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Solar radiation at the surface in the Baltic Proper*

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Abstract

Radiation data recorded at 12 sites around the central part of the Baltic Sea during 1996–2000 drawn from the BALTEX (Baltic Sea Experiment) meteorological data archives are used to study the spatio-temporal variability of daily global radiation totals. The annual average daily global radiation total varies from about 10 MJ m^{-2} at Visby (on Gotland) and Kołobrzeg (on the coast of Poland) to less than 9 MJ m^{-2} at Zīlāni (inland Latvia), Šilutė (Lithuania) and Jokioinen (Finland). The monthly average daily global radiation total over the whole region extends from 0.93 in December to 19.0 in June. The variability in global radiation is analysed on the basis of the fraction of the daily total at the top of the atmosphere. The spatial and temporal variability is the least in August – this shows that the variation in the cloud cover and atmospheric properties at this time of year is the smallest. The spatial correlation is the strongest between the two Finnish stations

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– Vantaa and Jokioinen. It is also high between Stockholm and Norrköping, on the east coast of Sweden. The correlation coefficients are the largest over the whole area in April. Radiation data from coastal stations are compared with an earlier parameterization based on ship observations (Rozwadowska & Isemer 1998, Isemer & Rozwadowska 1999). It is concluded that in climatological research, actinometric data from Visby can be used to characterize the radiation field over the northern part of the Baltic Proper and those from Kołobrzeg to characterize the radiation field over the southern part of this sea.

1. Introduction

Solar radiation at the water surface is one of the driving agents of marine dynamics and an important factor in marine biology. Solar radiation contributes to the thermal regime of the water layers as well as to photosynthesis, primary production and phytoplankton blooms.

Solar surface irradiance depends first of all on astronomical factors, but is greatly modified by cloudiness, atmospheric transparency and snow cover. The latter factors show significant spatial and temporal variability, which is reflected in the variability of solar fluxes.

There are three ways of estimating radiation fluxes over a water body. First, radiation fluxes can be calculated by applying an empirical model to marine meteorological observations. Second, outputs of some numerical weather prediction models can be used. Third, coastal actinometric measurements can be extrapolated offshore.

The first possibility relies on the meteorological properties over a water body to parameterize surface solar radiation. This field has been investigated widely, but the parameterization is closely dependent on the climate zone: the relationships established elsewhere may not necessarily be directly applicable to the Baltic Sea. A semi-empirical model for computing the climatological characteristics of the solar radiation flux at the surface of the Baltic Proper is briefly described by Rozwadowska & Isemer (1998). They applied their model to meteorological observations made on board ships during 1980–1992 and described the monthly averages of the incident solar radiation fluxes in three parts of the Baltic Proper.

A detailed model of solar energy input to the sea surface has been presented by Krężel (1997). Taking into account as many parameters as possible, the model is expected to describe the radiation field in any time scale. However, comparison with actinometric data shows that for short time periods the modelled totals of solar energy at the sea surface can differ significantly from the real values. The main factor responsible for these discrepancies is cloudiness.

Niemelä et al. (2001) give an overview of several short-wave downwelling radiative flux parameterizations suitable for the Baltic Sea region. The calculated fluxes were compared with hourly sums observed at Jokioinen and Sodankylä, both inland stations in Finland. The clear-sky fluxes were estimated rather well, but the cloudy-sky schemes showed a large scatter.

Surface radiative flux parameterizations are used to build radiative codes in numerical weather prediction (NWP) models (e.g. Morcrette 1991, Ritter & Geleyn 1992). Over the Baltic Sea region the HIRLAM NWP system is mostly used. For this system, the radiation codes were elaborated by Savijärvi (1990) and Sass et al. (1994).

The second means of estimating surface solar radiation uses operational NWP outputs. This has at least two advantages: one is that the spatial coverage of the open sea is not restricted, and the other is that the situation in the radiation field can be estimated nearly instantaneously, with the temporal frequency of the forecast scheme. However, the accuracy of this possibility should be checked for specific site and climatic conditions.

