# Solar radiation fluxes at the surface of the Baltic Proper. Part 2. Uncertainties and comparison with simple bulk parametrisations*

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## Abstract

An adjusted version of the semi-empirical model developed by Rozwadowska (1991) was applied to calculate monthly and annual estimates of incident solar radiation fluxes at the surface of the Baltic Proper during 1980 to 1992 using voluntary observing ship meteorological observations from COADS as input data. The semi-empirical model was specifically calibrated using measurements from the Baltic Proper region. In Part 1 of this study we described the resulting solar radiation flux climatology for the Baltic Proper as well as for its three sub-basins.

* This study is part of the BALTEX research programme.

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In this second part, we give estimates of the overall random and systematic errors of the climatological flux results, apply simple bulk parametrisations to the same COADS ship observations, and compare the results with those of the semi-empirical model presented in Part 1. This comparison shows that bulk parametrisations calibrated both in purely marine and in continental environments elsewhere on the globe produce surface radiation climates over the Baltic Proper which deviate systematically, in a seasonally and regionally varying manner, from the results of the semi-empirical model. We present evidence to show that the differences found may be due both to physical reasons and to problems with the calibration methodology. This indicates that the atmospheric conditions over the Baltic Sea require specific, regionally calibrated models and parametrisations for solar surface radiation. We suggest that international efforts be made in order, firstly, to build up inventories and accessible data compilations of existing surface radiation records from the Baltic Sea, and secondly, to initiate additional surface radiation measurement activities based on internationally accepted and co-ordinated strategies. The planned intensive observational and modelling phase of BALTEX scheduled for the years 1999 to 2001 (BRIDGE) would be an ideal start for such initiatives.

## 1. Introduction

Different methods for estimating the solar radiation flux density at ground level $E$ have been developed and applied in the past. They range from detailed radiation transfer models to rather simple bulk parametrisations, see *e.g.* Timofeyev (1983), Lenoble (1985), Dobson & Smith (1988), Louche *et al.* (1988), Davies & McKay (1989), and Gueymard (1993). The degree of complexity of these methods depends on such factors as the requirements of the specific application, available input data and computer resources. A variety of input data have been used based on both ground-based *in situ* and satellite measurements.

Rozwadowska & Isemer (1998, henceforth referred to as RI) have recently applied a semi-empirical model to thousands of basic synoptic ship meteorological observations and measurements (taken from the Comprehensive Ocean-Atmosphere Data Set COADS, see Woodruff *et al.* 1987) with the aim of calculating climatological and individual monthly means of $E$ for a 13-year period representative of three sub-basins of the Baltic Proper. These latter range in size from roughly 10 to $45 \times 10^3\,\mathrm{km}^2$.

Both RI and the present study are contributions to the BALTEX (Baltic Sea Experiment) research programme (BALTEX 1995), the aims of which include the investigation of processes governing the water and energy cycles in the climate system of the entire water catchment region of the Baltic Sea. BALTEX also involves the establishment of revised climatological budgets for water and energy quantities for both land and sea areas in the Baltic Sea catchment basin using revised models and methods in combination with new data sets. The semi-empirical model used by RI may be applied to the few basic meteorological observations being made on Voluntary Observing Ships (VOS) and is thus suitable for use in climatological investigations. In terms of complexity, the model used by RI (for details, see also Rozwadowska (1991)) lies well within the range of simple bulk models on the one hand and of sophisticated radiation transfer models on the other. The RI model explicitly considers processes such as

- radiation attenuation by a dry atmosphere,
- absorption by water vapour,
- attenuation by atmospheric aerosols,
- attenuation by clouds, and
- the effects of multiple reflection between the surface, and the atmosphere and clouds.

The model used by RI contains several parametrisation coefficients that were recently calibrated using various measurements taken either on the open Baltic Sea or at coastal stations (Rozwadowska 1991). When the semi-empirical model is used with COADS (the latter data set having only recently been applied in the Baltic Sea sub-basins), the possibilities of considering the individual processes determining solar radiation fluxes at ground level are quite different. Although *e.g.* the cloud attenuation algorithm of the model used in RI could be applied to the individual current cloud-cover and -type information available in COADS, the influence of atmospheric aerosols has had to be taken from climatological evidence because no current aerosol information is contained in the ship data set used. In RI we described the resulting solar radiation flux climatology for the Baltic Proper as well as for its three sub-basins, and we also included a discussion on the seasonally and regionally varying influences of astronomical and atmospheric factors.

The purpose of this second part of the Baltic Proper solar radiation study is twofold. To begin with, we give estimates of the overall uncertainty of the climatological flux results presented in RI. Secondly, we apply simpler bulk parametrisations for $E$ to the same COADS ship observations used in RI and compare the results with those of the semi-empirical model presented there. We choose parametrisations frequently used in earlier climate studies in different parts of the globe, and which have been specifically calibrated for application to either marine or continental conditions. This strategy thus attempts to obtain evidence on whether the atmospheric state over the Baltic Proper is dominated by marine and/or continental influences. We already note at this juncture that by doing so, we inherently assume that the calculated RI results represent the true radiation climate at the surface of the Baltic Proper.

In the following section we give estimates for the overall uncertainty of the solar radiation flux results presented in RI. Section 3 introduces the simple solar radiation bulk parametrisations used here for comparison with our results in RI, and section 4 highlights the differences found, with particular emphasis on a discussion on continental versus marine conditions over the Baltic Proper and its sub-basins. We summarise our findings and conclusions in section 5.

Note that for the sake of brevity we have used the term *radiation flux* throughout the paper, although physically it is the *surface density of the radiation flux* (or *downward irradiance*), expressed in $\mathrm{W\,m^{-2}}$.

## 2. Uncertainties in the estimation of monthly fluxes

Several factors contribute to the overall uncertainties in area-time mean estimates of the radiation fluxes, as calculated here using voluntary observing ship (VOS) meteorological observations (see *e.g.* Weare & Strubb 1981):

1. the systematic and statistical (random) error in the model used, including errors in the measured data used for calibration purposes,
2. insufficient sampling of weather parameters within the period and area chosen, including errors due to the irregular distribution of the VOS input data used,
3. systematic measurement and observational errors of the VOS input data used,
4. random measurement and observational errors of the VOS input data used, including data transmission and archival problems.

For the mean solar radiation estimates calculated in this study, we assume the uncertainties to have arisen mainly from errors in the formulae of the semi-empirical model used (type 1 uncertainty, see above), and from the insufficient sampling of all weather conditions in the period under analysis (type 2 uncertainty). The systematic and random errors due to measurement uncertainties in the meteorological observations (type 3 and 4) are assumed negligible. They are implicitly included in the model evaluation.

The model used in this study was evaluated for hourly mean values of the irradiance and transmittance. The solar irradiance and meteorological data for the evaluation were collected during 10 research vessel cruises to the Baltic Sea – in October 1992, April and September 1993, April, May, August and September 1994, March, June and September 1995. The data came mainly from the southern part of the Baltic Proper. For this data set, the systematic error was found negligible (+0.67%). The statistical error for hourly sums is $\pm 37\%$, but falls considerably as the averaging period increases. For our individual monthly means it varies from $> \pm 4\%$ in winter to $\pm 3\%$ in summer. Irradiance measurement errors were assumed negligible in the model evaluation. As the random uncertainty in irradiance measurements used for evaluation is never equal to zero, the real statistical error inherent in the model is expected to be even lower than the values given above. However, there may also be some undetermined systematic error in the irradiance measurements, which should not exceed 5% (*cf.* Paltridge & Platt 1976, Latimer 1978, Froehlich & London 1986). Hence, the expected systematic error inherent in the model performance is in the range $\pm 3$ to 5%.

The uncertainty caused by the sampling problem (type 2 uncertainty) is associated with the natural variability in meteorological conditions during a month and probably decreases when the number of observations increases. For a normal population and purely random sampling, the random error in the mean is reduced by $\frac{1}{\sqrt{N}}$ (the simple sampling theory). Hence, the standard error $\frac{\sigma}{\sqrt{N}}$ (where $\sigma$ denotes the usual standard deviation within the sample, *e.g.* a month) may be taken as a measure of uncertainty. However, given that meteorological observations are routinely made every 3 hours, it has been found that adjacent observations (*i.e.* the irradiance transmittances calculated on the basis of given observations) are indeed correlated in the Baltic region (Rozwadowska 1999). Moreover, meteorological ship observations are not regularly distributed and tend to be sampled in 'series' or 'batches'. The assumption that any reduction in random errors by averaging follows the simple sampling theory may therefore be inappropriate.

In order to estimate the type 2 uncertainty as a function of the number of observations of the daily total transmittance (flux), a simple numerical experiment is carried out. The largest monthly sets of the daily total transmittance computed from individual observations in the COADS in a given month from the western Baltic Proper, containing at least 400 observations, are taken into account. To simulate the 'batched' way of sampling, 20-element subsets are randomly removed from a monthly set until less than 20 elements are left. After each event of removal the mean transmittance is computed using the reduced sample. This procedure is repeated 250 times for each set leading to 250 different samples with a reduced number of observations $N_k = N_{\text{tot}} - 20\,k$. The normalised standard deviation of the mean (also called the standard deviation reduction parameter, see Weare 1989) is computed using

$$f_{\overline{T}}(N_k) = \frac{\sigma_{\overline{T}}(N_k)}{\sigma_T}, \tag{1}$$

where $\sigma_{\overline{T}}(N_k)$ is the standard deviation of the 250 sample means with sample population $N_k$, and $\sigma_T$ denotes the standard deviation of the monthly mean based on all individual observations in a month.

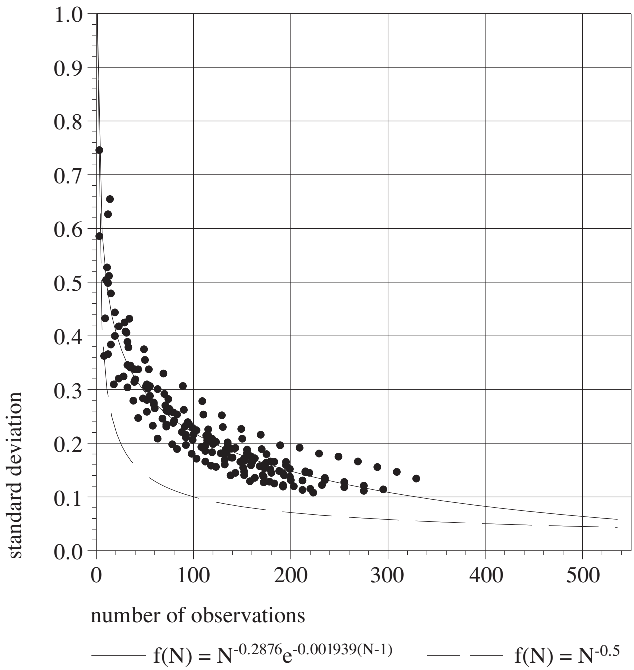



**Fig. 1.** Normalised standard deviation of the mean solar radiation flux (and the mean daily total transmittance) as a function of the number of observations. The dashed line denotes the relation derived from simple sampling theory, points denote simulated values and the solid line is the curve fitted to the latter

Figure 1 compares $f_{\overline{T}}(N_k)$ with the normalised traditional error of the mean, $\frac{1}{\sqrt{N}}$. For the number of data considered in this study, the standard deviation of the mean transmittance is considerably higher than the traditional error calculated under the assumption of simple sampling theory. For the mean irradiance in an individual month this error varies from $> \pm 20\%$ to $< \pm 2\%$, depending both on the number of meteorological observations and the natural variability of meteorological conditions within a given month. The simple simulation presented here has only been done to estimate the statistical error of the mean transmittance for this particular model and data set, and the reduction function found here cannot be generalised. Rozwadowska (1999) gives a more general analysis of the problem on the basis of regular 3-hourly observations from coastal and island stations in the Baltic Sea region.

