Communications

Preliminary comparison between various models of the long-wave radiation budget of the sea and experimental data from the Baltic Sea

OCEANOLOGIA, 42 (3), 2000.
pp. 359–369.

KEYWORDS
Long-wave radiation flux
Net infra-red radiation
Energy exchange between the sea and the atmosphere

Tomasz Zapadka
Institute of Physics,
Pedagogical University,
Arciszewskiego 22 B, PL–76–200 Słupsk, Poland;
e-mail: zapad@wsp.slupsk.pl

Sławomir B. Woźniak
Institute of Oceanology,
Polish Academy of Sciences,
Powstańców Warszawy 55, PL–81–712 Sopot, Poland;
e-mail: woznjr@iopan.gda.pl

Manuscript received 14 March 2000, reviewed 4 May 2000, accepted 30 June 2000.

Abstract

This paper discusses existing models of long-wave radiation exchange between the sea surface and the atmosphere, and compares them with experimental data. The latter were based on empirical data collected in the southern Baltic during cruises of r/v 'Oceania'. To a greater or lesser extent, all the models were encumbered with significant systematic and statistical errors. The probable reasons for these discrepancies are given.

1. Introduction

One of the fundamental processes determining the Earth's climate is the constant flow of radiative energy from the Sun reaching the Earth's surface. If all this energy were absorbed by the various ecosystems on the Earth, the planet's mean temperature would rise continuously. Some of this energy is, however, radiated back into space by the land, ocean and atmosphere in the form of electromagnetic waves, mainly from the infra-red (IR) part of the spectrum. The resulting balance between the reflection, absorption and re-emission of solar radiation shapes the Earth's climate. A proper understanding of these mechanisms should therefore enable us, for example, to gauge future temperature changes on our globe.

Owing to the differences in the thermal volumes of the land, ocean and atmosphere, it is important to discover their individual energy balances. Indeed, as seas and oceans cover most of the Earth's surface, it is crucial to determine their energy balances. In order to do this, we need to know the net radiation flux between sea and atmosphere. In the literature there are several practical algorithms for estimating this flux (Fung *et al.* 1984, Bignami *et al.* 1995, Woźniak *et al.* in press). The aim of this paper is to compare these models with empirical data based on *in situ* measurements made in the Baltic Sea.

2. Presentation of the physical problem

Every physical body with a finite temperature ($T > 0$ K) radiates electromagnetic waves. Now a body capable of absorbing all the radiation incident on it would have to be black. The emissivity of this ideal black body is given by the Stefan-Boltzmann law, which states that the energy flux radiated per unit surface area of a black body is proportional to the fourth power of its thermodynamic temperature $E = \sigma T^4$, where $\sigma = 5.7 \times 10^{-8}$ W m^{-2} K^{-4} is the Stefan-Boltzmann constant (see *e.g.* Garbuny 1965). But real bodies do not have the properties of a black body. However, it is assumed that, for the part of the electromagnetic spectrum which is of interest in this work, the properties of these bodies are similar to those of a black body. Hence, one of the assumptions made about a clean and deep sea is that it radiates almost in the same way as a black body. This is how empirical models of the effective IR radiation of a sea surface are derived.

The net IR radiation flux of a sea surface is the difference between the thermal radiation from the sea to the atmosphere $IR\uparrow$ and the thermal radiation from the atmosphere to the sea $IR\downarrow$ (see *e.g.* Dera 1992). The first empirical models of the exchange of long-wave radiation between the Earth's surface and the atmosphere appeared at the beginning of the 20th century. Ångström (1925) and Brunt (1932) were the pioneers in this field, obtaining a function linking the net long-wave radiation and the meteorological parameters of clear skies. Later, these models were adapted to aquatic environments on the basis of the definition of effective net radiation (Bignami *et al.* 1995)

$$IR\uparrow\downarrow = IR\uparrow - IR\downarrow = \varepsilon\sigma T^4 \, f(e) \, g(N), \tag{1}$$

where

ε – emissivity of the water surface,

e – near-surface vapour pressure (in millibars),

N – cloudiness on a 0–1 scale,

T – absolute temperature of the water surface or air.

