Solar radiation fluxes at the surface of the Baltic Proper. Part 1. Mean annual cycle and influencing factors*

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Abstract

Meteorological observations made on board Voluntary Observing Ships in the period 1980–1992 are used to estimate the climatological characteristics of the solar radiation flux at the surface of the Baltic Proper. A semi-empirical model developed for the Baltic region is used. Monthly and annual means of solar radiation fluxes reaching the sea surface, averaged over the northern, southern and western parts of the Baltic Proper are calculated. Seasonal and interannual variability of the fluxes as well as the impact of both meteorological and astronomical factors on the monthly and annual means of the fluxes are also analysed. The annual mean irradiance for the entire Baltic Proper is estimated at 117 ($\pm$ 4) W m^{-2}. The long-term monthly means for this area vary from 12 ($\pm$ 4) W m^{-2} in December to 241 ($\pm$ 21) W m^{-2} in June.

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1. Introduction

The physical conditions of the Baltic Sea have been a meteorological and oceanographic research topic for decades. Additional interest in the Baltic Sea has recently arisen in the context of complex climate research programmes such as BALTEX, the Baltic Sea Experiment. The principal aims of BALTEX include (1) a more detailed and precise understanding, and (2) the quantification, of energy and water cycles in the climate system of the entire Baltic Sea catchment area. The Baltic Sea is a very large water body making up over 20% of its catchment area; the atmosphere over it are subject to both marine and continental influences. Since the components of the energy and water cycles (*e.g.* solar radiation, evaporation, precipitation) are expected to differ in their characteristics from those over the terrestrial part of the catchment area, a separate investigation of the Baltic Sea is appropriate.

The implementation of BALTEX (see BALTEX, 1995) involves the analysis of historical data sets in order *e.g.* to establish climatological statistics as background information for studies of current events. The solar radiation flux at the sea surface is an important climatological variable. Unlike over land, where a network of actinometric stations exists, there are too few solar radiation measurements available at sea to make a climatological analysis feasible. Therefore, radiation fluxes at the Baltic Sea surface have usually been estimated either by extrapolation of the coastal actinometric measurements to the open sea area or by the application of radiation parametrisations to marine meteorological observations. A critical review of some of the parametrisations developed for various parts of the globe is given *e.g.* in Dobson and Smith (1988) and Timofeyev (1983).

A few earlier studies investigated solar radiation fluxes at the surface of the Baltic Sea or parts of it. Czyszek *et al.* (1979) used coastal data from Gdynia and Kołobrzeg to develop a very simple parametrisation of the solar radiation energy flux reaching the Baltic Sea. Krężel (1985) calculated the solar radiation over the Baltic Proper for the period 1964 to 1974. Though more complex than the earlier work cited here, his parametrisation is based on solar radiation fluxes both measured at coastal actinometric stations and estimated from coastal and inland meteorological data. The solar energy fluxes estimated by Dera and Rozwadowska (1991), Rozwadowska (1992) and Dera (1995) were based on ship meteorological observations, but the number of observations was very limited and the calculations were confined to the area of the Polish Economic Zone. Some papers, *e.g.* by Podogrocki (1969), Bogdańska *et al.* (1996), Rozwadowska (1994) and Russak (1994), analyse the long-term records of solar radiation at particular coastal stations in the Baltic Sea region.

However, the relationships established for either terrestrial or open-ocean conditions may not necessarily be directly applicable to the semi-enclosed Baltic Sea. Neither may coastal conditions be representative of the open sea; hence, caution is called for when coastal measurements and estimates are directly extrapolated to the area of the Baltic Proper.

An important source of climatological information from the open Baltic Sea, covering time periods on scales from years to decades, are the meteorological reports made on board Voluntary Observing Ships (VOS). In recent years the new global marine VOS data set COADS (Comprehensive Ocean–Atmosphere Data Set, see Woodruff *et al.*, 1987) has become available, which offers a much more comprehensive data base compared to earlier studies.

The basic aim of this study is to calculate monthly and annual estimates of incident solar radiation fluxes at the surface of the Baltic Proper by applying the semi-empirical model developed by Rozwadowska (1991) to the COADS data, thus combining high data coverage with recently developed parameterisations. Spatial distribution of the fluxes, their seasonal and interannual variability, as well as the impact of both meteorological and astronomical factors on the monthly and annual mean fluxes are analysed in part 1 of this study. Part 2 estimates the errors in the monthly fluxes and compares the present results with those obtained using other parameterisations, and will be published in a future issue of Oceanologia.

2. Data

The following surface meteorological observations from the COADS are used in this study: air pressure p, dew point temperature T_d, total cloud amount c, low cloud amount cl, low-, middle- and high-level cloud class. Moreover, a 1° digital sea-ice data set is used, which has been digitised from bi-weekly routine ice maps published by the Swedish Meteorological and Hydrological Institute (SMHI), see Isemer (1998). These parameters comprise the full set of meteorological information necessary in the model applied here. However, observations containing no other cloud information than the total cloud amount can also be used.

We have analysed the total cloud cover data in order to check for a possible diurnal cycle in the COADS cloud observations by computing the monthly means for daytime and night-time separately. The hypothesis that the night and day means are equal has been rejected at the 5% significance level (Kreyszig, 1970) using Student's t-test. At this point we are not investigating whether there is a real night-time versus daytime difference in cloud cover over the Baltic Sea or whether these differences may be artifacts caused by observer bias. As this study focuses on solar radiation and because the existence of diurnal cycles in cloud cover cannot be ruled out, only observations from the period of daylight (when $\cos\vartheta > 0$, where ϑ – solar zenith angle) are used in the model computations.

All the computations and further analysis are confined to the area of the Baltic Proper, which has been divided into 3 sub- regions (Fig. 1), following earlier studies, *e.g.* by Henning (1988):

- northern Baltic Proper – north of 57°N,
- southern Baltic Proper – south of 57°N and east of 15°E,
- western Baltic Proper – west of 15°E.

