Journal of Oceanography
Vol. 50, pp. 713 to 723. 1994

In situ Measurement of Incoming Solar Radiation by Voluntary Ships in the Western Pacific

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(Received 18 February 1994; in revised form 4 July 1994; accepted 4 July 1994)

We have been performing *in situ* measurement of downward short wave radiation (solar radiation) in the western Pacific Ocean in cooperation with voluntary ships since autumn 1990 in order to obtain much more precise knowledge of downward short wave radiation at the sea's surface than before. Preliminary result of the observation from autumn 1990 through spring 1992 is shown in this paper. The comparison of observed daily mean downward short wave radiation with that estimated from observed cloudiness by using Reed (1977) formula is also presented to show the necessity of *in situ* measurement in the study of the downward short wave radiation at the sea's surface.

1. Introduction

Solar radiation is the one and only energy source of the climate system of the Earth and, in total, more than 50% of the solar radiation irradiance at the top of the atmosphere reaches Earth's surface (e.g., Aida, 1982). Therefore, it has been recognized for a long time that the downward short wave radiation at the sea's surface has an important effect on the thermal structure and motions of the ocean and, therefore, on the climate system of the Earth. This is because more than 90% of the solar radiation irradiance at the sea's surface is absorbed by the ocean and because the ocean covers about 70% of the global surface.

Several researchers have estimated the climatology of the downward short wave radiation flux at the sea's surface (e.g., Budyko, 1973; Iwasaka and Hanawa, 1990). In these studies, irradiance of the downward short wave radiation was estimated by using empirical formulae such as Reed (1977). Although the downward short wave radiation at the sea's surface is determined by the condition of the entire atmospheric column through which the solar radiation comes, only surface meteorological variables such as total cloudiness observed by ships are used in the empirical formulae to estimate the flux. Therefore, it is obvious that estimated values of the downward short wave radiation flux in such studies are substantially uncertain due to the estimation method. To assess the uncertainty of the estimated value, and to improve the knowledge of the climatology of the downward short wave radiation at the sea's surface, a lot of *in situ* measurement data taken in wide regions under various conditions is definitely needed.

Recently, some investigators have developed algorithms to estimate the downward short wave radiation flux at the sea's surface using remote sensing data obtained from satellites (i.e., Gautier *et al.*, 1980). In the near future, such kinds of methods may provide precise estimation with very high spatial and temporal resolution. However, in order to develop the estimating method, again, a lot of sea truth data under various atmospheric conditions are needed.

Despite the need for observation of the downward short wave radiation at the sea's surface, as described above, there are a few temporary experiments (e.g., Reed, 1982; Otobe *et al.*, 1983; Hanawa and Kizu, 1990) and several weather stations which have observed the downward short wave radiation (e.g., Dobson and Smith, 1988) in the ocean. Therefore, we have been performing the direct observation of the downward short wave radiation at the sea's surface in the western Pacific Ocean since September 1990. This may be the first ever routine attempt to observe the downward short wave radiation at the sea's surface in a large area.

In this paper, we will describe the design of the experiment in Section 2. Preliminary results will be shown in Section 3. We will make a comparison of the daily mean observed downward short wave radiation to estimated value calculated by a conventional method using an empirical formula in Section 4, to demonstrate the importance of the direct measurement of downward short wave radiation in the ocean.

2. Experiment Design

2.1 Observation area

We have chosen the western Pacific as a study area (Fig. 1) where many ships ply between