Another possible source of error contributing to type 2 uncertainty in the mean irradiance estimation is the assumption that there are no significant trends in the meteorological parameters influencing atmospheric transmittance within a given month. This error was estimated by comparison of monthly solar radiation fluxes $D_M$ calculated by RI (see eq. (5) in RI, reproduced here as eq. (2a))

$$\begin{aligned} D_M(\varphi_k, \lambda_k) &= \sum_{\mathrm{day}=1}^{N_M} D_d^{\infty}(\varphi_k,\, d)\,\frac{1}{N_{\mathrm{mon}}} \times \\ &\times \sum_{j=1}^{N_{\mathrm{mon}}} T_{D_d}\Big(\mathrm{obs}_j,\, \varphi_k,\, \lambda_k,\, d\,(\mathrm{day},\, \mathrm{month})\Big), \end{aligned} \tag{2a}$$

with fluxes $D_M^*$ computed from the relation

$$\begin{aligned} D_M^*(\varphi_k, \lambda_k) &= \sum_{\mathrm{day}=1}^{N_M} D_d^{\infty}(\varphi_k,\, d)\,\frac{1}{N_{\mathrm{day}}} \times \\ &\times \sum_{j=1}^{N_{\mathrm{day}}} T_{D_d}\Big(\mathrm{obs}_j,\, \varphi_k,\, \lambda_k,\, d\,(\mathrm{day},\, \mathrm{month})\Big), \end{aligned} \tag{2}$$

taking into account variations of the meteorological situation from day to day. $N_{\mathrm{day}}$ and $N_{\mathrm{mon}}$ denote the respective number of observations during a day and a month in a given sub-basin. $D_d^{\infty}$ is the daily radiation flux at the top of the atmosphere and $T_{D_d}$ denotes the calculated transmittance of the daily flux for day $d$ of the year and geographical co-ordinates $\varphi_k$ and $\lambda_k$, based on the $j$-th meteorological observation in a given month (eq. (2a)) or on a given day (eq. (2)). The calculation was again carried out for the western Baltic Proper, because of the relatively regular observations for this area. The systematic error was found to be $+0.2\%$ and is considered negligible. The statistical error is $\pm 2.7\%$ .

The resulting total relative statistical errors (including both type 1 and 2 uncertainties) of the mean irradiance and transmittance for an individual month and for the 13-year averages of the monthly means are shown in Fig. 2. For the northern part of the Baltic Proper the irradiance and transmittance estimates have the highest uncertainty, which is due both to the relatively low number of observations and to the relatively low solar elevation in this area. The possible systematic error stems mainly from systematic errors inherent in the irradiance measurements employed in the model evaluation and is estimated at $\pm 3$–$5\%$.

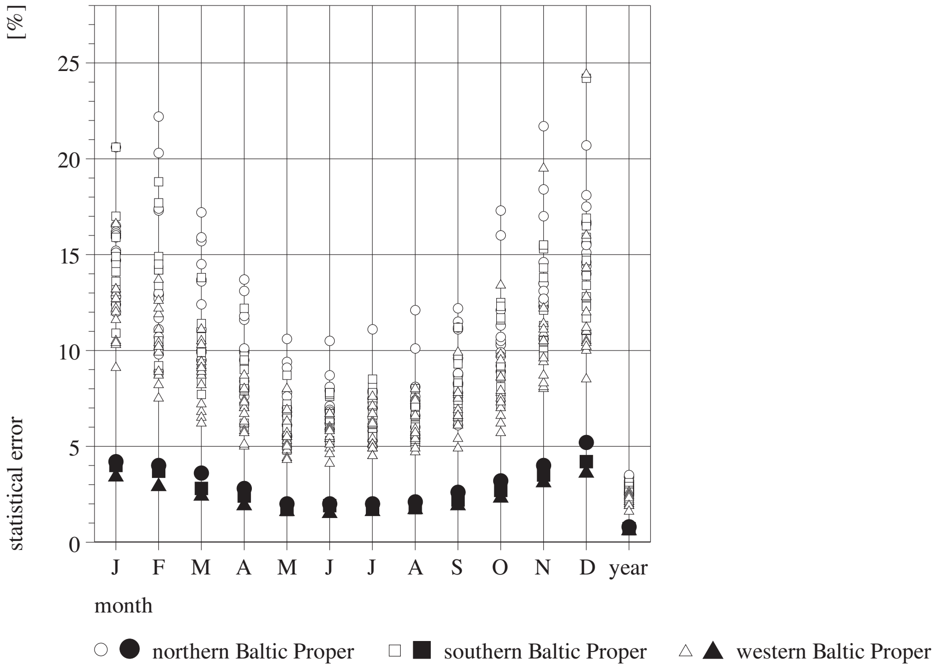



**Fig. 2.** Statistical (random) errors of the monthly mean solar radiation flux for individual monthly and annual means (open symbols), as well as for the related climatological values averaged over 13 years (black symbols)

## 3. Three bulk parametrisations for surface solar radiation flux

Numerous surface solar radiation flux parametrisations have been established in the past. The individual formulas or models differ considerably in their degree of complexity. We have selected three simple bulk formulas for comparative purposes, which have been derived for climate investigations, in particular with the option of being applied to simple synoptic ground-based meteorological observations or measurements such as cloud cover or surface air temperature and humidity. Application of these parametrisations has been found useful for different regions and climates over either the continents or the ocean. The three parametrisations used include

- the so-called Berliand-Budyko formula (Berliand 1960, Budyko 1963);
- the formula proposed by Reed (1977);
- the so-called 'okta' model established by Dobson & Smith (1985, 1988).

In the following three sub-sections we give a brief description of these parametrisations and we continue in sub-sections 3.4 and 3.5 with a comparison of some of their features.

### 3.1. The Berliand-Budyko formula

Berliand (1960) established a solar radiation formula exclusively for climate studies which has found wide application, in particular for the calculations of the global climatologies published by Budyko (1963, 1964, 1974, 1982), but also for air-sea interaction studies over *e.g.* the North Atlantic Ocean (Bunker 1976). The mean monthly incident solar radiation at the surface $\overline{E}^M$ is calculated using

$$\overline{E}^M = \overline{E}_0^M \left(1 - (a\, c_M + b\, c_M^2)\right), \tag{3}$$

where $\overline{E}_0^M$ is the clear-sky short-wave radiation reaching the surface, $a$ and $b$ are empirical dimensionless coefficients and $c_M$ is the monthly mean total cloud cover (in fractions of unity). It is important to note that (3) is calibrated only for use with *monthly* means. Both climatological averages of $\overline{E}_0^M$ as a function of latitude and month, and the cloud coefficient $a$ as a function of latitude, are given as tables containing 10° latitude increments of both parameters (see *e.g.* Budyko 1974); $b = 0.38$ is a constant. It is important to note that the Budyko-Berliand clear-sky radiation estimates were derived by interpreting the envelope fitted to the annual plot of the maxima of daily totals of $E$ from multi-year radiation records as the clear-sky radiation annual cycle. This method may give excessively high values, in particular over continents, because maxima of $E$ are likely to be caused by cloud-free situations with extremely low (and not average) atmospheric turbidities. Eq. (3) was formulated and calibrated using long-term radiation measurements at continental stations, most of which belong to the former Soviet Union's actinometric network (Berliand 1960). The Berliand-Budyko formula is therefore a suitable representative for a continental-type parametrisation and has already been identified and used as such in earlier studies (*e.g.* Dobson & Smith 1988).

We use individual monthly means of total cloud cover derived from the daylight COADS cloud observations during 1980 to 1992 for the three Baltic Proper sub-basins (see Fig. A1 in Appendix 1) in order to calculate $\overline{E}^M$ according to (3). Using the tabulated Budyko 10° latitude increments, both $a$ and $\overline{E}_0^M$ are linearly interpolated for the mean Baltic Proper sub-basin latitudes. This leads to $a = 0.375$, 0.405, and 0.41 for the Baltic Proper North, South, and West respectively. The Baltic Proper monthly mean is calculated by area-weighted averaging of the sub-basin means. In the following sections reference to the Berliand-Budyko results will be made by means of the abbreviation BUD.

### 3.2. The Reed (1977) formula

Reed (1977) suggested a formula for estimating solar radiation at sea. For calibration he relied on measurements of incident solar radiation performed at different coastal and island stations located in the subtropical Atlantic Ocean, mainly between 25°N and 45°N. Radiation records from research vessel cruises in the Pacific Ocean are included as well. The measurements used are expected to represent predominantly marine atmospheric conditions, with continental conditions exerting only a marginal influence. Reed's formula is defined for *daily* mean incident solar radiation. Reed (1977) showed that daily values of $E_0$ can be calculated adequately using a formula given by Seckel & Beaudry (1973) based on the Smithsonian Meteorological Tables. The atmospheric transmittance is simply set at a constant 0.7. As with the Berliand-Budyko formula (3), the influence of clouds is calculated using total cloud cover only. Reed's formula for daily values of incident solar radiation at sea level is

$$\overline{E}^D = \overline{E}_0^D \,(1 - 0.62\, c_D + 0.0019\, h), \tag{4}$$

where $c_D$ is the daily mean total cloud amount (in fractions of unity) and $h$ denotes the solar altitude (in degrees) at noon. Eq. (4) is applicable when $c_D > 2/8$, while a constant reduction of $\overline{E}_0^D$ by 5 per cent is recommended with $c_D = 1/8$ and $c_D = 2/8$.

As $\overline{E}^D$ depends linearly on cloud cover we can apply (4) to monthly sub-basin averages of cloud cover $c$. In order to account for changes in $h$ and $\overline{E}_0^D$ during a month, eq. (4) is calculated for each individual day within a month using $h$ and $\overline{E}_0^D$ for that day but the monthly average cloud cover. The monthly mean incident solar radiation flux is then obtained by integrating the individual daily values over a month. The Baltic Proper mean is again obtained by area-weighted averaging of the sub-basin means. Henceforth we shall use the abbreviation REED when referring to the Reed (1977) results.

