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A method of estimating longwave radiation over the Indian seas based on surface synoptic observations

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सार — मानसून ऋतु के दौरान, नियमित रूप से प्रेक्षित मौसम-वैज्ञानिक प्राचलों की सहायता से स्वआनुभाविक निदर्श का प्रयोग करते हुए समुद्र सतह से दीर्घ तरंग विकरित फ्लक्स के आकलन का प्रयत्न किया गया। दीर्घ तरंग फ्लक्स को आकलित करने के लिए उपयुक्त पद्धति का पता लगाने के लिए, आकलित मानों की तुलना प्रेक्षित मानों से की गई।

यह अध्ययन दर्शाता है कि दीर्घ तरंग फ्लक्स को निर्धारित करने में मेघ महत्वपूर्ण भूमिका निभाते हैं। यह पाया गया है कि सतह पर आधारित प्रेक्षणों से प्राप्त मेघों की विस्तृत जानकारी का अभाव दीर्घ तरंग फ्लक्स आकलन की त्रुटि के लिए उत्तरदायी है। मानसून-77 आंकड़ा समुच्चय पर आधारित समाश्रयण पद्धति का प्रयोग करते हुए इन त्रुटियों को कम किया गया है। फिर इस पद्धति को मोनेक्स-79 आंकड़ा समुच्चय के साथ परीक्षित किया गया जो कि एक स्वतंत्र आंकड़ा समुच्चय के रूप में कार्य करती है। अतः दीर्घ फ्लक्स के आकलन से संबंधित त्रुटियों को कम करने के लिए यह पद्धति विकसित की गई है।

ABSTRACT. An attempt has been made to estimate longwave radiative flux from sea surface using semi-empirical models with the help of routinely observed meteorological parameters during the monsoon season. The estimated values are then compared with observed values to find out an appropriate method to compute the longwave flux.

The study shows that clouds play an important role in determining the longwave flux. It is found that lack of detailed knowledge of clouds obtained from ground based observations is responsible for the errors in the estimation of longwave flux. The errors are reduced using a regression method based on Monsoon-77 data set. The method was then tested with Monex-79 data set which served as independent data set. The method thus developed considerably reduces the errors associated with the estimation of longwave flux.

Key words —Outgoing longwave radiation, Heat flux, Effective longwave radiation, Cloud cover, Counter radiation, Relative humidity.

1. Introduction

The effective outgoing longwave radiation (E) from the sea surface consists of two components : (*i*) net longwave energy radiated out from the sea surface ($F\uparrow$) and (*ii*) counter infrared radiation from the atmosphere ($F\downarrow$). In general, effective longwave radiation from the sea surface is the small difference of two comparatively large terms $F\uparrow$ and $F\downarrow$.

The outgoing radiation is simply a function of sea surface temperature (T_w) and sea surface emissivity (δ, 0.91) while downward atmospheric radiation depends on the air temperature (T_a), the liquid water content of the atmosphere (ω) and cloud cover (N). Thus

$$E = F\uparrow - F\downarrow = f(T_w, T_a, \delta, \omega, N) \qquad (1)$$

The effective outgoing longwave radiation from the sea surface can be directly estimated by actinometric observations like those carried out during special experiments (BOMEX, ATEX, GATE, MONEX etc). However, the measuring instruments are not perfect and encounter with a number of technical limitations during daytime due to the influence of solar radiation. Thus the experimental data still do not allow in solving many important practical problems of general interest such as heat balance of the underlying sea surface, inclusion of heat flux in the boundary layer models, determination of diabatic heat source/sink in the dynamic models of the atmosphere etc. In most of the studies E is obtained from the Eqn. (1). The functional relationship of E with the meteorological parameters [Eqn. (1)] is quite non-linear in their nature and generally obtained from the experimental data and physical concepts. These facts lead to the development of a number of semi-empirical relations for computations of E by various investigators. Sellers (1965), Morgan *et al.* (1971) and Mohanty (1981a) gave a detail review of the earlier work on the computations of E by semi-empirical relations.

