	277	240	120	81	311	182	–	–
12	–	59	–	55	89	–	89	67	94	82	–	–
13	116	198	317	705	332	448	498	280	335	218	280	126
14	–	99	120	126	148	139	169	124	121	205	95	–
15	–	243	230	78	–	–	181	445	284	292	449	291
16	–	–	–	–	127	–	–	–	—	–	–	–
17	–	65	99	96	61	123	95	81	–	59	99	–
18	92	212	260	226	245	298	453	498	179	192	214	117
19	–	–	74	–	84	–	68	78	89	–	167	–
20	–	–	56	–	–	–	–	–	63	–	–	–

Table 4. The transfer matrix F_{Sm} between the monthly totals of solar irradiation in Gdynia and those of the south-east Baltic. Positions of stations are presented in Figure 17

Station number	Months											
	1	2	3	4	5	6	7	8	9	10	11	12
11	–	–	–	1.03	1.06	0.99	1.08	1.07	1.10	0.83	–	–
12	–	0.96	–	1.00	1.09	–	1.10	1.03	0.90	1.11	–	–
13	0.89	0.90	1.01	1.01	1.06	0.99	1.03	0.99	0.95	0.99	0.91	0.90
14	–	0.99	0.97	1.07	1.07	1.07	1.04	1.02	1.01	0.96	0.94	–
15	–	0.97	0.83	1.16	–	–	0.92	0.98	0.82	0.75	0.74	0.60
16	–	–	–	–	1.20	–	–	–	–	–	–	–
17	–	0.99	0.96	1.06	1.17	0.94	1.07	1.08	–	1.11	0.80	–
18	0.69	1.11	0.93	1.02	1.17	0.91	1.02	1.02	0.94	1.00	0.83	0.76
19	–	–	0.87	–	1.13	–	1.07	1.11	0.94	–	0.78	–
20	–	–	1.10	–	–	–	–	–	0.97	–	–	–

rectangle. Table 3 contains the numbers of meteorological observations made within each rectangle from 1961 to 1980. Within rectangles 13, 14 and 15 the observations began earlier: in 1957 (rectangles 13 and 14) and 1959 (rectangle 15). It is commonly known that mean cloudiness over the Baltic Sea is often lower than that over the coast (Kwiecień, 1987). Therefore the actinometric and meteorological data from coastal stations cannot be used directly for describing the solar energy totals reaching the sea surface. We have found a transfer matrix F_{Sm} between the monthly totals of solar irradiation in Gdynia and those at sea under the following assumptions:

- irradiation monthly total of a month m at a certain point (Station S) of the south-east Baltic Sea surface is correlated with the monthly total in Gdynia,
- the ratio of these two totals depends only on the month of a year and geographical location of the point, and is constant over years.