### 3.3. The okta model of Dobson & Smith (1988)

Dobson & Smith (1988, henceforth abbreviated DS88) tested various bulk models with different degrees of complexity against year-long marine hourly radiation records measured at several Ocean Weather Stations (OWSs) in the Pacific and Atlantic Oceans. They found that one of their own models, the linear okta model, which uses total cloud cover only, performed well in reproducing hourly, daily, monthly and seasonal averages of incident solar radiation at sea. DS88 also concluded that neither the consideration of cloud-type information in the model formulation nor the use of a non-linear bulk model improved the model performance significantly as compared to the linear okta model. The okta model reads

$$E = S\Big(A(c) + B(c)\,s\Big)\,s, \tag{5}$$

where $s$ denotes the sine of the solar elevation angle and $S$ ($S = 1368$ $\mathrm{W\,m^{-2}}$) is the solar constant. $A(c)$ and $B(c)$ are dimensionless coefficients depending on total cloud cover $c$. The okta model (5) is calibrated for *hourly* values of $E$. Note that $A$ and $B$, in contrast to the coefficients and parameters in (3) or (4), describe the modification of solar radiation by both atmosphere and clouds. Different sets of parameters $A$ and $B$ were derived by DS88 for different locations (see also Dobson & Smith 1985, 1989). With a view to including a purely marine parametrisation in our comparison, we selected a set of $A$ and $B$ (see Table 1) derived by DS88 from a 17-year hourly radiation record measured at OWS P in the North Pacific Ocean (at 50°N, 150°W), thus taking a parametrisation calibrated for mid-latitude, open-ocean conditions into consideration.

**Table 1.** Okta model coefficients $A$ and $B$ according to Dobson & Smith (1988) derived from radiation measurements at Ocean Weather Station P in the North Pacific Ocean, stratified by total cloud amount

| Cloud amount [oktas] | $A$ | $B$ |
|---|---|---|
| 0 | 0.400 | 0.386 |
| 1 | 0.517 | 0.317 |
| 2 | 0.474 | 0.381 |
| 3 | 0.421 | 0.413 |
| 4 | 0.380 | 0.468 |
| 5 | 0.350 | 0.457 |
| 6 | 0.304 | 0.438 |
| 7 | 0.230 | 0.384 |
| 8 | 0.106 | 0.285 |
| sky obscured | 0.134 | 0.295 |

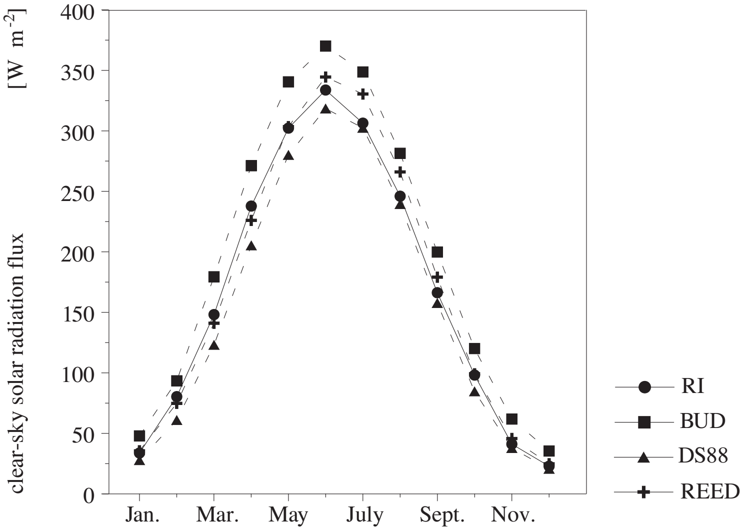
In order to calculate solar radiation fluxes from COADS we have used a computer routine identical to the one used by DS88 for both the okta model (5) and the equations necessary to compute the solar elevation angle. Using the individual COADS cloud observations together with observation time and location yields instantaneous values of incident solar radiation which may be interpreted directly as hourly values of $E$. As already pointed out in RI, the individual COADS observations are irregularly distributed in both time and space. Hence, simple averaging of the individual radiation fluxes would most likely lead to biased monthly and annual means. Instead, we integrate (5) with each individual cloud observation over the day and month when that observation was made. This is done for all individual cloud observations within a month and the resulting sample of integrated 'monthly' fluxes is averaged to form the monthly mean. This procedure is identical to the one we applied to the results of the semi-empirical model (see section 4.4 in RI).

### 3.4. Clear-sky radiation estimates

We have compared clear-sky solar radiation estimates calculated by the three parametrisations introduced for the mean latitude of the Baltic Proper (Fig. 3). The BUD clear-sky radiation estimates are the highest and the DS88 estimates the lowest values in all calendar months, while the REED estimates are in between the BUD and DS88 results, with smaller differences to the DS88 values. Differences between BUD and DS88 range from $15\,\mathrm{W\,m^{-2}}$ in December to more than $60\,\mathrm{W\,m^{-2}}$ in April. Clear-sky radiation estimates for the three parametrisations used here have also been compared for other latitudes (Isemer 1987) and display the same qualitative features as found here for 57°N.

We do not intend to present an in-depth discussion on continental versus marine atmospheres. Nevertheless, in what follows we would like to discuss briefly whether the differences found may be supported qualitatively by reasonable physical arguments. One possible explanation for the differences found is the higher water vapour in marine atmospheres, which may be expected to lead to stronger attenuation of the radiation flux compared to continental atmospheres. In addition, surface albedos over land surfaces (typical values lie between 0.4 and 0.6) are distinctly higher compared to an ice-free sea surface ($< 0.1$ in general). They may therefore be expected to lead to a stronger effect of multiple reflection between the ground and the atmosphere, thus contributing to higher clear-sky radiation at ground level in continental systems as compared to marine ones. However, the differences found between the parametrisations are most probably too high to be explained solely by the differences in the surface albedo and water vapour amount. For instance, Yegorov & Kirillova (1973) noticed that for cloudless sky conditions the differences between the land and ocean albedo do not noticeably influence the diffuse radiation. Furthermore, long-term mean monthly values of water vapour pressure over the Baltic Sea range from about 5 to 15 hPa, which is larger than typical land-sea differences. In RI we showed that the isolated effect of this water vapour variation may give rise to a change in irradiance of only up to 3%.

**a**




**b**

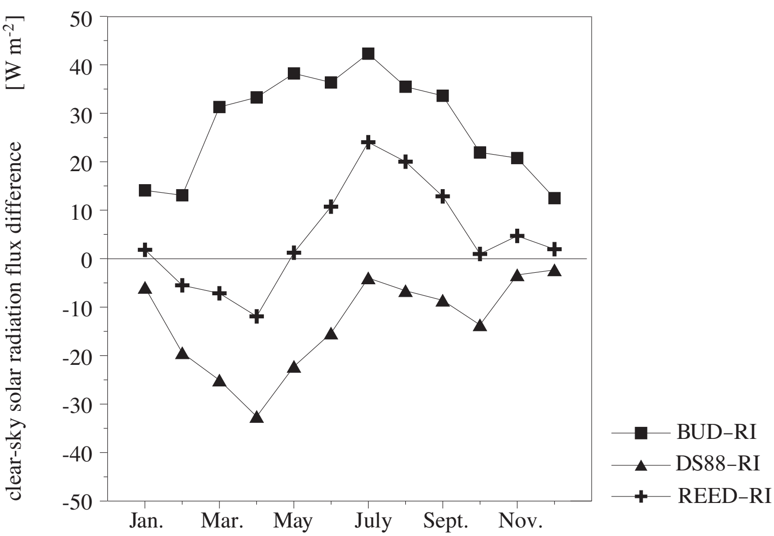



**Fig. 3.** Annual cycle of clear-sky solar radiation flux [W m$^{-2}$] at the surface of the Baltic Proper. Results of RI and three other parametrisation schemes are plotted for comparison. RI – results from Part 1 of this study (Rozwadowska & Isemer 1998), BUD – the Budyko-Berliand formula, DS88 – the okta model of Dobson & Smith (1988), REED – the formula of Reed (1977) (a); Annual cycle of clear-sky solar radiation flux differences [W m$^{-2}$] between RI and each of three different parametrisations for the Baltic Proper (b)

The higher relative humidity expected over the ocean may affect aerosols. Yegorov & Kirillova (1973) noted that in average cloudless conditions over the ocean the atmospheric transparency to direct solar radiation is relatively low, probably due to higher turbidity caused by condensation. On the other hand, there is observational evidence that the average aerosol optical thickness over the central parts of the oceans is lower than over the land, see *e.g.* Smirnov *et al.* (1994) and Villevalde *et al.* (1994). In addition, McClatchey *et al.* (1984) chose a lower aerosol optical thickness for a model maritime atmosphere than for model continental and urban atmospheres. We note that the clear-sky radiation differences found (see Fig. 3) may only in part be explained by the physical reasoning discussed above.

However, a note of caution should be sounded here: in general, clear skies occur much less often over oceans than over land (*e.g.* Warren *et al.* 1985). For example, at OWS P, DS88 found only 55 clear-sky situations during 1959 to 1975. One expects uncertainties for marine clear-sky radiation estimates due to low sample sizes to be larger than for continental situations. Furthermore, the method used by Budyko (but also others, *e.g.* Dobson & Smith 1985) to establish the annual cycle of clear-sky radiation could itself be a potential source of systematic errors. As already mentioned in section 3.1, this method interprets the envelope fitted to the annual plot of maximum daily totals of $E$ from multi-year radiation records as the clear-sky radiation annual cycle. This may yield excessively high monthly fluxes, because the maxima of the daily totals are likely to be caused by cloud-free situations with extremely low (and not average) atmospheric turbidities.

We conclude that the clear-sky radiation differences found between the three parametrisations may be physically plausible, but the possibility that some of the differences are due to methodological and climatological problems cannot be ruled out.

The RI clear-sky radiation estimates for the Baltic Proper are lower than those of BUD, and higher than the DS88 clear-sky estimates throughout the year, the smallest differences being recorded in winter (Fig. 3). The REED–RI clear-sky radiation differences change sign in the course of the year with higher RI values occurring only during February to April. We conclude that, on average, attenuation in the cloudless atmosphere over the Baltic Proper apparently tends to reduce solar radiation more strongly than in purely continental conditions and is weaker compared to purely marine systems. These differences change in the course of the year, being modulated by the influence of both water vapour and aerosol transmittance (see Figs. 5 and 8 in RI), which are explicitly considered in the model used by RI.

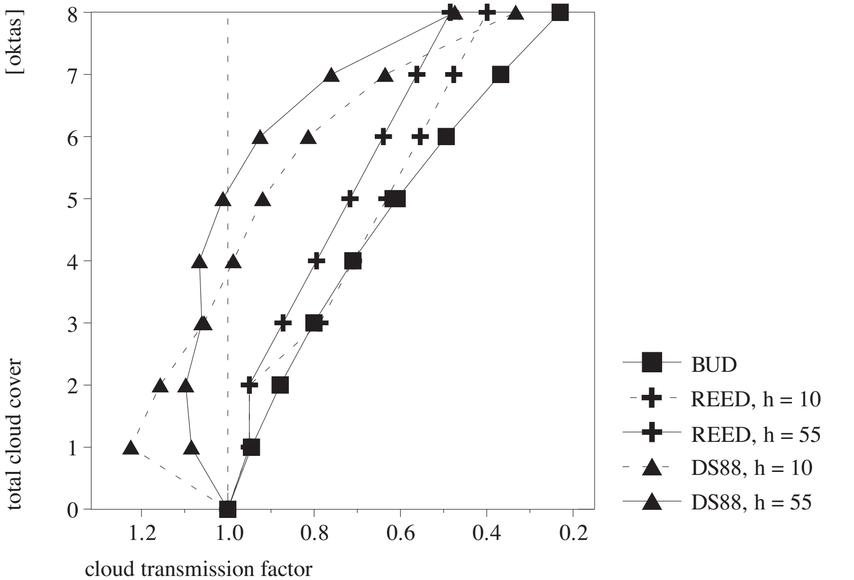
### 3.5. Reduction of clear-sky radiation by clouds

Figure 4a compares the reduction in clear-sky radiation by clouds (referred to as the cloud transmission function/factor in the following) of the three bulk parametrisations under consideration, all of which rely on total cloud cover alone. While both DS88 and REED explicitly consider solar altitude $h$, the BUD cloud transmission is a function of latitude and thus implicitly incorporates the dependence on $h$. Note the different time scales of monthly (BUD), daily (REED) and hourly (DS88) applications for which the parametrisations have been calibrated.

