Int. J. Climatol. 20: 1955–1964 (2000)

# INTERANNUAL VARIATIONS OF OUTGOING LONGWAVE RADIATION AND INDIAN SUMMER MONSOON RAINFALL

K.D. PRASAD* and S.D. BANSOD
*Indian Institute of Tropical Meteorology, Pune-411008, India*

*Received 1 September 1999*
*Revised 16 June 2000*
*Accepted 29 June 2000*

## ABSTRACT

The outgoing longwave radiation (OLR) over tropical Asia has been analysed for a relationship with the Indian summer monsoon rainfall (ISMR; June–September) total using 19 years' data. The ISMR is found to be negatively associated with a simultaneous period of OLR variation over west–central India and the south Equatorial Indian Ocean, and positively associated with that of the variation over the east of Madagascar Sea. The OLR of west–central India, particularly, is strongly coupled with the ISMR. The averaged OLR for west–central India (index A) accounts for 92% of the total variance of the ISMR, and hence, index A (with opposite sign) can be considered as a proxy of the ISMR variability.

The relationship between index A and the ISMR is found to be stable. The monthly scale variation of these two parameters (i.e. all-India rainfall and OLR averaged for west–central India) also exhibits a significant association during each of the summer monsoon (June–September) months. However, the association appears better in the latter half (August–September), as compared with the first half (June–July), of the season.

The ISMR can be estimated with a high degree of accuracy through a linear regression model using index A. Index A, thus, appears useful in updating the ISMR series, which is generally accomplished by averaging the area weighted rainfall of 306 stations distributed over India. Similarly, index A can be computed with a high degree of accuracy through a linear regression model using the ISMR.

The relationship can be utilized in filling the OLR data gap for 1978 over west–central India. The study further provides scope for investigating interannual variability of the Indian summer monsoon in relation to climate variability of the global tropics. Copyright © 2000 Royal Meteorological Society.

KEY WORDS: tropical Asia; regression analysis; outgoing longwave radiation; Indian summer monsoon rainfall

## 1. INTRODUCTION

The Indian summer monsoon rainfall (ISMR; June–September) plays a major role in the global climate system through the energy and hydrological cycles in the atmosphere–ocean–land system, and also provides feedback to the changes in the tropical circulation. India receives most of its total annual rainfall during this season, which exhibits large interannual variability. The agricultural economy of the country depends mostly on this rainfall, and hence, the study of interannual variability of the ISMR has significant importance in the social and economic development of the region. During the recent period, several studies have been made to investigate interannual variability of the ISMR. These studies show significant association of the ISMR with the regional and global climate variables (some of the examples are Hahn and Shukla, 1976; Banerjee *et al.*, 1978; Sikka, 1980; Bhalme *et al.*, 1987; Hastenrath, 1987; Mooley and Paolino, 1988; Prasad and Singh, 1988; Parthasarathy *et al.*, 1990).

The OLR obtained from the National Oceanic and Atmospheric Administration (NOAA) since June 1974 has been invaluable in the study of meteorological phenomena, both over land and ocean. The OLR data also bridge a wide gap of the conventional meteorological data over large remote land and oceanic areas. Over the tropical ocean, because of relatively stable surface temperature, OLR variations are almost

* Correspondence to: Indian Institute of Tropical Meteorology, Pune-411008, India; e-mail: frdmail@tropmet.ernet.in

entirely owing to changes in the distribution of cloudiness, and hence, are related to changes in precipitation (Arkin *et al*., 1989). In the tropics, OLR is largely modulated by cloud top temperature, and the regions of'intense convection in the tropics appear as the regions of low OLR, whereas cloud free regions appear as regions of relatively high OLR. These properties of OLR data make them extremely useful in monitoring and understanding tropical climate variability.

The OLR data were examined to study the annual and interannual atmospheric variability in the tropics by Heddinghaus and Krueger (1981). Horel *et al*. (1989) investigated the annual cycle of convective activity over the tropical Americas. Muthuvel and Arkin (1992) examined the interannual and long-term climatic variations in the tropics using OLR data. The OLR data were used in estimating quantitative precipitation over the tropical Pacific by Motell and Weare (1987), and over the tropical Atlantic Ocean by Yoo and Carton (1988). Janowiak and Arkin (1991) developed linear regression model to estimate precipitation over the global tropics. Xie and Arkin (1998) investigated the relationship between precipitation and OLR, and developed a new technique to estimate monthly precipitation for the entire globe. Prasad and Verma (1985) found OLR data useful in the study of large scale monsoon circulation and associated cloudiness and rainfall over the Indian regions. Prasad *et al*. (2000) also found OLR over the Indian Ocean useful in long-range prediction of the ISMR.