The third possibility relies on measurements at coastal actinometric stations and gives a rough overview of the average radiation field around the water body. This knowledge may be sufficient for climate studies but is rather sparse for the Baltic Sea. Long-term average surface global (direct plus diffuse) radiation for the Baltic Sea Basin has been estimated on the basis of three inland actinometric stations – at Sodankylä (120 km north of the Arctic Circle in northern Finland, 1971–2000), Tartu (Estonia, 1981–2000) and Lindenberg (lat. 52°13′N, eastern Germany, 1981–2000) (BACC 2008). Figure A.12 in the BACC (2008) monograph also shows long-term monthly averages based on parameterizations applied to meteorological observations made on board voluntary observing ships during 1980–1992 (Rozwadowska & Isemer 1998). As shown in BACC (2008), the average annual course of the global radiation obtained from this parameterization differs significantly from actinometric measurements at coastal stations. The difference is due mainly to differences in astronomic conditions, but also to differences in cloud cover, which during spring and summer is consistently less under open-sea conditions (Isemer & Rozwadowska 1999, Leppäranta & Myrberg 2009). The latitude of Tartu corresponds best to that of the Baltic Proper; therefore the difference between actinometric measurements and the offshore parameterization there is the least.

Leppäranta & Myrberg (2009) state that the monthly mean solar radiation (flux density) in the region of the Baltic Sea peaks to around 200–250 W m^{-2} in June but disappears almost completely in December. They also demonstrate the variability in the annual cycle of global radiation using the example of Visby (Gotland, 1961–1990).

One of the reasons for the foundation of BALTEX (The Baltic Sea Experiment) in the early 1990s was the necessity to collect oceanographic, meteorological and hydrological data from the Baltic Sea catchment area and to create an archive for modellers and other investigators (BALTEX 1995). The BALTEX Meteorological Data Centre (BMDC) collected synoptic and climate data until 2002, and has been gathering atmospheric radiation data since 1986 (BMDC 2002). During 1996–2001 global radiation was measured at more than 50 actinometric stations within the Baltic Sea catchment area.

The aim of the current paper is to refine the spatial and temporal distribution of the surface solar radiation in the region of the Baltic Proper. For this purpose, measurements at 12 actinometric stations during 1996–2000 are used. This time series is short for climatological analysis, but the results of the present study can be complemented by a detailed analysis of the radiation climate at Tartu-Tõravere during 1955–2000 (Russak & Kallis (eds.) 2003).

2. Radiation data

Global (direct plus diffuse) radiation data from the following coastal or inland actinometric stations are used in the present study (Figure 1): Jokioinen (60.82°N 23.50°E), Helsinki-Vantaa (60.32°N 24.97°E), Tartu-Tõravere (58.27°N 26.47°E), Zīlāni (56.52°N 25.92°E), Šilutė (55.35°N 21.47°E), Gdynia (54.52°N 18.55°E), Kołobrzeg (54.18°N 15.58°E), Lund (55.72°N 13.22°E), Växjö (56.93°N 14.73°E), Visby (57.67°N 18.35°E), Norrköping (58.58°N 16.15°E) and Stockholm (59.35°N 18.07°E).

The historical data set from the BALTEX (BACAR) archive for 1996–2000 is rather heterogeneous with regard to the available types of radiation and resolution. At most stations the downwelling global radiation is recorded, but only a few stations give direct and diffuse radiation separately. The measuring methods differ from country to country. Table 1 gives an overview of the equipment for radiation measurements.

The data in the BALTEX archive for the period 1996–2000 needed unification, as they exist in various forms. Finland, Sweden and Estonia all used a CM-11 pyranometer (Kipp & Zonen), but the radiation parameters were expressed in different units – hourly and daily totals of global radiation in Estonia (MJ m^{-2}), hourly and daily mean values of global radiation in Finland (W m^{-2}) and hourly mean values in Sweden (W m^{-2}). In Latvia and Lithuania the global radiation was calculated as the sum of direct and diffuse radiation on a horizontal surface, whereas the unit for expressing global radiation was MJ m^{-2} multiplied by 100. In Poland a Moll-Gorczynski pyranometer (Kipp & Zonen) was used to register the radiation data. Daily totals of global radiation were expressed in J cm^{-2}.

