Longwave radiation budget at the Baltic Sea surface from satellite and atmospheric model data

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Abstract

The net longwave radiation flux $LW\uparrow\downarrow$ in the Baltic Sea in 2001 has been subjected to spatial and temporal analysis. Maps of the mean monthly $LW\uparrow\downarrow$ over the Baltic were drawn using the new semi-empirical formula for the Baltic Sea (Zapadka et al. 2007). The input data for the formula, such as sea surface and air temperatures, and cloud cover, were obtained from the Tiros N/NOAA and METEOSAT 7 satellites and from the UMPL forecast model (see http://meteo.icm.edu.pl). The mean annual $LW\uparrow\downarrow$ for 2001 was estimated at 63 W m^{-2} and compared with available data from other sources. The monthly maps of the net flux $LW\uparrow\downarrow$ over the Baltic show that the total values reach a minimum ($LW\uparrow\downarrow \approx 50$ W m^{-2}) in April, September, October and a maximum ($LW\uparrow\downarrow \approx 80$ W m^{-2}) in November. The statistical error of daily maps, on which the monthly maps were based, is no more than 18 W m^{-2}.

The complete text of the paper is available at http://www.iopan.gda.pl/oceanologia/

1. Introduction

One of the principal components of the heat budget of the sea is the net (or effective) longwave radiation flux $LW\uparrow\downarrow$ (Dera 1992). $LW\uparrow\downarrow$ is the difference between the upward longwave radiation flux emitted by the sea surface to the atmosphere $LW\uparrow$ and the downward longwave radiation flux reaching the sea from the atmosphere $LW\downarrow$. The thermal radiation of the sea and atmosphere is subject to the laws of heat radiation, and as such plays a crucial part in maintaining the thermal equilibrium of the Earth. The proportion of this component in the thermal budget of the Baltic Sea is large: it has been estimated at between c. 25% and c. 30% of the total heat budget of this sea (on the basis of the data supplied by various authors, described in Bengtsson 2001).

To determine $LW\uparrow\downarrow$ one usually uses simple, semi-empirical formulas based on the Stefan-Boltzmann law, in which the variables (i.e. the input data from which the budget is calculated) are state parameters of the sea and atmosphere, such as air temperature, sea surface temperature, water vapour pressure, cloud cover and cloud type (Fung et al. 1984). The instantaneous values of $LW\uparrow\downarrow$ obtained with these formulas are usually encumbered with an absolute statistical error that may be as high as ± 20 W m^{-2} (Bignami et al. 1995, Zapadka et al. 2001, Josey et al. 2003). These formulas yield good results provided that sufficient input data are available, for instance, for areas with a dense network of measurement stations. If $LW\uparrow\downarrow$ is estimated for areas with few available input data, as in the case of the marine environment, these data may well be episodic (as in the Baltic Sea, for example), and the gaps in the data have to be filled with satellite data and/or model output. In the literature there are few reports of remote-sensing or model data being used to estimate $LW\uparrow\downarrow$, especially for the Baltic Sea. Such an approach, in which data of this kind are used to define the components of the Earth's longwave radiation budget, is the one taken by Gupta et al. (1992) and Brisson et al. (1994). But the possibilities of applying Gupta's et al. (1992) model to the Baltic are limited because of the specific insufficient spatial resolution of his data – just a few pixels cover the whole Baltic. Increasing the resolution of the input data would probably have an adverse effect on the quality of the results. Again, the algorithm of Brisson et al. (1994) can be applied only to the downward component of the net longwave radiation flux and requires special calculations to determine the cloud cover parameters. The empirical coefficients for these calculations may well be quite different for the Baltic than for the Azores region, where Brisson et al. (1994) carried out their study, and applying the original ones without modification in computations for the Baltic may give rise to considerable errors.

In the few reports on the net longwave radiation flux $LW\uparrow\downarrow$ in the Baltic Sea (e.g. Pomeranec 1966, Lindau 2002), their authors determined this magnitude from multi-annual in situ data or numerical models. But the values of $LW\uparrow\downarrow$ obtained on this basis are divergent and have not been verified empirically.

In recent years new data on $LW\uparrow\downarrow$ for the Baltic have emerged from the BALTEX project (Meier & Döscher 2002, Omstedt & Nohr 2004). In this research, the determination of $LW\uparrow\downarrow$ was a secondary aim in studies of the total energy budget of this sea. The values of $LW\uparrow\downarrow$ given in those reports are usually mean annual or mean monthly values for the whole Baltic Sea. The inference to be drawn from all the studies done so far for the Baltic is that $LW\uparrow\downarrow$ does not vary seasonally to any great extent. Nonetheless, the plots in Figure 7 (see page 162) show that there are considerable divergences in the mean monthly $LW\uparrow\downarrow$ calculated by different authors; the same applies to the mean annual $LW\uparrow\downarrow$ for the Baltic. The various computations show $LW\uparrow\downarrow$ to range from c. 35 to c. 70 W m^{-2} (see Table 1). Note, however, that the periods over which these values have been averaged (see the last column in Table 1) are different, which, of course, may be a reason for some of these divergences.

Table 1. Mean annual values of the net longwave radiation flux $LW\uparrow\downarrow$ in the Baltic Sea (from various sources)

Author	$LW\uparrow\downarrow$ [W m^{-2}]	Period [years]
Pomeranec (1966)	51	1867–1955
Omstedt & Rutgersson (2000)	43	1981–1995
Ruprecht (2000)	69	–
Jacob (2001)	57	1979–1988
Meier & Döscher (2002)	45	1988–1993
(two methods)	53	1988–1993
Lindau (2002)	69	1980–1995
Omstedt & Nohr (2004)	38	1999–2002
	39	2001

The numerous semi-empirical formulas for determining $LW\uparrow\downarrow$ given in the literature have usually been derived on the basis of empirical data from particular land or sea areas, and therefore 'belong' to those areas. Applying them to any other sea may give rise to additional errors, possibly exceeding the statistical error of the formula for the area for which it was originally derived. These errors can be greater than c. 10 W m^{-2} (see Zapadka et al. 2007). There are no reports on the spatial differentiation of $LW\uparrow\downarrow$ in the Baltic Sea. The papers cited earlier refer above all to the mean $LW\uparrow\downarrow$ for the whole Baltic or only for particular parts of this sea. No complete set of temporal (seasonal) and spatial $LW\uparrow\downarrow$ data exists for the Baltic. The reason for this appears to be that up to now no precise and effective indirect methods have been developed to estimate this flux from hydrometeorological data measured in the traditional way, obtained by remote sensing or computed using appropriate models.