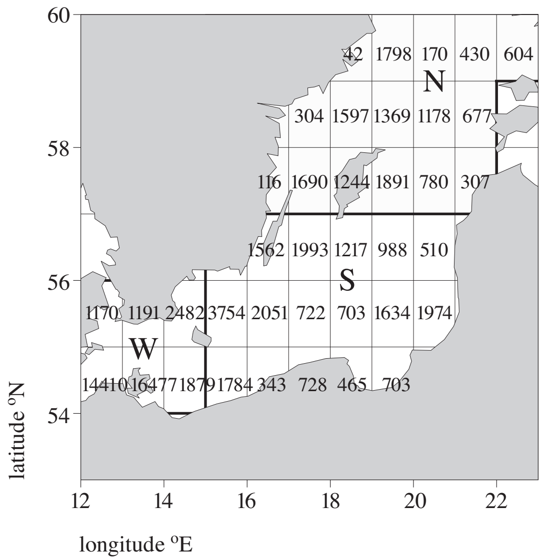

Fig. 1. Division of the Baltic Proper as used in this study. The number of COADS day-time ship observations containing the cloud cover information are given for each 1° latitude/longitude gridbox in the period 1980–1992

The period 1980 to 1992 is chosen because of the high number of observations in the COADS during this period. The spatial distribution within the total Baltic Proper is not even (Fig. 1), indicating that voluntary observing ships travel along certain shipping lanes. The western part of the Baltic Proper has the best coverage, the northern the worst. Neither are the distribution of the number of observations within the regions uniform. Note that in the southern Baltic the observations are mainly concentrated in the western and north-western parts, whereas the central part is very poorly

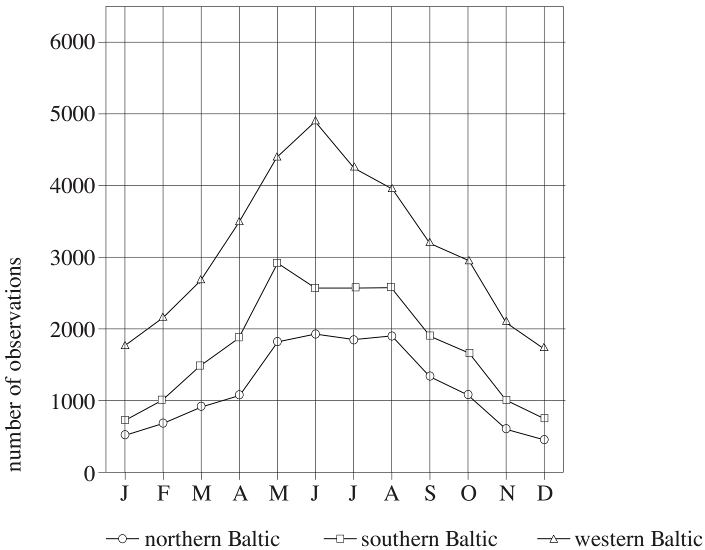

Fig. 2. The seasonal distribution of the total monthly number of COADS day-time observations in the period 1980–1992 containing cloud cover information

covered. The distribution of observations in time is quite regular. Due to the daytime selection the number of observations applicable to this study is about twice as high in summer as compared to winter (Fig. 2). Moreover,

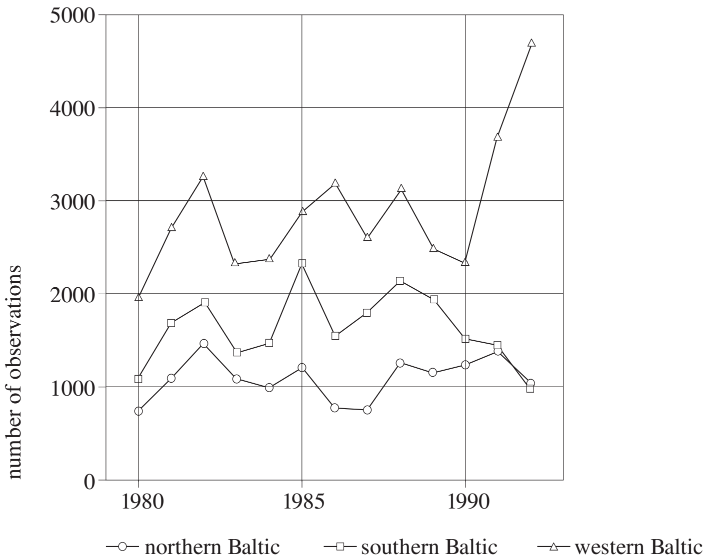

Fig. 3. The year-to-year variation in the total annual number of COADS daylight observations in the period 1980–1992 containing cloud cover information

there is no significant trend in the number of observations in the study period (Fig. 3). Figs. 1 to 3 show the number of observations containing the basic set of meteorological observations needed in the model used here, *i.e.* observations which contain at least total cloud cover but not necessarily the full cloud type information (see above and section 3). The number of such observations is typically 1.5 to 2 times higher than that of those containing the full cloud information set.

3. The semi-empirical model

The model is based on studies by Atwater and Brown (1974), Atwater and Ball (1978) and Krężel (1985). Only a brief description is given here; for details see Rozwadowska (1991). The input parameters to the model are the geographical co-ordinates of the area under investigation (ϕ, λ), day number of the year d, UTC time t_{UTC}, and the following surface meteorological observations: air pressure p, dew point temperature T_d, total cloud amount c, low cloud amount cl, low- (ctl), middle- (ctm) and high-level (cth) WMO (World Meteorological Organisation) cloud category as well as sea-ice cover information.

The algorithm includes the parameterisations of the following processes:

- attenuation by an ideal (dry) atmosphere, including molecular scattering, absorption by ozone and other gases,
- absorption by water vapour,
- attenuation by atmospheric aerosols,
- attenuation by clouds, and
- multiple reflection between the sea surface and the atmosphere.

The modelled downward irradiance at the sea surface is expressed by the relation

$$E(c,\, cc,\, \vartheta) = \frac{S\, f\,(T_i - A_{wa})\, T_{aer}\, T_{cl}\, \cos\vartheta}{1 - A_{sk}\; A_s}, \tag{1}$$

where

S – the solar costant (1368 Wm^{-2}, Willson, 1993),

$f(d)$ – the factor describing seasonal changes in S due to changes in the Sun–Earth distance (Spencer, 1971),

$\vartheta\,(t_{UTC},\, d,\, \phi,\, \lambda)$ – solar zenith angle,

$T_i\,(\vartheta,\, p)$ – transmittance for an ideal (dry) atmosphere (Atwater and Brown, 1974; Kastrov, 1956),

$A_{wa}\,(e_o,\, \vartheta)$ – absorbance of water vapour (McDonald, 1960),

$e_o(T_d)$ – water vapour pressure at the sea surface (Goff, 1965),

T_{aer} (ϑ, month, ϕ, λ) – aerosol transmittance (Krężel, 1985; Rozwadowska, 1991),
T_{cl} (c, cc, ϑ) – cloud transmittance function (Rozwadowska, 1991),
cc – cloud class (L, M, H) according to the classification used in the model (see section 4.1),
A_{sk} (c, cc) – sky albedo (Rozwadowska, 1991; Kamada and Flocchini, 1986; Kondratev and Binenko, 1984),
A_s (T_{atm}, ϑ, ice) – sea surface albedo (Payne, 1979; Isemer, 1998),
ice – fraction of the sea surface covered by ice,
T_{atm} – total atmospheric transmittance for the irradiance.