The objective of this paper is to investigate the simultaneous association between the ISMR and OLR over tropical Asia, and to develop an empirical technique to estimate precipitation from OLR. The paper is organized as follows. The data utilized in the study have been discussed in Section 2. The detailed examination of the relationship between OLR and the ISMR is made in Section 3, and an empirical technique is developed to estimate precipitation from OLR in Section 4. Finally, concluding remarks of the study are presented in Section 5.

## 2. DATA

The monthly OLR data analysed in this study are from June 1974 to September 1993 (except for March to December 1978, owing to failure of the satellite) at 2.5° latitude/longitude grids over tropical Asia, bounded between 30°N and 30°S and 40° and 100°E. These data were derived from the NOAA polar orbiting satellite, and were obtained from Climate Analysis Center, NMC, Washington. The OLR data corresponding to the summer monsoon period are obtained by averaging them over the period from June to September at each of the grid points. The monthly all-India rainfall and rainfall for each of the meteorological subdivisions (Figure 1) of India are taken from Parthasarathy *et al*. (1987) for the period 1974–1984. These have been updated to 1993 from weekly weather reports. The summer monsoon (June–September) period rainfalls for all-India and each of the meteorological subdivisions of India are obtained by averaging the corresponding data over the period June–September. These OLR and rainfall data are analysed for the study of their concurrent relationship, using a simple correlation technique.

## 3. RELATIONSHIP BETWEEN OLR AND PRECIPITATION

The summer monsoon total (June–September) rainfall of India has been correlated with the corresponding (June–September) period OLR at each of 2.5° latitude/longitude grids of tropical Asia (Figure 2). The OLR variations of three regions are found to have a significant association with the ISMR. These regions are the (1) Indian subcontinent and adjoining areas (west of 80°E), (2) south Equatorial Indian Ocean (west of 70°E), and (3) east of Madagascar Sea (west of 60°E). The OLRs of regions 1 and 2 have a negative association with the ISMR, whereas the OLR of region 3 has a positive association with the ISMR. The association of the ISMR is the highest, with variation of OLR over region 1. The areas of high and significant correlation coefficients (CC) (Figure 2) in these three cases are marked as regions A, B and C, respectively. The OLRs of the grid points within each of the regions (A, B and C) are averaged, and indexes for the summer monsoon season corresponding to each of the regions

 

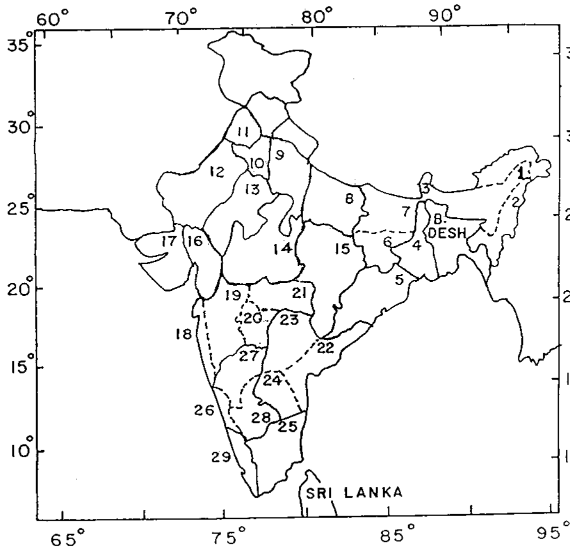


Figure 1. Map of India showing 29 meteorological subdivisions used in the study

are prepared. These indexes are, henceforth, referred to as indexes A, B and C, respectively. Each of the indexes is correlated with the ISMR, which further demonstrates an improvement in its relationship (the CCs in these cases are found to be $-0.96$, $-0.63$ and 0.68, respectively). The high CC obtained between index A and the ISMR can be of significant importance in representing the interannual variability of the ISMR with index A (accounting for 92% of total variance of rainfall). A detailed discussion of this can be found in Section 4. The negative CC indicates that the interannual variation of the ISMR and index A is in an opposite phase to the other, and hence, more convection (i.e. less mean OLR) than normal in area A represents high precipitation over the Indian subcontinent. This is because water vapour from the Arabian Sea and the Indian Ocean is being advected in the region of convection, which rises and cools and, ultimately, results in heavy precipitation. The interannual variations of index A and the ISMR appear to be in good resemblance to each other, with the only exceptions being the years 1976, 1984 and 1991, and in these cases, rainfalls are found close to the normal (Figure 3). Hence, index A (with opposite sign) appears to be a proxy of interannual variability of the ISMR.