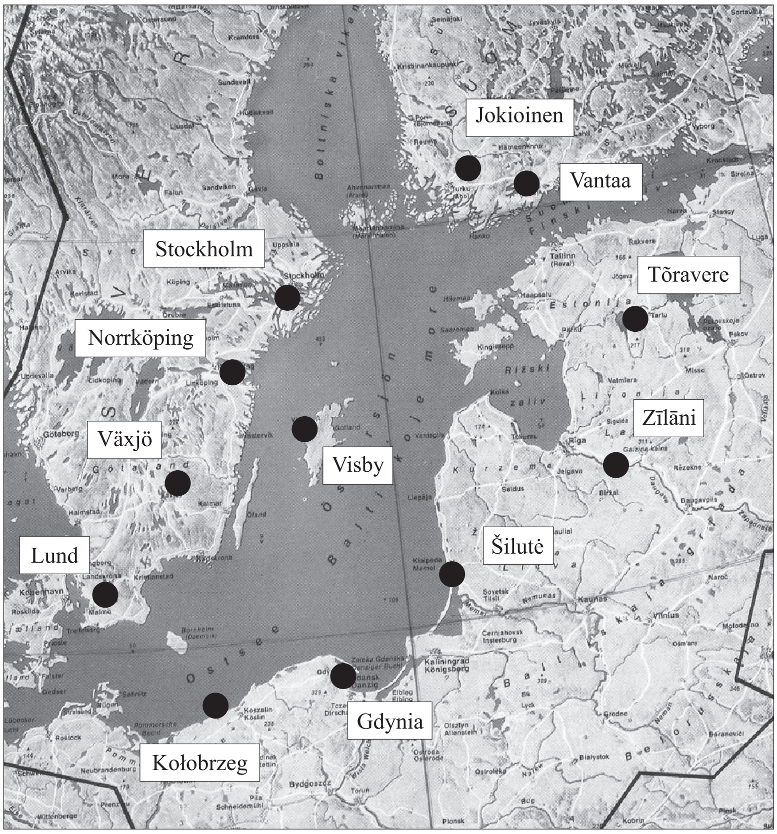

Figure 1. Actinometric stations around the Baltic Sea

Table 1. Information on radiation gauges in 1996–2000 (BMDC 2002)

Radiation type/Country	Finland	Estonia	Latvia and Lithuania	Poland	Sweden
global (Q)	Kipp & Zonen CM-11 pyranometer	Kipp & Zonen CM-11 pyranometer	$Q = S + D$	Kipp & Zonen pyranometer (Moll-Gorczynski)	Kipp & Zonen CM-11 pyranometer
diffuse (D)			pyranometer PP-1		
direct solar radiation on a horizontal surface (S)			actinometer AT-50		

To analyse the spatial distribution of the surface solar radiation, all measurement results were recalculated to daily totals and given in MJ m^{-2}. Since numerous data were missing, analysis of monthly totals was not possible.

In the BALTEX radiation data archive for 1996–2000 only the Estonian, Polish, Finnish and Norrköping global radiation data sets have no gaps. The missing data for the other stations are shown in Table 2.

Table 2. Number of days for which global radiation data are missing

Year	Zīlāni	Šilutė	Stockholm	Visby	Växjö
1996		30 (June) 2 (Dec.)		29 (Feb.) 31 (Mar.) 30 (April)	30 (Sept.)
1997		1 (Jan.) 16 (June) 21 (July) 16 (Oct.) 9 (Nov.) 19 (Dec.)			
1998	21 (Dec.)	3 (July) 16 (Aug.) 1 (Nov.)	30 (July)		
1999		9 (Dec.)			
2000		11 (Jan.) 15 (Feb) 2 (June) 7 (Sept.)	31 (Aug.)		

The December 1998 data set from Zīlāni was omitted from the analysis, as it showed random gaps, as well as two values of daily sums exceeding 11 MJ m^{-2} that were apparently erroneous.

3. Regional differences in the global radiation in 1996–2000

The annual average of daily totals over the whole region calculated from the data of the twelve actinometric stations is 9.44 MJ m^{-2}, but there are noticeable differences between different stations (Figure 2).

The amount of solar energy is the largest at Visby (10.32 MJ m^{-2}), even though it is not the southernmost station in this area. Fluxes are also above average on the Polish coast, reaching 10.19 MJ m^{-2} at Kołobrzeg and 9.99 MJ m^{-2} at Gdynia. The average daily total is the smallest at Zīlāni (8.68 MJ m^{-2}). These differences are due mostly to differences in summer,

