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Energy exchanges between ocean and atmosphere in relation to southwest monsoon performance over India

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सार–अधिकांशीय वायु-गतिक समीकरणों के प्रयोग से, वर्ष 1987 और 1988 के पूर्व-मानसून और मानसूनी महीनों के लिये, भारतीय समुद्रों के ऊपर ऊर्जा के प्रवाह का परिकलन किया गया है। इन समीकरणों में विनिमय गुणांकों का समावेश है जिनके मान पवन की गति और स्थिरता के साथ बदलते रहते हैं। वर्ष 1987 और 1988 इसलिये चुने गए हैं क्योंकि इनके दौरान भारतीय ग्रीष्मकालीन मानसून भिन्न-भिन्न रूप में सक्रिय रहा। ऊर्जा-प्रवाह के अतिरिक्त अन्य सागरीय प्राचलों का भी परिकलन और अध्ययन किया गया है, जैसे–समुद्र सतहीय तापमान, समुद्र और वायु के तापमान का अंतर, 'बॉवन अनुपात' और 'पवन-कार्य की दर'। वर्ष 1987 और 1988 के दौरान, भारतीय समुद्रों पर इन प्राचलों के बंटन से भिन्न-भिन्न प्रकृति के अनेक लक्षण प्रकाश में आए हैं। इनमें से कुछ लक्षण मानसून की सक्रियता की भविष्यवाणी के संकेत प्रदान करते हैं।

ABSTRACT. Energy fluxes over Indian seas have been computed for pre-monsoon and monsoon months of the years 1987 and 1988 using bulk aerodynamic equations with exchange coefficients which vary with wind speed and stability. The years 1987 and 1988 have been chosen due to the constrasting nature of the performances of Indian summer monsoon during these years. Besides energy fluxes several other oceanographic parameters, *viz.*, SST, sea-air temperature difference, 'Bowen ratio' and 'rate of wind work' have been computed and examined. The distributions of these parameters over Indian seas during 1987 and 1988 reveal several constrasting features. Some of these features provide predictive indications of monsoon performance.

Key words — Energy fluxes, Southwest monsoon, Drag coefficient, Bowen ratio, Rate of wind work, Cyclogenic sea area.