In view of the above, the present work had two objectives: 1) to work out a method to determine the net longwave radiation flux $LW\uparrow\downarrow$ for any locality and time in the Baltic Sea from satellite and model data; 2) to use this method to estimate the temporal and spatial variations in this flux for the Baltic Sea in a given year. To achieve these objectives we used a new, more accurate semi-empirical formula, derived especially for the Baltic Sea, in which the input parameters are simple hydrometeorological parameters (Zapadka 2006, Zapadka et al. 2007), as well as data obtained by satellite and computed with the relevant model. The sources of these latter data are the Tiros N/NOAA and METEOSAT satellites and the UMPL forecast model (http://meteo.icm.edu.pl). The present work concerns the whole Baltic Sea, and the results of certain detailed analyses supply further information about particular zones of the sea. The mean monthly and mean annual values of the net longwave radiation flux $LW\uparrow\downarrow$ for 2001 are compared with the corresponding data from other sources.

2. Material and methods

The algorithm used in these computations was based on a semi-empirical formula designed to determine the net longwave radiation flux $LW\uparrow\downarrow$ for the Baltic Sea (Zapadka et al. 2007). Table 2 explains this formula, as modified for the purposes of this work.

The input data for the computations come from three independent sources. Air temperature T_{ICM} , water vapour pressure e_{ICM} and the total cloudiness n_{ICM} were obtained from the UMPL model, developed by the Interdisciplinary Centre for Mathematical and Computational Modelling, Warsaw University (ICM) (see http://meteo.icm.edu.pl). The maps representing sea surface temperature for given period were obtained on the basis of all AVHRR[1] data received in that period (up to 12 scenes per day). After routine preprocessing (geographical referencing and geometric correction) and extracting the area of interest (Baltic Sea) the sea surface temperatures T_s were calculated (Krężel et al. 2005) for every single scene.

[1]The radiometer operating on Tiros N/NOAA satellites. Data from NOAA 12, 14, 15 and 16 were used.

Table 2. Algorithm for modelling the calculations of the net longwave radiation flux $LW\uparrow\downarrow$

Section A

Input parameters of the model: air temperature T_{ICM} [K], water vapour pressure e_{ICM} [mbar], total cloudiness n_{ICM} $[0-1]$ (**block 1**), cloudiness coefficient c $[0-1]$ (**block 2**), sea surface temperature T_s [K] (**block 3**).

Section B

Model formulas:

Block 4: Formula for the downward longwave radiation from a cloudless sky $LW\downarrow_0$:

$$LW\downarrow_0 = \sigma T_{ICM}^4 (0.685 + 0.00452 e_{ICM}) \quad \text{(Zapadka et al. 2007)}, \tag{T1}$$

where

σ – Stefan-Boltzmann constant.

Block 5: Cloud cover function $f(n)$ for UMPL data:

$$LW\downarrow = LW\downarrow_0 \, f(n), \tag{T2}$$

where

$$f(n) = 1 + d_i n_{ICM}^2, \tag{T3}$$

d_i – coefficient, different for every month:

$d_{Jan.} = 0.313$, $d_{Feb.} = 0.314$, $d_{Mar.} = 0.316$, $d_{Apr.} = 0.318$, $d_{May} = 0.317$,
$d_{June} = 0.313$, $d_{July} = 0.312$, $d_{Aug.} = 0.309$, $d_{Sept.} = 0.313$, $d_{Oct.} = 0.323$,
$d_{Nov.} = 0.319$, $d_{Dec.} = 0.318$ (Zapadka et al. 2007).

Block 6: Formula for the real downward longwave flux in the hours of daylight:

$$LW\downarrow = LW\downarrow_0 \, f(c), \tag{T4}$$

where

$$f(c) = 1 + 0.32 \tanh(3.3c), \tag{T5}$$

where

c – cloudiness coefficient calculated from METEOSAT data (Krężel et al. 2008, this volume)

Block 7: Formula for the upward longwave radiation flux $LW\uparrow$:

$$LW\uparrow = 0.985 \sigma T_s^4, \tag{T6}$$

where

T_s – sea surface temperature determined from a time series of sea surface temperature maps from the AVHRR radiometer.

Section C

Principal calculations:

Block 8: $LW\downarrow_0$ calculated using eq. (T1) for each day in the year on the basis of ICM files: water vapour pressure e_{ICM} and air temperature T_{ICM} for the whole Baltic at 00, 03, 06, 09, 12, 15, 18, 21 hrs.

Block 9a: $LW\downarrow$ calculated from eq. (T2) and $f(n)$ from eq. (T3) using the ICM general cloud cover coefficient n_{ICM} for the hours of darkness (i.e. the hours for which the cloudiness coefficient c is unavailable), then multiplied by the relevant values of $LW\downarrow_0$.

Block 9b: Real downward $LW\downarrow$ determined from (T4) and $f(c)$ from eq. (T5); maps of coefficient c are available every 0.5 hour for the hours of daylight. Maps of c converted to functions $f(c)$ are averaged around the hours for which maps are available of the downward flux from a cloudless sky $LW\downarrow_0$ and multiplied by them.

Block 10: Downward $LW\downarrow$ from the hours of darkness and daylight averaged for monthly periods.

Block 11: $LW\uparrow$ calculated according to eq. (T6) using available maps of the temperature T_s; the averaged monthly map of $LW\uparrow$ is drawn on the basis of the weekly maps.

Block 12: The difference between the calculated monthly upward and downward fluxes yields the net flux $LW\uparrow\downarrow$ for each month. The annual map of $LW\uparrow\downarrow$ is the average of the 12 monthly maps.

Then, all these scenes were used to obtain full cover of the whole sea with this information. This was done by means of mosaicking, which enabled gaps in the information due to cloudiness in one scene to be filled with information from other scenes. In the overlapping areas the maximum values of all components were assumed. This method used to determine the sea surface temperature T_s yielded an average of 0 to 5 maps of T_s distribution per week. The number of such maps depended on the number of images enabling at least one signal undistorted by cloudiness, i.e. for zero cloud cover, to be recorded for each pixel in the shortest possible time. If one week was too short a period to produce such a map, the time interval was prolonged. In such cases the mean monthly map of $LW\uparrow$ was based on two or three temperature maps. If the opportunity arose to obtain more than one cloud-free map per week, then the 24 h scene was additionally separated into day- and night-time scenes. The temperature maps for day and night were averaged to periods of one week. Cloudiness data during daylight hours were provided by the radiometric data of channel 1 (VIS) of the METEOSAT 7 satellite. The magnitude characterising the influence of cloudiness on radiation transmission through the atmosphere is the cloudiness coefficient c postulated by Krężel & Kozłowski (2004). The use of this coefficient required the regression coefficients in eq. (T5) to be found (see Table 2). Eq. (T5) is the best approximation of the dependence of the downward longwave radiation flux $LW\downarrow$ on coefficient c. The coefficients appearing in this equation were determined by nonlinear regression: in situ $LW\downarrow$ values were compared with c determined for the pixels within which the in situ values were measured (Zapadka 2006).