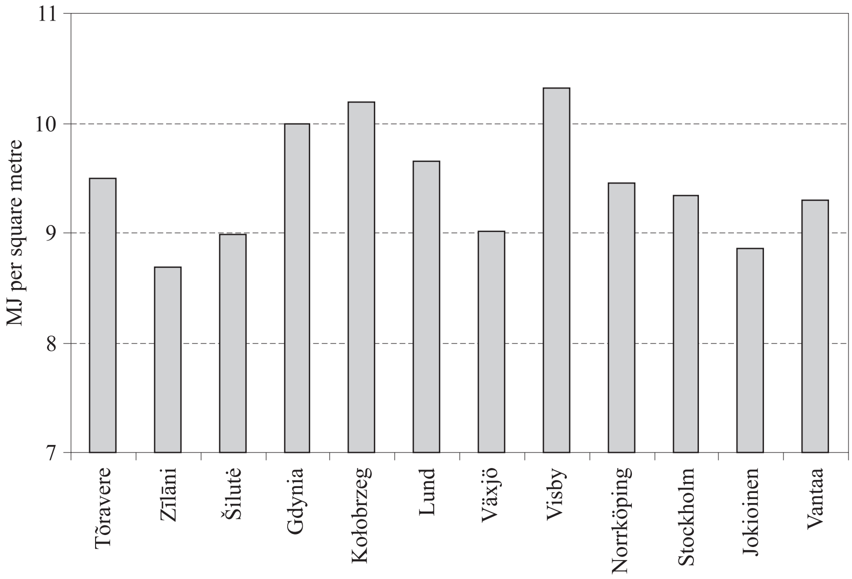

Figure 2. Regional differences in the annual average daily global radiation totals during 1996–2000

as the amount of solar radiation in winter is uniformly small. Figure 3 shows that in June the average daily total is 20.9 MJ m^{-2} at Visby, but only 16.0 MJ m^{-2} at Šilutė. Zīlāni, Šilutė, Växjö and Jokioinen, where the

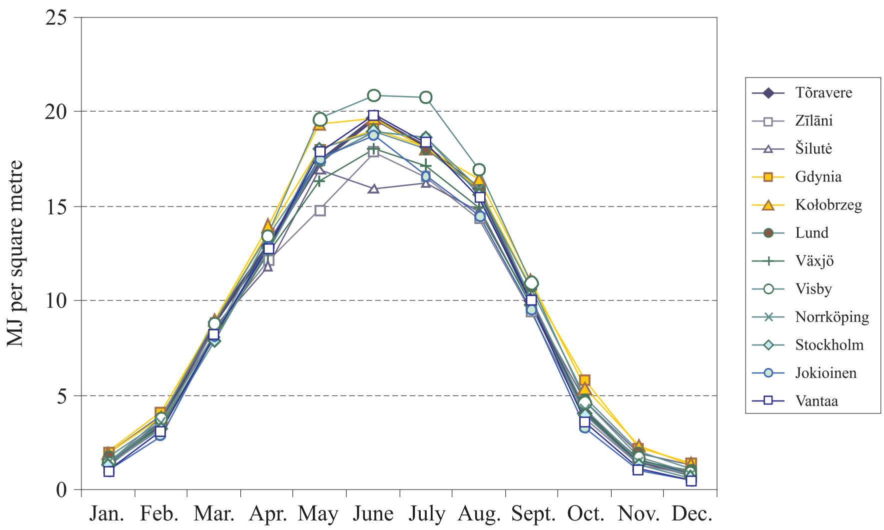

Figure 3. Monthly average daily global radiation totals at different sites during 1996–2000

annual average daily sum is < 9.0 MJ m^{-2}, are all inland stations where the cloud cover in summer is more extensive than over the coastal regions (Mietus 1998). Interestingly, Tõravere is also an inland station, but the atmospheric conditions seem to be more favourable for solar radiation here.

Spatial variability is due largely to astronomical factors. In summer the impact of the northward increase in the length of daylight compensates for the influence of the decrease in solar elevation on daily global radiation totals, but in winter both factors work in the same direction, so that there are large differences in the daily totals at the top of the atmosphere (TOA) between the northernmost and southernmost sites of the region under consideration (Table 3).