The BUD formula with its quadratic dependence on cloud cover $c$ shows the strongest reduction of all three parametrisations, in particular for $c > 4$ oktas, and coincides with the linear REED reduction only for low solar altitudes and $c \leq 4$ oktas. Only for overcast conditions does the strongly non-linear formula of DS88 agree with REED and, to a lesser extent, with BUD. DS88 indicates distinctly higher cloud transmission factors for situations with a partially cloudy sky. Particularly astonishing are the cloud transmission factors well above 1 for all $c$ less than 5 or 4 oktas (depending on $h$).

It is beyond the scope of this study to discuss in detail the different cloud transmission functions presented in Fig. 4a. Some of the differences in the functions considered may be explained by different cloud populations over oceans and continents, and also over different parts of the global ocean (see *e.g.* Warren *et al.* 1985, and Hahn *et al.* 1982). However, Isemer (1987) has pointed out that the latter cloud type climatologies do not entirely explain the differences in the transmission functions. Apart from variations in cloud amount and cloud type climatologies, differences in other parameters such as cloud drop spectra, drop concentrations or vertical and horizontal dimensions of clouds may lead to different attenuation functions over continents and oceans. Non-linear forms of transmission functions have also been found in other studies for various regions and atmospheric conditions (*e.g.* Kasten & Czeplak 1980, Kaiser & Hill 1976, Ashburn 1963, Tabata 1964, to name just a few). However, none of these other studies reported mean cloud transmission factors exceeding 1, as suggested by DS88. The dependence of the mean optical thickness on cloud amount, multiple scattering between the ground and the clouds and between individual clouds, and reflection of solar radiation at cloud edges, in particular for partially cloudy skies, have been suggested as reasons for the non-linear cloud transmission functions.

**a**




**b**

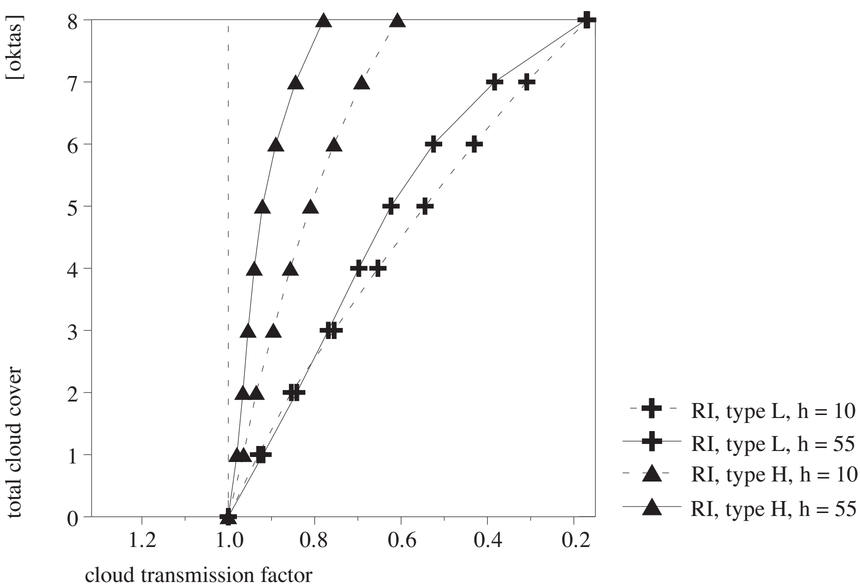



**Fig. 4.** Reduction of clear-sky radiation at ground level by clouds as a function of total cloud cover according to the parametrisations of BUD, REED, and DS88 (a) and RI (b). For RI, curves for cloud types L and H, respectively are given. See RI for definitions of cloud types; *h* denotes solar altitude in degrees; for an explanation of the abbreviations, see the text or the caption to Fig. 3

The latter were proven for partial cumulus cloud cover by model calculations (*e.g.* Schmetz 1983). The non-linear relation between the probability of the sun being shaded by clouds and the total cloud cover may also contribute to the non-linearity of the cloud transmission function, especially for low solar altitudes and clouds of higher vertical extent (*e.g.* Mullamaa 1972). Cloud transmission factors clearly in excess of 1 have been reported for instantaneous measurements or short-term averages (*e.g.* hourly values in extreme cases), but are unlikely to hold true for average conditions. We note in particular the following two cautionary comments regarding the high cloud transmission factors found by DS88 at OWS P. Firstly, in contrast to REED and BUD, the coefficients $A$ and $B$ (see eq. (3)) have been calibrated to consider the total transmission for both the atmosphere and clouds. Note that the cloud transmission function of DS88 as given in Fig. 4a is calculated from $E(c)/E(c = 0)$ using (5). The same holds true for the respective curves of RI given in Fig. 4b). The DS88 cloud transmission function as plotted in Fig. 4a may therefore additionally include atmospheric influences, providing that cloud cover and properties of the cloud-free part of the atmosphere such as humidity or aerosol content are correlated. Hence, in particular for DS88 but also for BUD and REED, the transmission function may not be independent of the clear-sky parametrisations suggested (see section 3.4). Secondly, OWS P and in general much of the mid- and northern latitude parts of the Pacific and Atlantic Oceans belong to regions with the highest mean total cloud cover on the globe (see also section 5). At OWS P, the mean monthly total cloud cover is equal to or larger than 7 oktas throughout the year (Dobson & Smith 1988, Hahn *et al.* 1982) and very few individual situations with $c \leq 4$ oktas occur at all. Using 3-hourly meteorological observations made at OWS P during 1959 to 1975 Niekamp (1992) found half of all individual daylight reports indicating fully overcast conditions (8 oktas) and only for 15% of the daylight reports was total cloud cover less than 6 oktas.

We conclude that the cloud transmission function for $c \leq 4$ oktas derived at OWS P may be especially uncertain because of the small sample sizes with these cloud cover situations. See also section 3.4 for a related discussion on clear-sky situations.

The RI parametrisation takes into account seasonal variations in the frequency of occurrence of cloud types grouped in 3 cloud classes H, L, M (see Table 1 in RI for definitions of cloud types). Hence, comparison with the three bulk parametrisations depending on total cloud cover alone is not directly possible. We therefore plot the RI cloud transmission functions for cloud types L and H in Fig. 4b for comparison. These cover almost the entire range of possible effective transmission functions in the RI model, which depend on the frequencies of occurrence of the individual cloud classes H, L, and M. The latter vary considerably in particular with the time of year (see Fig. 7 in RI).

Figure 4a indicates that the continental cloud transmission (BUD) is more strongly reduced compared to the marine ones (DS88 and REED). In general the cloudy atmosphere over the oceans is more transparent to short-wave radiation than is the atmosphere over continents for the same cloud amount. Timofeyev (1983) has pointed out that the optical thickness of oceanic clouds is usually less because they tend to contain fewer condensation nuclei, have a lower droplet concentration, and larger droplets. Low clouds (type L) over the Baltic Proper tend to influence atmospheric transmission in almost the same way as 'mixed' continental cloud populations (compare BUD and RI, type L, in Fig. 4) while high clouds (*e.g.* Cirrus), not surprisingly, influence solar radiation much less.

## 4. Results

### 4.1. The Baltic Proper annual cycle

Figure 5 shows the mean annual cycle of incident solar radiation over the Baltic Proper for 1980 to 1992 based on monthly values of the four different climatologies produced as described in section 3 and in RI. At first glance, the mean annual cycle seems to be reasonably well reproduced by all climatologies, with major apparent differences occurring in the summer season during May to August. There are, however, distinct differences, which become more evident when the respective differences between the three bulk parametrisation climatologies and RI are plotted (Fig. 6). First of all, it is obvious that these differences are not random, but tend to show distinct annual cycles, which, however, are clearly different for each parametrisation. Application of BUD instead of RI (Fig. 6a) results in lower solar radiation fluxes during spring and early summer, the absolute value of the difference attaining the highest value of $21\,\mathrm{W\,m^{-2}}$ in June. Slightly larger values of BUD than RI occur during autumn and winter, but the differences are always less than $+10\,\mathrm{W\,m^{-2}}$. The positive and negative monthly differences almost cancel each other out, resulting in a $-1\,\mathrm{W\,m^{-2}}$ long-term annual mean of the BUD–RI difference. Percentage differences are, however, largest in the winter season, reaching +52% in December. The $-21\,\mathrm{W\,m^{-2}}$ absolute difference in June translates into a –9% bias between BUD and RI (Percentage differences here and throughout the paper always relate to the RI results. See also Table A1 in Appendix 2 for the Baltic Proper monthly RI results and differences with respect to the other parametrisations).

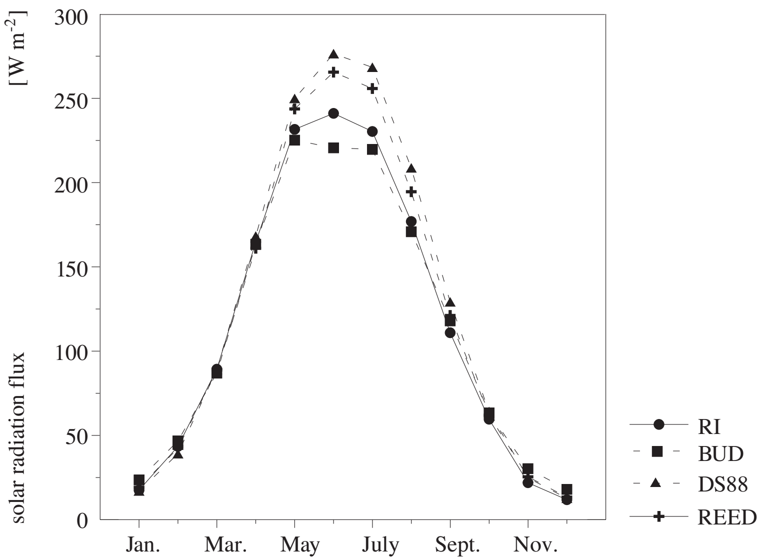



**Fig. 5.** Mean annual cycle of incident solar radiation flux [W m$^{-2}$] at the surface of the Baltic Proper for the period 1980 to 1992 based on COADS data. Results of RI and three other parametrisation schemes are plotted for comparison. For an explanation of the abbreviations, see the text or the caption to Fig. 3

The DS88–RI difference curve is completely different. The dominant feature are the higher DS88 fluxes during April to November, the differences peaking at +38 W m$^{-2}$ ($\cong$ +17%) in July, and only slightly lower values (absolute values of differences < 5 W m$^{-2}$) in January ($\cong$ –3%) and February ($\cong$ –10%, see Fig. 6b). The annual mean difference is positive at +12 W m$^{-2}$ ($\cong$ +10%). Comparison of REED and RI (Fig. 6c) indicates roughly the same behaviour of the absolute differences as with DS88–RI but shows a somewhat reduced amplitude with highest differences of + 26 W m$^{-2}$ ($\cong$ +11%) in July and an annual mean difference of +7 W m$^{-2}$ ($\cong$ +6%). The absolute values of the relative differences do not change as drastically as with BUD–RI, ranging as they do from <1% in March to 16% in November.