The respective functions $f(e)$ and $g(N)$ are the dependence of the long-wave flux on humidity and the cloudiness factor. The first part of the difference, $IR\!\uparrow$, is the long-wave radiation flux from the sea (of surface temperature T_s) to the atmosphere. Since it is assumed that the sea radiates almost in the same way as a black body, or more precisely, as a grey body whose total emissivity is reduced in relation to a black body of coefficient ε, one can write

$$IR\!\uparrow \approx \varepsilon\sigma T_s^4, \tag{2}$$

where ε is estimated at between 0.9 and 1, the greater value being closer to reality in the case of a very clear and deep sea. (Pomeranec 1966, Fung *et al.* 1984 and the papers cited there, Dera 1992).

The second part of the effective radiation is the IR flux emitted by the atmosphere to the sea. To describe this flux, empirical formulae are applied. Generally, for a clear sky, the following equation can be given:

$$IR\!\downarrow = \varepsilon\sigma T_a^4(a + be^{1/2}), \tag{3}$$

where a, b are empirically determined coefficients varying within the respective intervals $0.254 < a < 0.66$ and $0.03 < b < 0.09$ (Pomeranec 1966, Timofeyev 1983, Dera 1992 and the papers cited there, Sultan & Ahmad 1994), and T_a – air temperature.

If the sky is cloudy, the formula is more complicated. Clouds increase the IR flux reaching the surface, since they are better absorbers of radiation than a clear atmosphere; they are thus better emitters too. This flux is influenced by cloud cover, the type of clouds, and the place of observation (Fung *et al.* 1984). When skies are cloudy, the downward IR flux can be written as follows:

$$IR\!\downarrow = \varepsilon\sigma T_a^s(a + be^{1/2})\,(1 + cN), \tag{4}$$

where

N – cloudiness measured on a scale from 0 to 1,

c – an empirical coefficient selected by the algorithm's compiler, varying in the interval $0.05 < c < 0.84$ (Fung *et al.* 1984, Dera 1992, Sultan & Ahmad 1994).

Some have added to the function $g(N)$ a further parameter m which depends on cloud type and varies in the interval $1 < m < 2.5$. The term representing cloudiness then takes the form $(1 + cN^m)$ (Fung *et al.* 1984, Pomeranec 1966). Table 1 gives the empirical formulae for the radiative energy budget taken from Fung *et al.* (1984), Bignami *et al.* (1995) and Woźniak *et al.* (in press).

Table 1. Bulk formulae for the net *IR* radiation at the sea surface (Fung *et al.* 1984, and papers cited there, Bignami *et al.* 1995 and Woźniak *et al.* in press)

References	Formula
Swinbank (1963)	$\varepsilon\sigma(T_s^4 - 9.36\times10^{-6}\,T_a^6)(1-0.8\,N)^*$
Anderson (1952)	$\varepsilon\sigma(T_s^4 - T_a^4(0.74+0.0049e))(1-0.8\,N)$
Bunker (1976)	$0.22(\varepsilon\sigma(T_a^4(11.7-0.23e)(1-0.8\,N)) + 4\varepsilon T_a^3(T_s-T_a)$
Efimova (1961)	$\varepsilon\sigma T_a^4(0.254-0.00495e)(1-0.8\,N)$
Hastenrath & Lamb (1978)	$\varepsilon\sigma T_s^4(0.39-0.056q^{1/2})(1-0.53\,N^2)+4\varepsilon\sigma T_s^3(T_s-T_a)$
Clark *et al.* (1974)	$\varepsilon\sigma T_s^4(0.39-0.05e^{1/2})(1-0.69\,N^2)+4\varepsilon\sigma T_s^3(T_s-T_a)$
Berliand & Berliand (1952)	$\varepsilon\sigma T_a^4(0.39-0.05e^{1/2})(1-0.8\,N)+4\varepsilon\sigma T_a^3(T_s-T_a)$
Brunt (1932)	$\varepsilon\sigma T_s^4(0.39-0.05e^{1/2})(1-0.8\,N)$
Woźniak *et al.* (in press)	$\varepsilon\sigma T_s^4(0.39-0.0077e)(1-0.75\,N^2)+4\varepsilon\sigma T_s^3(T_s-T_a)$
Bignami *et al.* (1995)	$\varepsilon\sigma T_s^4-(\in\sigma T_a^4(0.653-0.00535e))(1+0.1762\,N^2)$