4. Application of the model to the COADS data

The application of the Rozwadowska (1991) model to the ship observations requires specific adaptations of the model, in particular for the cloud transmittance, the aerosol transmittance, and the albedo of the sea surface. These are briefly summarised in this section, together with a description of the averaging method used.

4.1. Calculation of cloud transmittance

The cloud transmittance function is expressed as a function of three types of cloud situations, which are chosen with respect to the types of clouds predominating in the sky:

- cloud class L – predominantly cumulus (Cu, Cb), low-level (St, Ns, Sc) or middle level layer clouds (As, Ac) covering a considerable part of the sky (c(As, Ac) $> 5/8$); when $c = 8/8$ this class includes situations when the clouds are opaque (for cloud type definitions, see *International cloud atlas*, 1956),
- cloud class M – predominantly middle-level or low-level clouds and $c = 8/8$; clouds at least partially semi-transparent,
- cloud class H – predominantly high-level clouds (Ci, Cs, Cc) or middle-level cloud cover with c(As, Ac) $\leq 5/8$.

This classification combines high-level clouds with middle-level clouds because the latter type is usually optically thin when appearing in small amounts, and often accompanies high level clouds. The cloud class M comprises cases when the layer of mainly middle or low clouds covers the sky entirely, but it reveals a relatively high transmittance due to a relatively small optical thickness.

The cloud observations included in the COADS data set are coded according to the WMO Ship Observation Code. They contain information on the total cloud amount (c), low level cloud amount (cl) as well as low- (ctl), middle- (ctm), and high-level cloud category (cth) (for details, see *International cloud atlas*, 1956). Based on this information each individual cloud observation is classified into one of three classes used in the model (L, M, H). However, information on cloud transparency is only given for some cloud types. Therefore, the following assumptions have been made during the classification:

- WMO cloud category coded as $ctm = 7$ (Ac at two or more levels or As or Ns present or opaque Ac predominant) are usually optically thin and are classified as M,
- the cases of $ctl = 5$ (Sc not formed by Cu spreading out), $ctl = 6$ (St or ragged St other than bad weather or both), $ctl = 8$ (Cu and Sc with bases at different levels) with $c = 8/8$ and $cl \geq 7/8$ are classified as M,
- when there are only low and high clouds present and low-level clouds dominate, the contribution of high clouds to the total cloud cover is neglected ($c = cl$) and the cloud situation is classified as L,
- thick fog obscuring the sky ($ww = 43, 45, 47, 49$ and $c = 9$) was treated like stratus clouds and $c = cl = 8$ (see Dobson and Smith, 1988).

The first two assumptions are justified by Dobson and Smith (1988), who showed that transmittances for cloud categories $ctm = 7$ and

Table 1. Cloud classification rules based on the COADS cloud data applied in the model

c	cl	ctl	ctm	cth	Additional condition	Cloud category
> 0	< 6	$= 0$	> -9	> -9	$ctm \neq 0$ or $cth \neq 0$	H
$> cl+2$ and > 0	< 4	> 0	> -9	> 0		H
$> cl+2$ and > 0 and < 6	< 4	> 0	> 0	$= 0$		H
$= 8$	> 0	> 0	> 0	> 0	other than H	M
$= 8$	> 5	$= 0$	$> 0; \neq 2$	≥ -9		M
$= 8$	> 5	$= 0$	$= 2$	> 0		M
$= 8$	> 0	> -9	$> 0; \neq 2$	$= -9$	other than H	M
$= 8$	> 6	$= 5, 6, 8$	≥ -9	≥ -9 and $\neq 0$		M
> 0					other than H, M	L

ctl $= 5, 6, 8$ are close to transmittances for *ctm* $= 1, 9$ (semi-transparent As and chaotic sky respectively).

An overview of the model cloud classification scheme as used here with the COADS cloud data is given in Tab. 1.

On the basis of observations containing full information about clouds, the frequencies of occurrence of cloud situations belonging to the class L, M or H for each total cloud cover amount, month and Baltic Proper sub-region have been computed. These relations are used further in the model with those observations that do not contain the full cloud information but just total cloud cover. Fig. 4 shows examples of the relations obtained.

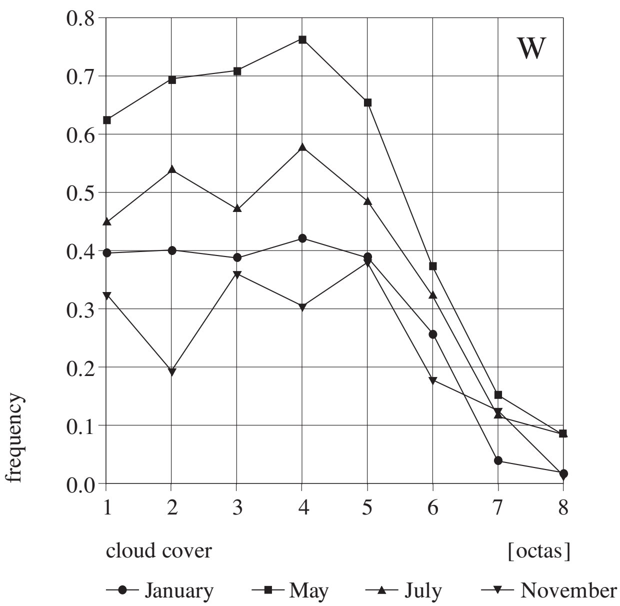

Fig. 4. Frequency of occurrence of cloud class H in January, May, July and November for the western Baltic Proper based on COADS observations from the period 1980–1992

4.2. Aerosol transmittance

Since the COADS does not contain any information about aerosols, the aerosol transmittances based on the data given by Krężel (1985) are adopted in the model (Rozwadowska, 1991). They are computed from the solar radiation measurements and meteorological observations made on cloudless days at Gdynia, Helsinki, Stockholm (1965–1974) and Copenhagen (1965–1970) and are extrapolated to the Baltic Sea.