We have calculated 95% probability ranges of the mean differences in order to judge whether the differences found are significantly different from zero at the 5% error level. Note that our significance estimates are calculated using only the interannual variation in the differences and should thus be regarded as minimum estimates. The 95% probability ranges are plotted as vertical bars in Figs. 6 and 7. If the bar does not include zero we interpret the respective mean as being significantly different from zero at the 5% error level (see Appendix 3 for details). Fig. 6a indicates that the BUD–RI differences are significantly different from zero during 7 months

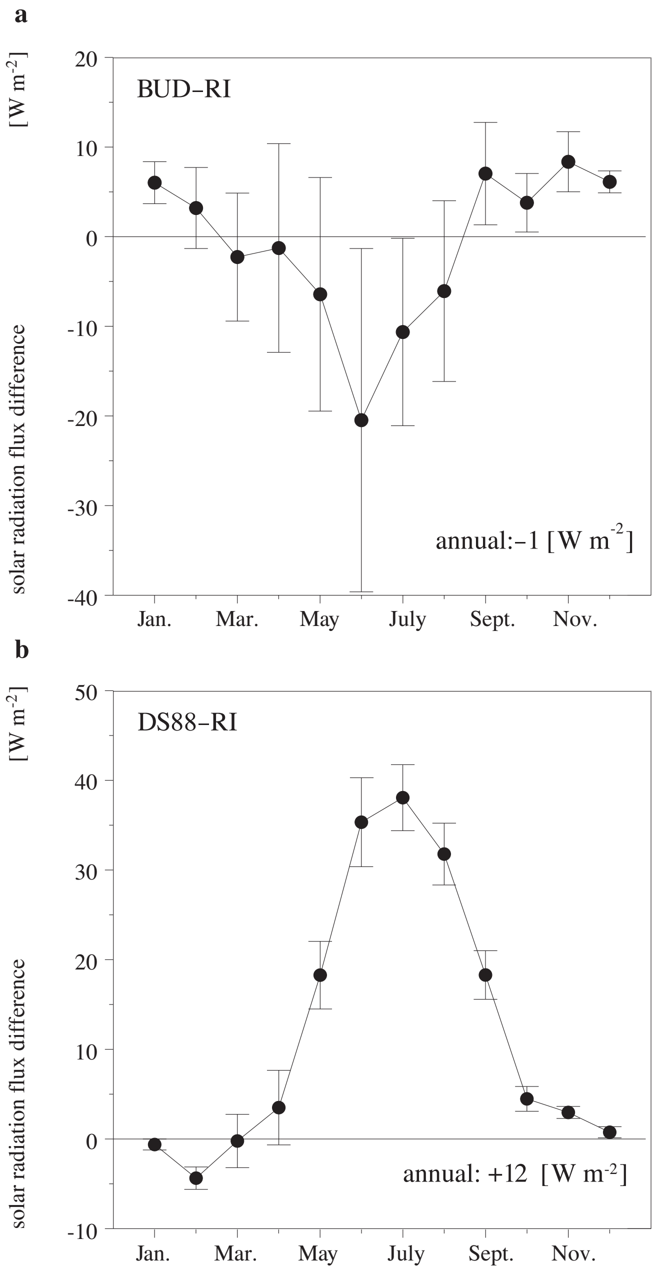



**Fig. 6.** Mean annual cycle of incident solar radiation flux differences [$\mathrm{W\,m^{-2}}$] between two different climatologies at the surface of the Baltic Proper for the period 1980 to 1992. Vertical bars indicate 95% probability ranges of the mean (see Appendix 3 for details) indicating significant (or non-significant) differences from zero at the 5% error level; BUD–RI (a), DS88–RI (b), REED–RI (c), DS88–BUD (d). For an explanation of the abbreviations, see the text or the caption to Fig. 3

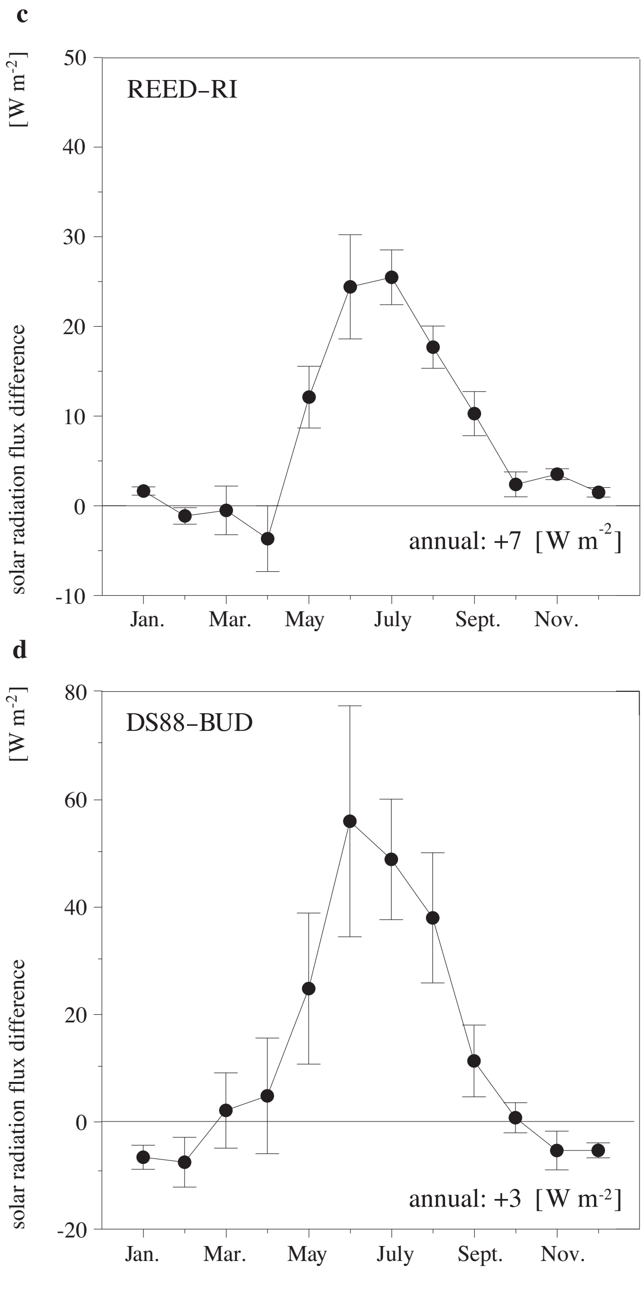
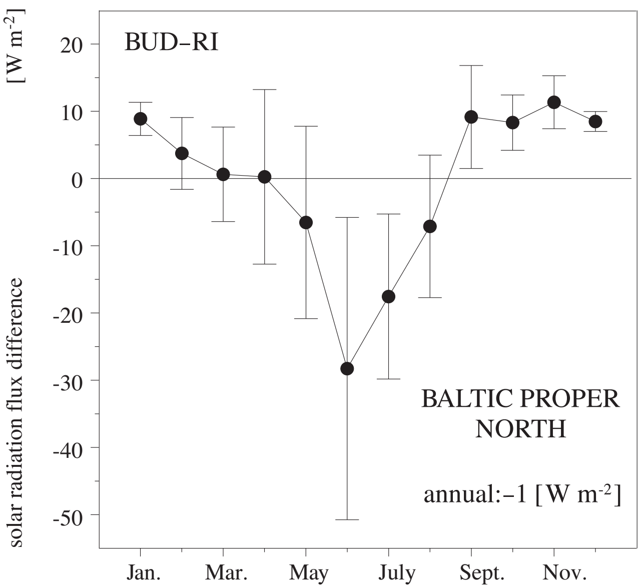



**Fig. 6.** (continued)

**a**

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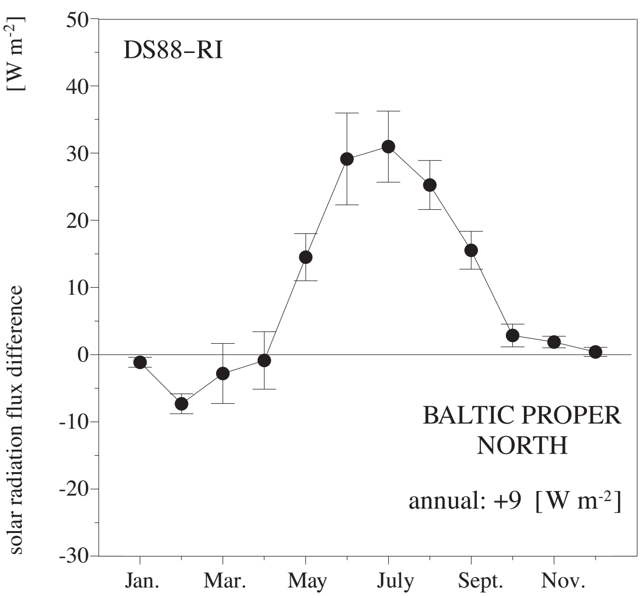
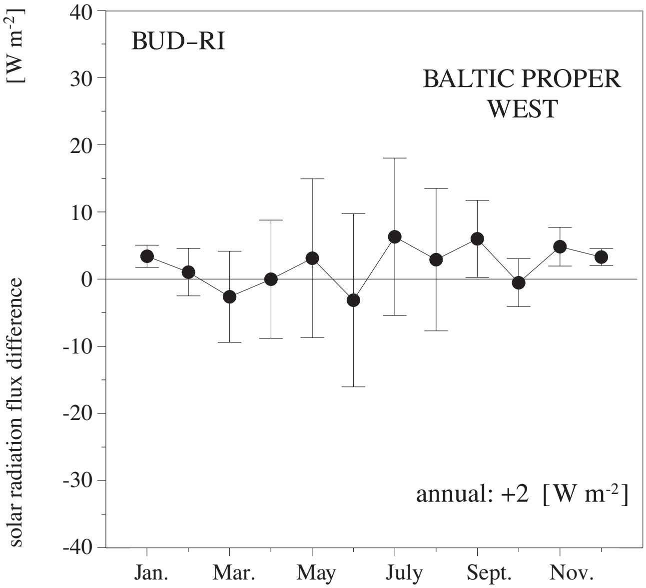



**Fig. 7.** As Fig. 6, but for different sub-basins of the Baltic Proper; BUD–RI for the Baltic Proper North (a), DS88–RI for the Baltic Proper North (b), BUD–RI for the Baltic Proper West (c), DS88–RI for the Baltic Proper West (d)

**c**




**d**

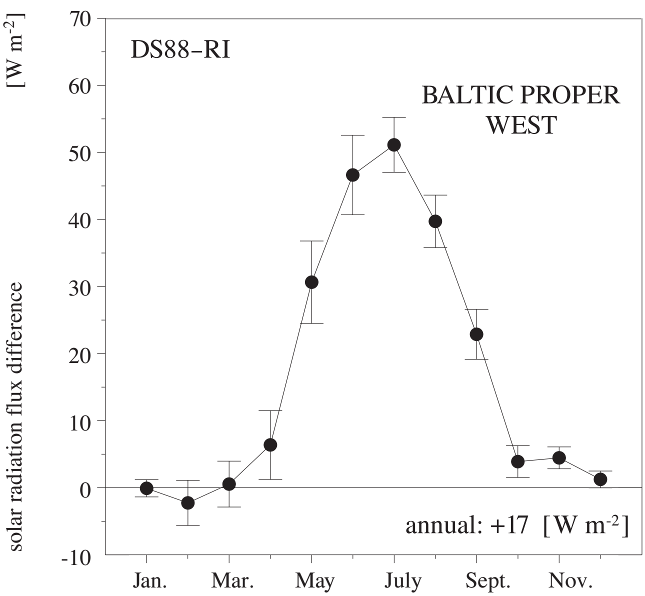



**Fig. 7.** (continued)

(June and July, September to January) in the year, four of the latter (June, July, September and October) displaying 95% probability range limits only slightly different from zero. Note that while the absolute differences in June and July are the largest, they do show high interannual variability as well. DS88 (Fig. 6b) is significantly different from RI during 8 months of the year.

