

Spectral studies of total cloud cover and effective long-wave radiation over the Bay of Bengal during Monex-79

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ABSTRACT. Using the data on air and sea surface temperature and total cloud cover recorded by a fixed polygon of ships over the Bay of Bengal during MONEX-79 from 11 to 23 July 1979, the effective long-wave radiation from the sea surface was calculated by a semi-empirical relation. This relation was found to agree satisfactorily with observed values of outgoing radiation during Monsoon-77. A statistical analysis revealed very good negative correlation between the effective outgoing radiation and the total cloud cover (N). In view of this correlation, we performed a spectral analysis of the effective outgoing radiation and the total cloud cover. The paper presents the results of the spectral analysis, including the square of the coherency and the phase difference between these two variates.

1. Introduction

The effective long-wave radiation (E) from the sea surface is the difference between outgoing and incoming long-wave radiation. It depends not only on the temperature of the water and the overlying air, but also on the total liquid water content of the atmosphere and the cloud cover. Over the sea surface, the temperature of the air and the vapour pressure are highly correlated; consequently, it is interesting to study how far the cloud cover, and the effective long-wave radiation emitted by the sea surface are related. The purpose of this paper is to study this aspect.

Earlier, a comparative study (Mohanty 1981) was made to estimate the effective long-wave radiation from the sea surface by empirical methods. For the present purpose, a semi-empirical formula, which fitted the observational values, was considered. The data collected during the Indo-USSR Monsoon-77 Experiment were used. Subsequently, the results were compared with actinometric observations recorded by four USSR vessels during the period 8-19 August 1977. As continuous actinometric observations were not available over the Bay of Bengal, continuous hourly synoptic data obtained by USSR research vessels during MONEX-79 were used for estimation of E .

2. Method of computation

An empirical method was developed by Girduk *et al.* (1973) for estimating the effective outgoing long-wave radiation (E) from a sea surface. This is the difference between long-wave radiation emitted by sea surface acting as a modified black body, and the counter radiation, directed downwards, by clouds, aerosols and liquid water drops. This is :

$$E = \delta \sigma T_w^4 - \delta [1.63 (\sigma T_a^4)^{1/2} - 0.775] \quad (1)$$

$$- \delta [1.63 (\sigma T_a^4)^{1/2} - 0.775] KN^m \quad (2.1)$$

$$(3)$$

where, E is the effective outgoing long-wave radiation, δ is the mean reflectivity of the sea surface (0.91) and σ stands for the Stefan-Boltzman constant ($0.813 \times 10^{-10} \text{ ly min}^{-1}, \text{ }^\circ\text{K}^{-4}$). The temperature of the sea surface and of the overlying air at 10 m is represented by T_w and T_a respectively. The total cloud cover is N , while K and m are empirical constants. K is approximately 0.157 for $T_a = 299.2 \text{ }^\circ\text{K}$, while m is equal to 2.0. K represents the difference in downward radiation for clear skies and for an overcast sky. We have :

$$K = (F_0^\downarrow - F_c^\downarrow) \div F_c^\downarrow \quad (2.2)$$

TABLE 1

Observed and computed values of outgoing radiation (E)

Ship	Mean values of E (ly min^{-1})		Percentage difference
	Computed	Observed	
(1) Shokalsky	0.052	0.047	11
(2) Priboy	0.056	0.047	17
(3) Akademik Shirshov	0.057	0.053	8
(4) Okean	0.062	0.053	17

TABLE 2

Observed and computed values of outgoing and counter radiation (in ly min^{-1})

Ship	Outgoing radiation ($F\uparrow$)		Counter radiation ($F\downarrow$)		Percentage difference ($F\uparrow - F\downarrow$)
	Computed	Observed	Computed	Observed	
	Shokalsky	0.612	0.610	0.550	
Priboy	0.614	0.610	0.558	0.563	0.7 0.7
Akademik Shirshov	0.612	0.610	0.555	0.557	0.3 0.4
Okean	0.611	0.610	0.548	0.557	0.2 1.3