Table 3. Average TOA daily totals (MJ m^{-2}) at the northernmost and southernmost stations of the study region

Station	June	December
Jokioinen	42.3	1.9
Kołobrzeg	42.6	5.2

Spatial variability is also caused by differences in atmospheric transmittance. To separate the meteorological factors from the astronomical ones, the recorded daily totals were expressed as fractions of the respective daily totals at the TOA. These fractions still contain some astronomical influence, as the atmospheric transmittance depends on the solar zenith angle. Fortunately, this influence is much less than that of the atmospheric

Table 4. Monthly averages and standard deviations of the fraction of the TOA daily total over the whole region (12 stations)

Month	Average	Standard deviation
January	0.30	0.14
February	0.35	0.14
March	0.45	0.15
April	0.44	0.13
May	0.46	0.14
June	0.45	0.12
July	0.44	0.12
August	0.47	0.11
September	0.44	0.13
October	0.32	0.14
November	0.24	0.12
December	0.26	0.12

variability. Table 4 shows the average fractions of the TOA daily totals for different months. As expected, these quantities are the smallest in November and December. The standard deviations of the fractions of TOA daily totals over all 12 stations were calculated for every day and then averaged over the respective months. Table 4 shows that spatial variability was the least in August.

4. Temporal variability in global radiation

Astronomical factors should also be taken into account in the analysis of temporal variability, as the measured daily totals at the TOA may differ considerably at the beginning and at the end of several months (mostly in spring and autumn) and introduce additional variability into the estimated quantities. The annual cycle of the variability in the fractions of the TOA daily totals of global radiation at different measurement sites is presented in Figure 4. As the shorter time series normally show larger variability, Figure 4 shows only those stations where there are no gaps in the data sets.

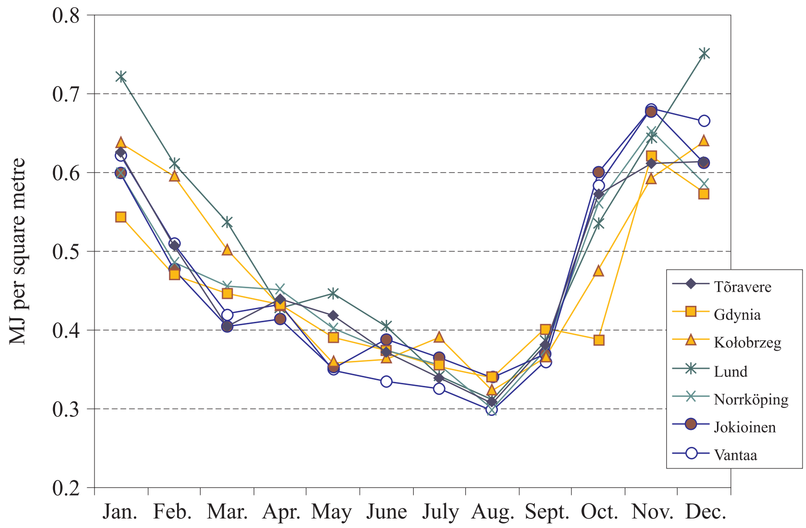

Figure 4. Coefficient of variation of the fraction of the TOA daily global radiation totals at different sites during 1996–2000

The coefficient of variation of the fractions of the TOA daily totals actually describes the variability in atmospheric transmittance (with regard to the daily totals). As is to be expected, the coefficient of variation is the largest from November to January, when the overall atmospheric transparency is low and variations in the amount of incoming energy due to atmospheric disturbances (clouds, aerosols, etc.) are comparable with the average flux. On the other hand, the variability of atmospheric transmittance is minimal not in June, when the incoming energy is maximal, but in August. Thus, the influence of atmospheric disturbances in this month is the weakest.

Figure 4 shows that in late winter and early spring the variability in the fraction of the TOA daily totals at Lund and Kołobrzeg is larger than at the other stations. In October the atmospheric transmittance on the Polish coast varies less than at the other measurement sites.

At most stations (with the exception of Lund) the coefficient of variation in December is smaller than in November and January. This fact can be explained by the uniform cloud cover that is typical of this month in the Baltic Sea region.

To detect the sites where the fractions of the TOA daily totals co-vary, correlation coefficients were calculated between the different stations. As one might expect, the fractions of the TOA daily totals are best correlated for the measurement sites that are situated close to each other. This is the case for Vantaa and Jokioinen, where the correlation coefficient is 0.92 in January and February and not less than 0.81, the June value. Evidently these sites are governed by similar cloud cover systems – stratiform cloudiness in winter and cumulus clouds in summer. The fractions of the TOA daily totals are also well correlated at Norrköping and Stockholm, where during most of the year the correlation coefficient is over 0.8; only in August, September, November and December is it between 0.75 and 0.8. Comparison of the correlation matrices for different months leads to the

Table 5. Correlation coefficients between the fractions of the TOA daily global radiation totals at different stations in April

