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MARINE PHYSICS

Assessment of Direct Determination Uncertainties of Incoming Radiation Fluxes Associated with the Ship Motion

A. V. Sinitsyn and M. P. Alexandrova
Shirshov Institute of Oceanology, Russian Academy of Sciences, Moscow, Russia
E-mail: sinitsyn@sail.msk.ru

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Abstract—The paper considers the impact of ship oscillations on the accuracy of radiation flux measurements in the absence of a gyroplatform and a gimbal suspension. As an example, we discuss the simultaneous determinations of the radiation fluxes and careen during the 20th mission of the R/V *Akademik Joffe*. A sampling rate of 10 s was found to be sufficient to neglect the careen when estimating the hourly sums of the short-wave solar radiation at sun heights exceeding 10°. At smaller sun heights, the careen is able to effect the estimates of the solar radiation within 20%. Due to the harmonic nature of such oscillations, these errors tend to become low against the instrumental accuracy if one deals with the hourly and daily means of the short-wave solar radiation fluxes during sufficiently long observations. In addition, a significant effect occurs at rather low sun and a sea roughness of Beaufort number 4 or higher. A rough sea is usually associated with the diminishing of the clear sky area and the higher repeatability of the cloudiness conditions, which reduces the effect of rolling upon the measurement accuracy.

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INTRODUCTION

The assessment of the fluxes of the short-wave solar radiation at the air–water interface are of critical importance for the reliable description of the features of the sea surface heat balance and its role in climate fluctuations. The available integral parameterizations of the short-wave solar radiation at the sea surface [2] provide calculation accuracy within 10–20 W/m^2, and their improvement is an important problem of the ocean–atmosphere interaction [4]. These parameterizations [2, 6, 8] are based exclusively on the general cloudiness data. The present day data bases of cloudiness characteristics provide a much wider set of cloudiness parameters for describing the short-wave radiation [5, 7]. However, performing high accuracy radiation measurements under the high seas conditions and different cloudiness regimes is of primary importance for the development of new parameterizations and improvement of the available ones because the direct determinations that are the basis for the above parameterizations were accompanied only by the simultaneous observations of the general cloudiness. Owing to the substantial dependence of the incoming solar radiation upon the sun's angle, conducting high accuracy shipboard measurements of the solar radiation at sea makes demands on both the accuracy features of the instrumentation and the horizontal position of the measurement carrier (a vessel) or, at least, requires quantitative accounting for the influence of the motions of the carrier on the accuracy of the solar radiation measurements. Stabilizing units solve this problem, but they are extremely expensive in installation and operation. Based on the large volume of direct measurements of radiation fluxes, along with the simultaneous recording of the ship's motions, the present work considers the opportunity of accounting for the effect of the nonhorizontality of the measurement carrier on the evaluation of the solar radiation and estimates the range of weather conditions suitable for measurements of the desirable accuracy without the use of stabilizing units.

FORMULATION OF THE PROBLEM

The strictly horizontal position of the receiving plain of the instrument, which prevents the distortion of the real sun height during measurement procedures, is one of the basic requirements for the shipborne installation of a pyranometer or a pyrgeometer for recording the short- and long-wave solar radiation incoming at the sea surface. This requirement is easy to meet using land-based instrumentation, but the problem of the maintenance of the horizontal position of the hardware carrier is inevitable when making observations on the ocean from a moving platform (a research vessel). In practice, excluding ideally calm weather, the receiving plain of the instrument is not properly horizontal, and additional engineering solutions are required to fulfill the observations. The problem is solved with a special gyroplatform (which is very expensive) or by means of a gimbals mount. The latter solution is feasible when

Fig. 1. The Kipp & Zonen CNR-1 radiometer.

the instrument involves a single receiving hemisphere of a pyranometer or pyrgeometer usually employed for measurement of radiation fluxes above the sea surface. A gimbal mount is difficult to use when taking advantage of the modern radiometers of the Kipp & Zonen CNR-1 type, whose pyranometers and pyrgeometers receiving both the incoming and outgoing short- and long-wave fluxes of radiation are combined in one and the same unit. This is easy to see in Fig. 1 showing a general view of the instrument used in our observations.

The above-described problem is the most burning in the cases when the incoming radiation fluxes are determined mainly by the direct flux of the shortwave radiation. When the scattered radiation flux exceeds the flux of the direct radiation within the total flux, it should be taken into account that the scattered radiation component comes from more numerous scattering elements of the celestial hemisphere from different angles, which results in a significantly lower error caused by the nonhorizontality of the receiving plain.