Different numbers of input data were obtained from the various sources. The UMPL model generated 8 maps daily at 00, 03, 06...hrs. METEOSAT supplied cloudiness information every half-hour during the hours of daylight, from which 8 to 16 maps of coefficient c were obtained, depending on the season. The maps showing the distributions of the various parameters in the formula for $LW\uparrow\downarrow$ as input data were reduced to a uniform format with a resolution of c. 4×4 km.

The block diagram of the modelling procedure (see Figure 1) is divided into three sections – Input Data (section A), Model Formulas (section B) and Computation (section C) – each of which is explained in detail

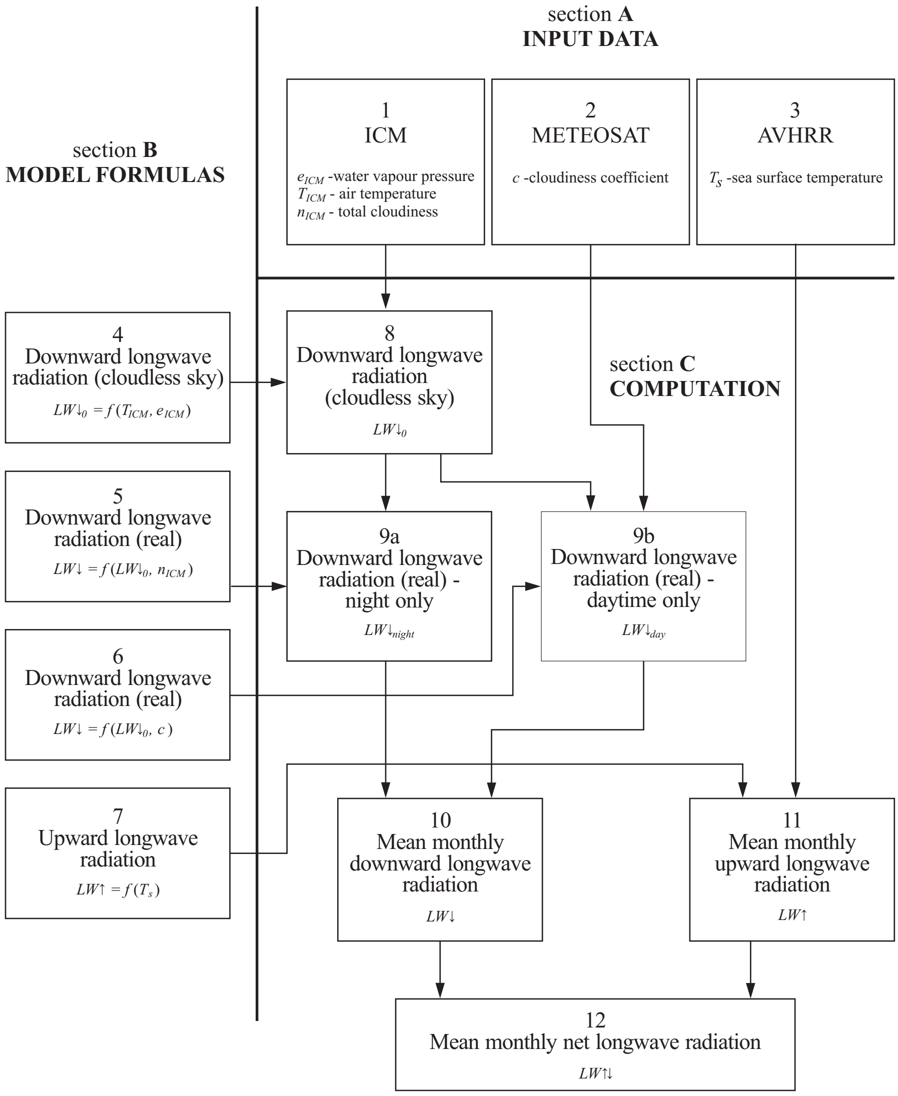

Figure 1. Block diagram of the model for calculating the net longwave radiation flux $LW\uparrow\downarrow$ in the Baltic Sea