For the purposes of comparison we have plotted the difference between the marine and continental parametrisations, DS88–BUD (Fig. 6d), which shows features very similar to those in Fig. 6b, but with a somewhat increased amplitude.

### 4.2. Annual cycles for the Baltic Proper sub-basins

The continental versus marine features discovered for the entire Baltic Proper have also been found in the respective difference plots for the three Baltic Proper sub-basins, but with noteworthy regional differences. For the Baltic Proper North, the largest sub-basin (see Fig. A1 for the sub-basin division used in this study), the BUD–RI (Fig. 7a) and DS88–RI (Fig. 7b) differences indicate that atmospheric conditions tend to be more marine in this sub-basin than the average conditions over the entire Baltic Proper (Figs. 6a,b). However, the differences from the continental climatology (BUD) are again smaller than those from the marine one (DS88). For the western Baltic Proper sub-basin, by far the smallest of the three sub-basins, the BUD–RI differences do not display any regular type of annual cycle, but tend to be randomly distributed, with only three of the monthly differences being significantly different form zero at the 5% error level (Fig. 7c). The summer signal of the difference from the marine parametrisation (DS88–RI) in the Baltic Proper West (Fig. 7d) is the most pronounced for all sub-basins with the maximum difference exceeding $+50\,\mathrm{W\,m^{-2}}$ ($\cong +24\%$) in July and an annual average difference amounting to some $+17\,\mathrm{W\,m^{-2}}$ ($\cong +15\%$), the largest mean annual differences found for all combinations of RI with any of the other three climatologies in all the sub-basins considered in this study.

The respective curves for the Baltic Proper South (not shown) are similar to those of the northern sub-basin with somewhat reduced amplitudes. As for the entire Baltic Proper, the REED–RI differences (not shown either) are always very near to the respective DS88–RI curves in all three sub-basins, again with slightly reduced amplitudes.

### 4.3. Individual monthly means

The individual monthly differences show a much higher scatter for BUD–RI compared to both DS88–RI and REED–RI. For the latter two comparisons the standard deviations of the monthly differences are less than

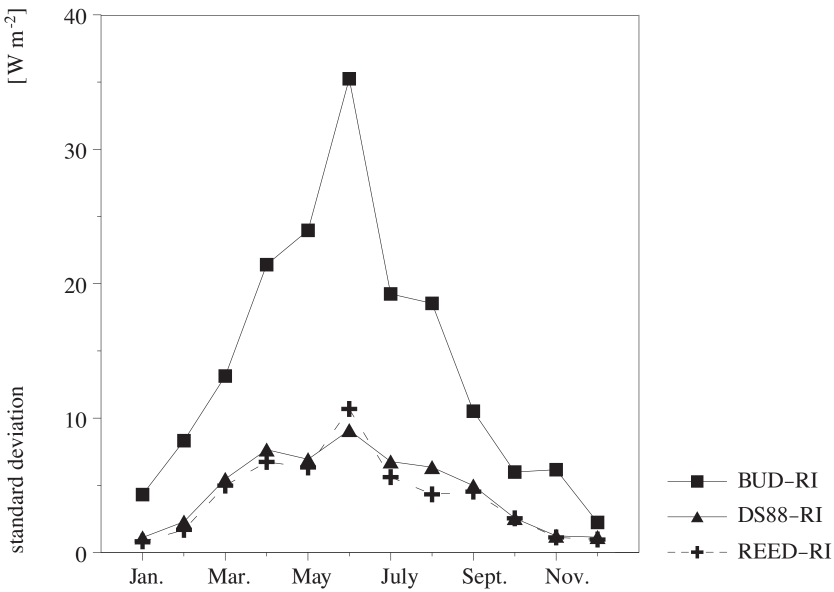



**Fig. 8.** Annual cycle of standard deviations of monthly solar radiation flux differences [W m$^{-2}$] at the surface of the Baltic Proper for the period 1980 to 1992. For an explanation of the abbreviations, see the text or the caption to Fig. 3

10 W m$^{-2}$ throughout the year (Fig. 8). The BUD–RI standard deviations are more than twice as large in all calendar months and exceed $\pm$ 35 W m$^{-2}$ in June (Fig. 8). This is also reflected in the distinctly different 95% probability ranges plotted in Figs. 6 and 7. The respective curves of the standard deviations for the Baltic Proper sub-basins (not shown) are qualitatively similar to the one for the entire Baltic Proper. Values are slightly higher in the northern basin (in excess of 40 W m$^{-2}$ for BUD–RI in June) and lowest in the Baltic Proper West (reaching $\pm$ 25 W m$^{-2}$, again for BUD–RI in June). Examples of the different scatter in the individual monthly values of BUD/RI versus DS88/RI are given for the month of June in Fig. 9.

We conclude that the application of the continental parametrisation (BUD) instead of RI leads to a much higher scatter of the individual monthly flux averages than the use of the marine model (DS88), even though the mean bias is higher for both marine parametrisations.

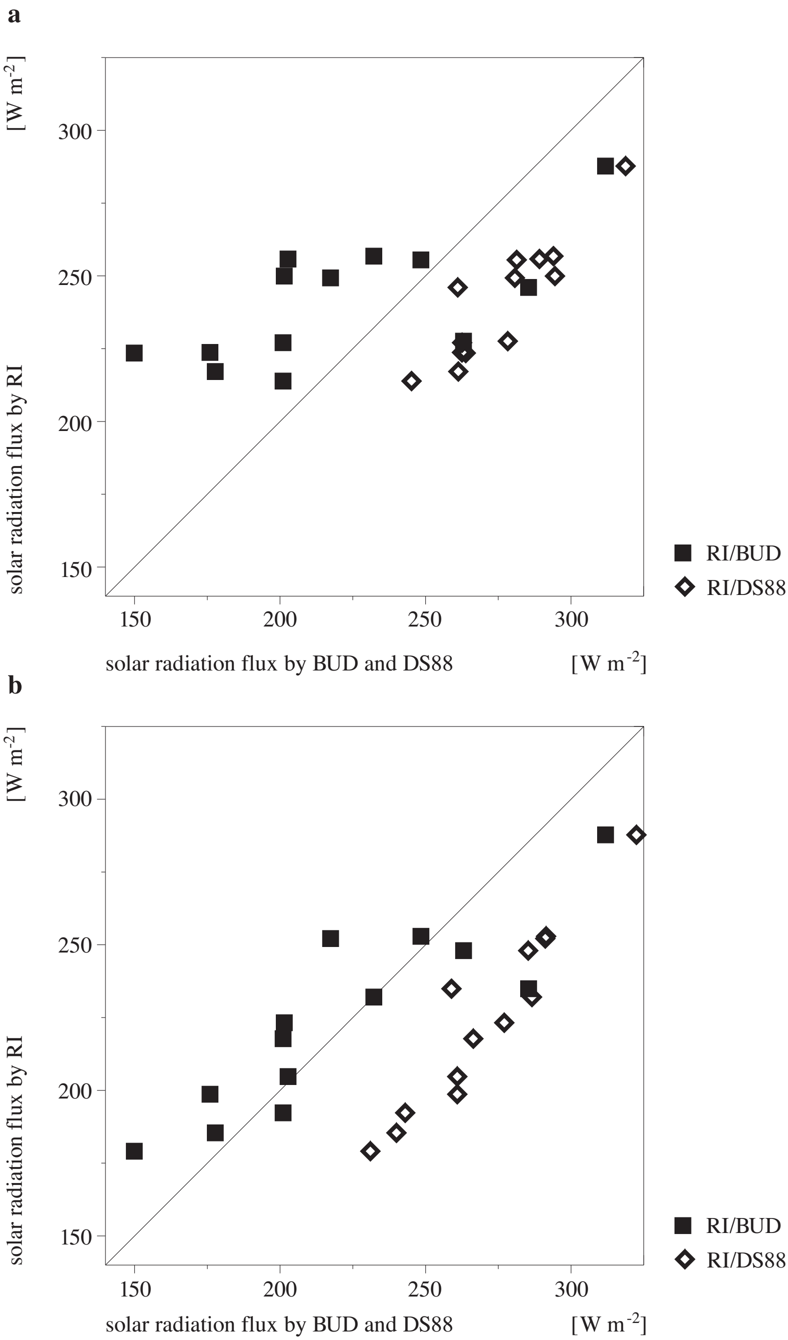



**Fig. 9.** Scatter plot of individual monthly solar radiation fluxes [$\mathrm{W\,m^{-2}}$] for June during 1980 to 1992. Full squares: RI/BUD comparison. Open diamonds: RI/DS88 comparison. RI is given on the ordinate while the respective values from BUD and DS88 are given on the abscissa. Baltic Proper (a), Baltic Proper West (b). For an explanation of the abbreviations, see the text or the caption to Fig. 3

## 5. Summary and discussion

We have used an adjusted version of the semi-empirical model developed by Rozwadowska (1991) to calculate monthly and annual estimates of incident solar radiation fluxes $E$ at the surface of the Baltic Proper during 1980 to 1992. Input data to the model used are voluntary observing ship (VOS) meteorological observations extracted from the Comprehensive Ocean – Atmosphere Data Set (COADS). In Part 1 of this study (Rozwadowska & Isemer 1998, RI) we described the resulting solar radiation flux climatology for the Baltic Proper as well as for its three sub-basins. In this second part of the study we firstly give estimates of the overall random and systematic errors of the climatological flux results. Secondly, we apply simple bulk parametrisations for $E$ to the same COADS ship observations used in RI and compare the results with those of the semi-empirical model presented in RI.

### 5.1. Random and systematic errors

The overall uncertainty of monthly and annual radiation flux estimates has been divided into random and systematic errors. The possible relative systematic error (which does not reduce with increasing observational density) stems mainly from systematic errors inherent in the irradiance measurements employed in the model evaluation and lies between $\pm 3$ and $\pm 5\%$. The random error is assumed to have major contributions from (i) the random error in the model used, and (ii) insufficient sampling of weather parameters within the period and area chosen, including errors due to irregular distribution of the VOS input data used. The total relative random errors for individual monthly values (both for the whole Baltic Proper and its sub-basins) range from $\pm 4$ to $\pm 11\%$ in June and $\pm 8$ to $\pm 24\%$ in December (see Fig. 2 for details).