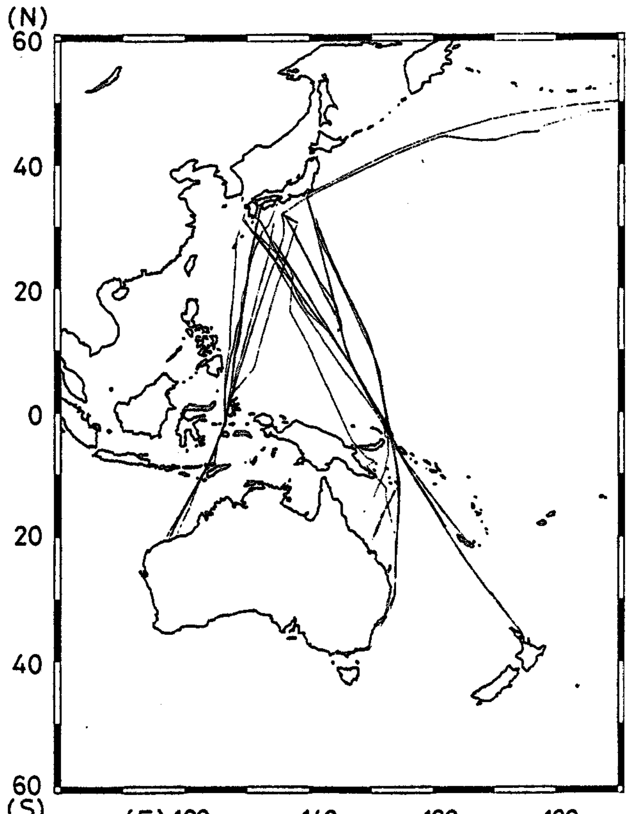

Fig. 1. Observation area. Lines indicate the ships' route between Japan and Indonesia, New Caledonia, Australia and New Zealand.

Japan and Indonesia, New Caledonia, Australia and New Zealand. The reason for choosing this area is that this region has three advantages in observing the downward short wave radiation. They are; 1) the ships' routes cover tropics and middle latitudes of both hemispheres, 2) unlike in the North Pacific in winter, the routes are seldom changed by weather conditions, and 3) meteorological and oceanographic observations have been enhanced in the tropical Pacific since the Tropical Ocean and Global Atmosphere Coupled Ocean-Atmosphere Response Experiment (TOGA-COARE) project started in 1990 (TCIPO, 1991).

The first point allows us to observe the downward short wave radiation at the sea's surface in the wide regions under various atmospheric conditions. The second one implies that we can make frequent observations in the same area continuously for a long time. Because of the third point, we can analyze the observed radiation data comprehensively with the meteorological and oceanographic data from TOGA-COARE, and, in turn, the downward short wave radiation data will contribute to the air-sea energy exchange study in the TOGA-COARE.

2.2 *Method*

The observations are made by voluntary merchant ships, which are bulk carriers and container ships, as summarized in Table 1. It takes each ship about 30–40 days to complete one round voyage. Some of the bulk carriers may go on one or two voyages to Canada or India a year. The experiment started with seven ships in autumn 1990 and thirteen more ships joined by the end of January 1992. However, one bulk carrier quit the observation in November 1992 and nine

Table 1. List of the voluntary ships. Ship ID, type and period of observation are shown.

Ship ID	Type	Beginning of the observation	End of the observation
YAS	Bulk Carrier	Sep. 1990	Nov. 1991
HYU	Bulk Carrier	Sep. 1990	Mar. 1993
KEN	Bulk Carrier	Sep. 1990	—
KUN	Bulk Carrier	Nov. 1990	Mar. 1993
ONO	Bulk Carrier	May 1991	—
TSU	Bulk Carrier	Jun. 1991	—
SHI	Bulk Carrier	Aug. 1991	Feb. 1993
KYO	Bulk Carrier	Aug. 1991	May 1993
OYA	Bulk Carrier	Aug. 1991	Apr. 1993
SIN	Bulk Carrier	Aug. 1991	Mar. 1993
ATA	Bulk Carrier	Oct. 1991	—
KII	Bulk Carrier	Dec. 1991	Aug. 1993
MIZ	Bulk Carrier	Jan. 1992	Apr. 1993
HEI	Bulk Carrier	Jan. 1992	May 1993
KIN	Bulk Carrier	Oct. 1993	—
WEL	Container	Aug. 1991	—
SOU	Container	Sep. 1990	—
HAK	Container	Sep. 1990	—
GOD	Container	Sep. 1990	—
NIC	Container	Dec. 1991	—
AUS	Container	Dec. 1991	Feb. 1993

of the nineteen ships stopped the observation by Spring 1993. Currently (July 1994) ten ships remain in the experiment, which will expire in March 1996.