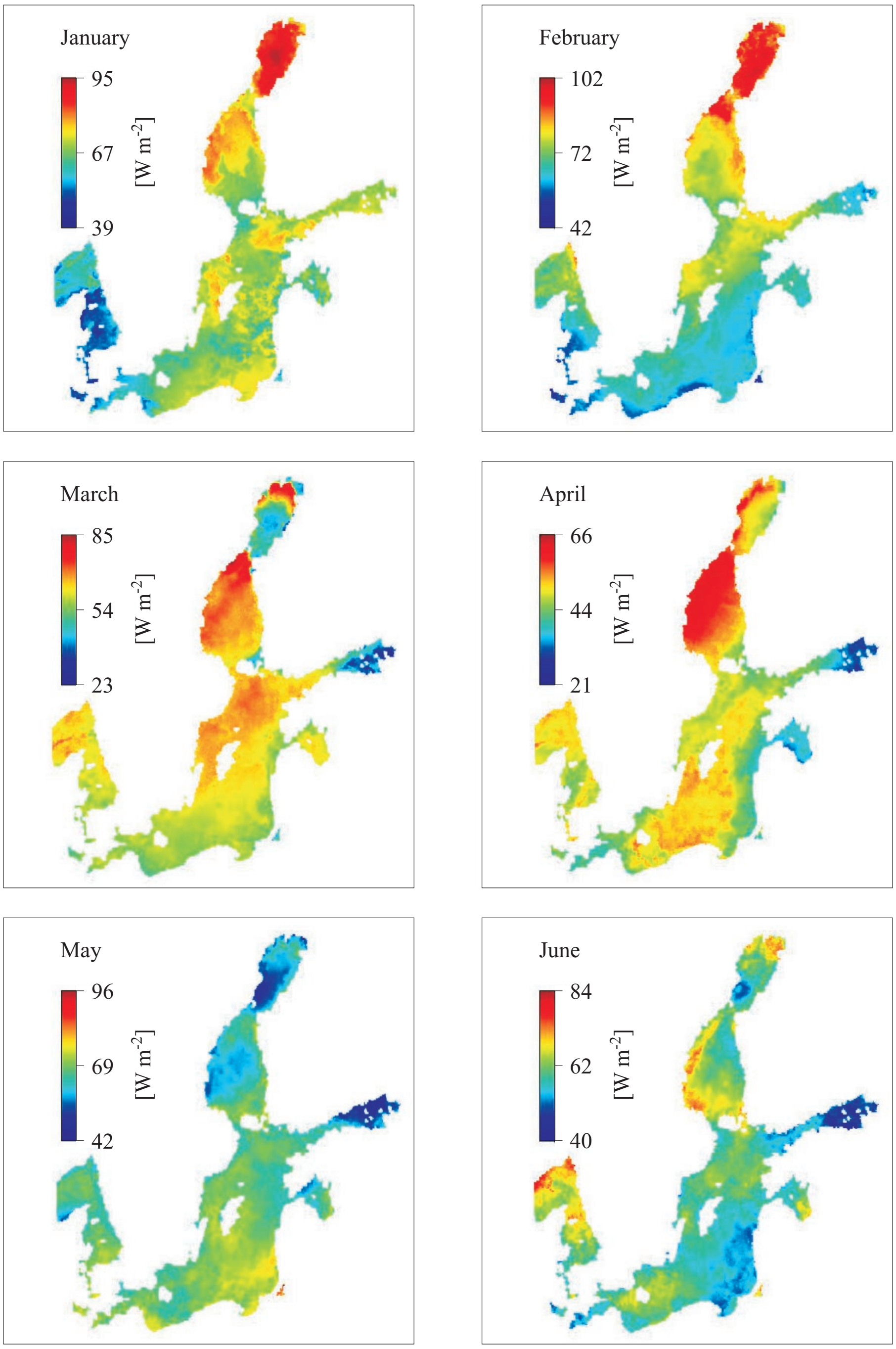

Figure 2. Maps of mean monthly net longwave radiation flux $LW\uparrow\downarrow$ for the Baltic Sea in 2001

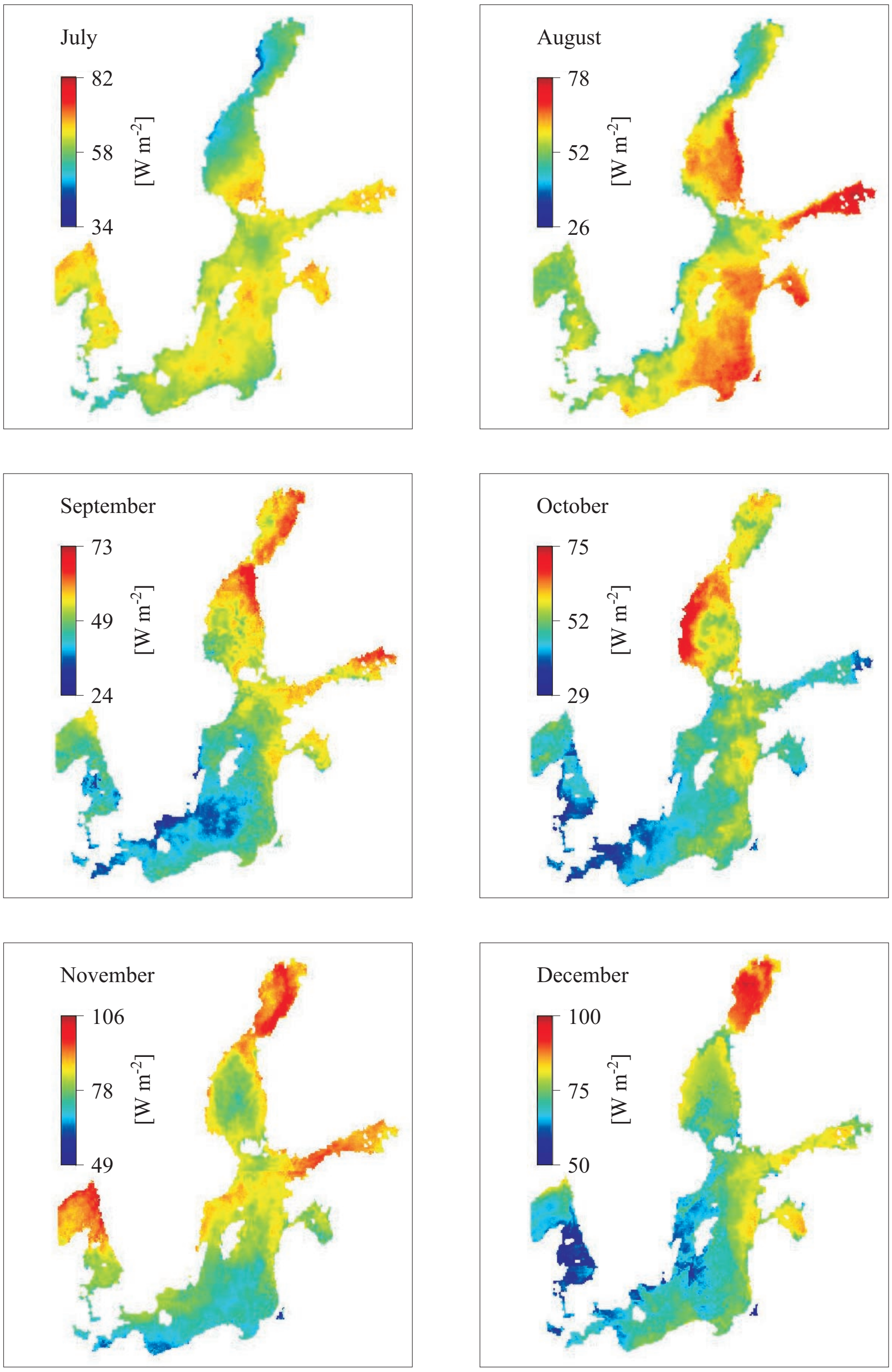

Figure 2. (*continued*)

in Table 2. Modelling of the net radiation flux $LW\uparrow\downarrow$ began with the determination of instantaneous $LW\uparrow$ and $LW\downarrow$ values. Maps showing the distribution of $LW\downarrow$ were computed every three hours for each day. Then, mean values of $LW\downarrow$ were calculated for longer periods of time (weeks and months). The number of useful maps showing the distribution of the upward flux $LW\uparrow$ was determined by the number of distribution maps of T_s obtained for a cloudless sky. With the mosaicking method, a minimum of two to four such maps could be produced per month. The net monthly maps of $LW\uparrow\downarrow$ were obtained by subtracting the mean monthly map of $LW\downarrow$ from the corresponding mean monthly map of $LW\uparrow$ (see Figure 1 and Table 2).

The seasonal and spatial variations in $LW\uparrow\downarrow$ in the Baltic Sea were computed with the above algorithm (Figure 1 and Table 2). Twelve maps of the mean monthly distributions of $LW\uparrow\downarrow$ were compiled (Figure 2), together with one similarly constructed map of its mean annual values (Figure 8, page 163). In addition, the mean monthly net $LW\uparrow\downarrow$ was calculated separately for the eight zones of the Baltic as defined by Łomniewski et al. (1975) (Figure 5, page 160). Table 3 summarises all the results.

