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An Improvement of Parametrization of Short-Wave Radiation at the Sea Surface on the Basis of Direct Measurements in the Atlantic

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Abstract—Based on the data of recent high-accuracy measurements of the incoming fluxes of short-wave radiation in 2004–2006 in the Atlantic, errors of existing short-wave radiation parametrizations are estimated. It is shown that the largest errors occur under large cloud amount. A parametrization scheme is proposed that takes into account not only total cloudiness, but also morphological types of clouds. The scheme improves parametrization under large cloud amount.

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INTRODUCTION

Energy fluxes between the ocean and the atmosphere are the key components of interactions between these primary media of the climate system. The main sources of data on the global fields of energy fluxes in the ocean–atmosphere system are long-term adaptive analyses of observations in the atmosphere (reanalyses), satellite data, and estimates derived from ship observations on the basis of integral parametrizations. The reanalyses provide global coverage and a sufficiently high resolution; however, they depend not only on parametrizations that are used in the models, but also on parameters diagnosed by the model. Satellite data are more promising; however, their series are still short and need more careful validation. As a result, the climatology of ocean–atmosphere energy fluxes based on ship observations remains the most important source of global permanent information about the interaction of the two media.

In the last 10–20 years, considerable progress has been made in the development of methods for calculation of heat fluxes at the sea surface. The main efforts have been aimed at improving the parametrizations of turbulent fluxes of sensible and latent heat. To some extent, this reflects the ideas formed in the 1980s that low accuracy of turbulent flux parametrizations hampers reliable estimation of the heat budget of the ocean. These works have resulted in the COARE-3 parametrization which provides turbulent flux estimation with an accuracy of ±5 W/m^2 for most conditions.

The short-wave radiation parametrizations stopped developing between the 1980s and 1990s [2–5], when a certain limit of accuracy has been reached for the parametrizations based on cloud data. It became clear that further improvement of the parametrizations was possible, but it required more detailed information on cloudiness. At the same time, such information could not be available widely, and thus any improved parametrizations turned out to be hardly applicable to the data from the International Comprehensive Ocean–Atmosphere Data Set (ICOADS).

As a result, the estimates of radiation fluxes in the ocean–atmosphere system are less accurate than the turbulent ones. It is known that global estimates of the ocean–atmosphere interaction (e.g., [2]) are characterized by bias and random errors (in the heat budget, up to 30 W/m^2). Given the relatively high accuracy of turbulent flux estimation and the impossibility of such errors arising from representativeness inaccuracies, the radiation fluxes seem to be the most probable source of them.

At the end of the 1990s, the ICOADS was significantly updated, so that not only the total cloudiness amount data, but those on amounts and types of clouds in different layers have been included in the initial data of ship observations. In the present-day archive, 50 to 80% of ship observations contain much more complete information on the cloud cover structure than that on the total cloud amount. This allows including these characteristics in the radiation parametrization. However, the existing parametrizations

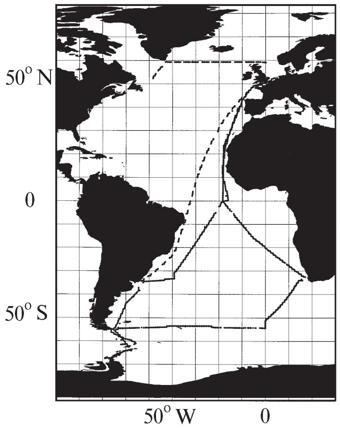

Fig. 1. Scheme of cruises of the research vessels.

make use of total cloudiness only (or total and low cloud amount, as in the GGO parametrization [2]) and cannot assimilate new, more complete data. So, at present, a new parametrization scheme is necessary to be developed, as based on more comprehensive information on atmospheric conditions over the oceans.

1. DIRECT RADIATION MEASUREMENTS WITHIN THE FRAMEWORK OF THE MORE PROJECT

The Meridional Oceanic Radiative Experiment (MORE) is a joint project by Shirshov Institute of Oceanology, Russian Academy of Sciences, and Leibnitz Marine Institute of Kiel University (IFM-GEOMAR, Germany), aimed at conducting high-accuracy measurements of radiation flux components at the sea surface, on an example for the Atlantic.