The instrument used in the observation consists of a pyranometer, gimbals and a data recorder. The pyranometer is an Ishikawa Sangyo K.K. model S-185 black and white type sensor. The sensitivity of the sensor is 7 mV/KW m^{-2} in a spectral band of 300–2,800 nm, the response time is 6 seconds in time constant e^{-1}, the accuracy is ±2%. Before being equipped to the instrument, each pyranometer was calibrated against the Eiko Seiki type MS41 pyranometer which had been calibrated by the Japan Meteorological Agency. The gimbals are used to avoid the effects of the ships' motion and tilting on the measurement, following recommendations in previous studies (e.g., Katsaros and DeVault, 1986; MacWhorter and Weller, 1991). The data recorder is KADEC-UP from KONA System Co., Ltd., which is a semiconductor memory type

(a)

(b)

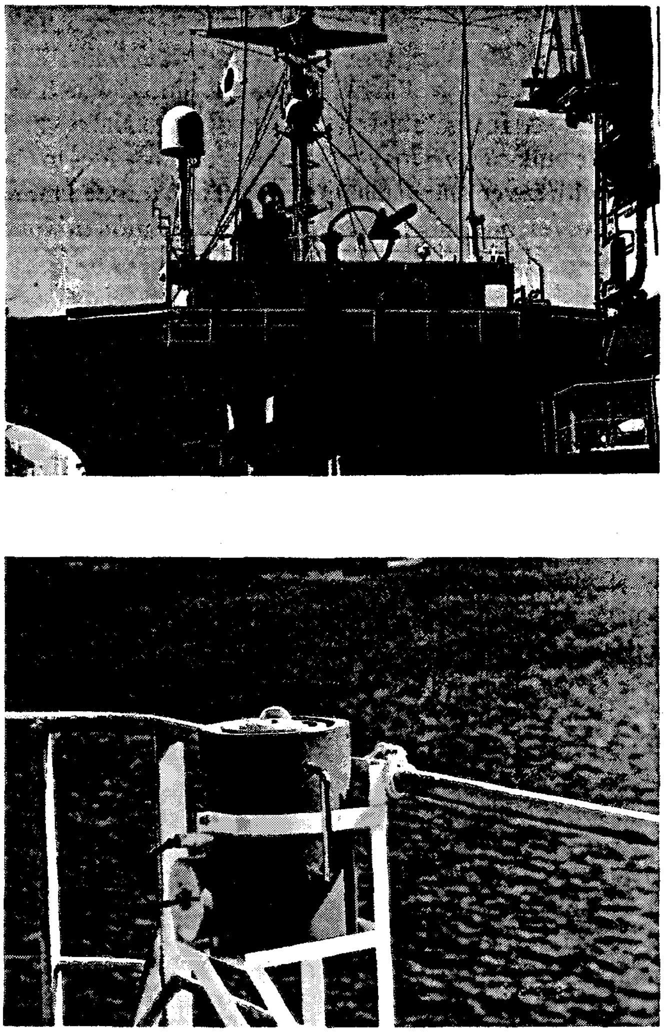

Fig. 2. Pictures of a front view of the bridge of a voluntary ship (a), and the instrument installed on the handrail in the front of the fling bridge of the ship (b). The circle drawn in Fig. 2(a) shows the position where the instrument is installed.

recorder (see Hanawa and Kizu, 1990). Data is obtained every ten minutes as a ten-minute average value. The instrument is independent, so it does not need electric power supply from the ship. The instrument is set in the front of the highest bridge of each ship (Fig. 2).

We have asked the officers and crew of each ship to wash the glass dome of the pyranometer with fresh water every morning. We have also asked them to record the ship's position every 4 hours during daytime, together with ordinary surface meteorological observations. Because they are very busy during the cargo handling and because the pyranometer is often shaded with cargo handling equipment of the port, we have not ask them to do the cleaning and the recording when the ship is in port. Thus, only the data obtained during the voyage in open ocean will be used for analysis.

3. Preliminary Results

In this section, we will present some preliminary results based on the data obtained during the period from autumn 1990 through January 1992.