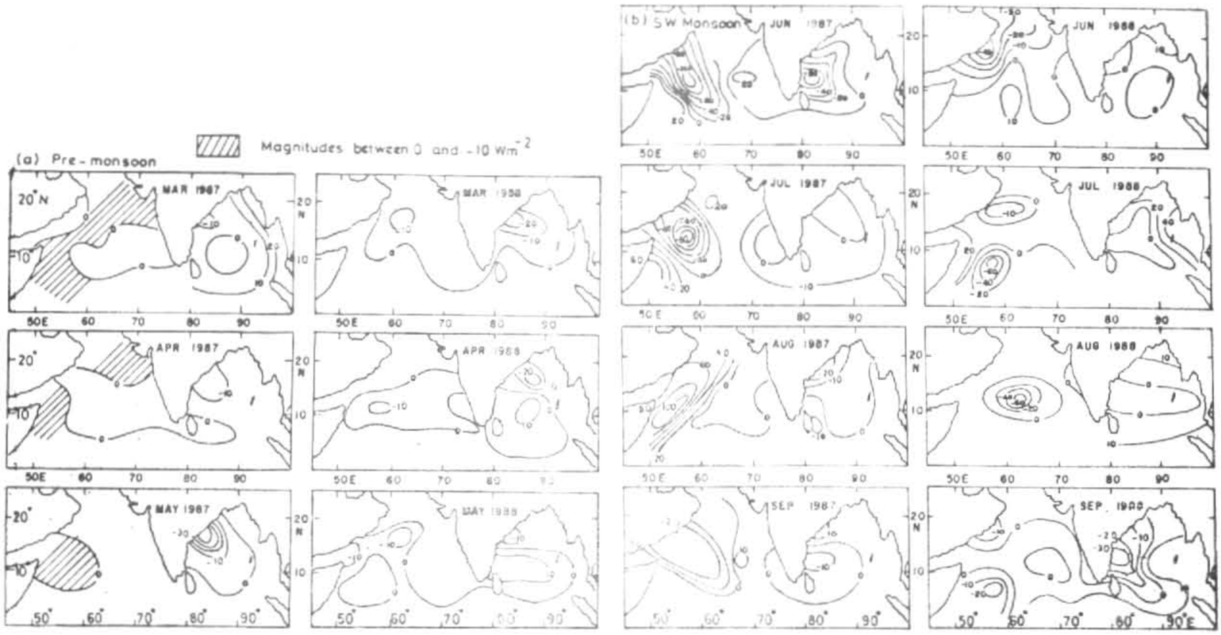
1. Introduction

Evaporation from the Indian seas is one of the main sources of energy for the Indian summer monsoon. This moisture is not only needed for the rains over India, but the large amount of latent heat released by the monsoon rains helps to intensify different components of the monsoon circulation. There have been indications of inter-annual differences in many oceanographic parameters including the evaporation. These differences are bound to be manifested in the southwest monsoon rainfall over India. The present study was undertaken with an objective of quantitative investigation of these manifestations.

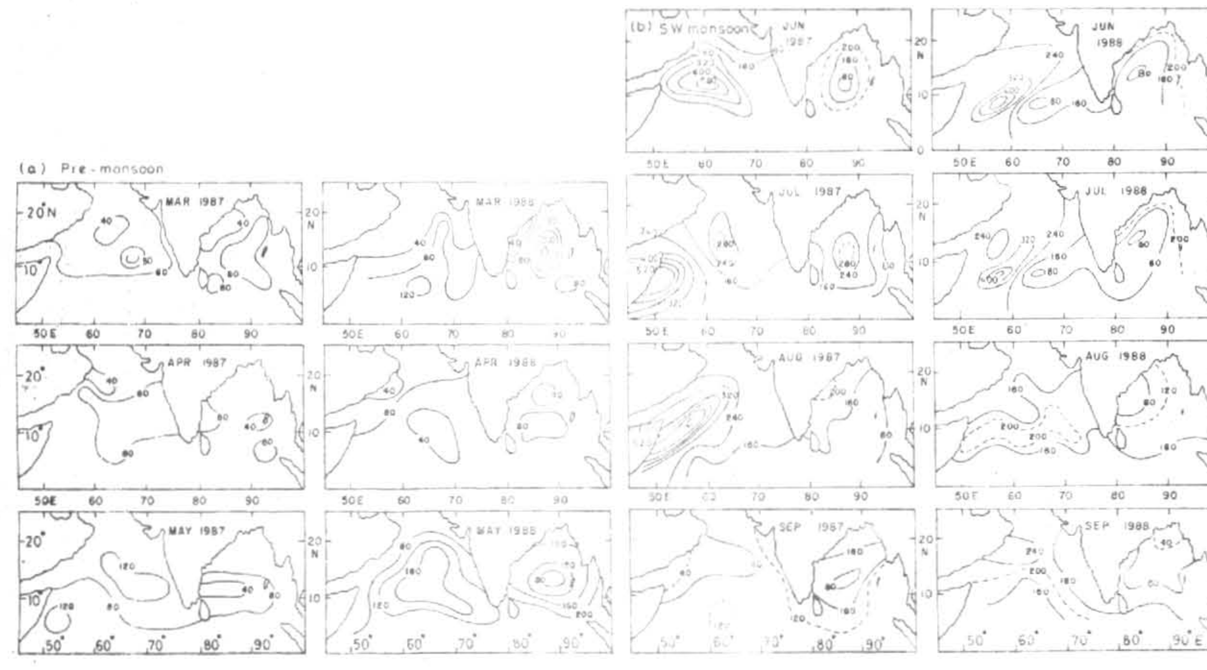
A few works are available on the computations of some of the oceanographic parameters pertaining to the Indian seas. In these studies the exchange coefficient which is vital input to many oceanographic parameters has been treated as the function of wind speed alone. In the present study more generalised exchange coefficients which depend upon wind speed and stability have been considered. Miller *et al.* (1963) have evaluated mean monthly fluxes of momentum and heat using International Indian Ocean Expedition data. Bunker (1965) has studied the heat budget of the Arabian Sea during southwest monsoon and observed an upward transport of moisture in the lower troposphere. Pant (1977) has computed wind stresses and heat fluxes over Arabian Sea using ISMEX-1973 data. His conclusion was that the flux of sensible heat was one order lower in magnitude than the latent heat flux with a well defined diurnal variation. Shahjahan (1980) has evaluated daily fluxes over selected locations in the Arabian Sea during onset phase of monsoon in 1979. He observed a fairly good dependence of the fluxes on the convective activity.