*The emissivity of a water surface $\epsilon = 0.98$ was taken from Bignami *et al.* (1995). Only in the model by Woźniak *et al.* (in press) was this coefficient set at 0.95.

These formulae are generally based on the above scheme, and are particularly conspicuous in the models of Berliand & Berliand (1952), Clark *et al.* (1974), Bunker (1976), Hastenrath & Lamb (1978) and Woźniak *et al.* (in press). However, these formulae differ in their selection of empirical coefficients a, b, c, and cloudiness functions. In their empirical model, Hastenrath & Lamb (1978) applied the specific humidity q, instead of the water vapour pressure e. These two values are functionally connected in the equation

$$e = q\,(100\,\mathrm{mbar}) \times \frac{p_s}{\gamma}, \tag{5}$$

where p_s (= 1000 mbar) is the air pressure at the surface, and γ (= 0.622) is the ratio of the molecular weight of water to the molecular weight of dry air. Brunt (1932) presents a formula which includes only the surface water temperature T_s; the air temperature is neglected. Efimova (1961), on the other hand, assumes that air and sea temperatures do not differ significantly, so her equation does not include the surface water temperature.

Since the existing formulae differ one from another in both their analytical form and the selection of empirical coefficients, it is important to assess their applicability to the estimation of the energy budget of marine basins in different regions and at different seasons. This paper compares the differences in the long-wave radiation budget calculated according to the formulae in Table 1 and empirical data from the Baltic Sea.

3. Empirical material

The following meteorological data collected during four cruises of r/v 'Oceania' (PAS) in March, September and October 1998 served to test the models presented in Table 1: water surface temperature, air temperature at 2 m above sea level, air humidity, air pressure, and the overall cloudiness estimated by the observer. The sea surface temperature ranged from 3 to 17°C, the air temperature from −3.5 to 18°C, and the humidity from 2.5 to 17 mbar.

In order to determine the long- and short-wave fluxes of the net radiation, a net radiometer R–7 (Radiation Energy Balance Systems) capable of detecting radiation from 250 to 60 000 nm was used. Because its operational spectrum also included visible radiation, pyrometers (Eppley, Kipp & Zonen) were additionally used to record downward and upward fluxes of short-wave radiation. From this, the long-wave (IR) part of the net radiation could be estimated. The reflection of visible radiation from the sea surface was eliminated using the formula given by Payne (1979) and modified by Rozwadowska (1992)

$$A = t_1 + t_2 \exp^{[h(i/t+j)]}, \tag{6}$$

where

t_1, t_2 – functions of atmospheric transmittances,

t – atmospheric transmittance,

h – solar altitude in degrees,

i, j – calibration constants.

Pyranometric data were collected continuously. For the purposes of comparison, they were averaged over 15-minute intervals, which corresponded to the times of weather observations. The meteorological data were then substituted in the formulae given in Table 1 and the net IR flux calculated. 70 points were obtained in this way, which were then compared with the corresponding empirical means of this flux.

4. Results

Testing the model involved comparing the predicted values with the empirical data obtained as described in Section 3. The discrepancies between the results are presented on the basis of an analysis of statistical and systematic errors (Table 2). Additionally, the correlation between the experimental data and those calculated from individual models and the histogram of errors are compared in Fig. 1. The net IR radiation fluxes calculated from the formulae are indicated by E_{model}, the data obtained experimentally by E_{real}; both are expressed in W m^{-2}.