Before we show them, we will explain the performance of the observation and one major problem. Figure 3 shows an example of a time series of one hour averaged downward short wave radiation observed on one of the voluntary ships from August 31, 1990 through December 6, 1990, for four voyages between Japan and the East coast of Australia. The course line of the ship is drawn between a port in Japan and a port on the east coast of Australia via the point around 5°S

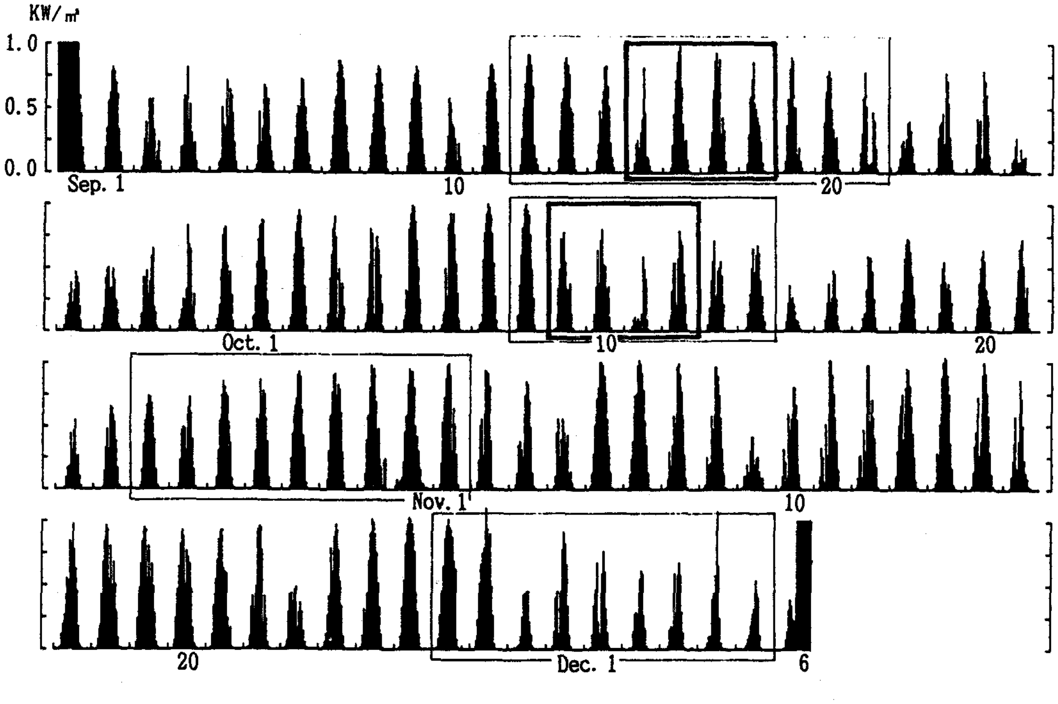

Fig. 3. An example of time series of one hour averaged downward short wave radiation observed on a voluntary ship during the period from August 31 through December 6, 1990. Thin lines enclosing the record indicate the period during which the data was obtained in open ocean. Time series of ten-minute average data in the period indicated with thick lines are shown in Fig. 4.

and 154°E in the Solomon Sea, as shown in Fig. 1. The line between Japan and the Solomon Sea varies depending on which port in Japan the ship arrives in or departs from. In Fig. 3, the data enclosed with thin lines was obtained during the voyages in the open sea. The ratio of the data taken in the open ocean, which we can use for analysis, to all recorded data is about one third in this case because it takes a week to about ten days for cargo handling on both sides of the ocean during a cruise. In general the ratio is about one third to a half for each cruise for each ship. The time series of ten-minute averaged value during the periods indicated with thick lines in Fig. 3 are displayed in Fig. 4. For the data of September 16, 17 and October 12, there are extremely low values at certain periods of the days despite the fact that the surface meteorological record shows that cloudiness was generally small (less than 0.3 in daily mean cloudiness) on those days. We suspected that these low values might be caused by the shadow of superstructure of the ship. We confirmed this assumption by simulating the shadow of the superstructure of the ship based on its general arrangement and records of the ship's position. Low values shown on the other days in Fig. 4 are thought to be due to clouds because it was cloudy (daily mean cloudiness was about 0.6–0.7) on those days and because the superstructure did not shade the pyranometer when the record showed small values. For our analysis, in order to exclude the data contaminated by the shadow of the superstructure of the ship, we choose the data which satisfies both of two conditions; 1) heading of the ship is within ±45° from north or south, and 2) noon solar altitude