The monthly (January–December) variation of OLR (averaged) for regions A and B (Figure 4) exhibits similarity in their annual behaviour. Both the indexes dip to the lowest value of about 225 $Wm^{-2}$ in the peak months of monsoon (July and August), and high value in pre-monsoon (April and May) and post-monsoon (October and December) months. However, annual variation is found to be quite large in the case of OLR of region A. The monthly variation of OLR (averaged) for region C, on the other hand, is found to be in the opposite phase to that of OLR for regions A and B. The annual variation, in this case, is found to be small, with a slightly higher value for the summer monsoon months and low value for the pre- and post-monsoon months. The OLR, in this case, remains above 260 $Wm^{-2}$ throughout the monsoon season. This indicates that region C is almost cloud free, and OLR during the summer monsoon season of the region appears to be modulated mainly in association with variation in the sea surface temperature. In contrast to these variations in OLR of regions A and B during the summer monsoon season are mainly owing to variation in the convective clouds. The variation in convective cloud of region

 

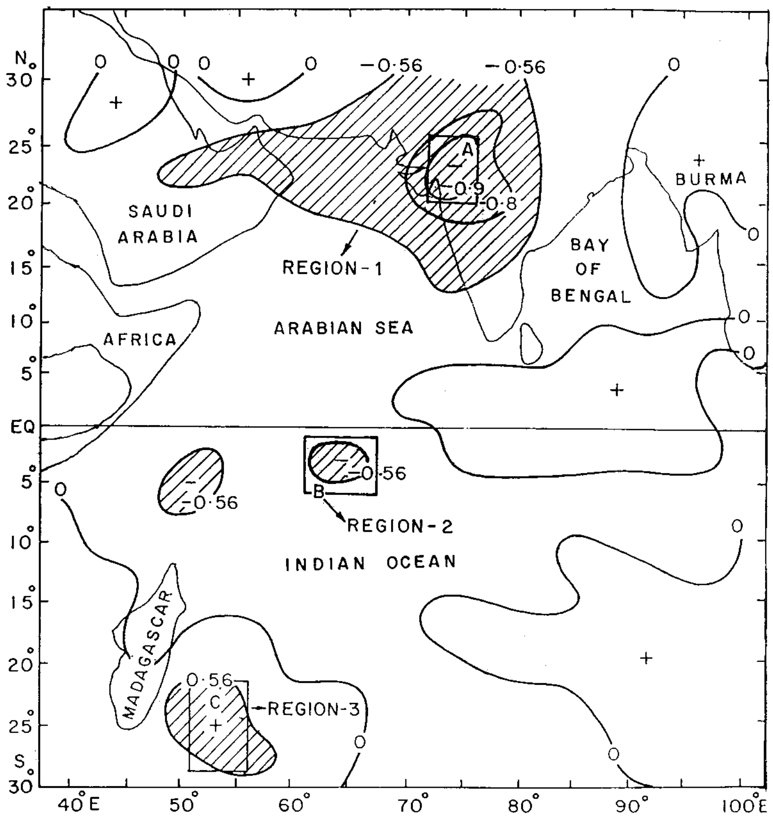


Figure 2. CCs of all ISMR with OLR (averaged for June–September) at each of the grid points of tropical Asia. Hatching shows CC significant at the 1% level. The rectangles, A, B and C, represent the regions for which OLR indexes are prepared

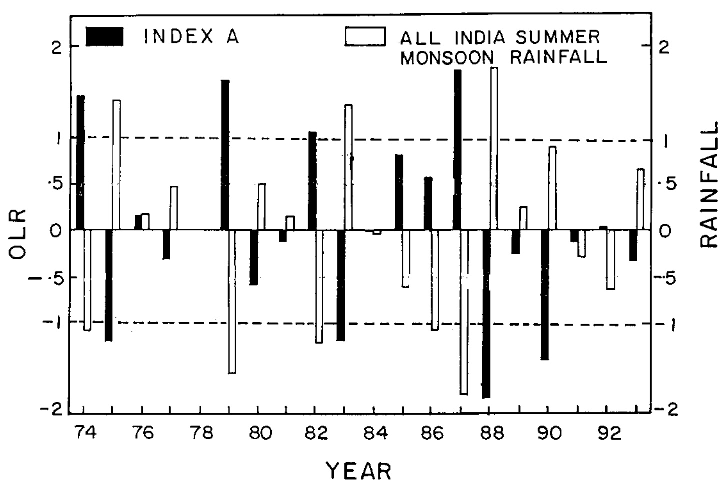


Figure 3. Interannual variations (standardized) of the ISMR and index A. Horizontal dashed lines show $\pm 1.0$ standard deviation

A during the monsoon season is owing to variation in the inter-tropical convergence zone (ITCZ), whereas that of region B is owing to a variation in the Equatorial trough. As the highest association of the ISMR is with index A, the index is further examined for detailed investigation of its relationship with the ISMR.