The work is based on observations performed onboard the research vessels (R/V) of the Russian Academy of Sciences (*Akademik Ioffe* and *Akademik Sergei Vavilov*) during 2004–2006. The cruises were conducted in different parts of the Atlantic (Fig. 1):

1. October–December 2004, R/V *Akademik Sergei Vavilov*, Kaliningrad (Russia)–Cape Town (South Africa)–Ushuaia (Argentina);
2. June–July 2005, R/V *Akademik Ioffe*, Gdansk (Poland)–Cape Farewell (Greenland)–St. John’s (Canada);
3. September–November 2005, R/V *Akademik Ioffe*, Bremerhaven (Germany)–Montevideo (Uruguay)–South Shetland Islands–Ushuaia (Argentina);
4. March–April 2006, R/V *Akademik Ioffe*, Montevideo (Uruguay)–Kaliningrad (Russia).

The short- and long-wave radiation fluxes are recorded with the total radiation radiometer Kipp&Zonen CNR-1, which measures radiation within the range of 0.3–50 μm. This spectrum covers solar radiation from 0.3 to 3 μm and infrared radiation from 5 to 50 μm. The field of view of the instrument is 180°, which ensures radiation measurement from both the upper and the lower hemispheres.

Onboard, radiation fluxes were measured with 10-s sampling; later, the data were averaged over 1 h. The algorithm for calculation of hour-mean totals of short-wave radiation flux is

$$\overline{Q} = \left(\frac{Q_1 + Q_{361}}{2}\right) + \sum_{2}^{360} Q_i \Big/ 360, \qquad (1)$$

where $\overline{Q}$ is the hour-mean flux of incoming short-wave solar radiation and Q_i is the instantaneous value of incoming total solar radiation. The time moment corresponding to $i = 1$ is that of half-hour to the integer hour, and $i = 361$ that of half-hour past integer hour. In total, for each hour, averaging over 361 instantaneous values is carried out.

In total, during the observation periods of all cruises, 131 days of radiation flux measurement were accumulated. From these data, 1598 hour-mean values of short-wave solar radiation were obtained for different solar elevations and cloud amounts (Table 1). For all calculated values of radiation fluxes, parallel observations of the following meteorological elements quantities are available: air and sea surface temperature, air humidity, wind speed and direction, atmospheric pressure, and a detailed description of clouds (total and low cloud amounts and morphological types of clouds). Note that total and low cloud

Table 1. Distribution of numbers of hour-mean values of short-wave radiation flux as dependent on cloud amount and the solar elevation h

$\sin h$	Cloud amount, octas								
	0	1	2	3	4	5	6	7	8
0.05–0.15	5	5	6	6	6	3	13	17	53
0.15–0.25	6	3	5	10	9	9	12	16	78
0.25–0.35	4	4	6	11	7	2	9	13	69
0.35–0.45	6	6	7	4	7	6	15	25	74
0.45–0.55	5	7	8	14	7	5	11	22	79
0.55–0.65	5	7	11	14	12	9	13	22	90
0.65–0.75	4	7	10	10	17	11	23	41	101
0.75–0.85	3	7	8	12	11	20	32	41	127
0.85–0.95	2	7	9	10	16	23	25	29	49
0.95–1.00	0	1	6	2	11	5	12	14	14

amounts are estimated not in a 10-point scale (as familiar for Russian meteorology), but in an internationally accepted 8-point scale (octas), because the measurements were carried out within the framework of the international project.

2. TESTING THE EXISTING PARAMETRIZATIONS

2.1. The Dobson–Smith Parametrization

In the Dobson–Smith parametrization, the short-wave radiation coming to the surface is expressed as

$$Q = S_a T_F, \tag{2}$$

where $S_a = S_0 \sin h$ is short-wave radiation at the top of the atmosphere, S_0 is the solar constant equal to 1368 W/m^2, h is the solar elevation, and T_F is the transmission coefficient of the atmosphere. In this parametrization, it is assumed that T_F depends on cloud amount and the solar elevation. For every cloud amount point, T_F is related to the solar elevation by simple linear dependence. Note that in the development of this parametrization, Dobson and Smith have used only the weather ship data, which have been obtained within strictly definite coordinate ranges in the midlatitudes of the ocean; they do not cover all variety of weather and climate conditions.