TABLE 3

Correlation coefficients

	Priboy				Akademik Shirshov				Shokalsky				Okean			
	E	N	T_a	T_w	E	N	T_a	T_w	E	N	T_a	T_w	E	N	T_a	T_w
E	1.0				1.0				1.0				1.0			
N	-0.6	1.0			-0.6	1.0			-0.5	1.0			-0.5	1.0		
T_a	-0.1	-0.2	1.0		-0.2	-0.3	1.0		-0.4	-0.2	1.0		-0.3	-0.2	1.0	
T_w	-0.1	-0.2	0.2	1.0	-0.1	0.1	0.3	1.0	-0.2	0.1	0.3	1.0	0.1	0.1	0.2	1.0

where F_0^\downarrow and F_c^\downarrow stand for the values of incoming counter radiation with an overcast and clear sky respectively. F_0^\downarrow and F_c^\downarrow are represented by the two empirical relations

$$F_0^\downarrow = 1.48 (\sigma T_a^4)^{1/2} - 0.569 \quad (2.3)$$

$$F_c^\downarrow = 1.63 (\sigma T_a^4)^{1/2} - 0.775 \quad (2.4)$$

The total cloud cover (N) is reported in octas. For the purpose of (2.1), N is taken to be the ratio of the sky which is covered with clouds. Thus, for six octas of clouds the value of N is 6/8.

We computed the contribution of the different terms, marked as (1), (2) and (3) in (2.1). The main contribution was by the outgoing long-wave radiation, which is (1) in (2.1). The ratio of (2) to (1) was between 80 and 90 per cent indicating a substantial contribution by the downward counter radiation even under clear skies. The ratio of (3) to (2) was around 15 per cent indicating that clouds increased the counter radiation by this amount.

A comparison between the computed values of E was made with the observations recorded by the USSR ships during 1977. The observed values were recorded by actinometers on board the USSR ships during night for the period 8 to

19 August 1977, over the Bay of Bengal. The results of the comparison are shown in Table 1. Approximately 120-150 observations were available for each ship for this period.

Table 1 suggested that (2.1) provided values of E which agree with observations to within 17 per cent. Considering the uncertainties in observations, this was fairly good agreement. It is relevant to point out that E is the difference between two large terms, namely, the outgoing radiation and the downward counter radiation. If we compare the observed values of these individual terms, then the results are still better. This is shown in Table 2.

In view of the agreement between an empirical relation (2.1) and field observations of E during the 1977 experiment, it was decided to examine the relation between E and the other meteorological variables T_a , T_w and N . Correlation coefficients were accordingly computed between E , T_a , T_w and N . We present the results in Table 3.

Table 3 suggests a significant negative correlation between E and the total cloud cover N . There was hardly any correlation between any of the other meteorological variables.

3. Spectral analysis

To examine the relationship between E and N , we make a spectral analysis of these two variables.

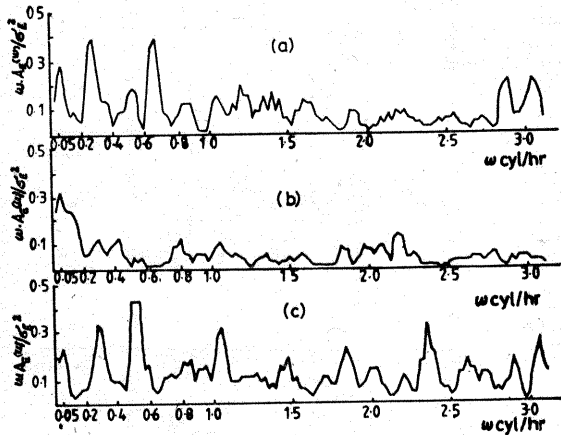


Fig. 1. Power spectra of effective longwave radiation (E) from the sea surface for Russian ships: (a) *Priboy*, (b) *Akademik Shirshov* (c) *Priliv*

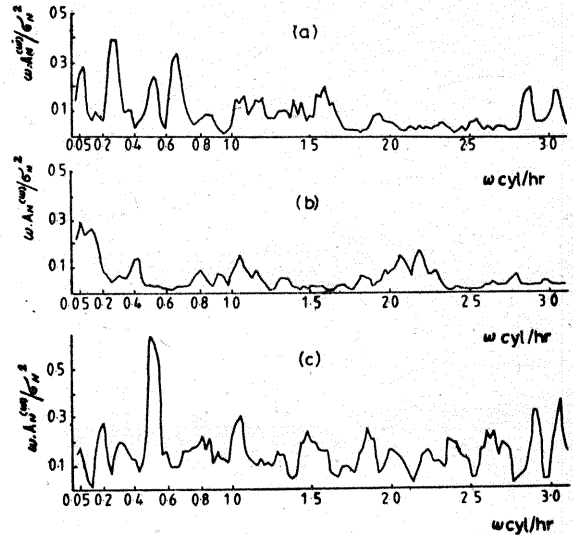


Fig. 2. Power spectra of total cloud cover (N) for ships: (a) *Priboy*, (b) *Akademik Shirshov* & (c) *Priliv*