In the present work, the probable errors in the values of the shortwave radiation caused by the ship's rolling have been estimated from careen measurements with the help of an inclinometer. This enables us to assess the error caused by the absence of stabilizing units and to determine the range of weather conditions under which this error can be neglected in the background of the instrumental errors when measuring the short-wave solar radiation fluxes at the sea surface.

ESTIMATES OF ERRORS OF SHORTWAVE SOLAR RADIATION MEASUREMENTS CAUSED BY THE NONHORIZONTALITY OF THE RECEIVING SURFACE

The field of view of a pyranometer is close to 180° and is assumed to be spectrally black; e.g., in theory, the radiation incoming in this sector is totally absorbed. These conditions make it possible to simplify the problem and reduce it to the 2D case. In the general case, the short-wave radiation flux falling upon the strictly horizontal instrument's surface (Q_{SW}) is written as

$$Q_{SW} = fQ_0 \sin h, \tag{1}$$

where f is the coefficient of the atmosphere transparency; Q_0 is the short-wave radiation flux at the upper boundary of the atmosphere, or the solar constant (1368 W/m^2); and h is the angular sun height. Let us assume that, when measuring the flux, the horizontal plain of the instrument declined by $\pm\alpha$ from the horizontal due to the ship rolling (Fig. 2). In this case, the flux recorded with the instrument is

$$Q_{SW1} = fQ_0 \sin(h \pm \alpha). \tag{2}$$

The simultaneous examination of expressions (1) and (2) allows us to assess the value of the error of an individual recording of the short-wave radiation resulting from the decline of the instrument's plain from the horizontal position. In agreement with the diagram in

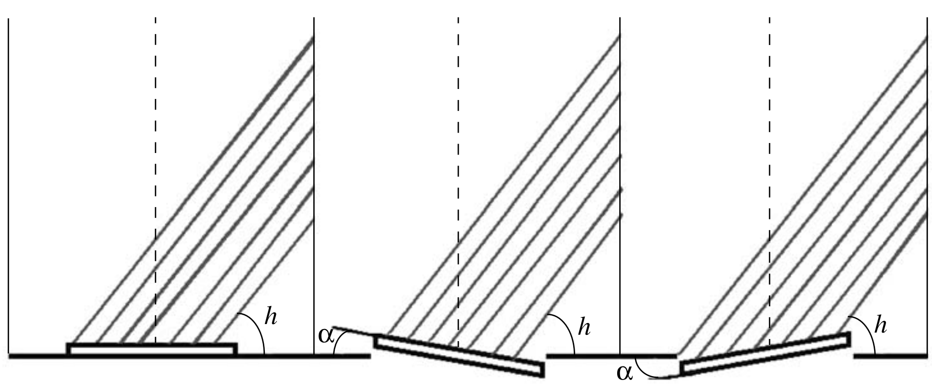

Fig. 2. The case of the 2D oscillations of a vessel.

Fig. 2 and after the mathematical manipulations of formulas (1) and (2), we obtain the following expression for such an error:

$$\delta = (Q_{SW} - Q_{SW1})/Q_{SW} = (1 - \cos\alpha) \pm \frac{\sin\alpha}{\tan h}. \qquad (3)$$

As follows from Fig. 2, the two-sided rolling always reduces the efficient sun height if its real value equals 90°. If the sun height is other than 90°, an individual ship's rolling can result both in a decrease and an increase of the efficient sun height (the same is true for the incoming solar radiation). Owing to Fig. 2 and expression (3), the effect of the sun's height increases under the rolling conditions, which leads to the longer instrument exposure with reference to the sun, and is not equal to the opposite effect. Our results of the analytical calculations of δ from expression (3) are given in Fig. 3 for different sun heights h and rolling angles of the platform α.

Figure 3 shows that the effect of the platform rolling on the measured values of the solar radiation substantially depends on the sun's height. When the latter exceeds 60°, the values of δ do not exceed 0.1–0.15 even though the careen is as large as 15°. A relative error higher than 20–30% is probable even at a small careen of a few degrees when the sun's angle is lower than 20°. It is evident from Fig. 3 that the effect of overestimating the incoming radiation at exposure to increasing careens is somewhat greater than the effect of underestimating at exposure to decreasing careens. Besides, the effect is at its maximum when the sun's angle is low. However, it should be noted that even a considerable error at low sun angles may be rather small in absolute units, since the solar radiation itself is extremely weak at low sun angles.