4.3. Albedo of the sea surface

The effective albedo of the sea surface is the weighted sum of the albedo of the ice-free sea surface A_{sea} and the sea ice A_{ice}, according to the fraction of the surface covered by ice (ice):

$$A_s\,(T_{atm},\,\vartheta,\,ice) = (1 - ice)\,A_{sea} + ice\,A_{ice}. \tag{2}$$

In this study the sea surface albedo values for various solar zenith angles and atmospheric transmittances are taken from Payne (1979).

In nature, the sea-ice albedo is highly variable and ranges from about 0.2 for young grey ice or ponded ice to about 0.8 for ice covered with a thick layer of fresh snow (*e.g.* Allison *et al.*, 1993; Perovich, 1996). Because no information about the state of the ice surface is available, the ice albedo is assumed constant and equal to 0.45, which is the middle value of the ice albedo expected in the Baltic Sea. The 1° data for the fraction of the surface covered by sea ice are taken from Isemer (1998), and describe the actual development of sea ice in the study period with a time resolution of 3 to 5 days.

4.4. Daily and monthly fluxes

The individual COADS ship observations are not regularly distributed in either time or space. Moreover, radiation fluxes at a given place and time depend not only on the meteorological conditions but also on the solar zenith angle and, in the case of *e.g.* daily means, on the length of daylight. Both are determined by the time and the geographical position, which vary correspondingly within a given averaging period and area. Therefore, simple averaging of the radiation fluxes calculated from the individual observations is likely to create substantial biases in monthly or annual means. In our calculations, we assume that a monthly set of meteorological observations is representative of each individual day of a given month for the Baltic Proper sub-region where the observation was made. Therefore, the transmittance of a daily total $T_{D_d}\,(obs_j,\,\varphi_k,\,\lambda_k,\,d)$ for the jth meteorological observation, the dth day of the year and the kth $1° \times 1°$ cell of the given sub-region of the Baltic Proper is calculated using

$$T_{D_d}\,(obs_j,\,\varphi_k,\,\lambda_k,\,d) = \frac{\int\limits_{t_r(\varphi_k,\,d)}^{t_s(\varphi_k,\,d)} E\,(obs_j,\,T_{aer}\,(d,\,\varphi_k,\,\lambda_k),\,\varphi_k,\,d)\,dt}{D_d^{\infty}\,(\varphi_k,\,d)}, \tag{3}$$

where

$$D_d^{\infty}(\varphi_k,\, d) = \int\limits_{t_r(\varphi_k,\, d)}^{t_s(\varphi_k,\, d)} S\, f(d)\, \sin\varphi\,(t,\, d,\, \varphi_k)\, dt, \tag{4}$$

$$obs_j = (p_j,\, T_{d,\,j},\, c_j,\, cc_j,\, ice_j),$$

t – local solar time,
$t_r(\varphi_k,\, d)$, $t_s(\varphi_k,\, d)$ are the local solar times of sunrise and sunset respectively.

The monthly total D_M and the monthly mean irradiance $\overline{E}^M$ for the kth cell of the Baltic are calculated by means of the following relation:

$$\begin{aligned} D_M(\varphi_k, \lambda_k) \;&=\; \sum_{\text{day}=1}^{N_M} D_d^{\infty}(\varphi_k,\, d)\, \frac{1}{N_{mon}} \,\times \\ &\times \sum_{j=1}^{N_{mon}} T_{D_d}(obs_j,\, \varphi_k,\, \lambda_k,\, d(\text{day},\, \text{month})), \end{aligned} \tag{5}$$

$$\overline{E}^M = \frac{D_M(\varphi_k,\, \lambda_k)}{N_M \times 24 \times 3600}, \tag{6}$$

where
N_M – denotes the length of a given month,
N_{mon} – denotes the total number of observations within a month and a subregion.

The mean monthly irradiance $\overline{E}^M(s)$, the monthly total $D_M(s)$, for the whole northern, southern and western Baltic Proper sub-regions are weighted according to the water area in the respective 1° gridbox.

The transmittance for the monthly total T_{D_M} in sub-region s is defined as

$$T_{D_M}(s,\, \text{month},\, \text{year}) = \frac{D_d(s,\, \text{month},\, \text{year})}{D_d^{\infty}(s,\, \text{month},\, \text{year})}. \tag{7}$$

The long-term mean monthly irradiance for the period 1980 to 1992 is calculated from the relation

$$\overline{E}^{Ms} = \frac{1}{13} \sum_{\text{year}=1980}^{1992} \overline{E}^M(\text{year}). \tag{8}$$

This approach compensates for the variable monthly number of observations from one year to another.

5. Results

5.1. Water vapour pressure

The computed average annual distributions of the water vapour pressure at the sea surface from the period 1980–1992 for the three parts of the Baltic Proper considered in this paper are based on the dew point temperature from the COADS data set and are shown in Fig. 5. The annual cycle is characterised by a maximum of about 15 hPa in July and August and a minimum of about 5 hPa in February. The spatial distribution is nearly uniform; however, the water vapour pressure over the northern part of the Baltic is slightly lower than in the other parts in autumn, winter and spring.

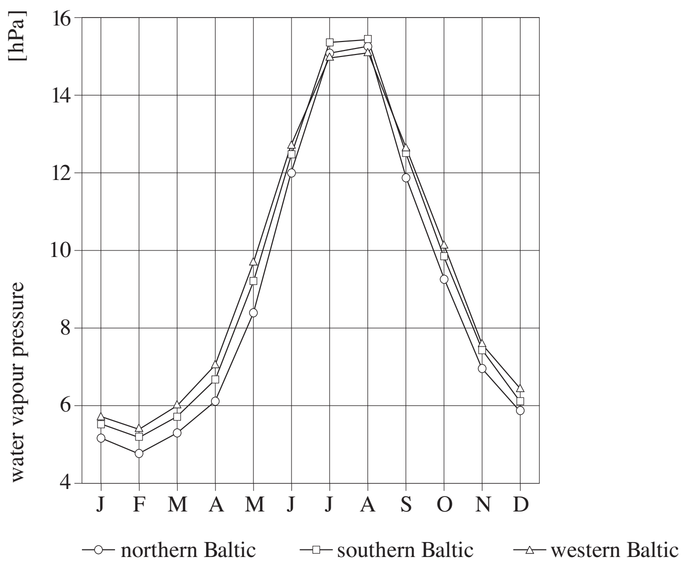

Fig. 5. Monthly mean water vapour pressure at the sea surface in the northern, southern and western parts of the Baltic Proper for the period 1980 to 1992, calculated from the dew point temperatures of the COADS

5.2. Total cloud cover and cloud classes

In general, the northern part of the Baltic Proper is characterised by the lowest total cloud cover and the highest number of clear days (see Figs. 6 and 7). Both the total cloud cover and the relative number of observations with cloud class L + M and cloud class H have strong annual cycles. Cloud cover varies from over 6/8 in winter and November to about 4/8 in May. A secondary minimum in total cloud cover is found in July. Similar annual variations, with a minimum in May and a maximum in November and winter, are found for the frequency of occurrence of cloud class L + M, whereas the clear sky and high cloud cases (cloud class H) are the most probable in May.