The Fourier decomposition of either E and N is

$$X(t) = \sum_{k=-\infty}^{\infty} A(k) \exp(2\pi ikt/T) \quad (3.1)$$

where, T is its period, and $X(t)$ stands for the normalised value of the variate E or N . As :

$$X_E(t) = [E(t) - \bar{E}] / \sigma_E \quad (3.2)$$

where σ_E is the variance E and \bar{E} is its mean. A similar expression may be developed for N .

The complex amplitude $A(k)$ is :

$$A(k) = \frac{1}{T} \sum_{-T/2}^{T/2} X(t) \exp(-2\pi ikt/T) \quad (3.3)$$

The average power of $X(t)$ may be decomposed into contributions at the fundamental frequency $w_k = 2\pi/T$, and the other harmonics $w_k = 2\pi k/T$. It is usual to plot the function :

$$S_k = w_k T |A^2(k)| = 2\pi k |A^2(k)| \quad (3.4)$$

against w_k . This gives the spectral density or the product of power and frequency for different values of k . As indicated by Zangvil (1975) it is a good indicator of the scale of the variate.

The cross-spectrum between effective outgoing radiation (E) and cloud cover (N) is :

$$g_{E,N}(w) = \beta(w) \exp[i\phi(w)] \quad (3.5)$$

where, β and ϕ represent the amplitude and phase of the cross-spectrum. β and ϕ may be represented by :

$$\beta(w) = [P^2(w) + Q^2(w)]^{1/2} \quad (3.6)$$

$$\phi(w) = \arctan[-Q(w)/P(w)] \quad (3.7)$$

$P(w)$, $Q(w)$ are the real and imaginary parts of $g_{E,N}(w)$ and are called the cospectrum and quadrature spectrum respectively.

Another useful function, which is derived from the cross-spectrum, is the squared coherency spectrum, which is :

$$C(w) = [P^2(w) + Q^2(w)] \div [g_{EE}(w) \cdot g_{NN}(w)] \quad (3.8)$$

where, $g_{EE} = A_E \cdot A_E^*$ and $g_{NN} = A_N \cdot A_N^*$ are the power spectra of E and N respectively.

4. Results

We did not have continuous actinometric observation of E during the fixed polygon period of the 1977 experiment. But, during Monex-79, three USSR ships were again in polygon formation over the north Bay of Bengal from 11 to 23 July 1979. The relative positions of the three ships during this period were :

- (i) *Priliv* (14.0 N, 89.0 E)
- (ii) *Akademik Shirshov* (16.2 N, 87.0 E)
- (iii) *Priboy* (18.0 N, 89.4 E)

Continuous records of T_a , T_w and N were provided by these three ships from which E was computed by (2.1). In view of the agreement between E and N during 1977, at approximately the same time and location, a spectral analysis was made of E and N with Monex data for 11 to 23 July 1979.

Figs. 1 and 2 represent the variation of $S(k)$ defined by (3.4) with $w(k)$ for effective outgoing

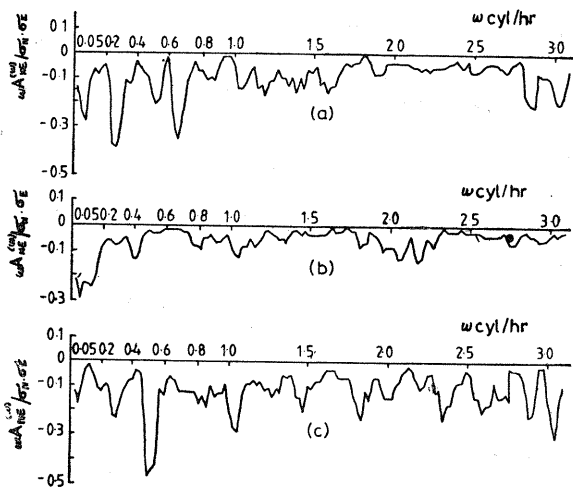


Fig. 3. Cospectra between effective long wave radiation and total cloud amount for ships: (a) *Priboy*, (b) *Akademik Shirshov* & (c) *Priliv*