In what follows, we have to establish the importance of the effect of the ship's careen on the time-averaged estimates of the radiation because the records of the incoming radiation are integrated over 10 minutes or hourly periods when developing the parameterizations. For this purpose, we will take advantage of the data from a special experiment aimed at high frequency measurements of ship's careen with an inclinometer and simultaneous recording of the incoming solar radiation.

ANALYSIS OF THE OSCILLATIONS OF THE VESSEL

The experiment was conducted in the Atlantic Ocean from March 23 to April 18, 2007, during the course of the 20th cruise of the R/V *Akademik Joffe* when she sailed from 35°S to 53°N. The shortwave radiation was recorded with Kipp & Zonen CM-21 and Kipp & Zonen CNR-1 radiometers (Fig. 1), and an NG543210 Dr. Seitner inclinometer served as the careen sensor. The accuracy of the careen measurement with the inclinometer was 0.1°, and the output signal of the sensor varied linearly with the careen of the vessel. Based on the time constants of our instrumentation, the data of the radiometer (CM-21) and inclinometer (NG543210) were sampled with a 2 s resolution, and a 10 s resolution was chosen for the CNR-1 radiometer. 23 daily measurement series of the incoming shortwave radiation and the features of the vessel's careen were obtained in the course of the experiment.

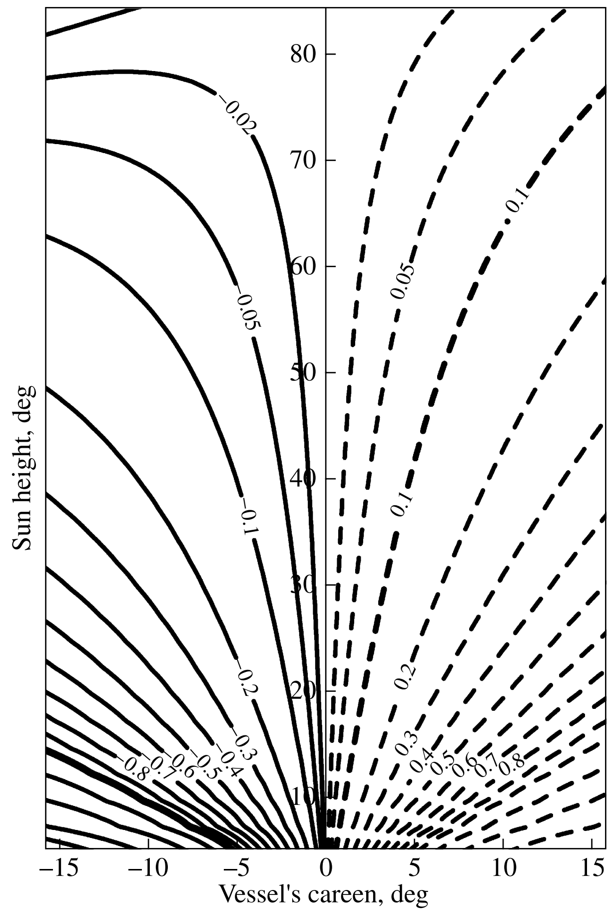

Fig. 3. The results of the analytical calculations of the quantity δ for different sun heights h and angles of rocking of the platform α.

The latter was accompanied by the standard meteorological observations, including the visual determination of the surface waves and the cloud amount and shape. This allowed us to mark out four fairly long (several hours) time periods whose meteorological regimes corresponded to the sea roughness of 1, 2, 3, and 4 Beaufort numbers with approximate wave heights of about 0.5–1, 1.5, 2.5, and 3 m. The averaged near-water wind speed varied from 4 to 14 m/s for these periods (see table).