Table 3. Mean monthly and mean annual values of the net longwave radiation flux $LW\uparrow\downarrow$ [W m^{-2}] for eight zones of the Baltic Sea and for the whole Baltic in 2001

Zone / Month	Baltic Sea	1	2	3	4	5	6	7	8
January	69	52	55	67	70	65	70	73	86
February	72	65	58	63	71	66	68	80	92
March	61	53	56	57	64	60	46	68	54
April	48	47	45	48	47	36	36	56	51
May	65	67	69	70	68	63	55	63	57
June	60	64	56	58	58	59	50	64	61
July	68	71	60	68	70	75	72	66	60
August	58	54	52	60	59	64	69	61	50
September	48	42	37	41	47	53	57	55	58
October	51	42	38	46	51	47	46	60	57
November	81	83	70	72	81	78	90	82	92
December	72	57	64	71	72	80	80	76	90
year	**63**	**58**	**55**	**60**	**63**	**62**	**62**	**67**	**67**

3. Empirical testing of the algorithm

The algorithm was tested empirically using data gathered during research cruises of r/v 'Oceania' at different seasons in the years 2000–03. The resulting data base consisted of directly measured, instantaneous (mean ten-minute) values of the net longwave radiation, air temperature, water vapour pressure, sea surface temperature, cloudiness and the corresponding

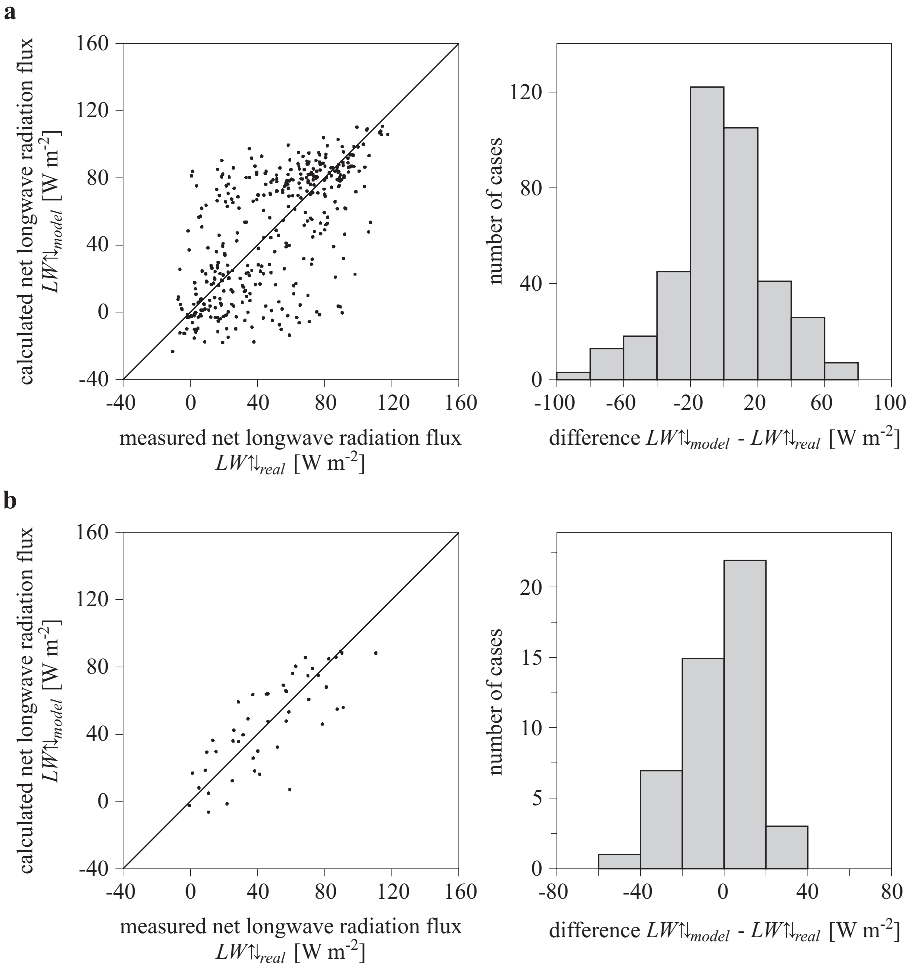

Figure 3. Comparison of measured net longwave radiation fluxes $LW\uparrow\downarrow_{real}$ with values $LW\uparrow\downarrow_{model}$ calculated using the algorithm presented in this work and error histogram for instantaneous values (a), for mean daily values (b)

Table 4. Bias error (MBE), Root Mean Square Error (RMSE) and the correlation coefficient k of the net longwave radiation flux $LW\uparrow\downarrow$ estimated using the algorithm (see text)

Cloud cover coefficient used in the algorithm	BIAS [W m^{-2}]	RMS [W m^{-2}]	k
n_{ICM} (3 hours)	-0.4	30.6	0.63
n_{ICM} (day)	-2.0	20.8	0.75
$n_{ICM} + c$ (3 hours)	-0.5	29.2	0.65
$n_{ICM} + c$ (day)	-0.7	18.1	0.79

spatial and temporal values of air temperature T_{ICM}, water vapour pressure e_{ICM}, cloudiness n_{ICM} provided by the ICM model, and the METEOSAT cloudiness coefficient c. The data base contained 410 points of comparison, including 90 values of c obtained from METEOSAT. The testing procedure involved comparing the net longwave radiation $LW\uparrow\downarrow_{model}$ calculated using the algorithm with the net radiation $LW\uparrow\downarrow_{real}$ measured in situ at sea (Figures 3a and 3b). Figure 3a shows instantaneous values of $LW\uparrow\downarrow$ and Figure 3b the mean daily values of $LW\uparrow\downarrow$ for 50 days (50 points of comparison). The figures also show error histograms: for the instantaneous data the scatter of points is clearly much greater. The RMS statistical error is 29 W m^{-2}. In the case of the second analysis (Figure 3b) the RMS error for the mean daily $LW\uparrow\downarrow$ is 18 W m^{-2}. The error histograms show that in relation to the measured values, the calculated values are slightly overestimated: this is corroborated by the values of the systematic BIAS error (see Table 4). The largest error was due to the total cloudiness parameter n_{ICM} from the UMPL model (for n_{ICM} the RMS is 3 oktas, the correlation coefficient $k = 0.62$; the correlation coefficient for the other parameters is 0.97). On the other hand, the introduction into the algorithm of the coefficient c, determined from METEOSAT data, reduced this latter error by several W m^{-2} (see Table 4). Table 4 lists the RMS statistical errors and the systematic BIAS for instantaneous values of $LW\uparrow\downarrow$, as well as the errors of the formula for $LW\uparrow\downarrow$ derived using cloudiness data based solely on the coefficient n_{ICM} for the whole 24 h, and n_{ICM} for the hours of darkness combined with c from METEOSAT for the hours of daylight. The RMS error of just the downward component of $LW\uparrow\downarrow$, calculated on the basis of coefficient c was estimated at 15 W m^{-2}. This value is barely 2 W m^{-2} greater than the RMS error calculated for the relevant algorithm using the total cloudiness parameter obtained from direct observations of the sky (Zapadka et al. 2007). Coefficient c combines information on total cloudiness with cloud type, which makes it a very useful parameter for estimating the downward radiation flux.