radiation (E) and total cloud cover (N). We notice two major peaks in E at short angular frequencies 0.27 and 0.54-0.64 cycles per hour (approx.). The corresponding periods are, approximately, 23 and 10-12 hours. The appearance of such diurnal and semi-diurnal harmonics of E can be caused by several ways: first, as relation (2.1) shows, E is a function of T_a , T_w and N , so any periodical components in T_a , T_w or N (in particular, in N) will be reflected in E ; secondly, for emitters of short and long wave radiations, diurnal and semi-diurnal periodicities in the radiation process are expected. It is interesting to note that the power spectrum of N (Fig. 2) is practically same as that of E (Fig. 1). The power spectrum of N shows two predominant maxima corresponding to 12 and 24 hours (approx.) periodicities. However, these harmonics are not common for all the three ships. Observations from *Priboy* show two maxima with periods of about 24 and 10 hours. *Priliv* showed a single 12 hour harmonic, while *Akademik Shirshov* showed no significant peak except one at about 64 hours.

The twentyfour hour harmonic in the spectrum of the total cloud cover (N) could be due to the diurnal variation of T_a and T_w which are responsible for convective activity. However, the 12 hour harmonic in cloud appear as a result of certain local physical processes. Among other possible

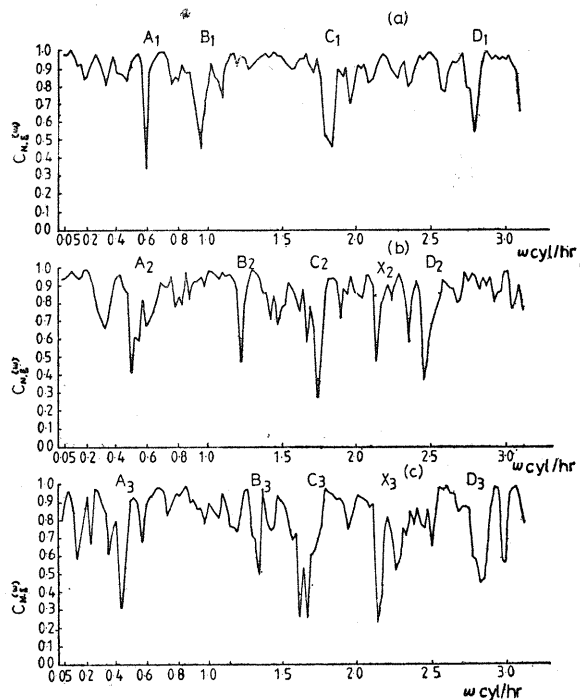


Fig. 4. Squared coherency spectra between effective long wave radiation and total cloud amount for ships: (a) *Priboy*, (b) *Akademik Shirshov* & (c) *Priliv*

reasons for the appearance of the 12 hour harmonic, semi-diurnal variation of the pressure field may be one.

In the spectra of N , E (Figs. 1 and 2) as well as their co-spectra (Fig. 3) over these three ships mainly three maxima are observed. They correspond to (i) 5 days, (ii) 12-24 hours and (iii) 2-3 hours harmonics. However, as the time series do not exceed 12-13 days of continuous observations over the Bay of Bengal during Monex-79 stationary polygon and observations may be treated as super-imposition of some periodic waves and noise spectrum, it is not desirable to confirm statistical significance of 5 days period with this limited data source. The appearance of a 2-3 hours harmonic in the spectrum of N , which is also reflected in E and in their cospectra for *Priboy* and *Priliv* would be attributed to mesoscale cloud clusters (50 to 100 km long) over these two ships. This agrees well with the observation of mesoscale convective clouds over the Atlantic trade wind zone (Ivanov *et al.* 1974).