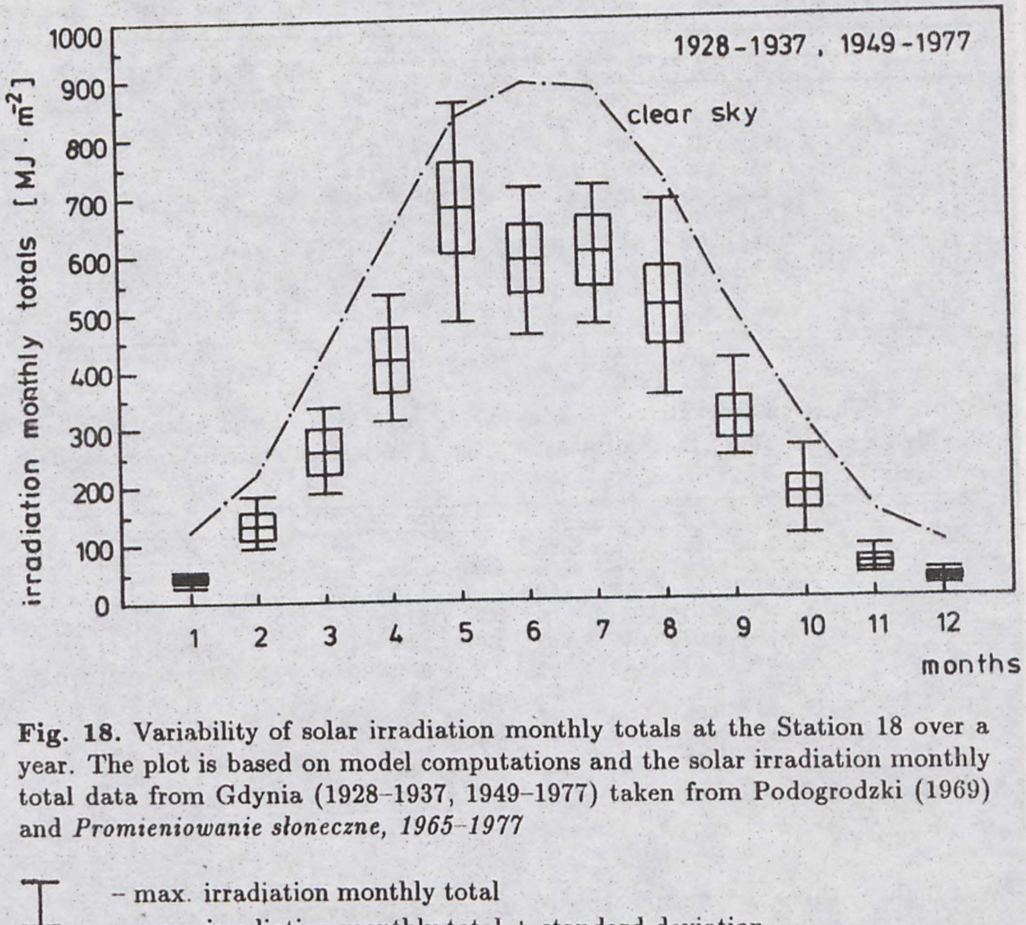

Fig. 18. Variability of solar irradiation monthly totals at the Station 18 over a year. The plot is based on model computations and the solar irradiation monthly total data from Gdynia (1928–1937, 1949–1977) taken from Podogrodzki (1969) and *Promieniowanie słoneczne, 1965–1977*

– max. irradiation monthly total
– mean irradiation monthly total + standard deviation
– 38-year mean irradiation monthly total
– mean irradiation monthly total – standard deviation
– min. irradiation monthly total

Thus the monthly total $D_M(m, y, S)$ of the month m of the year y at the Station S can be expressed as:

$$D_M(m, y, S) = F_{Sm} \cdot D_M(m, y, \text{ Gdynia}), \tag{12}$$

where $D_M(m, y, \text{Gdynia})$ is the monthly total in Gdynia.

The transfer matrix was obtained from both model results (for the sea) (equations (10)–(11)) and experimental data (from Gdynia) (Podogrodzki, 1969; *Promieniowanie słoneczne, 1965–1977*). This matrix is given in Table 4.