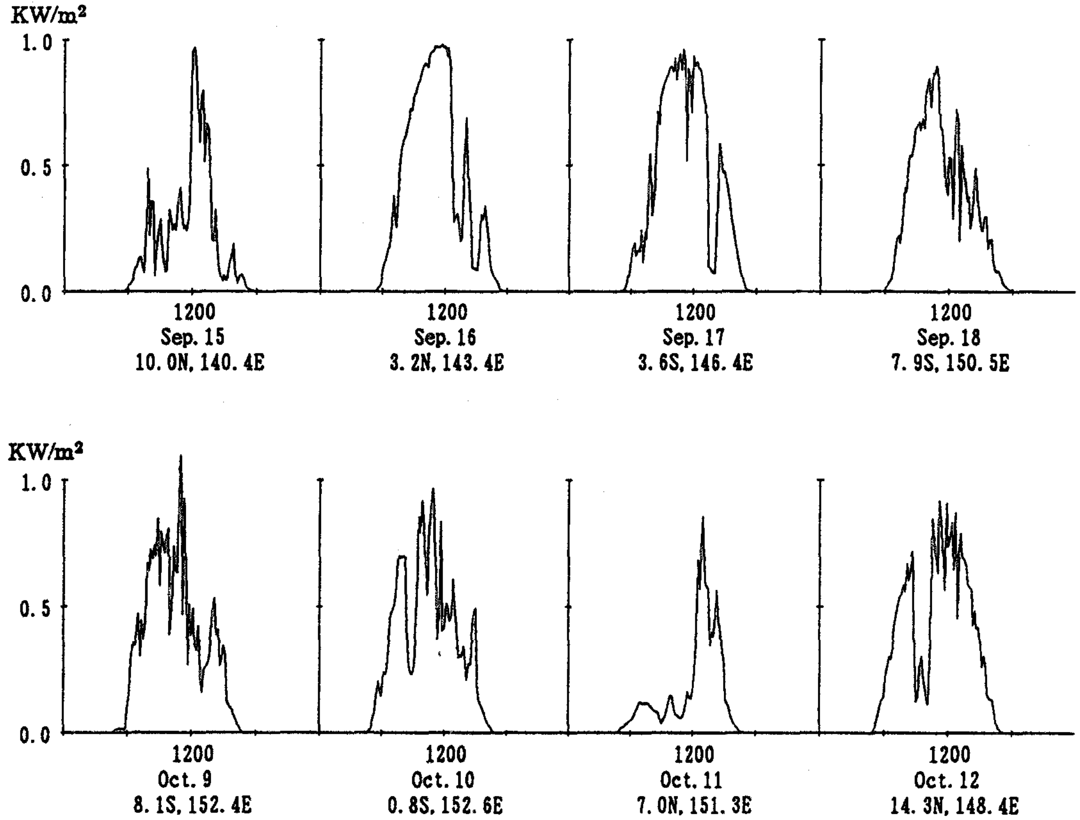

Fig. 4. Time series of ten-minute averaged value of downward short wave radiation observed during the period indicated with thick lines in Fig. 3.

is within 90° from the ship's direction.

Figures 5(a) through 5(d) show the meridional distributions of daily mean downward short wave radiation for the season from February through April, from May through July, from August through October, and from November through January, respectively. Each daily mean value is