In these studies the variations of different fluxes have been discussed for the limited periods of the respective expeditions. None of these deals with the relationship of the fluxes with Indian summer monsoon performance.

In the present paper the fluxes of momentum, sensible and latent heat have been computed over the Indian seas, *i.e.*, Arabian Sea and Bay of Bengal during pre-monsoon and monsoon months of the years 1987 and 1988. Besides the energy fluxes, other parameters like, 'Bowen ratio', 'rate of wind work', SST, sea-air temperature difference have also been evaluated and examined. The object of the study was to bring out the differences in the fields of oceanographic parameters over Indian seas before and during the contrasting monsoons of 1987 and 1988. It has been found that some of these parameters can give very useful indications of ensuing monsoon performance over India.



Figs. 1(a & b). Sensible heat flux (Wm^{-2}) : (a) pre-monsoon, and (b) southwest monsoon



Figs. 2(a & b). Latent heat flux (Wm^{-2}) : (a) pre-monsoon, and (b) southwest monsoon

2. Data used

All real-time & non-real-time ships' observations from Indian seas available for the years 1987 and 1988 have been used. Monthly averages of the parameters like surface pressure, zonal and meridional components of the wind, SST, air temperature, dew point temperature etc were arranged in $5°\times5°$ quadrangular grids over Indian seas. The grid arrangement is depicted in Fig. 3.

3. Methods of computation

3.1. *Energy fluxes*

The following energy flux computations were made using bulk aerodynamic formulae :

(*i*) Sensible heat flux (Wm^{-2})

$$Q_s = \rho_a c_p C_D (T_w - T_a) V$$

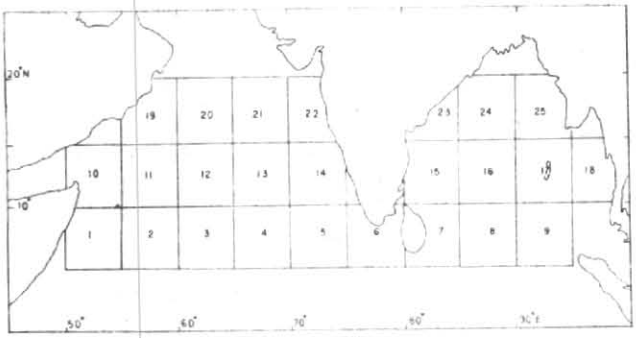


Fig. 1. The grid arrangement

TABLE 1

Distribution of positive sensible heat flux over Bay of Bengal

Month	Square Nos. over Bay of Bengal for which sensible heat flux was $\geqslant 0$	
	1987	1988
Apr	7, 8	7, 8, 9, 15, 16
May	7, 9	7, 8, 9, 15, 16, 17
Jun	9, 17, 23, 25	7, 9, 15, 24, 25
Jul	16, 17, 24	7, 8, 17, 23, 25,
Aug	7, 9, 15, 25	7, 8, 9, 16, 18, 24
Sep	9, 17, 23, 24, 25	7, 9, 16, 17

(*ii*) Latent heat flux (Wm^{-2})

$$Q_E = \rho_a L C_D (q_w - q_a) V$$

(*iii*) Momentum flux (Nm^{-2})

$$\tau_0 = \rho_a C_D V^2$$

where, ρ_a—Air density ($kg\ m^{-3}$), c_p—Specific heat at constant pressure ($J\ kg^{-1}$), L—Latent heat of evaporation ($J\ kg^{-1}$), C_D—Drag coefficient, T_w—SST (°C), T_a—Air temperature ((°C), q_w—Saturation specific humidity at sea surface ($kg\ kg^{-1}$), q_a—Specific humidity at deck level ($kg\ kg^{-1}$), V—Wind speed ($m\ s^{-1}$), q_w has been corrected for salinity of water.