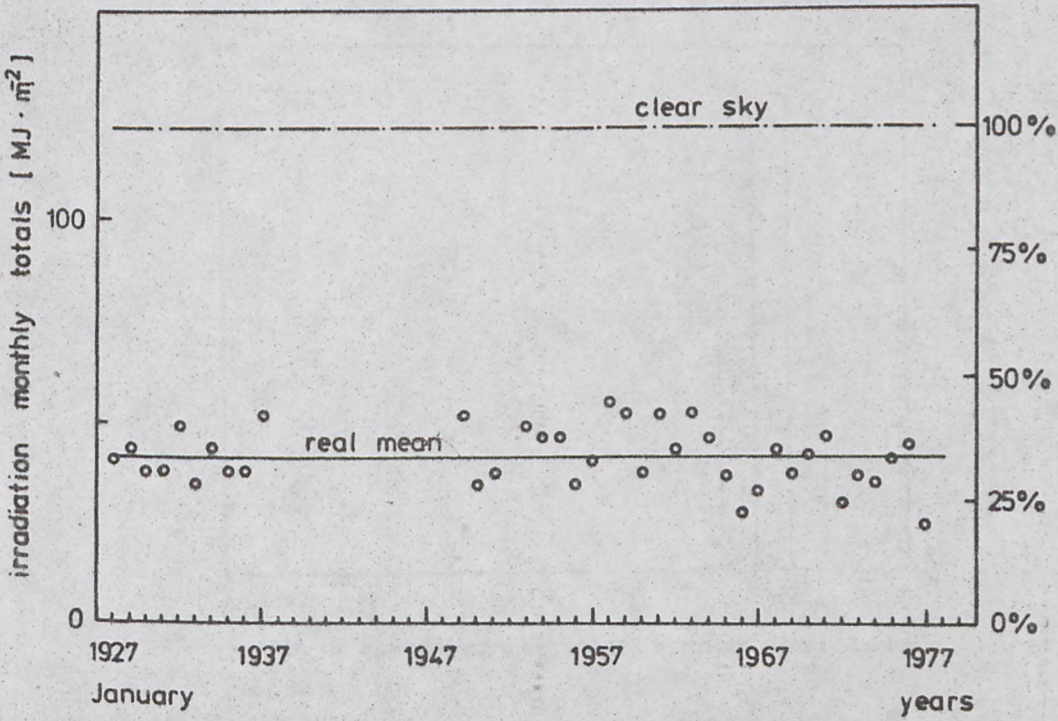

Fig. 19. The 38-year variability of solar irradiation monthly totals for January at the Station 18, based on model computations and the solar irradiation monthly total data for Gdynia (1928–1937, 1949–1977) taken from Podogrodzki (1969) and *Promieniowanie słoneczne, 1965–1977*

Using irradiation monthly totals over 38 years in Gdynia (Podogrodzki, 1969; *Promieniowanie słoneczne, 1965–1977*), 38-year monthly totals (Fig. 18) at Station 18 (northern part of the Gulf of Gdańsk; see Figure 17) were calculated. Long-term mean values of irradiation monthly totals, standard deviations and extreme values for the considered period 1928–1977 (there is a lack of data for the period 1938–1948) are shown in these figures. The dashed lines denote clear sky irradiation monthly totals based on relations (2), (5), (6) and (8).

The most cloudy months over the South Baltic are January, December and November, when less then 40% of clear sky solar energy reaches the sea surface during the month. The highest percentage of clear sky irradiation monthly total reaches the considered part of the Baltic surface in May (81%). The highest difference between the maximum and minimum values of the irradiation monthly total, as well as the highest standard deviation of the monthly totals, were observed in May ($\Delta D_M = 377$ MJ $\cdot$ m^{-2},

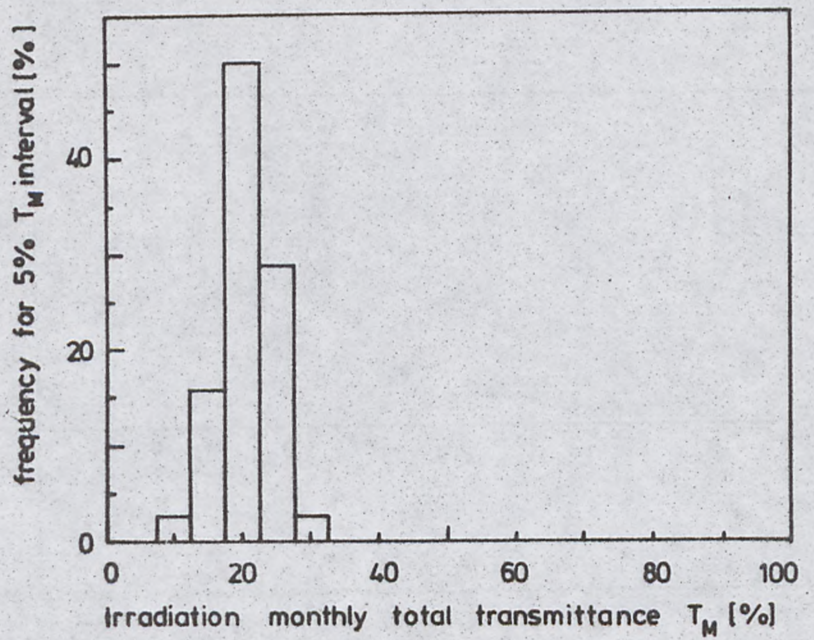

Fig. 20. Frequency distribution of irradiation monthly total transmittance for January, based on the data of Figure 19

$\sigma_{D_M} = \pm 79$ MJ $\cdot$ m^{-2}) and August $\Delta D_M = 337$ MJ $\cdot$ m^{-2}, $\sigma_{D_M} = \pm 68$ MJ $\cdot$ m^{-2}). Maximum monthly total values are probably too high (the maximum computed monthly total for May is higher then that for clear sky), which is caused by the assumption that the transfer matrix is constant over the years. Comparing the standard deviations and the differences between maximum and minimum irradiation monthly totals with those of the clear sky it turned out that irradiation monthly totals expressed in terms of percentage of clear sky totals changed from year to year, the most markedly in February, May, August, March and October ($\sigma_M > 9\%$), whereas the weakest variations were observed in January and December ($\sigma_M < 6.5\%$).