The resulting formula for calculation of short-wave radiation coming to the sea surface, in the Dobson–Smith parametrization, is

$$Q = S_a(a_i + b_i \sin h), \tag{3}$$

where a_i and b_i are empirical coefficients depending on cloud amount [4].

2.2. The GGO Parametrization

A large volume of observations under different weather and climate conditions allows developing a rather comprehensive parametric model for indirect estimation of short-wave radiation at different latitudes in the ocean. In this work, for comparison, two parametrizations developed at GGO are considered: in the first one, a single layer of clouds is suggested, that is, only total cloud amount is taken into account; in the second one, total and low cloud amounts are included.

As a starting point to develop the GGO parametrization, the following representation of short-wave radiation Q_0 reaching the sea surface under clear sky is used:

$$Q_0 = S_a p_0, \tag{4}$$

where p_0 is the coefficient of attenuation in the cloudless atmosphere. Usually, p_0 is taken equal to the Bouguer coefficient of transparency for the optical air mass of 2 (that is, for the solar elevation of 30°).

On the basis of the fact that the attenuation of short-wave radiation by water vapor over the oceans far exceeds the attenuation by aerosols, empirical formulas have been proposed in [2] for dependence of the transparency coefficient p_2 on vapor partial pressure.

The short-wave radiation flux in the case of clear sky in this scheme is parameterized as

$$Q_0 = c(\cos h)^d, \tag{5}$$

where c and d are empirical coefficients, which depend on the transparency coefficient p_2.

For cloudy sky, the main factors affecting solar radiation coming to the sea surface are cloud amount, their distribution over the sky, the rate of Sun screening, vertical thickness of the clouds, their base height, and microphysical characteristics. In this case, the incoming solar radiation flux is calculated from a function $f(n_t, n_l)$ depending on total, n_t and low, n_l, cloud amounts and defined as the ratio of real radiation Q to the possible one Q_0, that is,

$$f(n_t, n_l) = Q/Q_0. \tag{6}$$

From the available volume of the data, for each point of the total cloud amount, as dependent on solar elevation, S.P. Malevskii-Malevich [2] has calculated the coefficient of transparency. Unlike the analytical form for the transmission coefficient in the Dobson–Smith parametrization, the transmission coefficient in the GGO parametrization is represented in tabulated form. This is made to decrease the error arising from linear approximation, especially under low points of cloudiness, when the linear approximation is rather coarse.

In [2], it has been also suggested to use the function f as divided into two parts: for low clouds and for middle and upper ones, owing to the fact that the attenuation of the short-wave radiation flux by the low clouds is much stronger than that caused by middle and upper clouds. The values of $f(n_t, n_l)$ have been determined from statistical processing of the data for different solar elevations.

The radiation flux Q, which reaches the surface, in the case of cloudy sky is determined from the formula

$$Q = Q_0 f(n_t, n_l). \tag{7}$$

2.3. Estimation of Accuracy of the Parametrizations

As criteria for estimation of the parametrizations, the following quantities are chosen: mean difference between the observed radiation values and those calculated from the proposed parametrization schemes: the difference shows the parametrization bias; root-mean-square deviation of observations from the calculated values, which shows random error; and correlation between the observed and calculated values, showing their degree of connectedness. For the calculated criteria, the plots of their dependence on the total cloud amount are presented in Fig. 2. It can be seen that the GGO parametrization mainly underestimates the radiation flux, while the Dobson–Smith parametrization underestimates it under small and large total cloud amounts, but overestimates it under middle amounts.