The purpose of this paper is to compare the estimation of E using semi-empirical expressions, with the actual actinometric observations during the Indo-USSR expeditions of 1977 over the Arabian Sea. As none of these empirical relations is unanimously accepted by scientific community for all geographical and meteorological conditions we believe that the comparative study of various methods could lead to find out a suitable method to estimate E over the Arabian Sea during the active monsoon conditions. An attempt is also made to modify the semi-empirical method suggested by Girduk & Malevaski (1973) which tends to provide a better fit

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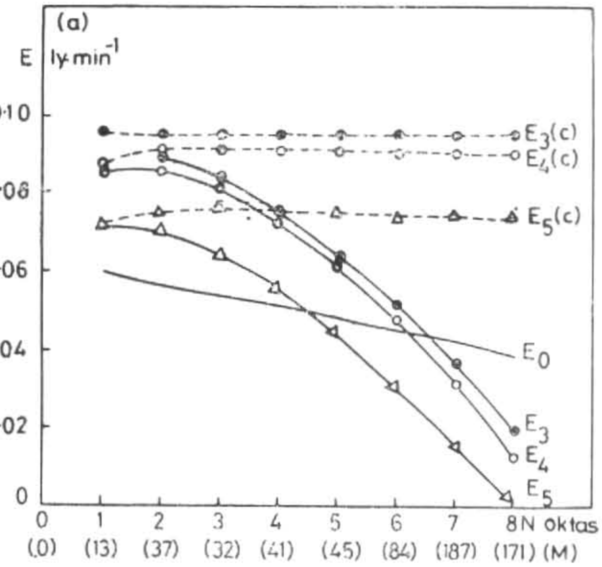

Fig. 1 (a). Mean longwave flux obtained by methods E_3-E_5

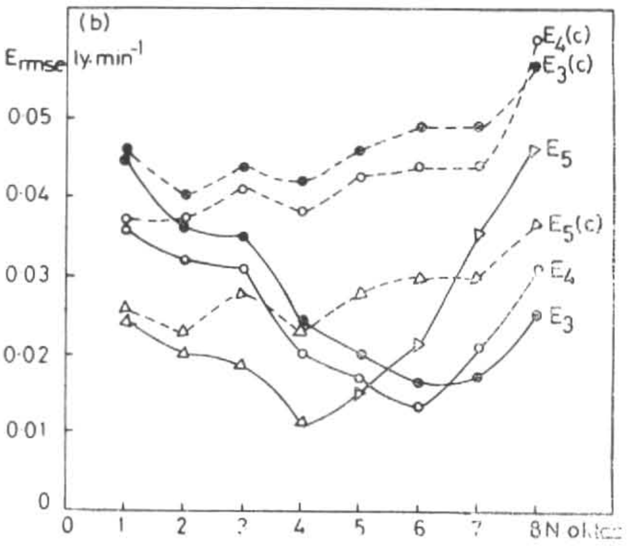

Fig. 1(b). Root mean square error of the effective longwave radiation by methods E_3-E_5

TABLE 1

Empirical expressions and statistics for surface effective longwave radiation (ly/min) for all sky conditions. Values in parenthesis are for clear sky only

Author and year	Expressions	Mean (*M*)	Standard deviation (S.D.)	Root mean square error (r.m.s.e.)
Observed	E_0	0.0471	0.0148	—
Girduk & Malevaski(1973)	$E_1=\delta\sigma T_w^4-\delta\,[1.63\,(\sigma T_a^4)^{1/2}-0.775]\times(1-kN^2)$	0.0497	0.0144	0.0235
Hastenrath and Lamb (1979)	$E_2=\delta\sigma T_w^4(0.39-0.05q^{1/2})\cdot 1.053N^2$ $+4.0\delta\sigma T_w^3\,(T_w-T_a)$	0.0672	0.0184	0.0275
McDonald (1957)	$E_3=0.165-0.769\times10^{-3}r$	0.0454 (0.0948)	0.0240 (0.0019)	0.0295 (0.0501)
Swinbank (1963)	$E_4=\delta\sigma T_w^4-9.35\times10^{-6}(\delta\sigma)T_a^6$	0.0400 (0.0899)	0.0249 (0.0035)	0.0248 (0.0452)
Brunt (1932)	$E_5=\delta\sigma T_w^4-\delta\sigma T_a^4(0.66+0.39e^{1/2})$	0.0230 (0.0144)	0.0225 (0.0030)	0.0342 (0.0309)

T_a, T_w — Sea surface and overlying air temperature (°K), k — Constant defined in text,

N — Cloud amount in oktas, q — Specific humidity of air (gm/kg),

r — Relative humidity (%), σ — Stefan-Boltzman constant (0.813×10^{-10} ly. min.$^{-1}$ °K^4), and

e — Water vapour pressure (mb), δ — Sea surface emissivity (0.91).