3.2. *Drag coefficient and air density*

In earlier studies (Miller *et al.* 1963, Bunker 1965, Pant 1977) the drag coefficient C_D was taken to be dependent on wind speed alone. Bunker (1976) gave a table of drag coefficients dependent on wind speed and stability. He formulated six normal equations from the tabular values of $(u^2+v^2)^{\frac{1}{2}}$ (u, v are zonal and meridional wind components) and $\triangle T(T_a - T_w)$ and solved by least square method for the coefficients of the best fitting second degree polynomial. The best fit is given by :

$$C_D = 0.934\times10^{-3} + 0.788\times10^{-4}\ (u^2+v^2)^{\frac{1}{2}} + \\ +0.868\times10^{-4}\ \triangle T - 0.616\times10^{-6}(u^2+v^2) \\ -0.120\times10^{-5}(\triangle T)^2 - 0.214\times10^{-5}(u^2+v^2)^{\frac{1}{2}}\triangle T$$

Using the above formula drag coefficient is computed. Air density ρ_a as a function of latitude ϕ is computed using the following formulae (Hellerman 1967) :

$$\rho_a = \begin{cases} (0.00220+1.136)\times10^{-6} & \text{for } \phi>20 \\ (1.18\times10^{-3}) & \text{for } -20\leqslant\phi\leqslant20 \\ (-0.00280+1.124) & \text{for } \phi<-20 \end{cases}$$

3.3. *Bowen ratio*

Bowen ratio 'R' is defined as :

$$R = Q_S/Q_E$$

3.4. *Rate of wind work*

A knowledge of the rate of mechanical energy transfer between atmosphere and ocean is essential for an accounting of the energy balance in the mixed layer. By mechanical stirring, the centre of gravity of the upper ocean is raised as the warmer surface waters are forced to sub-surface layers. Heat storage capacity of the sea, a major influence on climate, is thus enhanced. Therefore, the rate of wind work 'W' is an important variable in the study of southwest monsoon performance. It is given by