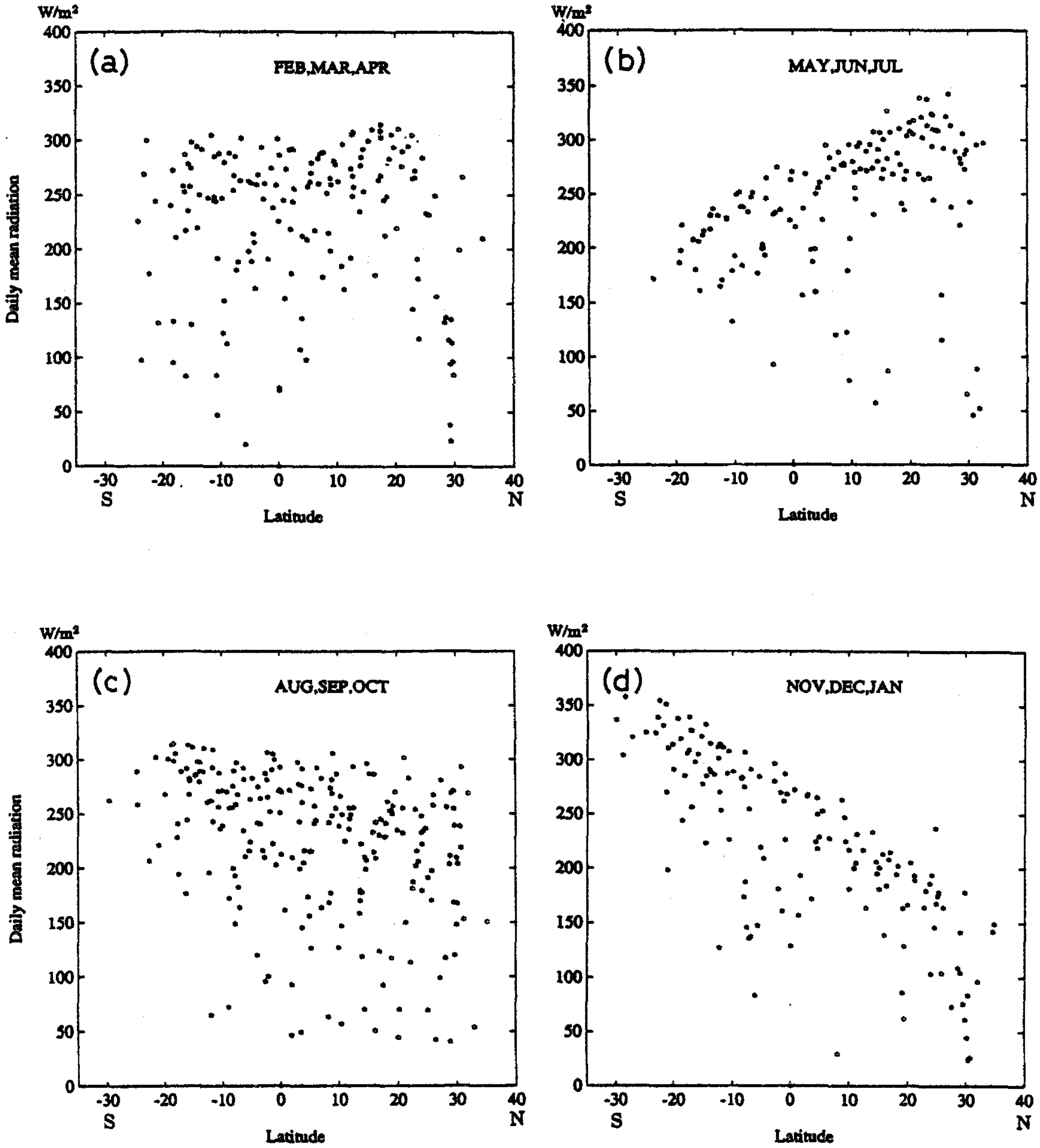

Fig. 5. Meridional distributions of daily mean downward short wave radiation, for the season from February through April (a), from May through July (b), from August through October (c), and from November through January (d), respectively. Each daily mean value is assigned to the noon position of the ship on which the data was obtained.

assigned at the noon position of the ship. The length of daytime of the time series obtained aboard is also adjusted to that of the noon position of the ship. Although data is dispersive, the character of the meridional distribution of downward short wave radiation in each season is clearly seen in each figure, that is, 300–360 W m^{-2} of downward short wave radiation is observed on the latitude belt between 30°S and 20°S while less than 200 W m^{-2} of radiation flux is obtained north of 20°N in the season from November through January, and the distribution is reversed north and south around the equator in the season from May through July. In the seasons including equinoxes, the distributions are symmetrical around the equator and daily mean values are up to about 300 W m^{-2}, regardless of the latitude of the observed position. We are not discussing the detail of the meridional distribution of the downward short wave radiation climatology based on Fig. 5, because the amount of data is not enough for statistical analysis. However, we hope we will accumulate enough data by the end of the project in order to reconstruct statistically significant climatology of the meridional distributions of downward short wave radiation in the western Pacific based on direct observation alone.