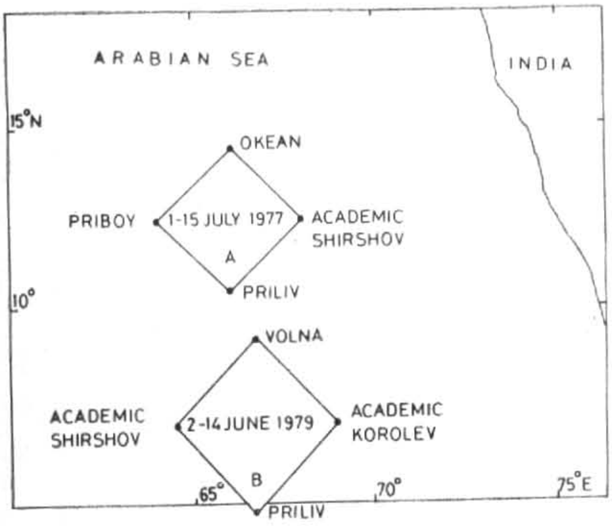

Fig. 2. Positions of USSR research vessels during Monsoon-77 experiment and Monex-79

with the actinometric observations than the other empirical expressions currently in use for the Bay of Bengal (Mohanty 1981 a & b) and the Arabian Sea, by using Monsoon-77 data set. Hereafter, the modified version of the semi-empirical method by Girduk & Malevaski (1973) will be referred to as method E_M. This method E_M was tested with Monsoon-77 (dependent) and Monex-79 (independent) data sets.

2. Data and method of computation

Hourly actinometric observations were recorded for a period of 1-15 July 1977 by four USSR research vessels which formed a fixed polygon over the Arabian Sea (Fig. 2) during the Indo-USSR Monsoon-77 experiment. As the day time observations were not reliable, for the present study only night time data are used which consisted of 610 cases.

In addition to actinometric observations hourly synoptic observations of air and water temperature, total cloud cover, relative humidity (r) and specific humidity (q) were taken into consideration for the estimation of E by various semi-empirical relations.

Similar data sets, obtained by four USSR research vessels which formed a fixed polygon over the Arabian Sea (Fig. 2) during Monex-79 for the period 2-14 June 1979, were taken into consideration for further confirmation of some of the findings with Monsoon-77 data and for validation of the method E_M suggested in the present study based on Monsoon-77 data set.

A number of semi-empirical expressions have been developed for the estimation of effective longwave radiation by different authors. Some of the recently developed and well known expressions were examined using a limited number of observations (14 cases) by Morgan *et al.* (1971). The performance of these expressions was examined by Mohanty (1981a) with a total number of 556 cases over the Bay of Bengal. In the present study five semi-empirical expressions as described in Table 1 are utilised to estimate E over the Arabian Sea during southwest monsoon period. This table also indicates the efficiency and validity of various methods based on 610 observations.

In Table 1 the relationship of Girduk & Malevaski (E_1) and Hastenrath and Lamb (E_2) take account of cloud cover in the estimation of effective longwave radiation flux, whereas rest of the expressions were developed for clear sky conditions.

The study on influence of cloud cover on the atmospheric longwave radiation is of much importance, especially during the southwest monsoon period, as during this period the sky is almost cloudy over the Arabian Sea. Since the sky is not clear, the empirical relation for clear sky conditions should be modified suitably to incorporate the effect of cloudiness. Such a relation suggested by Bolz (Gieger 1965 and Morgan *et al.* 1971) is given as

$$F\downarrow = F_c \updownarrow [1 + k\,(N / 8)^2] \tag{2}$$

where, k is a constant to be determined from the observations and N the cloud amount in oktas. k is defined as the ratio of: (*i*) the difference between the longwave counter radiation for an overcast and clear sky to, (*ii*) the value corresponding to clear sky. Thus we have,

$$k = (F_o\downarrow - F_c\downarrow) / F_c\downarrow \tag{3}$$

where, $F_o\downarrow$ and $F_c\downarrow$ denote the downward radiation for an overcast and clear sky respectively. $F_o\downarrow$ and $F_c\downarrow$ are :

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

$$F_0\downarrow = 1.48\,(\sigma\, T_a^4)^{1/2} - 0.569 \tag{5}$$

The numerical constants in the above expressions suggested by Girduk & Malevaski (1973) were based on actinometric observations over sea suface and these were validated against GATE data by Egorov (1976).