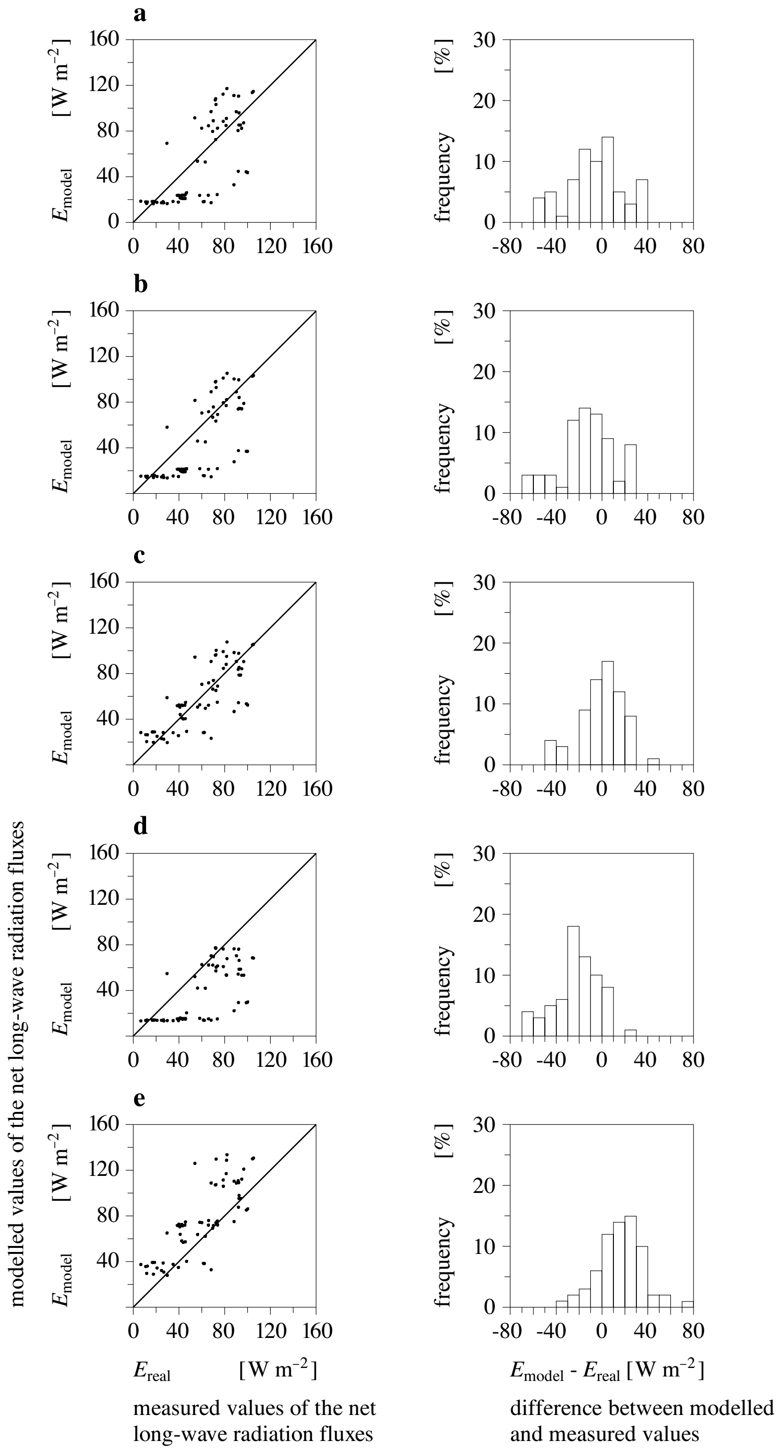
Table 2. The systematic and statistical errors of models, and correlation coefficients