$$W = \rho_a C_D V^3$$

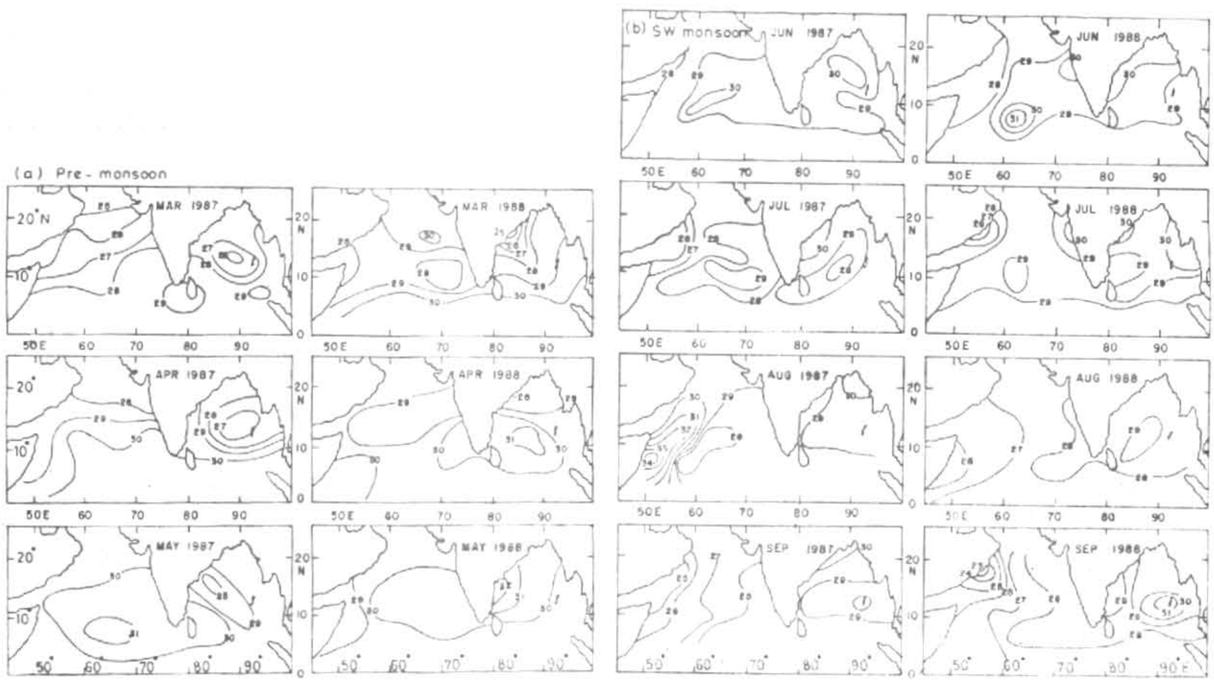
4. Results and discussion

4.1. *Sensible heat flux*

The distribution of computed sensible heat flux over Indian seas during pre-monsoon and monsoon months of 1987 and 1988 has been depicted in Figs. 1 (a & b). The significant feature is that during the months April-August of 1987 a large portion of the area vulnerable to cyclogenesis over Bay of Bengal was dominated by negative flux of sensible heat whereas the flux was mostly positive over that area during the same period of 1988. In September also the sensible heat flux was positive over larger part of cyclogenic area in 1988 as compared to 1987 (over 4 and 2 squares respectively over central and adjoining south Bay of Bengal). Thus during April-September 1988 the instability in the surface layer prevailed over larger parts of cyclogenic areas. Table 1 shows the square numbers over Bay of Bengal (*see* Fig. 3) for which sensible heat flux was $\geqslant 0$ during the months April-September of 1987 and 1988.

Table 1 reveals that it is not only the extent of area that is larger (having sensible heat flux $\geqslant 0$) during 1988 (except September) but this condition holds good especially over those areas of Bay of Bengal that are vulnerable to cyclogenesis. For instance, during the months April-May the central Bay of Bengal (square Nos. 15, 16 and 17) which is the seat of cyclogenesis during these months is dominated by negative sensible heat flux in 1987 whereas during the same months of 1988 the flux was predominantly positive over this area. Similarly during June-August the extent of area over north Bay of Bengal (square Nos. 23, 24, and 25) and during September the area over central and adjoining south Bay of Bengal having positive sensible heat flux are more in 1988. In other words the condition : sensible heat flux $\geqslant 0$ is more valid over cyclogenic areas of Bay of Bengal during 1988 as compared to 1987.

The computed values of sensible heat flux for the year 1987 and 1988 were compared with standard normals



Figs. 4(a & b). Sea surface temperature (°C) : (a) pre-monsoon, and (b) southwest monsoon

(Hastenrath and Lamb 1979). It was found that large positive anomalies of sensible heat flux prevailed over cyclogenic areas of Bay of Bengal during April-September 1988 whereas the anomalies were significantly negative over these areas during April-September 1987.

After the examination of sensible heat flux distribution over Arabian Sea it was noticed that higher positive values prevailed over western sector of south Arabian Sea during monsoon months of 1987 as compared to 1988. This was probably due to subdued upwelling in 1987.

4.2. *Latent heat flux and Bowen ratio*

The distribution of latent heat flux is shown in Figs. 2(a & b). During March 1988 significantly higher values of latent heat flux were observed over Bay of Bengal as compared to the corresponding values of March 1987. During April, however, the values were comparable. The values of latent heat flux over southern parts of Indian seas (5°-15°N) during the month of May were much higher in 1988 as compared to those of 1987. In May 1988 positive anomalies (40-80 Wm^{-2}) prevailed whereas in May 1987 anomalies were negative (—40 Wm^{-2}) over these areas. Thus higher evaporation rate over southern parts of Indian seas preceding the onset of southwest monsoon (in the month of May) appears to be a favourable factor for the ensuing monsoon performance. During the monsoon months the latent heat flux generally appears to be higher in 1987 as compared to the corresponding values of 1988. This is, however, not true over the Arabian Sea during the month of September.

Above observations show that it is the state of Indian seas just before the beginning of southwest monsoon that is of paramount importance rather than the state of the Indian seas during monsoon itself. The state of Indian seas before the monsoon is cause while the state during the monsoon is effect of monsoon. This indicates that oceanographic and related parameters of pre-monsoon (particulary of May) give better indications of ensuing monsoon.

The distribution of Bowen ratio over Indian seas reveals that during April-September 1988 the cyclogenic areas over Bay of Bengal were dominated by positive values of Bowen ratio whereas during the same months of 1987 Bowen ratio was mostly negative over these areas.

4.3. *Momentum flux*

In May 1988 the field of momentum flux over south Arabian Sea and south Bay of Bengal was very strong as compared to the field during May 1987 over these areas. Over some squares the values of momentum flux were 10-12 times higher in May 1988 than the corresponding values during May 1987. Over south Bay of Bengal the positive anomalies up to 1.5 N m^{-2} (actual values about 4 times higher than the normal) prevailed during May 1988 whereas the anomalies were negative during May 1987. Over other areas also the field of momentum flux was generally stronger in May 1988 as compared to that of May 1987. This is, however, not true for north Bay of Bengal.