Meteorology of four periods of observations of incoming solar radiation and the vessel's careen

Beaufort scale number	Date, time UTC	Wind speed, m/s	Wave frequency MAX, Hz	Mean amplitude, °	Wave height, m	Roughness type
1	10.04.2006 10:00–18:00	4.4	0.09–0.11	3.5	up to 1 m	swell
2	30.03.2006 9:00–20:00	9	0.072	3.5	1.5	wind wave
3	26.03.2006 14:00–21:00	11	0.072	6	2.5	wind wave
4	24.03.2006 10:00–19:00	14	0.075	21	3	wind wave

Hence, the latter represented four different regimes of the sea roughness and, respectively, of the vessel's careen. The spectral analysis of the 2-second characteristics of the vessel's careen was fulfilled for each of the periods. Based on Walsh's method [1], the spectral functions were calculated for fragments of realizations with the subsequent averaging of the spectral estimates over the ensemble of realizations. The spectral function estimates were highly accurate, since relevant periods belong to the 20–30 s range and the original recordings were several hours long. Alternative procedures of the spectral estimation were also used for comparison, but their outcomes were virtually indistinguishable from those of the Walsh method. Figure 4 shows the spectra of the vessel's oscillations computed from the data of four observation series.

Figure 4 agrees well with the typical spectra of wind waves on the open ocean [3] with the spectra being characterized by peaks generally corresponding to swell and wind waves. For instance, the careen frequency falls within the range of 0.065 to 0.095 Hz with the peak at about 0.075 Hz and an amplitude of ~21° if the sea roughness is 4 Beaufort numbers strong (Fig. 4). Under calm conditions (Fig. 4, left-hand side, April 10, 2006), the amplitude reduces to ~3.5° and the frequency range widens up to 0.05–0.12 Hz. Now we are able to estimate the careen effect upon the accuracy of the shortwave radiation recordings and calculated the hourly radiation used for the development of the integral parameterizations.

To solve this problem, hourly series of the shortwave radiation flux under clear sky conditions were

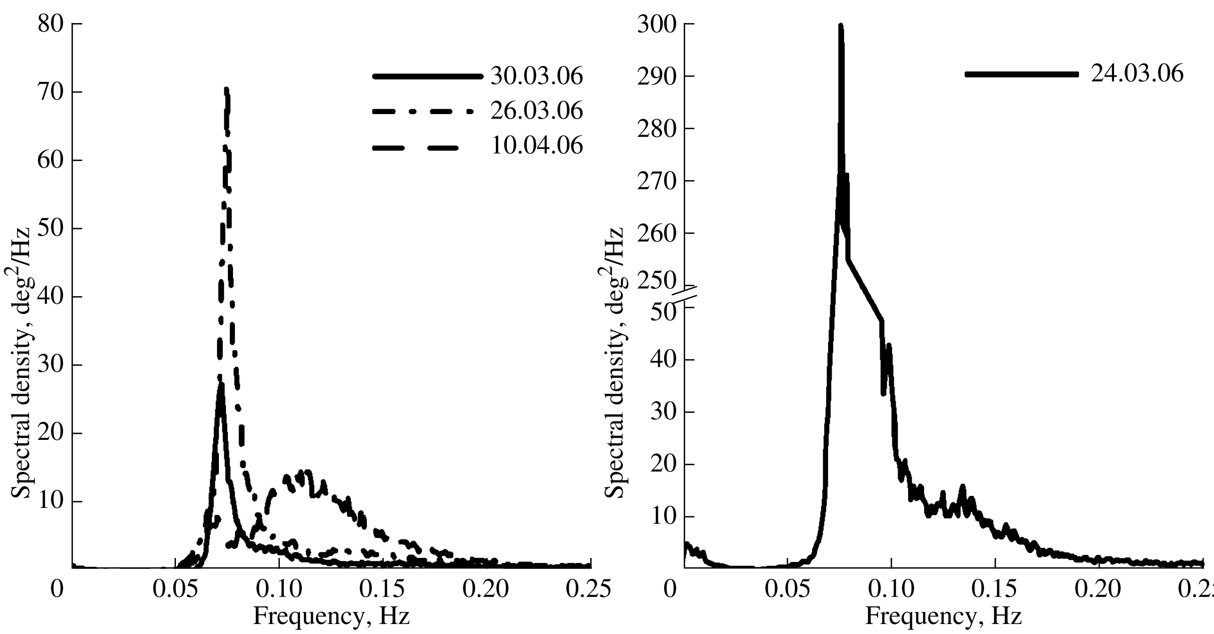

Fig. 4. Spectra of the vessel's oscillations computed from four series of observational data. Left panel: spectra for calm conditions (10.IV.2006) and for wind waves (30.3 and 10.4.2006). Right panel: spectrum for wind waves 4 Beaufort number strong (24.3.2006).