References	Systematic error $\langle\varepsilon\rangle$ [W m^{-2}]	Statistical error σ_ε [W m^{-2}]	Correlation coefficient r
Swinbank (1963)	–5.7	24.6	0.73
Anderson (1952)	–11.8	22.4	0.73
Bunker (1976)	–0.1	18.4	0.76
Efimova (1961)	–21.9	20.1	0.69
Hastenrath & Lamb (1978)	16.3	19.2	0.79
Clark *et al.* (1974)	13.3	22.1	0.79
Berliand & Berliand (1952)	–0.5	21.2	0.77
Brunt (1932)	–14.1	20.9	0.73
Woźniak *et al.* (in press)	20.4	27.3	0.78
Bignami *et al.* (1995)	32.4	18.3	0.79

where
$\varepsilon = E_{\mathrm{model}} - E_{\mathrm{real}}$,
$\langle\varepsilon\rangle$ – arithmetic mean of errors (systematic error),
σ_ε – standard deviation of errors (statistical error),
$r = \frac{\langle E_{\mathrm{real}}\, E_{\mathrm{model}}\rangle - \langle E_{\mathrm{real}}\rangle\, \langle E_{\mathrm{model}}\rangle}{\sigma_{E_{\mathrm{real}}}\, \sigma_{E_{\mathrm{model}}}}$.

As shown in Table 2, the systematic errors of the models differ significantly over a range from -21.9 to 32.4 W m^{-2}. This means that the net radiation flux has been considerably over- or underestimated.

Fig. 1. Comparison between modelled and measured values of the long-wave radiation fluxes and error histograms for the formulae given by Swinbank (1963) (a), Anderson (1952) (b), Bunker (1976) (c), Efimova (1961) (d), Hastenrath & Lamb (1978) (e), Clark *et al.* (1974) (f), Berliand & Berliand (1952) (g), Brunt (1932) (h), Woźniak *et al.* (in press) (i), Bignami *et al.* (1995) (j)



a
b
c
d
e
modelled values of the net long-wave radiation fluxes
E_{model} [W m^{-2}]
frequency [%]
E_{real} [W m^{-2}]
measured values of the net long-wave radiation fluxes
E_{model} - E_{real} [W m^{-2}]
difference between modelled and measured values

Fig. 1.