4. The Comparison between the Observed Value of the Downward Short Wave Radiation and the Estimated Value by Reed (1977) Formula

In this section, we are examining the uncertainty of the estimated downward short wave radiation by using a bulk formula, based on the direct observation data mentioned in the previous section, as a demonstration of the importance of *in situ* measurement of the downward short wave radiation at the sea's surface.

Bulk formulae are widely used to estimate the downward short wave radiation for climatological purposes. Reed (1977) is one of them, which has been used in various studies (e.g., Weare *et al.*, 1981; Iwasaka and Hanawa, 1990). Reed's formula gives daily mean downward short wave radiation at the sea's surface calculated from daily mean total cloudiness and noon solar altitude. The formula is as follows:

$$Q_S / Q_{S0} = 1.0 - 0.62C + 0.0019\alpha \quad \text{for} \quad C \geq 0.3,$$

and

$$Q_S / Q_{S0} = 1.0 \quad \text{for} \quad C < 0.3,$$

where C is total cloudiness in tenth, α is noon solar altitude in degree, Q_S is global downward short wave radiation of the day and Q_{S0} is downward short wave radiation at the surface under clear sky condition given by Seckel and Beaudry (1973).

It is obvious that the estimated value given by the formula must have substantial uncertainty because of its simple treatment of cloud effect, i.e., only total cloudiness is considered in the formula.

Figure 6 shows a scatter plot of the observed daily mean downward short wave radiation against the estimated value. The estimation was made based on the total cloudiness reported by each ship. Data of observed value less than 150 W m^{-2} is rather scattered. In Fig. 7 all 10 W m^{-2} interval averages are shown, together with their standard deviation. The amount of data used to calculate the averages is also shown as a bar diagram. The dashed line denotes the regression curve calculated from the averaged value. From this figure, Reed's formula seems to give a good estimation in average value despite its simplicity. However, each 10 W m^{-2}-interval

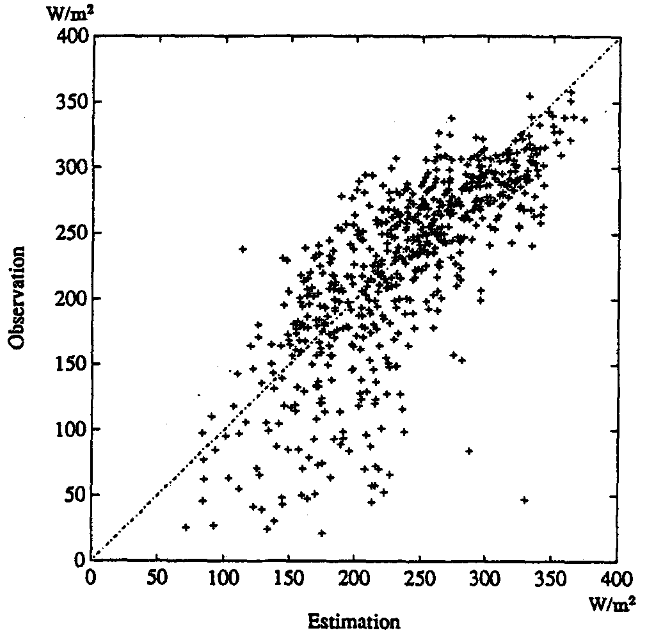

Fig. 6. Scatter plot of observed daily mean downward short wave radiation against the estimated value by using Reed's (1977) formula.