4. Spatio-temporal variation in the net longwave radiation flux $LW\uparrow\downarrow$ for the Baltic Sea: results of computations

As the aforementioned maps show, the net longwave radiation fluxes $LW\uparrow\downarrow$ obtained for the eight zones of the Baltic for 2001 vary from c. 20 to c. 100 W m^{-2}. The higher value applies to the winter, in particular, to parts of the northernmost zone of the Baltic (No. 8 on the map; the division of the Baltic into these zones was suggested by Łomniewski et al. (1975)). The lower value applies above all to the spring months and the southern zones of the sea. Obviously, one cannot draw definitive conclusions about the spatial

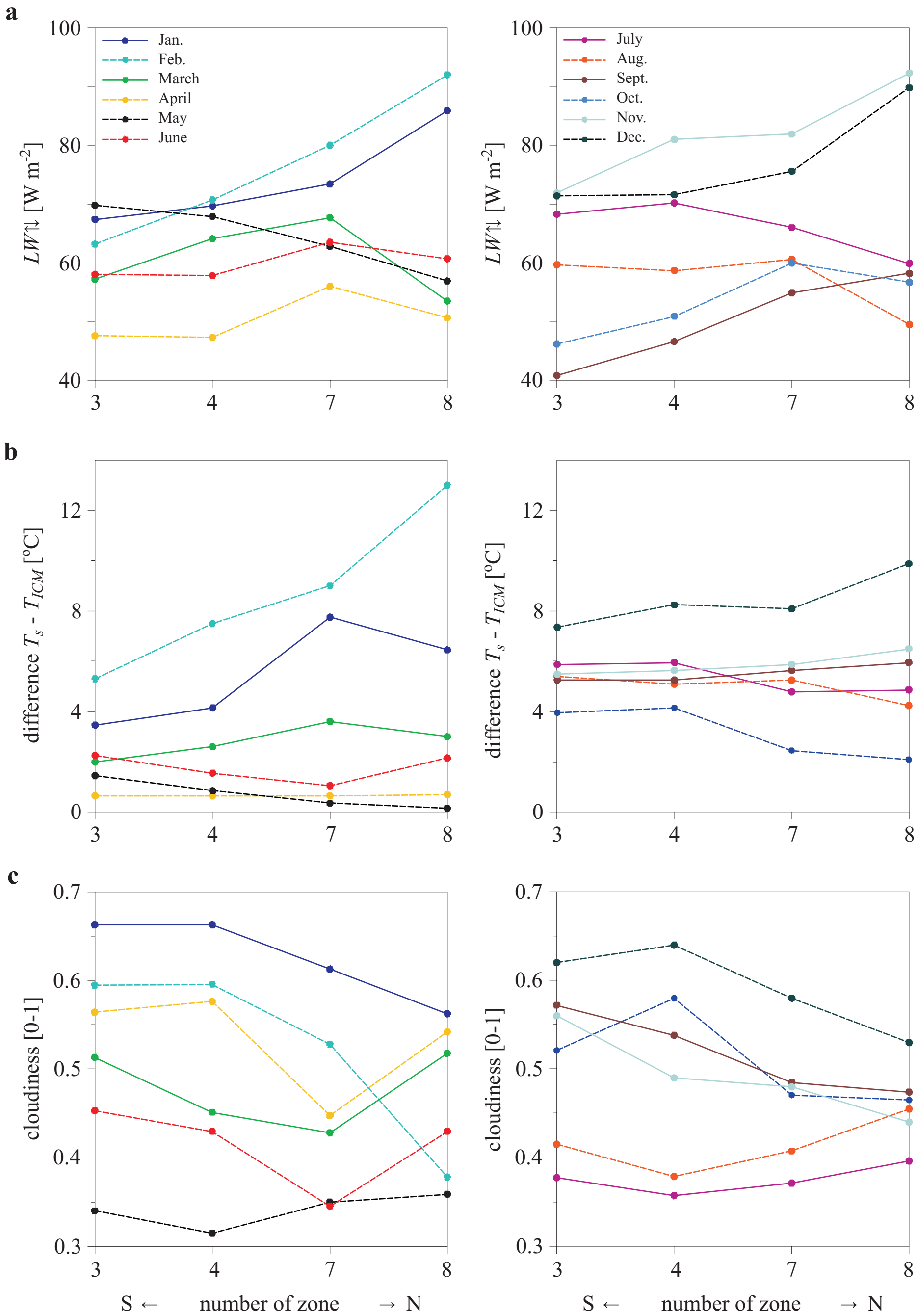

Figure 4. Variability in the monthly net longwave radiation flux $LW\uparrow\downarrow$ (a), difference between sea surface temperature T_s and air temperature T_{ICM} (b), cloudiness c (c) in 2001 as a function of latitude (see Figure 2)

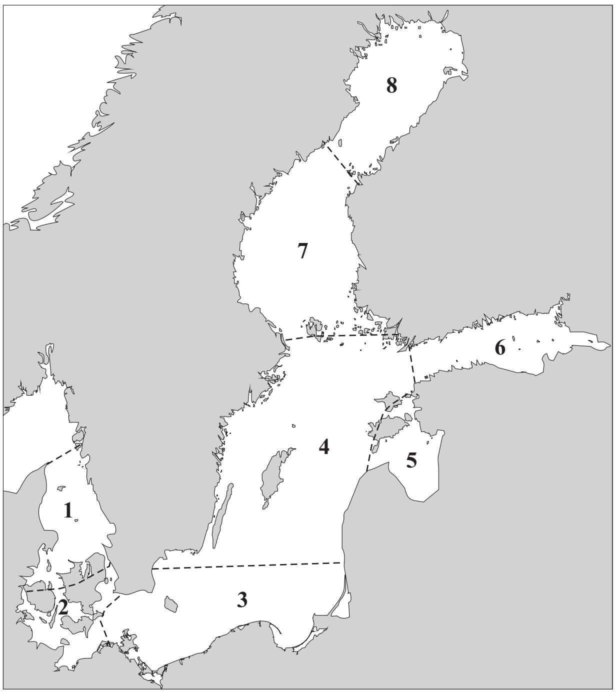

Figure 5. The eight zones of the Baltic Sea (Łomniewski et al. 1975)