Station	Tõravere	Zīlāni	Šilutė	Gdynia	Kołobrzeg	Lund	Väjö	Visby	Norrköping	Stockholm	Jokioinen
Zīlāni	0.72										
Šilutė	0.45	0.71									
Gdynia	0.28	0.46	0.64								
Kołobrzeg	0.20	0.33	0.49	0.75							
Lund	0.22	0.30	0.43	0.52	0.66						
Väjö	0.34	0.37	0.47	0.46	0.54	0.80					
Visby	0.39	0.33	0.41	0.43	0.49	0.45	0.65				
Norrköping	0.38	0.34	0.40	0.37	0.43	0.64	0.83	0.71			
Stockholm	0.48	0.39	0.44	0.39	0.41	0.51	0.67	0.70	0.81		
Jokioinen	0.49	0.31	0.18	0.09	0.17	0.21	0.33	0.29	0.37	0.57	
Vantaa	0.62	0.32	0.19	0.14	0.20	0.26	0.37	0.41	0.39	0.54	0.84

finding that the fractions of the daily totals of global radiation show the strongest correlation over the whole region in April (Table 5). This feature is also supported by Figure 4: the temporal variability of the atmospheric transmittance is similar all over the region under consideration.

5. Coastal measurements and parameterization from offshore meteorological observations

Comparison of our results with those obtained by Rozwadowska & Isemer (1998) shows that the average daily totals over the whole region (all data from 12 stations) differ somewhat from the daily totals obtained by the parameterization of ship-based observations (Figure 5). The meteorological parameters constituting the input to the parameterization model are cloud cover, humidity and air temperature. The number of observations during 1980–1992 was large, but they were distributed unevenly in time and space. As our estimates from coastal measurements were obtained during 1996–2000, the time periods do not coincide. Therefore, a rough estimate of the possible differences between these periods based on Tartu-Tõravere data (Russak & Kallis (eds.) 2003) is shown in Figure 6. Although the annual total for the later period is larger by only 2%, the monthly totals are smaller by 18% in December, by 12% in January and by 13% in February. They are larger by 7% in March, by 15% in August and by 22% in September.

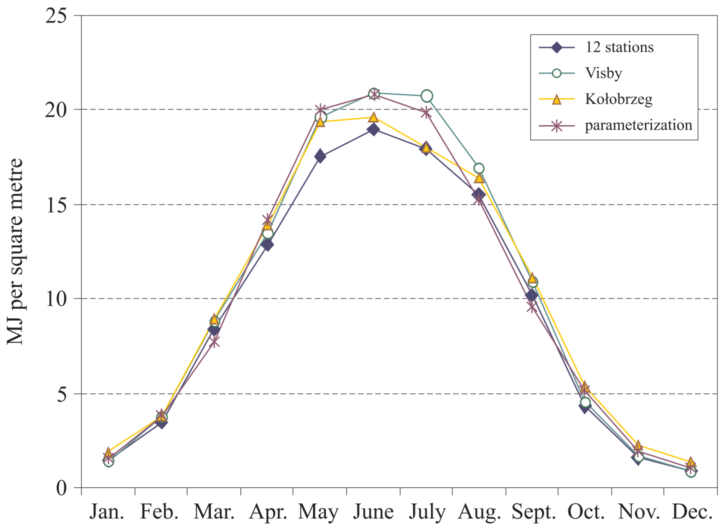

Figure 5. Annual cycle of the average daily global radiation total according to several sources: parameterization from ship measurements (1980–1992) (Rozwadowska & Isemer 1998), average over 12 coastal stations and at two measurement sites (1996–2000)

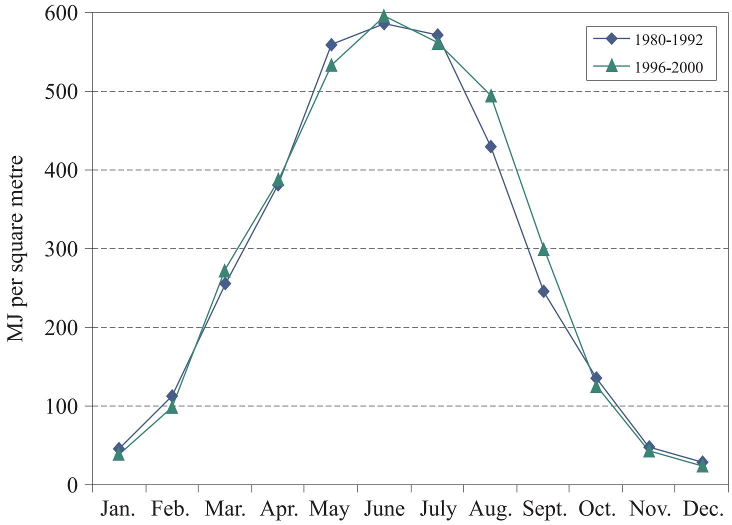

Figure 6. Monthly global radiation totals at Tartu-Tõravere for different time periods