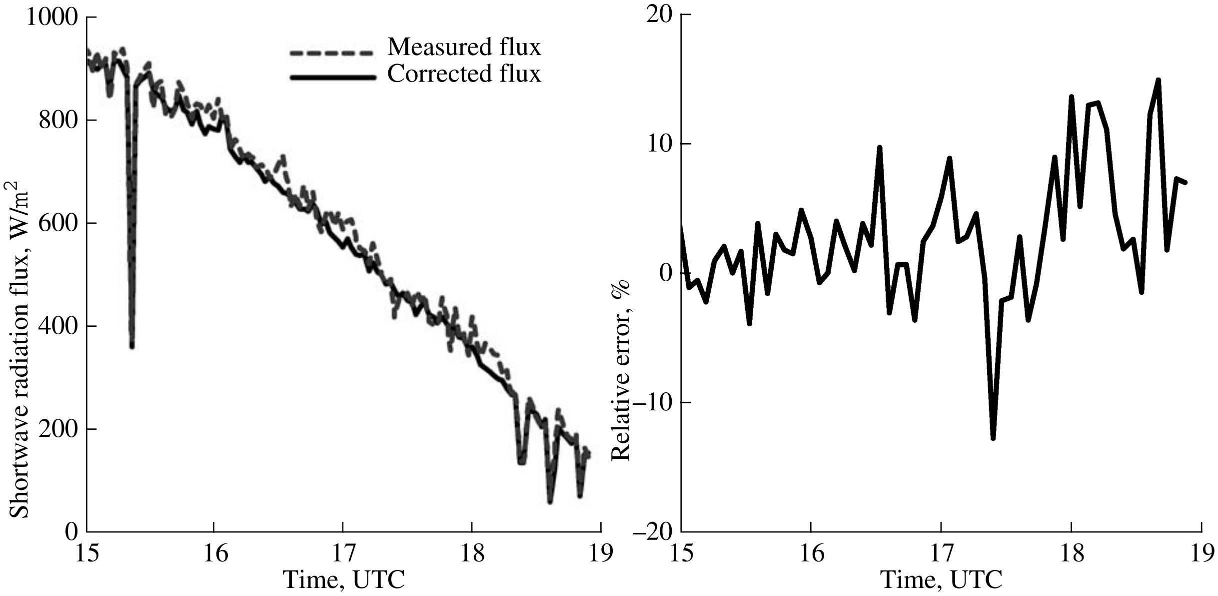

Fig. 5. Outcomes of the measurement corrections for the vessel's careen and the value of the relative error.

chosen from the available data set, which excludes the influence of the cloudiness induced variability of the shortwave radiation signal on the desired estimates. Notice that this approach makes it possible to estimate the maximum possible effect of the vessel's careen, because the careen effect on scattered radiation recording is much weaker as compared to the same effect in the case of direct radiation.

The high-frequency 2-second measurements of the vessel's careen enable one to apply careen corrections for all the recordings of the shortwave radiation according to the formula

$$Q_{\text{real}} = \tilde{Q}\sin h, \tag{4}$$

where

$$\tilde{Q} = Q_{\text{meas}}/\sin(h+\alpha), \tag{5}$$

and α is the instrument declination from the horizontal.

The results of the measurements correction for the vessel's careen and the resulting relative error are given in Fig. 5. Evidently, this error is less than 20% even for the sunset, e.g., at small sun angles. When the sun is high and the measured solar radiation is relatively strong, this error does not exceed 3–5%.

However, we are the most interested in the data averaged over the periods of 10 min and longer, because exactly such periods are used when developing new parameterizations of the shortwave radiation at the sea surface. Our estimates allow us to compare the corrected average data and the averaged data of 10-second measurements. This comparison is shown in Fig. 6 for the observations of April 10, 2006, from 15:00 to 19:00 UTC. Both data sets have been averaged over the 10 min period.

As follows from Fig. 6, the averaged estimates of the shortwave radiation fluxes are systematically rather lower against the corrected values. The absolute errors range from 20 to 10 W/m^2, while the relative error does not exceed 8% at the sun height of 5°, being as low as 0.7% at 60°. Comparing such error values with the rated accuracy of the instruments gives grounds to explain the former by the instrument accuracy rather than by the influence of the careen correction. Specifically, notice that the rated accuracy of the CM-21 radiometer is 2%, while the Kipp & Zonen CNR-1 model features 10% accuracy. The instrumental and measurement errors have to be compared in terms of the central limit theorem. According to the latter, the error of the mean of n observations decreases with $(n-3)^{1/2}$. Thus, the 10% error of the individual measurement transforms into a 2% error of the mean of the 10 minute period. However, this error too can explain the uncertainties of the radiance determinations at sun heights greater than 10° by the rated accuracy of the instrument. At the same time, the careen effect may not be negligible when the sun height is relatively low and the sea roughness exceeds three Beaufort numbers.