Random errors of the 13-year averages of monthly means are smaller and are estimated to be from $\pm 2$ to $\pm 3\%$ in June and $\pm 4$ to $\pm 5\%$ in December. Note that the standard deviations of the individual monthly means (given in section 5 in RI), which range from $\pm 9$ to $\pm 14\%$ ($\pm 10$ to $\pm 17\%$) in June (December), are considerably larger than the sum of systematic and random errors of the long-term means. However, when compared to the errors in the individual monthly means, they are only higher for May, June, July and September. For the other months the interannual variations of the individual monthly means are comparable to the mean estimation errors. Random errors of annual values are between $\pm 1$ and $\pm 4\%$. Separate estimation of errors for the Baltic Proper sub-basins indicates that errors for the northern Baltic Proper tend to be largest, which is due both to the relatively low number of observations and to the low solar elevation in this area.

## 5.2. Comparison with simple bulk parametrisations

The selected bulk parametrisations, which have been specifically calibrated for application to either marine or continental conditions, include

- the so-called Berliand-Budyko formula (Berliand 1960, Budyko 1963), which was calibrated using long-term radiation measurements at continental stations (BUD);
- the formula proposed by Reed (1977), which was calibrated against radiation measurements at coastal and island stations, thus representing a mixture of marine and continental atmospheric conditions (REED);
- the so-called 'okta' model established by Dobson & Smith (1988), which was derived from radiation measurements at OWS P in the North Pacific Ocean, thus representing mid-latitude, open-ocean (purely marine) conditions (DS88).

We summarise our findings and conclusions in the following 9 points:

1. With regard to *clear-sky radiation* estimates, the BUD results are the highest and the DS88 estimates the lowest values in all calendar months, while the REED estimates are in between the BUD and DS88 results. These differences may be explained partly by physically plausible arguments, but the possibility that some of the differences are due to methodological and climatological problems cannot be ruled out. The RI clear-sky radiation estimates for the Baltic Proper are systematically lower than those of BUD, and higher than the DS88 clear-sky estimates throughout the year. The REED–RI clear-sky radiation differences change sign in the course of the year with higher RI values occurring only during February to April. We conclude that, on average, the attenuation in the cloudless atmosphere over the Baltic Proper apparently tends to reduce solar radiation more strongly than under purely continental conditions and is weaker compared to purely marine systems. These differences change in the course of the year, as they are modulated by the influence of water vapour and aerosol transmittance, both of which are considered explicitly only in the RI model.
2. The differences in the mean monthly *incident solar radiation* flux at ground level of all three bulk parametrisations to RI are not random but show distinct annual cycles which clearly differ from one another. Compared to RI, BUD gives lower solar radiation fluxes during spring and early summer and slightly larger values during autumn and winter. The DS88–RI differences are completely different, DS88 fluxes being higher during summer and autumn and only slightly lower in winter

(especially during January and February). The REED–RI comparison indicates roughly the same behaviour of the absolute differences as with DS88–RI but shows a reduced annual amplitude. In summer the atmospheric influences over the Baltic Proper (represented here by the RI results) appear to produce slightly higher solar radiation fluxes when compared to pure continental conditions (as represented here by the BUD climatology), but distinctly lower fluxes when compared to purely marine atmospheres (as indicated by the DS88 climatology). During the winter months the results tend to be reversed, with the Baltic Proper conditions producing lower radiation fluxes as compared to pure continental atmospheres, and higher ones as compared to marine conditions. The summer signal, however, is much more pronounced than the winter one. To put it simply, we note that the RI annual cycle lies in between the continental (BUD) and marine (DS88) cycle. The long-term mean monthly and annual differences between RI and BUD are much smaller than those between RI and DS88, both for the entire Baltic Proper and its separate sub-basins.

3. Considering the sub-basin differences in detail we found the RI results to be the closest to the BUD results in the western Baltic Proper, while in the northern Baltic Proper the RI–DS88 differences are the smallest of all the three sub-basins considered. This is in agreement with the notion that the atmosphere over the small western Baltic Proper has a greater likelihood of being influenced by conditions from the surrounding land areas, whereas above the northern part of the Baltic Proper, the largest sub-basin, atmospheric conditions are more likely to be marine.

4. For a balanced discussion of our results it is important to note that the observed differences of RI versus the other parametrisations may partly be influenced by uncertainties inherent in the parametrisations. Dobson & Smith (1988) noted that their okta model (DS88) tends to overestimate fluxes in June, July and August and to underestimate them in February and March, even for the OWS P (the Pacific Ocean) for which it was calibrated. Dobson & Smith (1988) further found that the application of the marine REED and DS88 parametrisations to Atlantic OWSs (I and J) data leads to systematic overestimation of the long-term mean fluxes (compared to the measured ones) – REED by 7 and 12 $\mathrm{W\,m^{-2}}$ and DS88 by 26 and 32 $\mathrm{W\,m^{-2}}$. Comparison with the measurements performed at several OWSs in both the Atlantic and Pacific Oceans (A, I, J, K and P) showed that BUD tends

to overestimate winter and underestimate summer (and the annual mean) fluxes (Timofeyev 1983).

5. We also find that the application of the continental parametrisation (BUD) instead of RI leads to a much higher scatter of the *individual* monthly flux averages than when the marine parametrisations (DS88 and REED) are used, although the mean bias is higher for both marine parametrisations. This indicates in particular that the rather simple cloud reduction function used in BUD is the least suitable for reproducing realistic monthly radiation fluxes based on the cloud data at hand. On the other hand, Fig. 9a exhibits a more or less constant bias between DS88 and RI, whereas the BUD–RI differences are more irregularly scattered. This result suggests that a simple parametrisation of the 'okta' model type as suggested by DS88 could be readily re-calibrated for Baltic Proper conditions, provided that representative long-term regular radiation measurements and cloud observations are at hand. It is noteworthy in this context that Moll & Radach (1992) found the DS88 parametrisation with unchanged marine (OWS P) coefficients suitable for simulating surface radiation for long time-scales in coastal seas such as the German Bight in the North Sea.
6. It was our intention to gain evidence of whether the atmospheric state over the Baltic Proper is dominated by either marine or continental influences. We conclude that neither the continental nor the marine parametrisations agree with the RI results. Providing that the RI represent the true surface radiation climatology in the Baltic Proper, evidence is presented that the atmospheric conditions over the Baltic Proper are a mixture of continental and marine conditions. Application of both purely continental and marine bulk parametrisations to Baltic Proper data may lead to seasonally (and regionally) varying biases as detailed in this study, so related results have to be interpreted with caution. With respect to the smaller scatter in the individual monthly DS88–RI differences, application of the marine parametrisation such as the DS88 okta model seems preferable for Baltic Proper conditions, so long as the apparent mean bias, which is larger than with *e.g.* BUD–RI, is properly accounted for.
7. We would like to point out that the annual cycle of total cloud amount over the Baltic Proper is much closer to European continental (and also North Sea) than to mid-ocean Atlantic conditions. In Fig. 10, we compare the annual cycle of total cloud amount over the Baltic Proper with those of Warsaw, Poland, two sites in the North Sea, and

one location in the North Atlantic at 56°N. While the last-mentioned has monthly values of more than 6.5 oktas throughout the year and a maximum monthly value in July (a similar feature was found for OWS P in the North Pacific, see *e.g.* Niekamp (1992)), all other locations show a distinct annual cycle with lowest cloud cover during the summer months, the latter being lower by 1.5 to 2 oktas compared to the respective winter values. Note that the Baltic Proper shows the lowest cloud cover of all locations chosen, in particular during April to July. This indicates that the Baltic Proper (together with other European near-coastal regions such as the North Sea) receives much more radiation during summer months compared to open-ocean regions in the Atlantic and Pacific Oceans at the same latitudes.

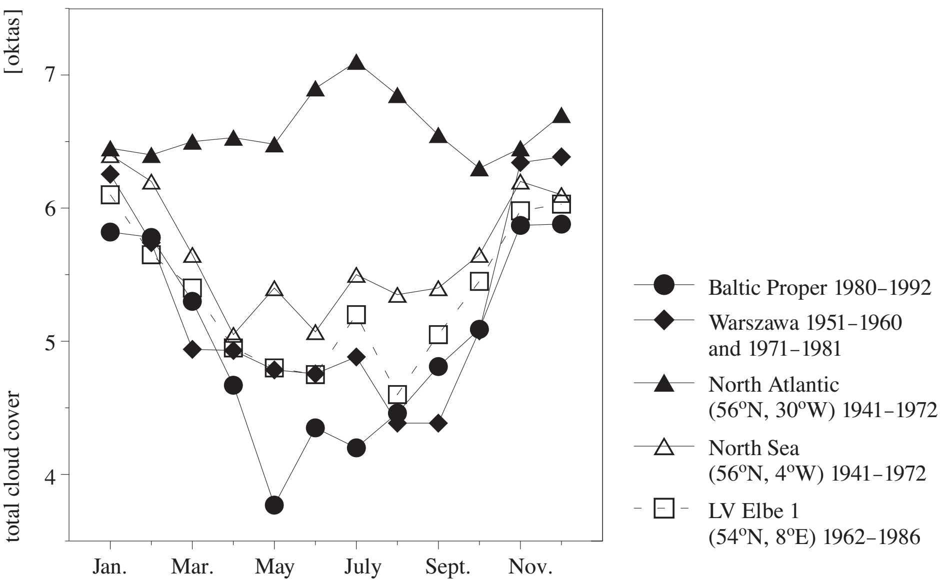



**Fig. 10.** Comparison of mean annual cycles of total cloud cover [oktas] for various regions. See Table 2 for details on locations, data sources used and periods covered

8. The semi-empirical model used considers more of the physical processes influencing solar radiation in the atmosphere than *e.g.* the much simpler bulk formulae, and it already exploits almost all of the available respective VOS data. A significant improvement in the performance of the present model in the Baltic Proper is expected, particularly in the following areas: (i) the use of open-sea, ship-borne (and not coastal, as used here) aerosol measurements for deriving of a more realistic parametrisation of the aerosol optical thickness over

**Table 2.** Sources of the climatological cloud cover data plotted in Fig. 10

| Location | Period | Source | Reference |
|---|---|---|---|
| Baltic Proper | 1980–1992 | Voluntary Observing Ships from COADS, irregularly distributed in time and space | this study |
| Warszawa | 1951–1960<br>1971–1981 | station data, regular observation times | Meteorological Yearbook, Institute of Meteorology and Water Management, Polish Weather Service |
| North Atlantic Ocean (56°N, 30°W) | 1941–1972 | Voluntary Observing Ships, irregularly distributed in time and space | Isemer & Hasse (1985), Fig. 23 |
| North Sea (56°N, 4°E) | 1941–1972 | Voluntary Observing Ships, irregularly distributed in time and space | Isemer & Hasse (1985), Fig. 24 |
| Light Vessel Elbe 1 (North Sea at 54°N, 8°E) | 1962–1986 | station data, fixed position, regular observation times | Moll & Raddach (1992) |

the Baltic Proper; (ii) the re-calibration of the cloud transmittance function using only ship measurements, which will certainly require additional measurements, especially during the cold season of the year and in the northern basin of the Baltic Proper; (iii) the parametrisation of the surface ice albedo as a function of the ice (and/or snow) surface conditions and the solar zenith angle.