The cospectra of the bivariate process E and N (Fig. 3) is practically the mirror image of the total cloud cover (N) power spectrum (Fig. 2). Further, this indicate the scale of interaction of E and N

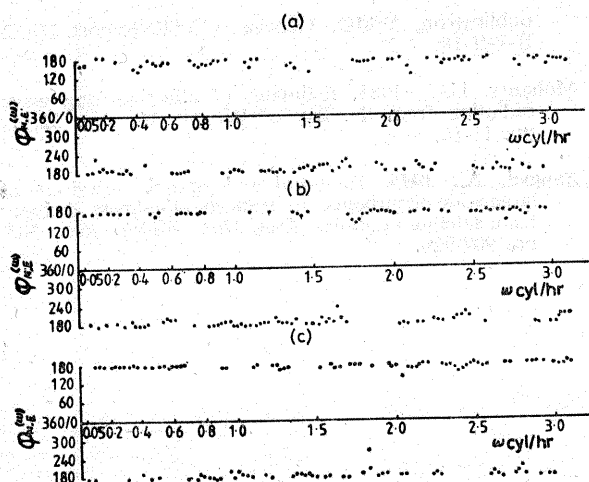


Fig. 5. Phase spectra between effective long wave radiation and total cloud cover for ships: (a) *Priboy*, (b) *Akademik Shirshov* & (c) *Priliv*

which has periodicities similar to that of N . Negative values stand for negative correlation between E and N . The cospectrum of E and N , again confirms the fact that E is mainly dependent on N .

The squared coherency spectrum defined by (3.8) resembles to the square of the correlation coefficient between the two variates over the entire frequency domain and gives a measure of the influence of noise in the system. The squared coherency spectrum of the bivariate process E and N is presented in Fig. 4. This reveals that:

- (i) Over a wide range of frequencies a very high value of $C_{E,N}(\omega)$ for all the three ships are observed, which suggests a higher degree of linear relation between E and N for most of the frequency domain with considerably less noise.
- (ii) It is interesting to note that a number of minima [considerably lower values of $C_{E,N}(\omega)$ being less than 0.5] are appeared in the coherency spectra corresponding to points A, B, C, D and K in the frequency domain.
- (iii) Points A correspond to lower frequencies (ω) of 0.44 to 0.57 cycles per hour (cph) (11 to 15 hours period), B and C to the medium frequency ranges of 1.0 to 1.38 cph (5 to 7 hours period) and 1.63-1.82 cph (3 to 4 hours period) respectively, while D correspond to higher frequencies of 2.45 to 2.83 cph (2 to 3 hours period), X_2 and X_3 correspond to 2.14 cph frequency (3 hours period). Thus, these minima appear mainly at the meso-scale periods.

- (iv) Over *Priboy* the minima (A_1 , B_1 , and C_1) appear at 4 hours interval (11, 7 and 3 hours), while over *Akademik Shirshov* A_2 and B_2 appear at 8 hours interval and over *Priboy* A_3 and B_3 appear at 10 hours interval. Further, it is found that A_1 , B_1 and A_2 differ from A_2 , B_2 and A_3 by 2 hours respectively, which may be due to a phase lag in space over the region of the fixed polygon. Existence of such meso-scale processes may be due to the appearance of mesoscale convective cloud clusters as discussed above.

The phase spectra $\phi(\omega)$ defined by the relation (3.7) shows whether the frequency components in one series lag or lead the components at the same frequency in the other series.

Fig. 5 illustrates the variation of the phase $\phi(\omega)$ with $\omega(k)$ for outgoing radiation (E) and total cloud cover (N). It is observed that the phase lag between the variates E and N is practically equal to 180 deg. over entire frequency domain. This may be because of the fact that they are negatively correlated and this lead to total interference of the two kinds of waves.

5. Conclusions

The semi-empirical relation (2.1) gave satisfactory performance with Monsoon-77 and Monex-79 data for computation of effective long-wave radiation (E).

The observed as well as computed values of E show a significant negative correlation with N , while air and water temperatures show no appreciable correlation with E . The spectral studies confirmed this and provided the periodicities and scale of interaction between E and N . The sensitivity test shows that the contribution of cloud cover towards incoming counter radiation increases from less than 1 percentage for 1 okta cloud to nearly 15 percentage for overcast sky.

Thus for parameterization of the effective outgoing long-wave radiation (E) the cloud observations should be taken with more accuracy and the amount of low cloud may be taken into account along with total cloud cover. The two hour periodicity of total cloud cover can be confirmed by hourly satellite pictures from geostationary satellite.

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