In the months of June-September the values of momentum flux were slightly higher over Arabian Sea during 1988 as compared to the corresponding values of 1987, However, over Bay of Bengal opposite is true. The values of momentum flux appear to be higher during 1987.

This further confirms that the conditions over Indian seas before the onset of monsoon (say in May) have got more influence on the ensuing monsoon.

4.4. *Rate of wind work*

The 'rate of wind work' is proportional to the energy available for bringing heat and mechanical energy to sub-surface layers and is proportional to V^3 (V is the wind speed). Indian seas being one of the regions of 'World Ocean' where considerable wind energy is available for ocean stirring it would be desirable to look into the fields of 'rate of wind work' during pre-monsoon and monsoon months.

In May 1988 the field of 'rate of wind work' is very strong as compared to May 1987 especially over south Bay of Bengal. Over Arabian Sea throughout the period May-September (except perhaps July) the field is generally stronger in 1988 as compared to that of 1987. Over Bay of Bengal, however, during June-September the field is considerably stronger during 1987. Another remarkable difference is over north Bay of Bengal where the values are higher during May 1987 as compared to those of May 1988.

Thus, it appears that the amount of wind energy available for the stirring of southern parts of Indian seas (especially south Bay of Bengal) before the beginning of southwest monsoon (during May) influences the monsoon performance. More the energy available the better are the chances of monsoon performance.

4.5. *Sea surface temperature (SST) and sea-air temperature*

SST pattern [Figs. 4(a & b)] shows that in March 1988 SST was substantially higher over south Arabian Sea and south Bay of Bengal than that of March 1987. In April 1988, SST was generally higher over north Arabian Sea & north and central Bay of Bengal than that of April 1987. However, no notable difference was observed over southern parts of Indian seas during the month of April. In May 1988, SST was significantly higher over Bay of Bengal between 10° & 20° N as compared to the corresponding values of May 1987. However, no significant difference was observed over the Arabian Sea between 10° & 20° N in May. Over 5°-10° N in May 1988 also SST was lower than the corresponding values of May 1987.

Thus, it appears that higher SST in the beginning of pre-monsoon season over southern parts of Indian seas and higher SST in the later period of pre-monsoon over northern parts of Indian seas are the favourable factors for the performance of ensuing monsoon.

As far as monsoon months are concerned during June-July there is no significant difference between the SST fields of 1987 and 1988. In August-September the SST values are generally lower over Indian seas during 1988 as compared to 1987. This is expected as a vigorous monsoon lowers the SST considerably. But this phenomenon is an effect of monsoon and hence has no predictive application.

The SST distribution over Indian seas during pre-monsoon season appears to be an important input to the ensuing monsoon. The present study reveals that the SST of March over southern parts of Indian seas and the SST of April-May over central and northern parts play an important role.

The distribution of sea-air temperature difference shows that during April-September 1988 this quantity was positive over larger parts of cyclogenic areas over Bay of Bengal as compared to April-September 1987.

5. Conclusions

The following conclusions are drawn from the study :

(*i*) *The condition :* Sensible heat flux $\geqslant 0$ (Bowen ratio $\geqslant 0$ or SST—Air temperature $\geqslant 0$) holding good over larger parts of the cyclogenic areas of Bay of Bengal during April-September is favourable factor for southwest monsoon performance over India.

(*ii*) Higher evaporation rate over the southern belt of Indian seas (between 5° & 15° N) during the month of May is favourable for the ensuing southwest monsoon.

(*iii*) A strong field of momentum flux over Indian seas (particularly over south Bay of Bengal) during the month of May generates good monsoon.

(*iv*) Computed values of heat fluxes over Indian seas during pre-monsoon and monsoon seasons reveal that the latent heat flux is about an order of magnitude higher than the sensible heat flux. Thus the major energy exchange between the Indian seas and the atmosphere occurs through evaporation. The exchange through conduction is not very significant.

(*v*) A strong field of 'rate of wind work' over southern parts of Indian seas (especially over south Bay of Bengal) during the month of May induces good monsoon.

(*vi*) Higher SST over southern parts of Indian seas in the beginning of pre-monsoon season and the higher SST over northern parts of Indian seas during the later period of pre-monsoon appear to be favourable for ensuing southwest monsoon.

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