CONCLUSIONS

These are the inferences of our study:

(1) Sampling the radiometer signal at a rate of 10 s allows one to neglect the vessel's careen when estimating the hourly shortwave solar radiation at sun heights greater than 10°. The careen effect can be as high as

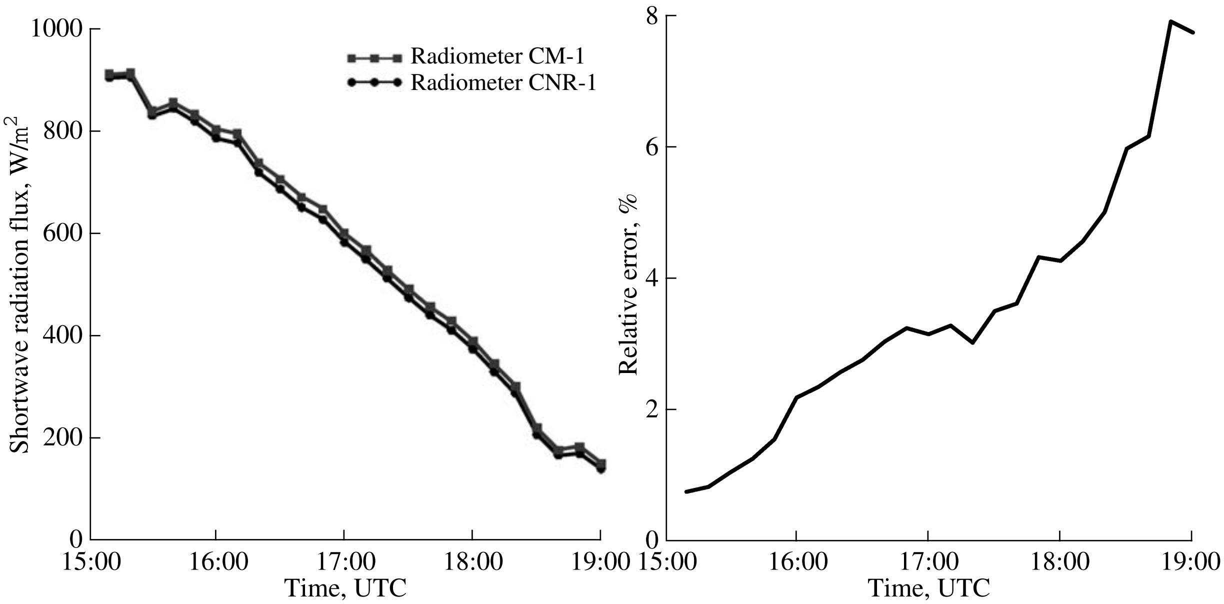

Fig. 6. Comparison of the corrected averaged data with the data of 10 s resolution.

20% at lesser sun heights. Notice that the solar radiation is weak at low sun positions, so that even meaningful values of the relative errors make up only a small fraction of the absolute error.

(2) Owing to the harmonic nature of the careen oscillations, the errors of fairly long observations, on averaging, turn out to be small as compared to the rated instrumental accuracy when estimating the hourly and daily shortwave radiation fluxes. A meaningful effect occurs at relatively low sun angles and sea roughness stronger than four numbers of the Beaufort scale. Notice as well that, as a rule, considerable waves are associated with the diminishing of the clear sky percentage and the higher repeatability of the cloudiness conditions, which reduces the careen effect on the measurement accuracy.

(3) Thus, our theoretical and experimental assessments allow us to infer that the careen effect on the measurement of the hourly solar radiation is mostly negligible. In many cases, it is possible to perform high-accuracy measurements of the shortwave radiation in the open ocean without involving expensive stabilizing platforms and to use the obtained results for the subsequent development of the integral parameterizations.

(4) We have obtained error estimates for the case of a significant effect of the careen on the features of the measured shortwave radiation. Advantage can be taken of these estimates for the evaluation of the accuracy the inferences.

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