Under clear sky, the only factor affecting the radiation flux changes is represented by the Sun elevation over the horizon; so, the parametrizations should describe well the clear sky condition; this can be clearly seen at the plots for the GGO parametrization. The Dobson–Smith parametrization is developed for midlatitudes and on the data for separate sites; so, it underestimates the flux. The results of both parametrizations under middle amounts of clouds are almost similar, with differences up to 30 W/m^2. Under larger amounts of total cloudiness, in the GGO parametrization, differences between real and calculated values grow up to 60 W/m^2, which reflects high variability of radiation fluxes under cloudy sky. Under overcast conditions, small differences are caused by small values of observed and calculated values.

The correlation coefficient is significant; the character of its changes is similar for both parametrizations: under small amounts of clouds (< 3 octas), it is about 0.95; with increasing cloudiness, and thus increasing number of factors affecting radiation flux variability, the correlation coefficient decreases: for middle cloudiness it is about 0.90, and for overcast sky, 0.75 (Fig. 2c).

The partitioning into total and low clouds in the two-layer GGO parametrization is most efficient for total cloud amounts of 6–8 octas. In this case, the correlation coefficient for some scenarios of cloud evolution (e.g., the total cloud amount is constant, while the low cloud amount varies) can be significantly higher than in the one-layer model. For example, under total cloud amounts of 7–8 octas, the correlation coefficient in the two-layer model is about 0.75, while under low cloud amounts of 7–8 octas, it increases up to 0.85–0.90.

3. THE LVOAMKI PARAMETRIZATION

After analyzing deficiencies of the parametrizations of short-wave radiation at the sea surface, a new scheme is developed called parametrization by Laboratory of Ocean–Atmosphere Interaction and Climate

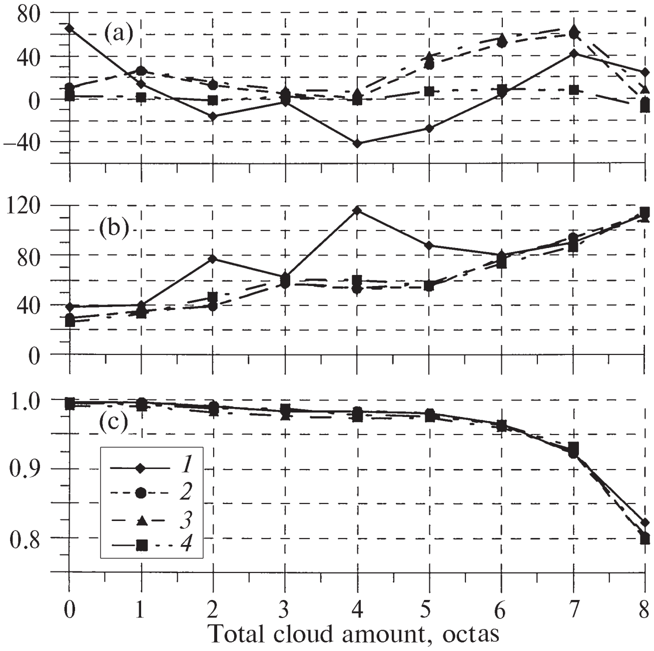

Fig. 2. Dependences on total cloud amount for statistical characteristics of errors for (*1*) Dobson–Smith, (*2*, *3*) GGO (one-layer model and two-layer model, respectively), and (*4*) LVOAMKI parametrizations. (a) Mean difference (W/m^2) between measured and calculated radiation fluxes; (b) rms deviation (W/m^2); (c) correlation coefficients.

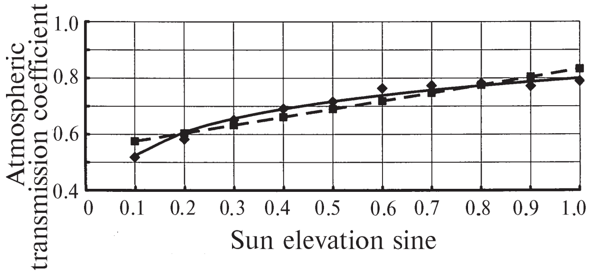

Fig. 3. Dependence of the transmission coefficient on sine of the solar elevation for cloud amount of 1 octa from the LVOAMKI parametrization. Dashed line: linear approximation ($y = 0.28x + 0.54$; $R^2 = 0.85$), solid line: logarithmic approximation ($y = 0.12\ln x + 0.80$; $R^2 = 0.97$).