The difference between the coastal measurements averaged over the whole region during 1996–2000 and the parameterization estimates during 1996–2000 is the largest in May, when the parameterization shows an average daily sum of 20.0 MJ m^{-2} and coastal measurements of 17.6 MJ m^{-2} (Figure 5). On the other hand, coastal measurements show somewhat (0.27…0.72 MJ m^{-2}) larger values in March, August and September. According to Figure 6, this can be attributed to some extent to differences between the various periods.

Figure 5 shows that the match is the best between the parameterization model outputs and the measurements at Visby, i.e. the site where the amount of the solar radiation is the largest. Figure 5 also shows the annual cycle at Kołobrzeg (second best according to the annual average), but this differs from the parameterization estimates to a greater extent than that at Visby. From this comparison, one can regard measurements of global radiation at Visby as representative of the average global radiation over the whole Baltic Proper.

A similar analysis for three parts of the Baltic Proper (Isemer & Rozwadowska 1999) shows that Visby data can be used to describe the solar radiation fluxes over the Baltic Proper between 57°N and 60°N. In Table 6 this region is denoted by N. The Kołobrzeg data give a good approximation for the region west of 15°E (denoted by W). The relative difference in both cases is maximal in March and September but does not exceed 20%. At least part of this difference as well as the difference in August can be ascribed to

Table 6. Average daily totals (in MJ m^{-2}) for different parts of the Baltic Proper from offshore parameterization and coastal actinometry

Month	Isemer & Rozwadowska 1999			Visby	Kołobrzeg
	Region N	Region S	Region W		
January	1.3	1.7	1.7	1.4	1.9
February	3.7	3.7	3.9	3.8	3.8
March	7.5	7.9	7.7	8.8	9.0
April	14.1	14.4	14.1	13.5	13.9
May	20.0	20.2	19.2	19.7	19.4
June	21.5	20.7	19.3	20.9	19.6
July	20.5	19.8	18.4	20.8	18.1
August	15.4	15.4	14.5	17.0	16.4
September	9.4	9.7	9.7	11.0	11.2
October	4.8	5.4	5.5	4.6	5.4
November	1.6	2.0	2.2	1.7	2.3
December	0.8	1.1	1.3	0.9	1.4

the differences between the time periods (Figure 6): in March the relative difference between the monthly totals at Tõravere is 7%, in August 15% and in September 22%. To describe the radiation field in the region south of 57°N and east of 15°E (the region denoted by S), Visby and Kołobrzeg give the best approximation, but both show rather large relative differences in winter. The Kołobrzeg measurements display larger values and the Visby measurements smaller values than those obtained by the parameterization of ship measurements. Very probably, this can be explained, at least partly, by astronomical factors.

6. Conclusions

Solar surface radiation varies considerably around the Baltic Proper. This variability is caused not only by astronomical factors, but also by spatial and temporal variability in atmospheric properties (cloudiness, aerosols).

The spatial and temporal variability in the fraction of the TOA daily totals of global radiation (practically atmospheric transmittance) is the least in August. In late winter and early spring, the temporal variability in the western part of the region under consideration is somewhat larger than in other parts of the Baltic Proper. In October it is smaller at Gdynia and Kołobrzeg than at other stations.

The spatial correlation of the fraction of TOA daily totals is the best between Jokioinen and Vantaa, but it is also good between Norrköping and Stockholm. All over the region these values are correlated best in April.

Comparison of coastal radiation data with those obtained by parameterization based on measured offshore meteorological parameters shows that the monthly average global radiation at Visby is a good approximation for the whole Baltic Proper region and especially for its northern part. For the south-western Baltic Sea, the measurements at Kołobrzeg describe the radiation field best.

Radiation measurements at Visby and Kołobrzeg can be used to characterize the radiation field over the sea if climatological problems or the phenomena of monthly and seasonal scales are studied. For short-term (daily) phenomena, some other method, e.g. in situ measurement or a numerical weather prediction model output, has to be used.

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