9. The ideal case for a study such as the one presented here would of course be the comparison against representative, high-quality long-term and regular station measurements of surface radiation and simultaneous cloud observations over the open Baltic Proper sub-basins. Few marine records of this kind are available for certain parts of the oceans (such as the multi-year records taken at various Ocean Weather Stations in the Atlantic and Pacific Oceans, see *e.g.* Dobson & Smith 1988). However, we are at present not aware of comparable radiation records taken over the Baltic Proper or its sub-basins. For climate and climate variability studies, continuous

long-term radiation measurements and cloud data over the open Baltic Sea at *e.g.* lighthouses, platforms or buoys at selected locations are urgently required. A few continuous radiation measurements are presently being made at lighthouses (*e.g.* at Kiel lighthouse, by the Kiel Institute for Marine Sciences IfM) or buoys (*e.g.* at the MARNET station at Darss Sill, operated by the Baltic Sea Research Institute IOW in Rostock-Warnemünde). We suggest that international research efforts be undertaken in order firstly to build up inventories and accessible data compilations of existing radiation records in the Baltic Sea, and secondly to initiate further measurement activities based on internationally accepted strategies. The planned intensive observational and modelling phase of BALTEX scheduled for the years 1999 to 2001 (BRIDGE, see BALTEX 1997) would be an ideal start for such initiatives.

## Acknowledgements

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# Appendix 1

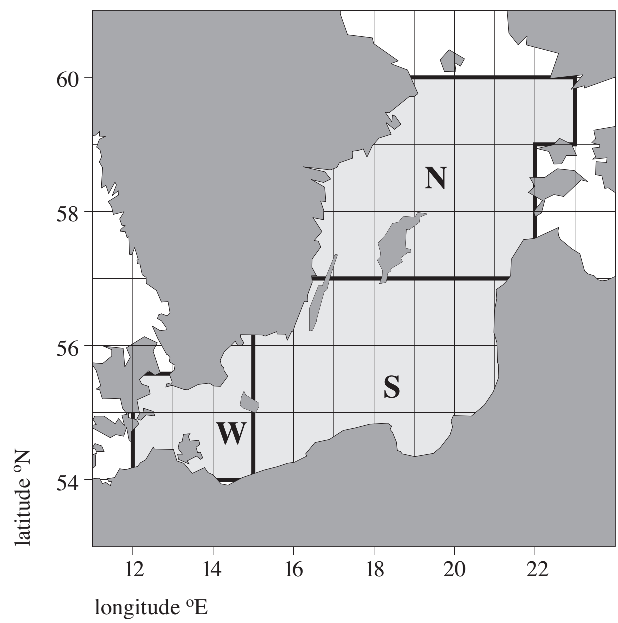


**Fig. A1.** Division of the Baltic Proper into northern (N), southern (S) and western (W) basins, as used in this study

# Appendix 2

**Table A1.** Monthly and annual solar radiation fluxes at ground level (RI), and absolute and percentage flux differences BUD–RI, DS88–RI, and REED–RI for the Baltic Proper. Percentage differences are related to RI estimates

| Month | RI | BUD–RI | | DS88–RI | | REED–RI | |
|---|---|---|---|---|---|---|---|
| | [W m$^{-2}$] | [W m$^{-2}$] | [%] | [W m$^{-2}$] | [%] | [W m$^{-2}$] | [%] |
| January | 17.5 | 6.0 | 34.3 | –0.6 | –3.4 | 1.6 | 9.1 |
| February | 43.5 | 3.2 | 7.4 | –4.4 | –10.1 | –1.1 | –2.5 |
| March | 89.3 | –2.3 | –2.6 | –0.2 | –0.2 | –0.5 | –0.6 |
| April | 164.7 | –1.3 | –0.8 | 3.5 | –2.1 | –3.7 | –2.3 |
| May | 231.6 | –6.4 | –2.8 | 18.3 | 7.9 | 12.1 | 5.2 |
| June | 241.1 | –20.5 | –8.5 | 35.3 | 14.6 | 24.4 | 10.1 |
| July | 230.3 | –10.6 | –4.6 | 38.1 | 16.5 | 25.5 | 11.1 |
| August | 176.9 | –6.1 | –3.4 | 31.8 | 18.0 | 17.7 | 10.0 |
| September | 110.9 | 7.0 | 6.3 | 18.3 | 16.5 | 10.3 | 9.3 |
| October | 59.6 | 3.8 | 6.4 | 4.5 | 7.6 | 2.4 | 4.0 |
| November | 21.9 | 8.4 | 38.4 | 3.0 | 13.7 | 3.5 | 16.0 |
| December | 11.8 | 6.1 | 51.7 | 0.7 | 5.9 | 1.5 | 12.7 |
| year | 116.6 | –0.9 | –0.8 | 11.5 | 9.9 | 7.3 | 6.3 |

**Table A2.** As Table A1 but for the northern Baltic Proper

| Month | RI | BUD–RI | | DS88–RI | | REED–RI | |
|---|---|---|---|---|---|---|---|
| | [W m$^{-2}$] | [W m$^{-2}$] | [%] | [W m$^{-2}$] | [%] | [W m$^{-2}$] | [%] |
| January | 14.7 | 8.9 | 60.5 | –1.1 | –7.5 | 0.2 | 1.4 |
| February | 42.9 | 3.7 | 8.6 | –7.3 | –17.0 | –5.2 | –12.1 |
| March | 86.4 | 0.6 | 0.7 | –2.8 | –3.2 | –4.1 | –4.8 |
| April | 163.2 | 0.3 | 0.2 | –0.9 | –0.6 | –8.7 | –5.3 |
| May | 231.7 | –6.5 | –2.8 | 14.5 | 6.3 | 6.4 | 2.8 |
| June | 248.9 | –28.3 | –11.4 | 29.1 | 11.7 | 18.4 | 7.4 |
| July | 237.3 | –17.6 | –7.4 | 31.0 | 13.1 | 18.8 | 7.9 |
| August | 178.0 | 7.1 | –4.0 | 25.3 | 14.1 | 11.1 | 6.2 |
| September | 108.8 | 9.2 | 8.5 | 15.5 | 14.3 | 7.0 | 6.4 |
| October | 55.0 | 8.3 | 15.1 | 2.9 | 5.3 | –0.3 | –0.6 |
| November | 18.9 | 11.4 | 60.3 | 1.9 | 10.1 | 2.0 | 10.6 |
| December | 9.5 | 8.5 | 89.5 | 0.4 | 4.2 | 0.5 | 5.3 |
| year | 116.3 | 0.1 | 0.1 | 8.4 | 7.2 | 3.8 | 3.3 |

**Table A3.** As Table A1 but for the southern Baltic Proper

| Month | RI | BUD–RI | | DS88–RI | | REED–RI | |
|---|---|---|---|---|---|---|---|
| | [W m$^{-2}$] | [W m$^{-2}$] | [%] | [W m$^{-2}$] | [%] | [W m$^{-2}$] | [%] |
| January | 19.3 | 4.2 | 21.8 | –0.2 | –1.0 | 2.7 | 14.0 |
| February | 43.3 | 3.3 | 7.6 | –2.4 | –5.5 | 1.5 | 3.5 |
| March | 91.8 | –4.8 | –5.2 | 1.8 | 2.0 | 2.3 | 2.5 |
| April | 166.5 | –3.0 | –1.8 | 6.5 | 3.9 | 0.1 | 0.0 |
| May | 234.3 | –9.1 | –3.9 | 18.0 | 7.7 | 14.1 | 6.0 |
| June | 239.1 | –18.5 | –7.7 | 37.6 | 15.7 | 26.8 | 11.2 |
| July | 229.0 | –9.3 | –4.1 | 40.6 | 17.7 | 27.7 | 12.1 |
| August | 178.6 | –7.8 | –4.4 | 35.2 | 19.7 | 21.4 | 12.0 |
| September | 112.5 | 5.4 | 4.8 | 19.2 | 17.1 | 11.5 | 10.2 |
| October | 62.4 | 0.9 | 1.4 | 5.9 | 9.5 | 4.6 | 7.4 |
| November | 23.6 | 6.7 | 28.4 | 3.4 | 14.4 | 4.6 | 19.5 |
| December | 13.2 | 4.8 | 36.4 | 0.9 | 6.8 | 2.2 | 16.7 |
| year | 117.8 | –2.3 | –2.0 | 13.9 | 11.8 | 9.9 | 8.4 |

**Table A4.** As Table A1 but for the western Baltic Proper

| Month | RI | BUD–RI | | DS88–RI | | REED–RI | |
|---|---|---|---|---|---|---|---|
| | [W m$^{-2}$] | [W m$^{-2}$] | [%] | [W m$^{-2}$] | [%] | [W m$^{-2}$] | [%] |
| January | 20.1 | 3.4 | 16.9 | –0.1 | –0.5 | 2.7 | 13.4 |
| February | 45.6 | 1.1 | 2.4 | –2.3 | –5.0 | 2.8 | 6.1 |
| March | 89.6 | –2.6 | –2.9 | 0.5 | 0.6 | 0.9 | 1.0 |
| April | 163.5 | –0.0 | –0.0 | 6.4 | 3.9 | –1.0 | –0.6 |
| May | 222.0 | 3.1 | 1.4 | 30.7 | 13.8 | 23.3 | 10.5 |
| June | 223.8 | –3.1 | –1.4 | 46.6 | 20.8 | 34.9 | 15.6 |
| July | 213.4 | 6.3 | 3.0 | 51.1 | 24.0 | 38.5 | 18.0 |
| August | 167.9 | 2.9 | 1.7 | 39.7 | 23.7 | 25.6 | 15.3 |
| September | 112.0 | 6.0 | 5.4 | 22.9 | 20.5 | 16.3 | 14.6 |
| October | 63.9 | –0.5 | –0.8 | 3.9 | 6.1 | 3.2 | 5.0 |
| November | 25.4 | 4.8 | 18.9 | 4.5 | 17.7 | 4.7 | 18.5 |
| December | 14.7 | 3.3 | 22.5 | 1.2 | 8.7 | 2.1 | 14.3 |
| year | 113.5 | 2.2 | 1.9 | 16.0 | 14.1 | 12.9 | 11.4 |

# Appendix 3

### Calculation of the 95% probability range

Following textbooks on statistics (*e.g.* Schönwiese 1985) we calculate the 95% probability range (or confidence interval) $M_{95}$ of the difference sample mean $\mu$ according to

$$M_{95} = t_{n,\,95}\,\frac{\sigma}{\sqrt{n}}, \tag{A1}$$

where $n$ denotes the sample size, $\sigma$ is the standard deviation of the individual differences against the sample mean, and $t_{n,\,95}$ is the argument of the $t$-distribution for a sample size $n$ and the given probability range of 95%. In our application to monthly values from 1980 to 1992, $n = 13$ and $t_{n,\,95} = 2.21$ (Schönwiese 1985). The $t$-distribution has to be taken instead of the normal distribution because of the low sample size. If the range $(\mu \pm M_{95})$ does not include zero, we interpret $\mu$ as being significantly different from zero at the 5% error level.