Change Monitoring (LVOAMKI) of the Institute of Oceanology of the Russian Academy of Sciences. The existing parametrizations, which take into account total cloud amount only, are mainly linear, while in Fig. 3, it can be seen that under low solar elevations, dependence of the transmission coefficient on h deviates significantly from the linear one.

To obtain a logarithmic approximation of $T_F(h)$, the ratios Q/S_a are grouped with respect to the total cloud amount. Then, for each group, the averaged ratio is calculated within the ranges of sine of the solar elevation, with a 0.1 step; these averaged ratios are approximated by logarithmic dependences for each octa i of cloud amount; the coefficients are determined by the least-squares technique. As a result, the following empirical coefficients are obtained for logarithmic approximation for the transmission coefficient of the atmosphere:

i	0	1	2	3	4	5	6	7	8
a_i	0.16	0.13	0.13	0.13	0.17	0.15	0.14	0.15	0.12
b_i	0.82	0.80	0.78	0.76	0.74	0.71	0.67	0.60	0.39

Using these values, in the proposed parametrization, the total solar radiation Q coming to the sea surface can be found from the formula

$$Q = S_a(a_i + b_i\ln(\sin h)), \tag{8}$$

Table 2. Comparison of errors of logarithmic approximation of LVOAMKI and of Dobson–Smith and GGO parametrizations

Parametrization	Cloudiness, octas	$\overline{Q}_{\text{obs}}$	$\overline{Q}_{\text{mod}}$	Δ	rms	r
Dobson–Smith	0	476	411	65	38	0.991
GGO						
One-layer		476	465	11	29	0.996
Two-layer		476	465	11	29	0.996
LVOAMKI		476	473	3	26	0.995
Dobson–Smith	1	610	596	14	40	0.990
GGO						
One-layer		610	584	26	35	0.996
Two-layer		610	583	27	35	0.996
LVOAMKI		610	608	2	33	0.993
Dobson–Smith	2	576	592	–16	77	0.982
GGO						
One-layer		576	563	13	39	0.991
Two-layer		576	561	16	39	0.991
LVOAMKI		576	577	–1	46	0.987
Dobson–Smith	3	526	529	–3	63	0.977
GGO						
One-layer		526	522	5	58	0.983
Two-layer		526	518	9	58	0.983
LVOAMKI		526	524	2	60	0.978
Dobson–Smith	4	592	633	–41	116	0.974
GGO						
One-layer		592	590	1	53	0.984
Two-layer		592	585	7	54	0.984
LVOAMKI		592	593	–1	61	0.978
Dobson–Smith	5	636	664	–27	88	0.974
GGO						
One-layer		636	605	32	55	0.981
Two-layer		636	596	40	57	0.981
LVOAMKI		636	629	7	56	0.977
Dobson–Smith	6	555	550	4	80	0.960
GGO						
One-layer		555	503	52	77	0.964
Two-layer		555	498	57	77	0.965
LVOAMKI		555	546	9	73	0.964
Dobson–Smith	7	465	424	41	90	0.927
GGO						
One-layer		465	405	60	94	0.923
Two-layer		465	400	65	94	0.923
LVOAMKI		465	457	8	87	0.932
Dobson–Smith	8	245	222	25	112	0.805
GGO						
One-layer		245	249	–4	112	0.802
Two-layer		245	237	9	108	0.823
LVOAMKI		245	254	–9	115	0.798

Note. $\Delta = \overline{Q}_{\text{obs}} - \overline{Q}_{\text{mod}}$, rms is the root-mean square deviation.

where S_a is the short-wave radiation at the top of the atmosphere, calculated theoretically; a_i and b_i are empirical coefficients given above for every octa of cloud amount.

Like other parametrizations in which the transmission coefficient depends on the total cloud amount, the proposed parametrization is most efficient for clear (or almost clear) sky conditions. As could be expected, the logarithmic approximation, instead of the linear one, for the atmospheric transmission coefficient dependence on the solar elevation sine allows improving the parametrization, as compared with the Dobson–Smith one. The accuracy of the new approximation is close to that of GGO parametrization; still, the latter, when considered for separate octas, remains more accurate, possibly due to shorter series of observations. The data in Table 2 allow comparing the errors of LVOAMKI, Dobson–Smith, and GGO Parametrization.