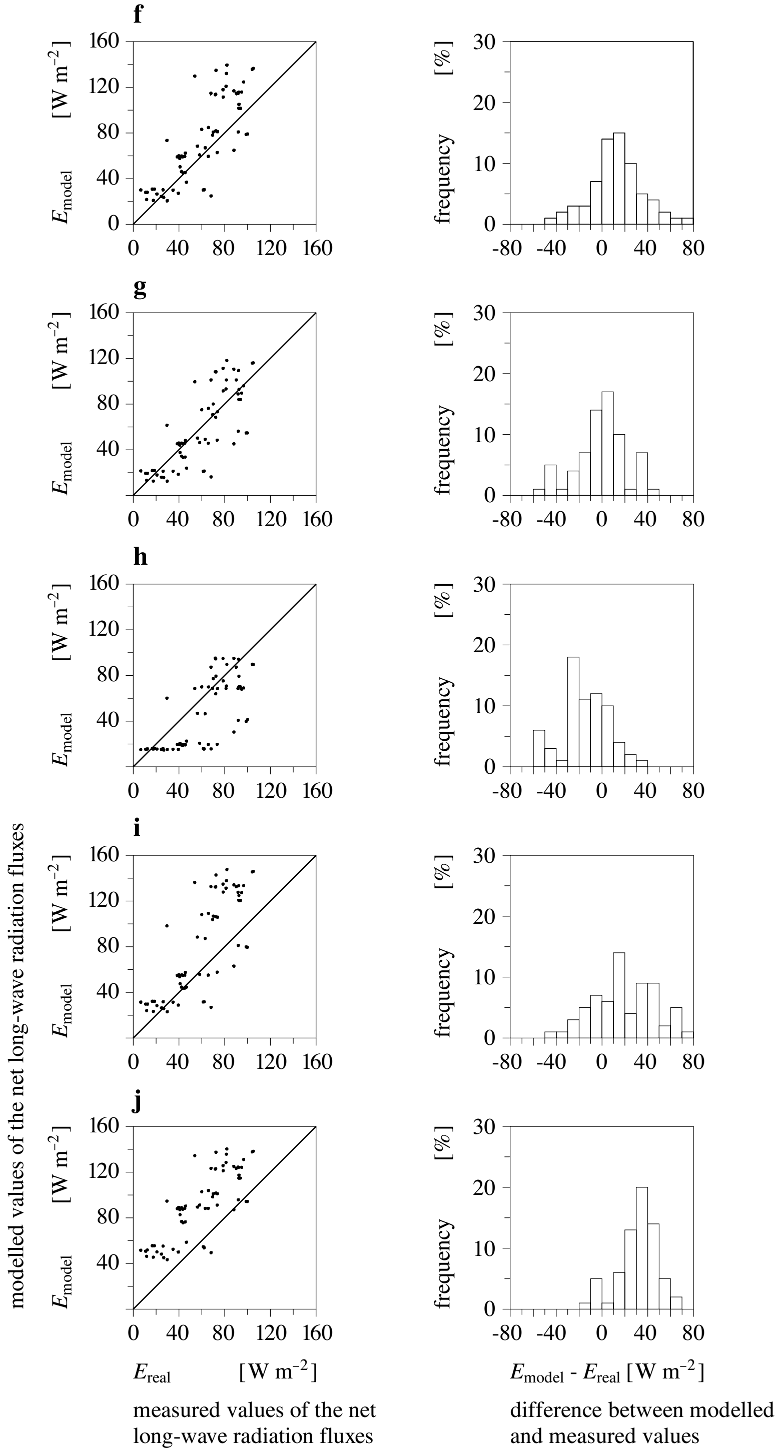


Fig. 1. (continued)

The models of Berliand & Berliand (1952) and Bunker (1976) give the best value (closest to zero), those of Efimova (1961) and Bignami *et al.* (1995) yield extreme values.

The statistical errors of all the models are rather high, ranging from 18.4 W m^{-2} for Bunker's (1976) model to 27 W m^{-2} for the formula by Woźniak *et al.* (in press).

The correlation coefficient between the real and predicted values can be used as another statistical criterion. It is rather low (Table 2), varying from 0.69 for Efimova's (1961) formula to 0.79 for those by Clark *et al.* (1974), Hastenrath & Lamb (1978), and Bignami (1995). It is significant that the correlation coefficient is smallest for all the formulae that omit one of the environmental parameters, such as the surface water temperature (Efimova 1961), humidity (Swinbank 1963) or air temperature (Brunt 1932).

If all three statistical criteria are taken into account, none of the models discussed here is in good agreement with the empirical data, and so none can be applied in unmodified form to Baltic Sea conditions.

This may be due to the fact that these models were devised not only for land (soil) and sea, but also for different geographic regions. Furthermore, the atmospheric conditions in a given basin are characteristic of that basin only. Thus, *e.g.* the Bignami *et al.* model (1995) was based on data collected over the Mediterranean Sea. The air and sea temperatures there ranged from 13 to 16°C, figures which only partly coincide with Baltic Sea data. The various models thus only work well in the conditions for which they were derived.

5. Conclusions

The aim of this paper was to discuss the existing models of long-wave radiation exchange between the sea surface and the atmosphere, and to compare them with experimental data. The latter were based on empirical data collected in the southern Baltic during cruises of r/v 'Oceania'. The utility of particular model formulae for the Baltic Basin can be determined on the basis of error analysis (Table 2). To a greater or lesser extent, all the models were encumbered with significant systematic and statistical errors. This is probably due to the IR radiation emitted by the atmosphere being measured inaccurately as a result of the analytical approximation of this flux. It would be important to define more precisely the influence of cloudiness parameters on this balance, because the optical properties of clouds are highly diverse. A detailed analysis of the possibility of adapting these formulae to Baltic Sea conditions requires, among other things, the collection and analysis of a broader data base, as well as an improvement in the methods of estimating cloud cover. The authors are at present investigating these very problems.

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