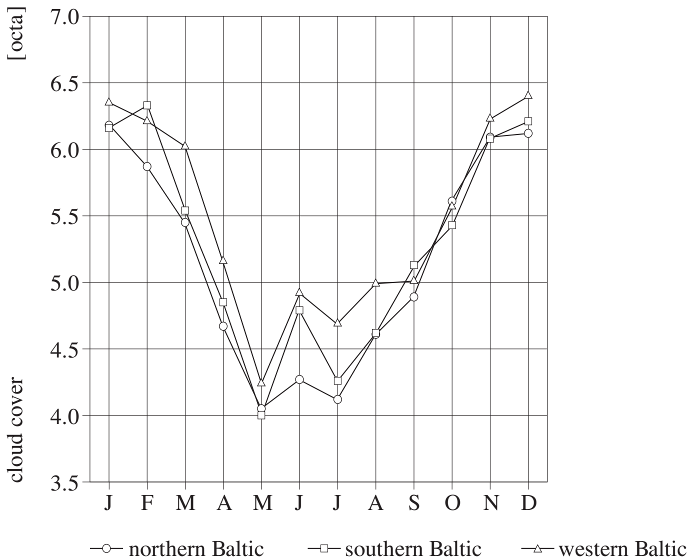

Fig. 6. Annual cycle of mean total cloud cover in the northern, southern and western Baltic Proper, based on daylight observations of COADS during 1980–1992

5.3. Aerosols

The zenithal value of the aerosol transmittance for the downward irradiance is a parameter characterising the optical properties of the aerosols over the given area. It is calculated using

$$T_{aer}(\varphi = 0) = (T_{aer}(\varphi))^{1/m_{aer}}, \tag{9}$$

where m_{aer} denotes the relative optical mass of the atmosphere for aerosols (*e.g.* Robinson, 1966).

The zenithal aerosol transmittances used in the modelling, averaged over time *i.e.* over seasons, and area, *i.e.* over the northern, the southern and the western Baltic respectively, are shown in Fig. 8. The zenithal transmittance falls to a minimum in summer and rises to a maximum in winter in all parts of the Baltic region. Throughout almost the whole year the aerosol transmittance is highest over the northern Baltic Proper; according to Krężel (1985), this could be due to the relatively longest distance from the industrial regions and intensive agricultural areas of western and central Europe.

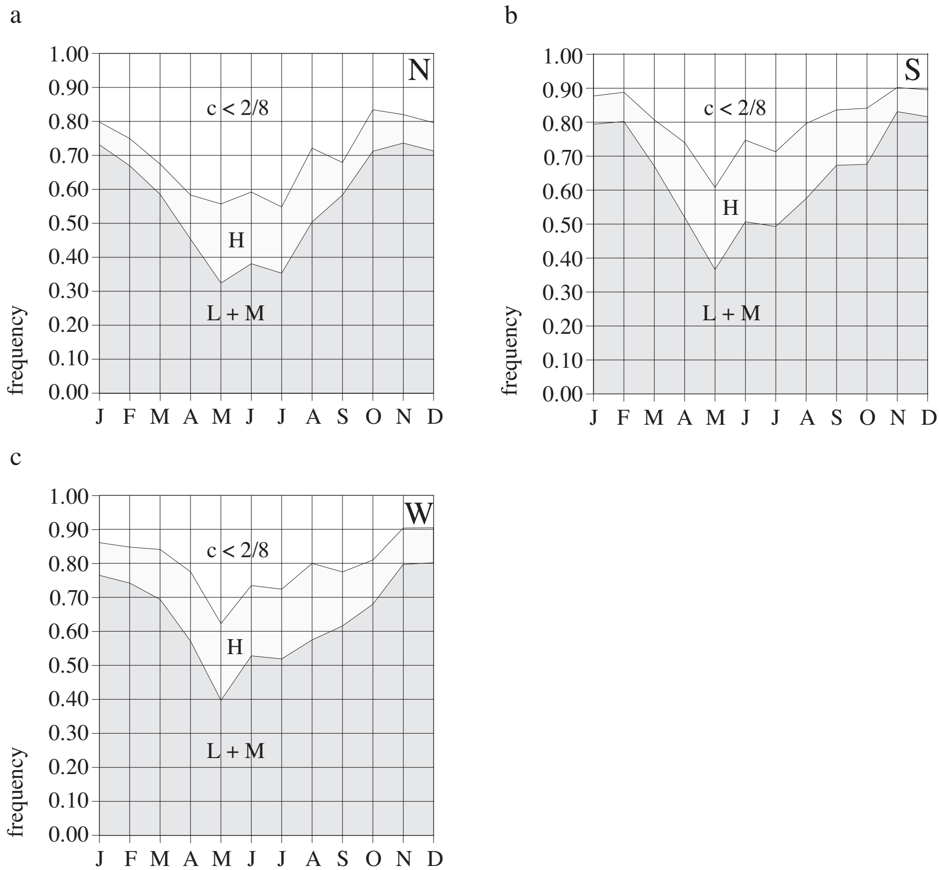

Fig. 7. Seasonal distribution of the frequency of occurrence of a practically cloudless sky ($c < 2/8$), and $c \geq 2/8$ with clouds belonging to cloud class H, and classes L and M over the northern (a), southern (b) and western (c) Baltic Proper for the period 1980–1992, based on COADS observations

5.4. Flux at the top of the atmosphere

The daily mean flux at the top of the atmosphere over the Baltic Proper varies in time and space due to variations in astronomical factors, *i.e.* length of daylight and solar zenith angle (Fig. 9). In winter, when both the period of daylight and the maximum solar elevation above the horizon decrease northwards, the daily mean irradiance varies from 50–60 W m^{-2} over the southernmost to 25–27 W m^{-2} over the northernmost parts of the Baltic Proper (values for the winter solstice). In the spring and summer months (between the spring and autumn equinoxes) the length of daylight increases northwards and partly compensates for the negative gradient in the solar elevation. This results in a nearly uniform latitudinal distribution of the