The following Figures (19 and 21) show the values of monthly totals of chosen months (January and May) at Station 18 in the south-east Baltic, as well as frequency distributions of these total transmittances (Figs. 20 and 22). The average monthly total transmittance is 20.8% in January and 58% in May. As is shown in Figure 18 the irradiation monthly total transmittance values are most reproducible from year to year in January. In both demonstrated cases the modal values of frequency distributions are approximately equal to the mean values. The differences between the maxi-

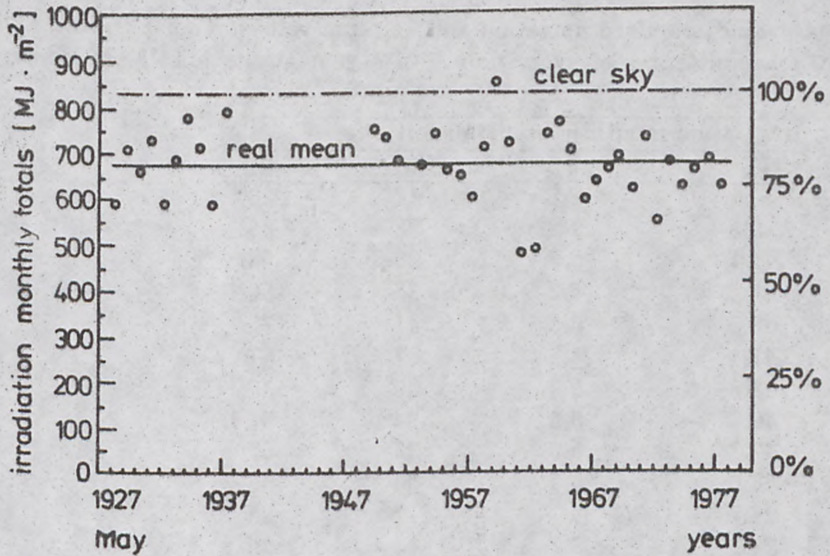

Fig. 21. The 38-year variability of solar irradiation monthly totals for May at the Station 18, based on model computations, and the solar irradiation monthly total data from Gdynia (1928–1937, 1949–1977) taken from Podogrodzki (1969) and *Promieniowanie słoneczne, 1965–1977*

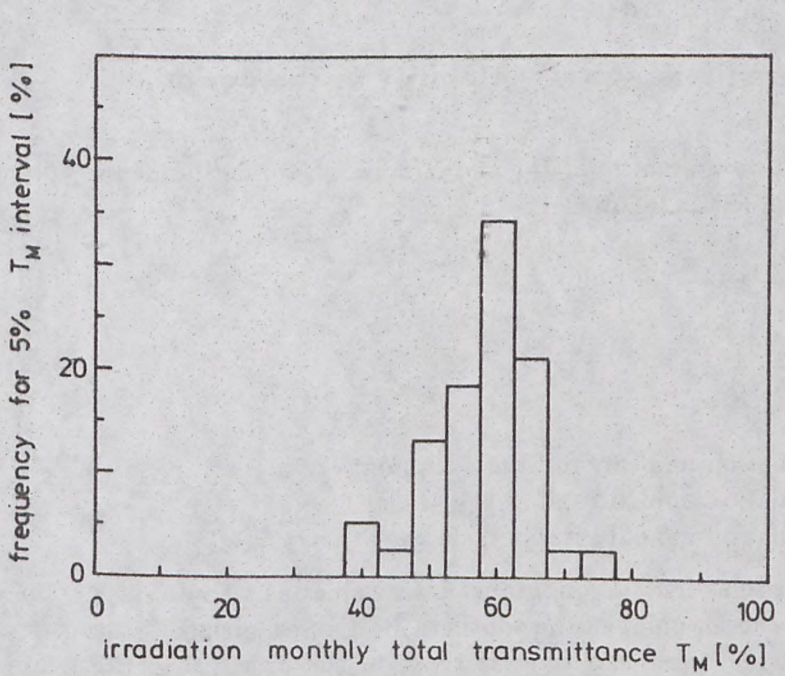

Fig. 22. Frequency distribution of irradiation monthly total transmittance for May, based on the data of Figure 21

Table 5. Mean value, standard deviation and extreme values of solar irradiation monthly total transmittances of every month of a year at Station 18, based on 38-year data