trend in the variation of $LW\uparrow\downarrow$ for each month from an analysis of just one year (2001); if the map of the mean annual $LW\uparrow\downarrow$ is analysed, however, such a trend is discernible (see Figure 8, page 163). It is clear from Figure 8 (and also from Table 3, page 156) that in 2001 the mean annual $LW\uparrow\downarrow$ was smallest in the southernmost zone (No. 2) (c. 55 W m^{-2}) and rose with increasing latitude to attain the highest values of c. 67 W m^{-2} in the northernmost zone (No. 8). But the relationship of the monthly mean $LW\uparrow\downarrow$ with latitude is much more complex. This is confirmed by the plots in Figure 4, which illustrate the variations in these values for each month in 2001 with respect to each zone. The analysis of the latitudinal dependence of the variation in $LW\uparrow\downarrow$ took only zones 3, 4, 7 and 8 into account (see Figure 5). Figure 4 makes it clear that rises or falls in $LW\uparrow\downarrow$ in the various zones are linked to the time of year. It shows that $LW\uparrow\downarrow$ rises with latitude in January and February, and again in September November and December. In October and March similar latitudinal rises in $LW\uparrow\downarrow$ take place from zone 3 to zone 7. In April $LW\uparrow\downarrow$ remains constant in zones 3 and 4, but is c. 10 W m^{-2} higher in zones 7 and 8. In May there is a distinct tendency for $LW\uparrow\downarrow$ to fall with latitude. A similar trend is discernible in July, although only from zone 4. In August $LW\uparrow\downarrow$ drops abruptly in zone 7. The physical interpretation of these changes should be sought in the seasonal changes in the parameters governing this flux: clouds and air/water temperatures have the greatest influence on its values. Water vapour pressure is significant only when the sky is cloudless. That is why Figures 4b and 4c show only how cloudiness varies with latitude and the temperature difference between the water surface and the air $T_s - T_{ICM}$. The figures show that when the temperature difference remains relatively constant with latitude, $LW\uparrow\downarrow$ is affected only by changes in cloudiness. Lower cloudiness means higher $LW\uparrow\downarrow$: that is the situation in September, for example. Higher values of $LW\uparrow\downarrow$ may in turn broaden the temperature difference: that is the situation in the winter months (e.g. February), when air temperatures fall well below zero while the water temperature remains above zero. Once the water freezes (zone 8), this difference becomes smaller, as a result of which $LW\uparrow\downarrow$ is also lower. The reverse situation, that is, when $LW\uparrow\downarrow$ falls with latitude and cloudiness increases, prevails, for example, in zone 8 in April. The changes in $LW\uparrow\downarrow$ in May deserve closer examination: $LW\uparrow\downarrow$ falls with increasing latitude, despite the relatively constant level of cloudiness. This decrease is due primarily to the difference $T_s - T_{ICM}$ becoming smaller with latitude. This is because after the winter at high latitudes the water warms up much more slowly than the air. When the cloudiness is as low as it is in May, changes in the water vapour pressure may also significantly influence $LW\uparrow\downarrow$.

The seasonal change in $LW\uparrow\downarrow$ in each of the eight zones of the Baltic was the next question to be analysed. There are certain local maxima and minima of $LW\uparrow\downarrow$ in particular months (see Figure 6). $LW\uparrow\downarrow$ generally attains the highest values in November and December, and in zones 7 and 8 also in January and February, when the temperature of the water is usually

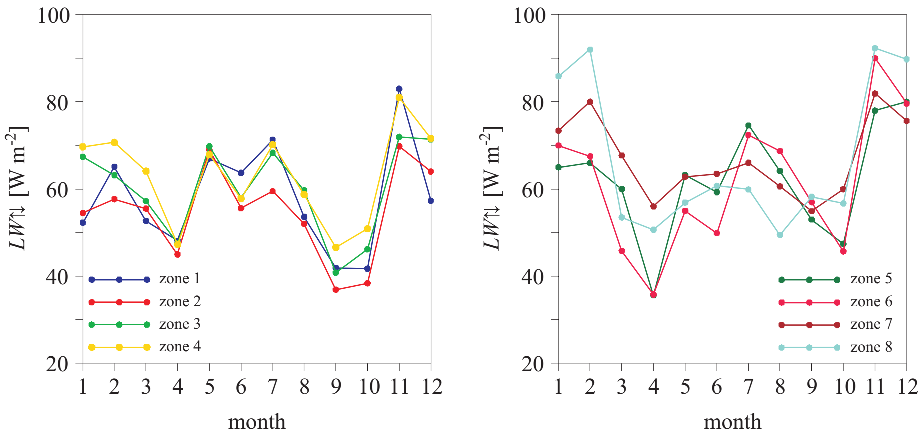

Figure 6. Monthly variations in the net longwave radiation flux $LW\uparrow\downarrow$ for each zone

higher than that of the air and the sea releases more heat to the atmosphere, and the lowest values in some months in spring and autumn (depending on the zones). In the summer, $LW\uparrow\downarrow$ remained stable, neither rising nor falling to any great extent.

Also analysed were the seasonal variations in mean monthly $LW\uparrow\downarrow$ calculated for the entire Baltic Sea (Figure 7a); these were compared with the seasonal changes in this flux determined by other authors (see the caption to Figure 7). This figure shows the seasonal maximum and minimum values of $LW\uparrow\downarrow$. In the present work, the computed total values were lowest in April and in late September-early October (c. 50 W m^{-2}), and highest in late November-early December (c. 80 W m^{-2}). It is clear from Figure 7 that, as in the previous analyses, the monthly changes in $LW\uparrow\downarrow$ are due principally to changes in cloudiness and the difference in sea surface and air temperatures during the year. Analysis of Figures 7a and 7b shows that for small temperature differences $LW\uparrow\downarrow$ increases with decreasing cloudiness and vice versa. Exceptional in this context are the months of February, when a small decrease in cloudiness is compensated by a large air-water temperature difference, and December, when the much higher temperature of the water than the air is compensated by an increase in cloudiness.