3. Discussion of results

The Table 1 gives the statistics of the performance of each individual expressions (E_1–E_5) along with the observed flux (E_0) when there was no classification of data according to the cloud amount. We note that the net longwave flux estimated by Girduk & Malevaski (E_1) is in best agreement with the observed flux (E_0) as the r.m.s. error (0.0235) and standard deviation (0.0144) are minimum. These results confirm an earlier study carried out for the Bay of Bengal (Mohanty 1981a).

The influence of cloud cover on estimation of E is of considerable interest and also emphasised in the earlier works Mohanty (1981 a,b). Considering this aspect the whole data were divided into eight groups in terms of the total cloud cover in oktas.

In order to find out the role of cloud cover on the effective longwave radiation (E), the relations (E_3–E_5) are used to estimate E under clear sky conditions in their original form and for sky with cloudiness by suitable modifications of these relations as suggested by Bolz (Eqn. 2). A comparison of these two ways of estimation is illustrated in Figs. 1 (a & b).

Fig. 1 (a) indicates that the mean values of E computed with suitable adjustment to include cloudiness decrease

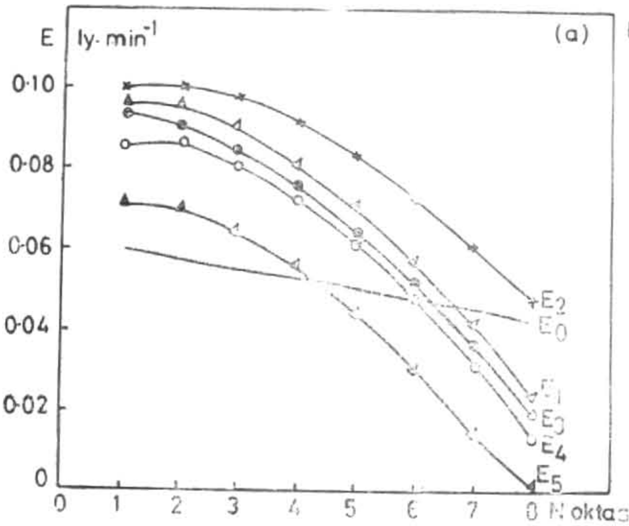

Fig. 3(a). Mean of the effective longwave radiation by methods E_1–E_5

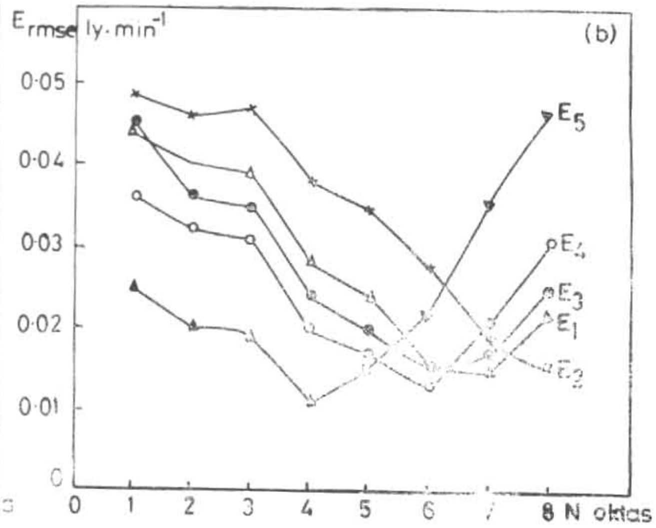

Fig. 3(b). Root mean square error of the effective longwave radiation by methods E_1–E_5

considerably from that of E, computed under clear sky conditions, and approach the corresponding observed values. These three methods in their original form (without taking into account the cloud effect) give overestimates of E. When these methods are modified to include cloudiness, they give good estimates of E for high cloud amounts. It can be seen that the computed values are very close to the observed values in the range of 4-6 oktas cloud cover. The methods E_3–E_5 invariably give overestimated values of E for cloud cover less than 4 oktas and underestimated values for overcast sky conditions. This may be due to the fact that Bolz modification is suitable only for moderate cloud cover (4-6 oktas) or it is difficult to have an accurate estimate for extreme ranges of cloud covers (1-3 and 7-8 oktas).

The root mean square error (r.m.s.e.) of the effective longwave radiation estimated by these methods is depicted in Fig. 1(b). We observe that the r.m.s. error of E computed by these methods, confirms the above results that the inclusion of the effect of cloud cover gives a better estimate of effective longwave radiation. This can be attributed to the fact that there is a large departure of underestimated value of E computed with suitable adjustment of cloudiness from the observed value compared to overestimated value of E obtained under clear sky conditions.