Months	Irradiation monthly total transmittance T_M [%]			
	$< T_M >$	σ_{T_M}	$T_{M_{min}}$	$T_{M_{max}}$
January	20.8	3.7	12	28
February	39.5	7.1	28	55
March	41.1	6.3	30	53
April	46 .5	6.2	35	59
May	58.0	6.8	41	73
June	47.4	4.8	37	57
July	48.8	5.0	39	58
August	49.3	6.6	34	67
September	42.7	5.0	34	57
October	38.8	6.1	24	56
November	24.7	4.7	17	38
December	21.2	3.7	14	30

mum and minimum transmittances vary from 16% in January to 33% in August. A statistical description of irradiation monthly total transmittance variability is summarized in Table 5.

6. Annual irradiation total variability in the period 1928–1977

The irradiation *annual total* D_A and irradiation *annual total transmittance* T_A are defined as follows:

$$D_A = \sum_{i=1}^{12} D_M, \tag{13}$$

$$T_A = \frac{D_A(0)}{D_A(\infty)}, \tag{14}$$

where:

D_M – irradiation monthly total in i-th month of a year,
$D_A(0)$ – irradiation annual total at the sea surface,
$D_A(\infty)$ – irradiation annual total outside the atmosphere.

The 38-year solar irradiation annual total values as well as their transmittances at a chosen point of the southern Baltic Sea surface (Station 18; the same point and period of time as those in the previous section), obtained both by model computations and from empirical data (see the previous section and Rozwadowska, 1990), are presented in Figures 23 and 24. On average, about 45.8% of the solar radiation coming to the outer limits

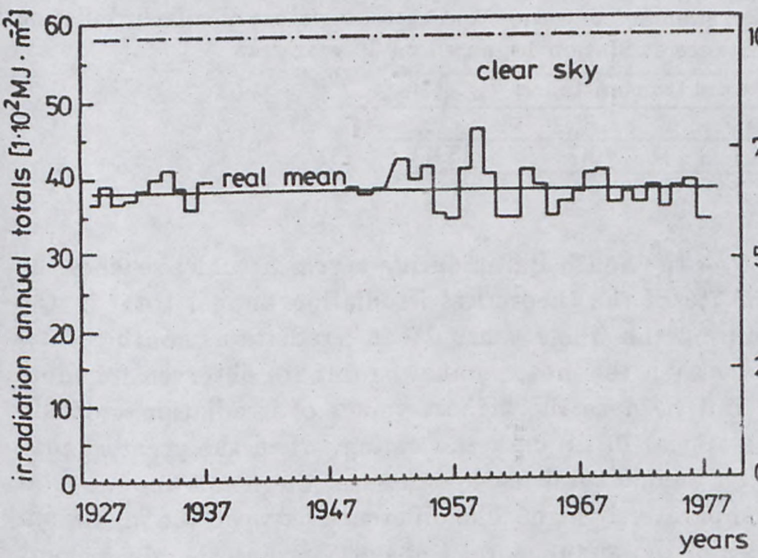

Fig. 23. The 38-year variability of solar irradiation annual totals at the Station 18, based on model computations, and the solar irradiation monthly total data for Gdynia (1928–1937, 1949–1977) taken from Podogrodzki (1969) and *Promieniowanie słoneczne, 1965–1977*

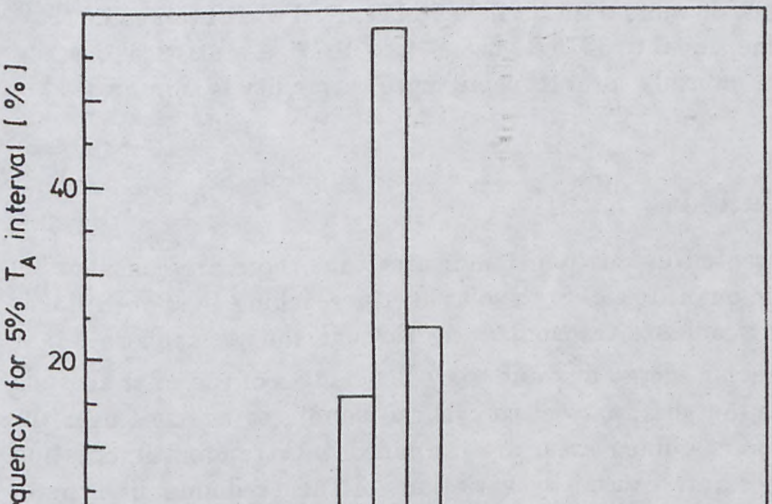

Fig. 24. Frequency distribution of irradiation annual total transmittance based on the data of Figure 23