The most complicated cases for the short-wave radiation parametrization are those with overcast or almost overcast sky. Because of that, it is decided, for 7–8 octas, to use more information on the clouds, that is, not only the amount but also morphological types of clouds, according to [1]. For this purpose, for total cloudiness of 8 octas, basing on the observational data, three morphological classes of cloudiness are distinguished:

(1) Bad weather clouds. In this class, cases with 8 octas of low clouds are observed (St fr or Cu fr) or 8 octas of middle-level clouds (As op or Ns).

(2) Middle-level clouds. In this class, the cases are included with 8 octas of Ac op, not transparent and lying at different levels; non-transparent layer of clouds which do not move; Ac together with As and/or Ns.

(3) Stratocumulus clouds. In this class, the cases of 8 ostas of Sc are included, which can arise from cumulus clouds.

For the selected classes, the analogous formulas are obtained to calculate the incoming flux of short-wave radiation:

$$Q = S_a(a_i + b_i\sin h) \tag{9}$$

(S_a = 1368sin$h$; a_i and b_i are empirical coefficients depending on the cloud class). In this case, for 8 octas cloudiness, the linear, not logarithmic, approximation was used (the same as in the Dobson–Smith parametrization), because, under low h, nonlinearity is essential only for small amounts of clouds; under overcast sky, the transmission coefficient depends linearly on the solar elevation. The empirical coefficients in (9) for cloud classes (i), as obtained by the least-square technique, are as follows:

i	1	2	3
a_i	0.14	0.34	0.33
b_i	0.12	0.19	0.17

With partitioning of the cases with 8 octas of total cloudiness, the parametrization efficiency increases. This allows developing a complex scheme of parametrization: for cloud amounts of 7–8 octas: approximation for the corresponding class of clouds is preferable, while in other cases, the logarithmic approximation for octas should be used.

Comparison of the results of radiation flux calculation using the parametrization with the logarithmic approximation only and with overcast cloudiness classification shows that rms deviation decreases from 119 W/m^2 in the former case to 101 W/m^2 in the latter, that is, in the complex scheme. Simultaneously, the correlation coefficient increases from 0.76 to 0.82.

CONCLUSIONS

On the basis of observations aboard the RAN ships, an archive is developed of data on short- and long-wave fluxes of incoming and outgoing radiation over the Atlantic.

For short-wave solar radiation coming to the sea surface, a parametrization is developed, in which the transmission coefficient depends logarithmically, not linearly, on the solar elevation, which improves the calculation accuracy significantly.

Unlike the GGO parametrization, which also takes into account the transmission coefficient dependence on the solar elevation sine, analytical expressions are given for this dependence (instead of tables), which is more convenient for practical calculations using modern computational facilities.

It is shown that introducing the classification for overcast sky, which accounts for amounts of both total and low clouds and for morphological types of clouds, allows improving the parametrization.

REFERENCES

1. *Atlas of Clouds*, Ed. by A. Kh. Khrgian and N. I. Novozhilova (Gidrometeoizdat, Leningrad, 1978) [in Russian].
2. G. V. Gidryuk, B. N. Yegorov, and S. P. Malevskii-Malevich, *Determination of Radiation Budget of the Sea Surface. Handbook* (Gidrometeoizdat, St. Petersburg, 1992) [in Russian].
3. A. M. daSilva, C. C. Young, and S. Levitus, *Atlas of Surface Marine Data 1994*, NOAA, Atlas Nesdis7, U.S. Dept. of Commerce, NOAA, Washington D.C. (1994).
4. F. W. Dobson and S. D. Smith, “Bulk Models of Solar Radiation at Sea,” Quart. J. Roy. Meteorol. Soc., **114** (1988).
5. R. K. Reed, “On Estimating Insolation over the Ocean,” J. Phys. Oceanogr., **7** (1997).