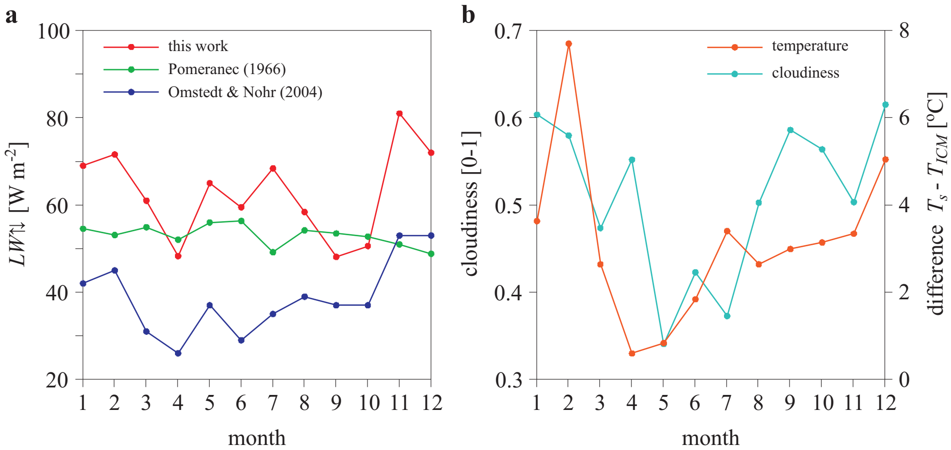

Figure 7. The monthly variation in mean net longwave radiation flux $LW\uparrow\downarrow$ calculated according to Pomeranec (1966), Omstedt & Nohr (2004) and the authors of the present work. The data from Pomeranec (1966) are long-term means; the data from Omstedt & Nohr (2004) and those given by the authors of this work are for 2001 (a). The same dependences for cloudiness and difference between sea surface T_s and air temperatures T_{ICM} (b)

The difference between maximum and minimum values of $LW\uparrow\downarrow$ in 2001 of c. 30 W m^{-2} is greater than the difference between the long-term means of c. 8 W m^{-2} calculated by Pomeranec (1966), but is comparable with the difference between the maximum and minimum $LW\uparrow\downarrow$ for 2001 (c. 27 W m^{-2}) obtained by Omstedt & Nohr (2004). Figure 7 shows that the flux analysed by Pomeranec (1966) did not vary much during the whole year, oscillating around 50 W m^{-2}. The values of $LW\uparrow\downarrow$ calculated by Pomeranec (1966) were smaller than those we computed and coincide with ours only in the zones where we registered minima. Omstedt & Nohr's (2004) data suggest quite a different picture, however. The plot drawn from their results follows a very similar course to ours, especially if the data from the first half of the year are compared, but their absolute $LW\uparrow\downarrow$ for the individual months are c. 25 W m^{-2} lower than ours.

Finally, the 2001 mean annual $LW\uparrow\downarrow$ map was computed (Figure 8): it shows $LW\uparrow\downarrow$ increasing with latitude. In the southern Baltic it also increases with longitude. Our value of 63 W m^{-2} differs quite considerably from the values given in other recent papers (Table 1). Omstedt & Nohr (2004) obtained mean $LW\uparrow\downarrow$ (for the whole Baltic except zones 1 and 2) of 38 W m^{-2} for 2000–02 and 39 W m^{-2} for 2001. If we, too, exclude zones 1 and 2, our mean $LW\uparrow\downarrow$ for the Baltic becomes 63.5 W m^{-2}. On the basis of long-term hydrometeorological data, Pomeranec (1966) estimated this flux at 51 W m^{-2} and Lindau (2002) at 59 W m^{-2}. Using oceanic, atmospheric and mixed models, Jacob (2001) and Meier & Döscher (2002) obtained respective mean fluxes $LW\uparrow\downarrow$ of 57 W m^{-2}, 45 W m^{-2} and 53 W m^{-2} (Table 1). Analysis of the monthly maps of $LW\uparrow\downarrow$ reveals further local maxima and minima, for example, at river mouths and in sea areas temporarily covered with ice.

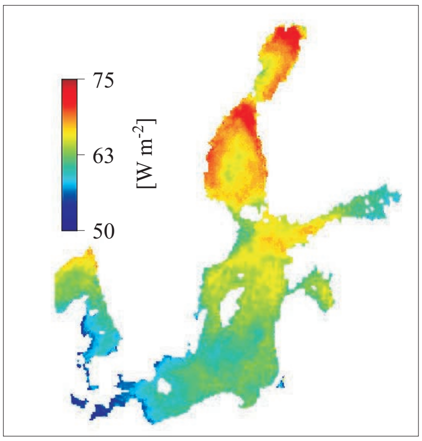

Figure 8. Distribution of the mean annual net longwave radiation flux $LW\uparrow\downarrow$ in the Baltic Sea in 2001

5. Conclusion

The algorithm presented in this paper for determining the net longwave radiation flux $LW\uparrow\downarrow$ enables this magnitude to be computed for any time and location in the Baltic Sea from satellite and model data. With this method, mean daily fluxes $LW\uparrow\downarrow$ can be determined with an RMS statistical error of c. 18 W m^{-2}, and instantaneous values with an RMS error of c. 29 W m^{-2}. The greatest errors in these calculations resulted from the application of UMPL cloud cover data. Replacing these data with the corresponding satellite data greatly improved the precision of the results.

The modelling procedure implemented here yielded twelve maps showing the distribution of mean $LW\uparrow\downarrow$, one for each month of 2001, as well as one map of the annual mean. Analysis of these maps revealed very considerable differentiation of $LW\uparrow\downarrow$ in time and space. The mean monthly values of this flux in the whole Baltic varied from c. 50 to c. 80 W m^{-2} (Table 3). In the separate months of 2001 the differences in $LW\uparrow\downarrow$ in the eight zones of the Baltic were as high as 60 W m^{-2}. The mean annual value of $LW\uparrow\downarrow$ for the whole Baltic was estimated at 63 W m^{-2}; this is higher than the values of the same parameter given by other authors (see Table 1). The distribution maps of $LW\uparrow\downarrow$ show that this parameter varies seasonally during the year and that there is a tendency for the mean annual $LW\uparrow\downarrow$ to increase with latitude. No such trend could be detected in the monthly means, however.

As has already been mentioned, the mean monthly and mean annual $LW\uparrow\downarrow$ for the Baltic given by various authors differ, in some cases very widely. This differentiation is only partly due to the fact that they based their analyses on empirical data from different years or that they averaged them for different, not necessarily coincident, periods of time. It seems to us, however, that the main reason for these divergences lies in methodological errors. These result either from using models and algorithms derived for seas other than the Baltic (e.g. oceanic models), or from the random selection of the empirical data, gathered (mostly on an occasional basis) from randomly located stations in the Baltic. In contrast, the model that we have applied in the present work is founded on the relationships between the net longwave radiation flux $LW\uparrow\downarrow$ and a set of meteorological and hydrological parameters characteristic of this particular sea and established for it; it is not an adaptation of a model based on empirical data from elsewhere. Our algorithm thus enables the net longwave radiation flux $LW\uparrow\downarrow$ of the Baltic Sea to be monitored with greater reliability and effectiveness, and practically on a continuous basis. This is possible using satellite data, or information from operational hydrometeorological models such as UMPL.

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