Figs. 3 (a & b) illustrate the r.m.s. errors of E, estimated by five different empirical expressions (Table 1), for different cloud amounts, from the observed value of effective longwave radiation. This figure helps to evaluate the efficiency of various methods over the entire spectrum of cloud cover. We note that the observed value of E decreases as cloud cover increases. This is to be expected because the counter radiation increases with the increase of cloud amount. The stratified data do not reveal merit of any single method over entire cloud spectrum. In general, the method by Brunt gives better estimation of E with a cloud cover less than 5 oktas, whereas the computed values of E by empirical relation suggested by Girduk & Malevaski (1973) yields almost better results for more than 6 oktas. The r.m.s. error (Fig. 3b) of E by Brunt is minimum over 1 – 4 oktas cloud cover whereas no single method gives minimum r.m.s. error for 5–8 oktas cloud cover. In order to arrive at a general conclusion on the efficiency of the empirical relations, the entire data set has been divided into two groups based on cloud cover (1–4 and 5–8 oktas). Table 2 contains the mean values of E and its r.m.s. errors as determined for these two groups. We observe that in more than 80% of observations the sky was covered with 5–8 oktas cloud cover, which is to be expected over the southern Arabian Sea during summer monsoon. Mean and r. m. s. error of E indicate that the method proposed by Brunt is suitable when the cloudiness does not exceed 4 oktas, whereas the method suggested by Girduk & Malevaski (1973) gives better results with minimum r. m. s. error for a cloud cover of more than 4 oktas. During summer monsoon season a period having more than 4 oktas cloud cover in more than 80% occasions, the method proposed by Girduk & Malevaski (1973) may be considered to be the most suitable for estimating the effective longwave radiation from the Arabian Sea. This result confirms an earlier study for the Bay of Bengal (Mohanty 1981 a).

Though the method proposed by Girduk & Malevaski (1973) is considered to be the most suitable one for estimating E from the Arabian Sea during southwest monsoon period, it does not give satisfactory result for the entire cloud spectrum. This may be due to the fact that none of methods used in this study takes into account the type and structure of the cloud cover and its vertical extent which thus may introduce systematic error in the estimation of E. As it is not practicable to take a detail account of clouds (*i.e.*, structure, vertical extent and type of cloud) from the usual synoptic observations to incorporate their effect in the estimation of E, an indirect approach can be made to overcome some of the systematic errors in the estimation of E. One such approach is to establish statistical relationship between the observed and best estimated values of E (between E_0 and E_1). In order to study the relation between the observed and best estimated values of E, the value of E *versus* E_0 and the regression line are illustrated in Fig. 4. The regression equation obtained by the least square method is as follows :

$$E_0 = 0.3174\, E_1 + 0.0308 \qquad (6)$$

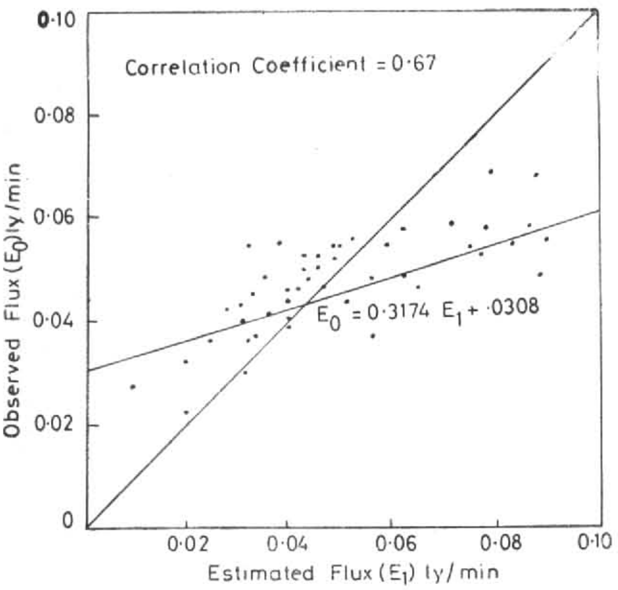

Fig. 4. The regression line between observed and best estimated value

TABLE 2

Comparative statistics for different formulae

Methods/ Stratification	E_0	E_1	E_2	E_3	E_4	E_5
Mean effective outgoing radiation (ly/min)						
1-4 oktas (20%)	.0539	.0887	.0964	.0841	.0797	.0639
5-8 oktas (80%)	.0453	.0397	.0598	.0356	.0298	.0109
Root mean square error (ly/min)						
1-4 oktas	—	.0368	.0439	.0332	.0289	.0178
5-8 oktas	—	.0180	.0214	.0203	.0237	.0373