Table 6. Mean value, standard deviation and extreme values of solar irradiation annual total transmittance at Station 18, based on 38-year data

Irradiation annual total transmittance T_A [%]			
$< T_A >$	σ_{T_A}	$T_{A_{min}}$	$T_{A_{max}}$
45.8	3.1	40.7	55.4

of the atmosphere over the South Baltic during a year actually reaches the sea surface, *i.e.* 65.7% of the theoretical irradiation annual total in the case of clear sky during the whole year. Mean irradiation monthly total transmittances, lower than the mean annual figure, are observed for more than half a year. But because the highest values of irradiation monthly total transmittance appear in summer and spring, when the greatest proportion of irradiation annual total reaches the sea, the mean annual total transmittance is comparatively high. The difference between the maximum and minimum values of the annual total transmittance at the given point and period of time is 15%. The standard deviation of the transmittance is only 3.1%. Over the years 1949–1977 the year-to-year variations of the irradiation annual totals were considerably higher (standard deviation equal to 3.4%) than those over the period 1928–1937 ($\sigma_{T_A} = 2.1\%$). The highest value of the irradiation annual total (4594.9 $\mathrm{MJ \cdot m^{-2}}$) was obtained in 1959, and its lowest value, equal to 3376.8 $\mathrm{MJ \cdot m^{-2}}$, in 1977. A statistical description of irradiation monthly total transmittance variability is summarized in Table 6.

7. Final conclusions

The data presented in this paper indicates that there are considerable fluctuations in the quantities of both solar energy reaching the South Baltic surface and solar irradiance transmittances through the atmosphere.

Variability of solar energy flux due to cyclic changes of the solar altitude over the day and the year, as well as cyclical cloudiness changes over the year typical of the examined area, are combined with random fluctuation components. These are caused by variations of the predominant type of atmospheric circulation over years in certain months, as well as moving cyclones and anticyclones, and broken clouds shading the sun. When the sun is unobscured, the irradiance under the sea surface additionally fluctuates due to the refraction of solar rays at the surface.

In the case of irradiation annual totals the amount of solar energy reaching the northern part of the Gulf of Gdańsk varied from 3377 $\mathrm{MJ \cdot m^{-2}}$ to 4595 $\mathrm{MJ \cdot m^{-2}}$, *i.e.* from 40.7% to 55.4% of the annual total outside the atmosphere (over 38 years, 1928–1937 and 1949–1977). The standard deviation of irradiation annual total transmittance is 3.1%.

As far as monthly totals are concerned, the year-to-year variations are higher than the variation of annual totals. As it was found, for example, from 12% to 28% of solar energy from outside the atmosphere reached the sea surface in January and from 41% to 73% in May. The transmittance standard deviation, however, varied from only 7.1% in February to 3.7% in January and December. The highest variations of solar energy totals expressed in energy units per month per square meter of the sea surface were observed in May and August, whereas the lowest in December and January (see the standard deviations in Figure 18).

In the case of daily totals its irradiation transmittance varies from day to day over a month from a few percent to about 67% ÷ 84% (depending on the month) that is, for example, from 2914 $\mathrm{kJ \cdot m^{-2}}$ to 32884 $\mathrm{kJ \cdot m^{-2}}$ in June and from 99 $\mathrm{kJ \cdot m^{-2}}$ to 3300 $\mathrm{kJ \cdot m^{-2}}$ in December.

As for solar energy fluctuations due to clouds, the maximal variations are observed under skies covered with cumulous clouds (Cumulus and Cumulonimbus) with cloudiness about 0.7. In this case the momentary irradiance transmittance can range from 10% to 95%, and the standard deviation is 25%.

The highest variability is observed in the case of underwater irradiance fluctuation due to focusing of sunlight by the surface waves. In this case the momentary irradiance for $\lambda = 525$ nm at the 1 m depth may exceed the mean value by a factor of 6, *i.e.* it may reach a value of about 400% of the solar irradiance at the top of the atmosphere for this wavelength. Some lower intensity light flashes are commonly present in the upper water layer, to depth of a few meters, during sunny weather. Their mean frequency reaches 100 to 300 flashes per minute under suitable conditions.

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