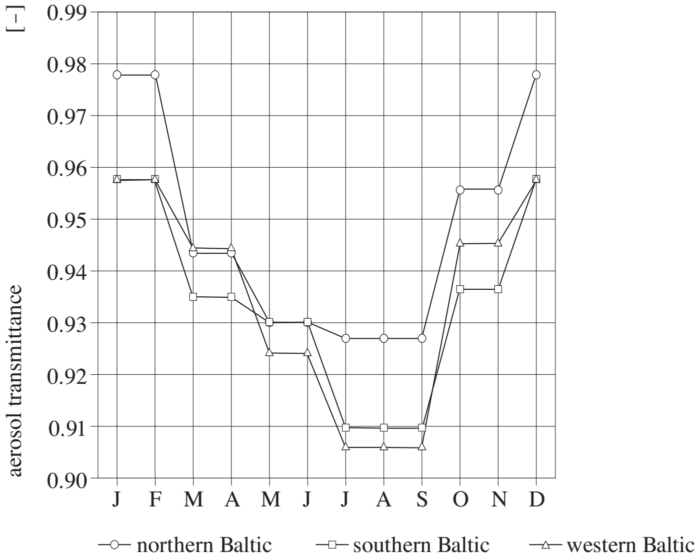

Fig. 8. Zenithal values of the aerosol transmittances used in the model, averaged over the northern, southern and western Baltic. See text for details

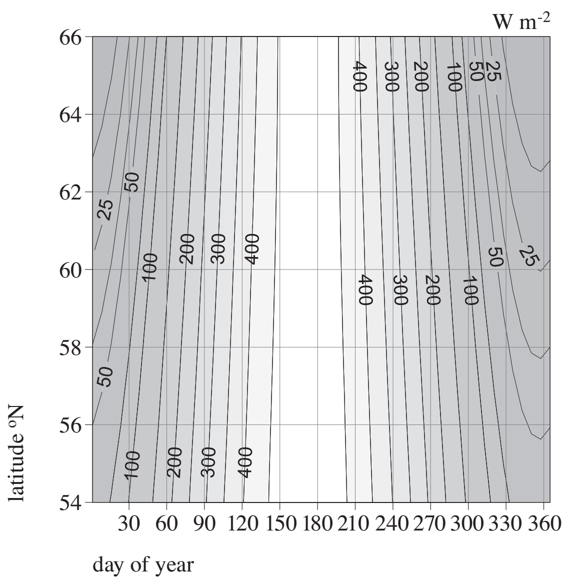

Fig. 9. Daily mean solar radiation fluxes [W m^{-2}] at the top of the atmosphere in the Baltic Sea region

daily mean irradiance at the top of the atmosphere. Near the summer solstice the irradiances are one order of magnitude higher than in winter and amount to 483 and 480 W m^{-2} for the southernmost and the northernmost parts of the Baltic Proper respectively.

5.5. Atmospheric transmittance

The joint influence of the atmospheric parameters on the solar radiation transmission through the atmosphere can be expressed as the downward irradiance transmittance for the theoretical case of the sun at the zenith (Fig. 10). The zenithal transmittance for the Baltic atmosphere varies from 0.59–0.63 in May to 0.42–0.48 in the period from November to February. The annual cycle is largely determined by the annual variation in cloud cover and frequency of occurrence of different cloud classes. Their seasonal variability results in seasonal changes in transmittance of about 30–40%. Seasonal cycles in both mean water vapour pressure and zenithal aerosol transmittance act in the opposite direction to the observed seasonal changes in the total zenithal transmittance. The respective isolated effects of mean water vapour pressure and zenithal aerosol transmittance may result in up to 3 and 6% increases in the total zenithal transmittance in winter when compared to summer.

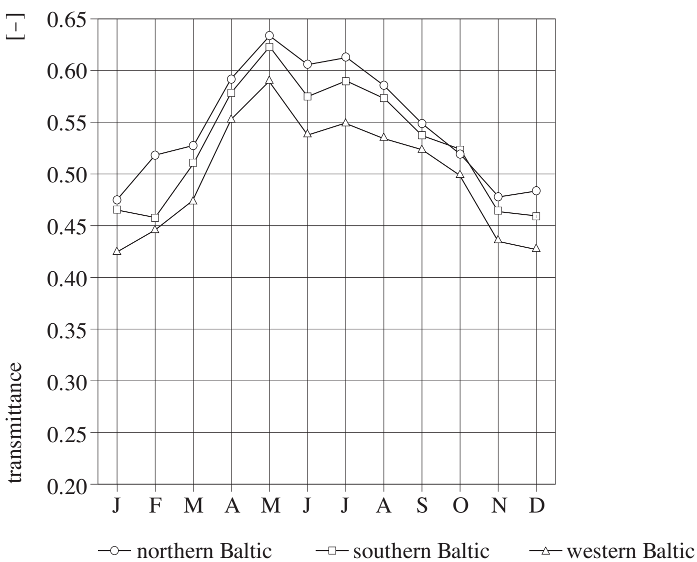

Fig. 10. Mean atmospheric transmittance of the irradiance for the Sun at the zenith in the northern, southern and western Baltic Proper in 1980–1992

Throughout the year the atmosphere over the northern Baltic has the highest zenithal transmittance, over the western Baltic the lowest. For winter and summer these differences are up to 12–13%. They are smaller in spring and autumn. The spatial distributions of mean cloud cover, zenithal aerosol transmittance and water vapour pressure act in the same direction. However, the influence of water vapour pressure on the spatial distribution of the zenithal transmittance is negligible, whereas the role of clouds is dominant. Spatial differences in zenithal transmittance caused by the mean total cloud cover may be in excess of 10%.

Spatial and seasonal variations in the real atmospheric transmittance for the solar radiation monthly totals depend on the temporal and spatial variability in both the atmospheric parameters and the average optical mass of the atmosphere (the average solar zenith angle). Because the transmittance decreases with increase in the solar zenith angle, the seasonal cycle in the real transmittance is more pronounced than that of the zenithal transmittance, while the spatial variations are weaker (Fig. 11).