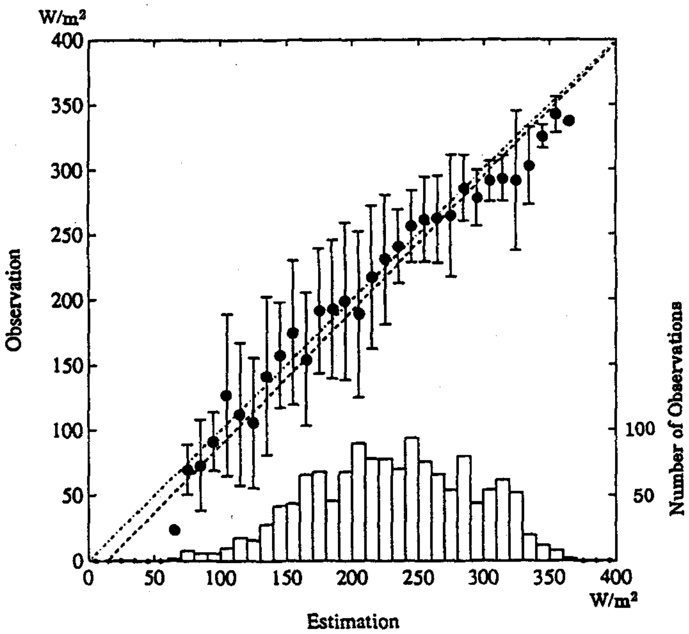

Fig. 7. Average observed downward short wave radiation for each 10 W m^{-2} range of estimated value by Reed's formula and its standard deviation. Amount of data used to calculate each averaged value is shown at the bottom of the panel with a bar diagram.

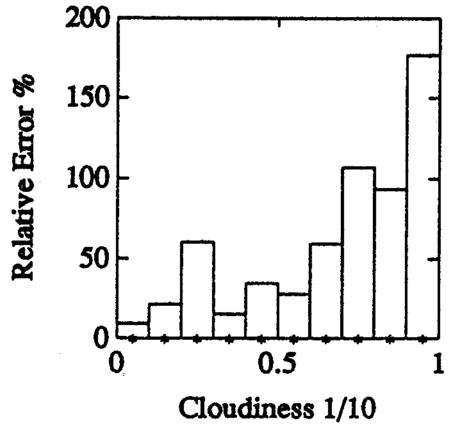

Fig. 8. Average normalized discrepancy between observed daily mean downward short wave radiation and estimated value by Reed's (1977) formula for every one tenth of total cloudiness.

average observed value is significantly apart from the estimated value and has a large standard deviation σ, up to 70 W m^{-2}. As can be expected from the formula, the more cloudy it becomes, the more uncertainty of estimated value increases, as shown in Fig. 8. The figure shows relative uncertainty, i.e., the average ratio of root mean square of the difference between observed and estimated value to estimated value for every one tenth of total cloudiness.

Based on this comparison, one may conclude that Reed's formula gives a fairly good estimation of the downward short wave radiation at the sea's surface in terms of average, despite its simplicity in the treatment of cloud effect on the radiation. However, according to the central limit theorem, which indicates an uncertainty of sample mean, ε, can be evaluated as $\varepsilon = \sigma/\sqrt{n}$, where n is sample size, more than 100 observations are needed to reduce the uncertainty to smaller than 10 W m^{-2}. And, as mentioned in Dobson and Smith (1988), one must be aware of substantial systematic error (up to about 20 W m^{-2} in the average value in this study) even though enough data can be obtained to calculate the estimated value.

5. Concluding Remarks

We have been performing the direct measurement of the downward short wave radiation at the sea's surface by using voluntary ships. In this paper, we have shown the preliminary results of the direct observation. We have also demonstrated the importance of direct measurement of downward short wave radiation in the ocean by showing the significant uncertainty of the estimation of solar radiation calculated with a conventional empirical formula.

The data obtained in the experiment will be disclosed to the public within a few years, after we examine the quality of each individual observation. We believe that the data will be used in a variety of studies, such as the study of the climate and satellite remote sensing. It will also contribute to these studies.

Acknowledgements

We sincerely express our appreciation to Asahi Shipping Co., Ltd., Daiichi Chuo Kisen Kaisha, Kawasaki Kisen Kaisha, Ltd., Mitsubishi Ore Transport Co., Ltd., Mitsui O.S.K. Lines, Ltd., Navix Line, Ltd., NYK Line, NYK Ship Management, Ltd., Shinwa Kaiun Kaisha, Ltd., Showa Line, Ltd., and Tokyo Senpaku Kaisha, Ltd. and their ships' officers and crew for their cooperation. We also express our deepest gratitude to Wanbish Industry, Co., Ltd., for its financial support of the experiment. This project was also financially supported by the Japanese Ministry of Education, Science and Culture, as part of J-COARE (chairman: Professor A. Sumi, University of Tokyo).

In addition, we are grateful to Mr. Kaneko of the Ocean Research Institute, University of Tokyo for his help in developing the instruments and we thank Mr. Kawada for drawing the diagrams.

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