where the numerical values 0.3174 and 0.0308 are the regression coefficient and the intercept (in ly/min) respectively. It may be noted that the low values of the regression coefficients in the above equation support the fact that the change to the recomputed values of E due to the present modification is small. Further, the correlation coefficient between E_0 and E_1 is found to be 0.67. All these facts give clear evidence of mutual correlation between the observed and estimated values of E by method suggested by Girduk & Malevaski (1973). In order to evaluate the efficiency of the regression equation which may improve the estimated values of E, the Eqn. (6) is used with E_1 as predictor to obtain the newly estimated predictant E_M. The statistics of E_0, E_1 and E_M are illustrated in Table 3. The mean values of E_M become much closer to E_0 in comparison to the corresponding values of E_1. Thus, mean percentage deviation of the estimated values decrease considerably over the entire cloud spectrum in particular for the low cloud cover, 1-4 oktas (decrease is almost ten times) in which range E_1 show a poor picture. The r. m. s. error between E_0 and E_1, E_0 and E_M also depict similar results.

TABLE 3

Evaluation of the regression relation with Monsoon-77 data

Stratification	E_0	E_1	E_M
Mean effective outgoing radiation (ly/min)			
1-4 oktas (20%)	0.0539	0.0887	0.0571
5-8 oktas (80%)	0.0453	0.0397	0.0439
1-8 oktas	0.0471	0.0497	0.0466
Root mean square error (ly/min)			
1-4 oktas	—	0.0368	0.0154
5-8 oktas	—	0.0180	0.0136
1-8 oktas	—	0.0235	0.0140

TABLE 4

Performance of the regression equation with Monex-79 data (Independent data set)

Cloud amount (oktas)	Observed mean (ly/min)	With regression equation		Without regression equation	
		Calculated mean (ly/min)	R.m.s. error	Calculated mean (ly/min)	R.m.s. error
>4 (152)	0.0713	0.0614	0.0179	0.0963	0.0267
<4 (34)	0.0853	0.0655	0.0230	0.1094	0.0377
Total (186)	0.0738	0.0621	0.0190	0.0987	0.0359

The r. m. s. error between E_0 and E_M (Table 3) is least in comparison to the r. m. s. error between E_0 and E_1–E_5 (Table 2). Thus the proposed method E_M, which is a modified version of the method by Girduk and Malevaski (1973), to estimate E, is found be superior to all the other methods for the entire cloud spectrum.

The performance of the regression relation developed is tested with Monex-79 data set which served as independent data set. Results of this study are presented in Table 4. From this table, it can be seen that r. m. s. error obtained using the regression equation is found to be minimum for the entire cloud spectrum. Thus the regression method developed using Monsoon-77 data set is found to be superior over other methods and applicable to independent observations.

4. Conclusions

The estimation of E over the Arabian Sea during the southwest monsoon season by the different empirical relations, using the Indo-USSR Monsoon-77 and Monex-79 data sets lead us to the following conclusions:

(*i*) During the monsoon season about 80% of observations are with 5 oktas or more cloud cover. This emphasises the importance of cloud cover on the effective longwave radiation.

(*ii*) There is definite merit in applying the correction of Bolz to clear sky values of the estimated counter radiation from the atmosphere.

(*iii*) For overcast sky, or cloud cover exceeding 5 oktas the semi-empirical relation (E_1) by Girduk & Malevaski (1973) may be considered more suitable, but for cloud cover not exceeding 4 oktas Brunt's formula may be recommended for estimating E. However, the method E_M, suggested in this study modifying E_1 value with Monsoon-77 data set (*i.e.*, method E_M) is found to be better than E_1 and E_5.

(*iv*) In the present situation during southwest monsoon on the average the method suggested by Girduk & Malevaski (1973) may be recommended to estimate E.

(*v*) A close correlation between E_0 and E is obtained from the semi-empirical relation by Girduk & Malevaski (1973) leads to a regression relation between E_0 and E_1. The estimated values of E_1 from the regression equation is found to be the most suitable one over the entire cloud spectrum and recommended to be the best method for its use in estimating E.

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