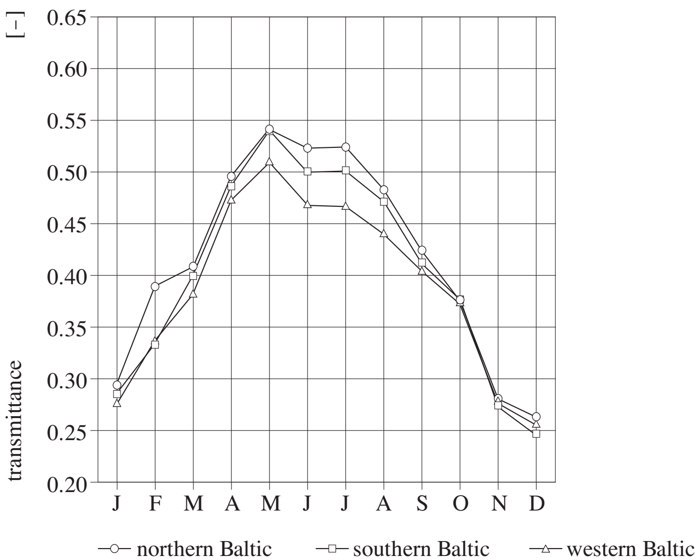

Fig. 11. Mean atmospheric transmittance of the monthly solar radiation totals for the northern, southern and western Baltic Proper in 1980–1992

Mean transmittance for monthly sums of incident solar radiation varies from 0.54 ($\pm$ 0.05), 0.54 ($\pm$ 0.05) and 0.51 ($\pm$ 0.06) in May to 0.26 ($\pm$ 0.05), 0.25 ($\pm$ 0.04) and 0.26 ($\pm$ 0.03) in December for the northern, the southern and the western Baltic Proper respectively (Fig. 10). Standard deviations of the individual monthly means are given in parentheses.

5.6. Solar radiation fluxes

Monthly mean incident solar radiation fluxes at the sea surface in the northern, southern and western Baltic Proper averaged over the period

1980–1992 are shown in Fig. 12a. The monthly mean downward irradiance reflects the annual cycle of the irradiance at the top of the atmosphere and varies from 249 W m^{-2} for the northern, 239 W m^{-2} the southern and 224 W m^{-2} for the western Baltic Proper in June to 9, 13 and 15 W m^{-2} in December respectively. The mean irradiances averaged over the entire Baltic Proper are given in Tab. 2.

Table 2. Long-term monthly means of the incident solar radiation fluxes [W m^{-2}] at the surface of the entire Baltic Proper, standard deviations of the individual monthly means and the absolute extreme values for the period 1980 to 1992

Month	Mean	Standard deviation	Minimum	Maximum
January	17.5	2.2	14.5	22.3
February	43.5	3.6	36.8	48.1
March	89.3	8.8	73.2	99.9
April	164.7	12.4	135.6	184.4
May	231.6	19.9	194.9	261.4
June	241.1	21.1	213.9	287.8
July	230.3	16.7	199.3	254.7
August	176.9	10.5	159.9	192.6
September	110.9	9.7	93.9	126.6
October	59.6	4.0	52.9	66.2
November	21.9	2.0	18.0	25.0
December	11.8	1.4	9.9	14.0
year	116.6	3.9	111.0	123.6

From September to March the spatial distribution of radiation fluxes is strongly influenced by astronomical factors, *i.e.* day length and solar elevation, which results in lower fluxes in the northern than in the southern and the western parts of the Baltic Proper. In June and July, when the latitudinal gradient of the solar radiation flux at the top of the atmosphere is weakest, the spatial distribution of the flux is controlled by the atmospheric transmittance and reaches a maximum at the surface of the northern and a minimum at the surface of the western Baltic Proper (Fig. 12b).

Standard deviations (SD) of the individual monthly means of the incident solar radiation fluxes (irradiances) at the surface of the northern, southern and western Baltic Proper from the long-term monthly means and the absolute extreme values for the period analysed are shown in Figs. 13a–13c respectively. The weakest absolute variations are found for winter months (standard deviations below 2 W m^{-2}), the highest for May and June (20–30 W m^{-2}). However, these variations, expressed as a percentage of the

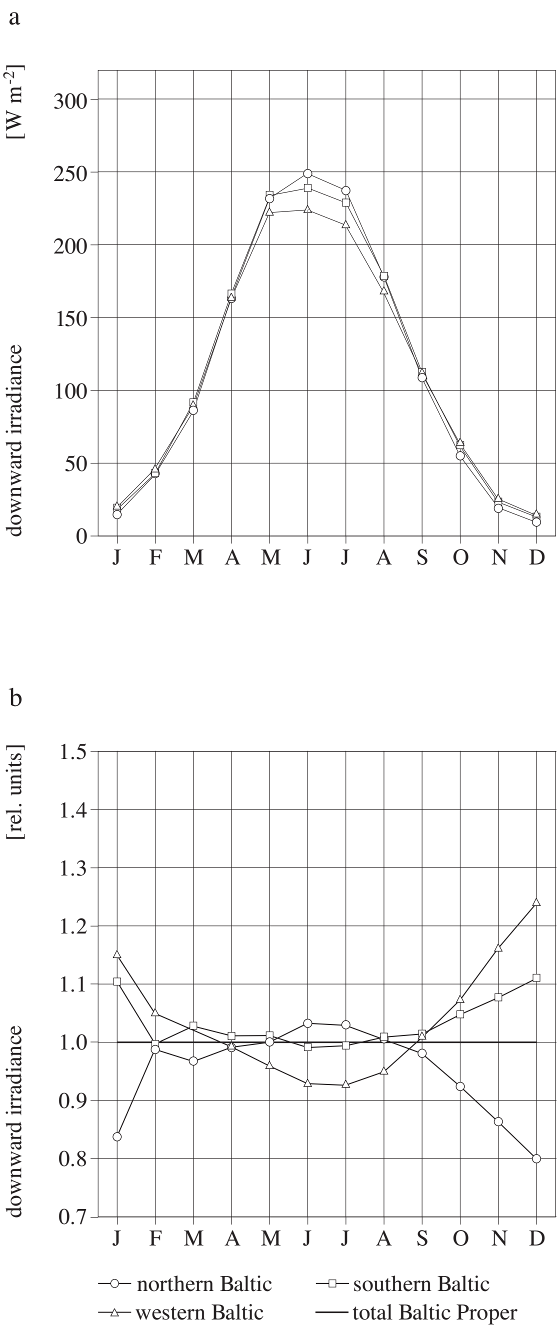

Fig. 12. Monthly mean incident solar radiation fluxes [W m^{-2}] (a) at the sea surface in the northern, southern and western Baltic Proper for the period 1980 to 1992. These fluxes are expressed as a fraction of the mean flux for the total Baltic Proper (b)

mean irradiance, are 6–7% in August to 10–17% in winter. Values higher than 10% also appear in spring and autumn.

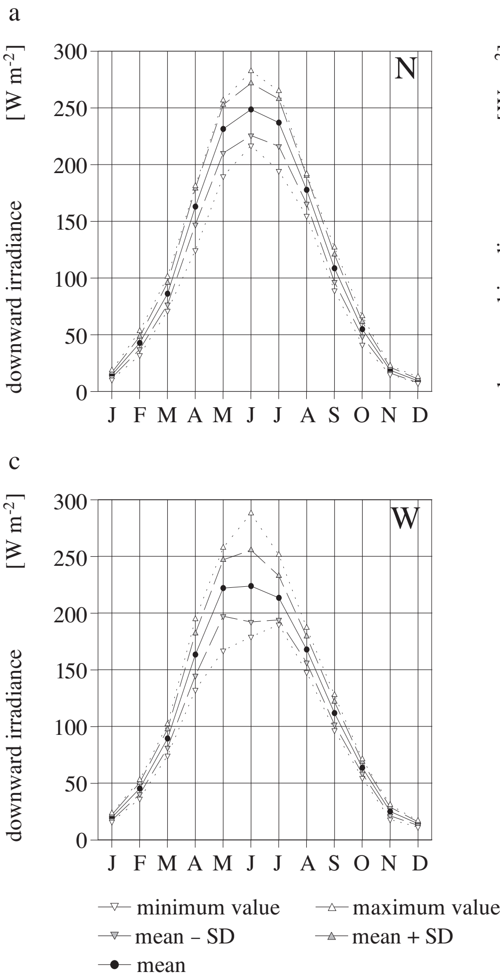

Fig. 13. Long-term monthly means of the incident solar radiation fluxes [W m^{-2}] at the sea surface in the northern (a), southern (b) and western (c) Baltic Proper, standard deviations SD of the individual monthly means and the absolute extreme values for 1980–1992

The annual mean downward irradiance at the sea surface averaged over the period 1980–1992 is 118 W m^{-2} ($\pm$4 W m^{-2}) for the southern, 116 W m^{-2} ($\pm$4 W m^{-2}) for the northern and 113 W m^{-2} ($\pm$5 W m^{-2}) for the western Baltic Proper. The annual mean irradiance for the entire Baltic Proper is estimated at 117 ($\pm$4) W m^{-2}. The numbers in parentheses denote the standard deviations of the individual annual means.

Fig. 14 illustrates the year-to-year variability in annual mean irradiance at the surface of the 3 parts of the Baltic Proper considered in this paper. These time variations are in agreement with the records from the coastal actinometric stations at Gdynia and Kołobrzeg (*cf.* Rozwadowska, 1994).

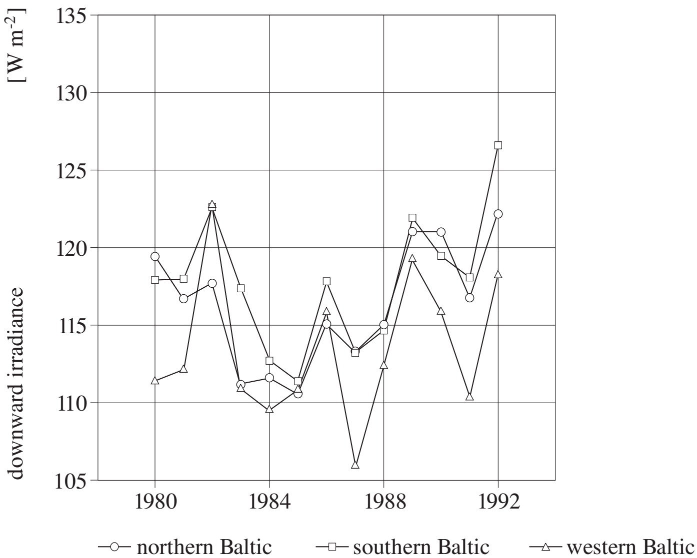

Fig. 14. Interannual variations in the annual mean solar radiation fluxes at the sea surface in the northern, southern and western Baltic Proper from 1980 to 1992

6. Conclusions

Monthly and annual estimates of incident solar radiation fluxes at the surface of the Baltic Proper are estimated, based on voluntary observing ship meteorological observations from the open Baltic Proper, extracted from the COADS (Comprehensive Ocean–Atmosphere Data Set). The semi-empirical model developed by Rozwadowska (1991) is used after several adjustments to the scope of the meteorological information available from the COADS. These modifications concern mainly the parametrisation of the influence of clouds on the solar radiation transmission through the atmosphere. The following meteorological parameters available from COADS are used in the calculations: air pressure, dew point temperature, total cloud amount, low cloud amount, low-, middle- and high-level WMO cloud category. A 1° digital sea-ice data set is also used (Isemer, 1998).

The respective monthly mean downward irradiances at the surface of the northern, southern and western parts of the Baltic Proper, computed using the semi-empirical model applied to ship meteorological observations, range from 249 ($\pm$23), 239 ($\pm$21) and 224 ($\pm$32) W m^{-2} in June to 9 ($\pm$2), 13 ($\pm$2) and 15 ($\pm$2) W m^{-2} in December. Standard deviations of the individual monthly means are given in parentheses.

The annual mean downward irradiance at the sea surface averaged over the period 1980–1992 is 118 W m^{-2} ($\pm$4 W m^{-2}) for the southern, 116 W m^{-2} ($\pm$4 W m^{-2}) for the northern, and 113 W m^{-2} ($\pm$5 W m^{-2}) for the western Baltic Proper. The annual mean irradiance for the entire Baltic Proper is estimated at 117 ($\pm$4) W m^{-2}. Standard deviations of the individual annual means are given in brackets.

From September to March the spatial distribution of radiation fluxes is strongly influenced by astronomical factors, *i.e.* day length and solar elevation, which results in lower fluxes in the northern than in the southern and western parts of the Baltic Proper. In June and July, when the latitudinal gradient of the solar radiation flux at the top of the atmosphere is weakest, the spatial distribution of the flux is controlled by the atmospheric transmittance, *i.e.* meteorological factors.

Cloud cover is the crucial atmospheric factor influencing atmospheric transmittance. However, the impact of spatial distribution of aerosol transmittance is also significant.

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