 

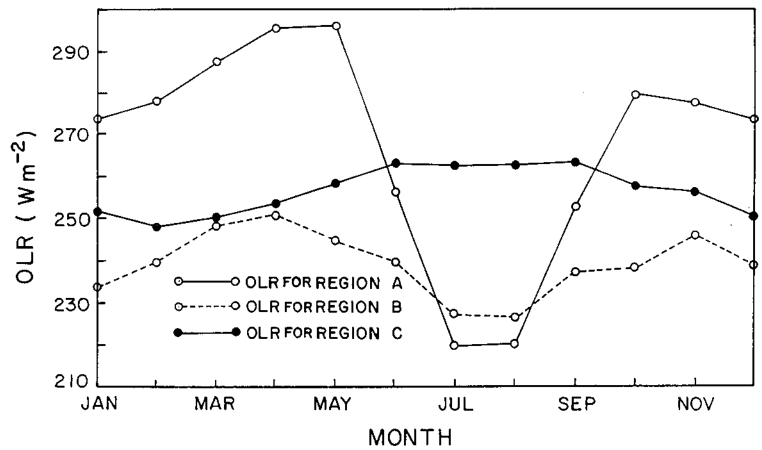


Figure 4. Annual cycle of monthly mean OLR averaged for each of regions A, B and C

The stability of the relationship of index A with the ISMR is analysed by applying a 10 year running window. In this process, a 10 year data set of both the series is considered in moving manner for calculating the CC in each case. The CCs obtained are plotted against the middle year of the running window. The CCs are found to remain almost constant over the period of analysis (Figure 5). Hence, the relationship of the ISMR with index A appears to be stable. The interannual variation (Figure 3) of both the series (standardized) also exhibits that variation of index A and the ISMR is in an opposite phase to the other throughout the period of analysis. Hence, this also shows that the relationship found between them is stable.

The monthly OLR of region A and the all-India (monthly) rainfall have been analysed for the annual variation of their relationship. A significant negative relationship is found during each of the individual months of the summer monsoon season (Figure 6). However, the relationship appears to be minimal during July and at a maximum during September. Hence, the association between them is found to be weaker during the first half (June and July, CC = − 0.84), as compared to the second half (August and September, CC = − 0.95) of the season. Index A has been further examined for spatial variation of its relationship with the summer monsoon rainfall. For this purpose, index A has been correlated with the summer monsoon rainfall of each of the contiguous meteorological subdivisions (Figure 1) of India. The spatial pattern of CC has also been obtained by correlating the ISMR with the summer monsoon rainfall of each of the meteorological subdivisions of India. The patterns of CC (Figure 7) found in these two cases appear to be almost similar to each other. In both cases, high and significant CCs are found to be orientated in the northwest–southeast direction, across central India. This further confirms index A to be the proxy of interannual variability of the ISMR. This is also evident from the following analysis. Index A is correlated with the summer monsoon period OLR at each of the grid points of tropical Asia (Figure

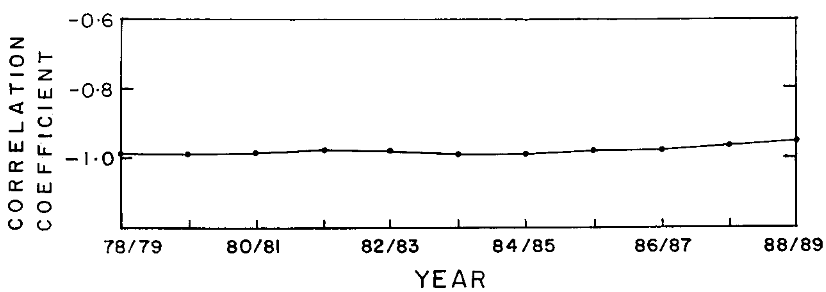


Figure 5. Variation of CCs over sliding window of 10 years between all ISMR and index A. The CCs are plotted against middle year of the window

 

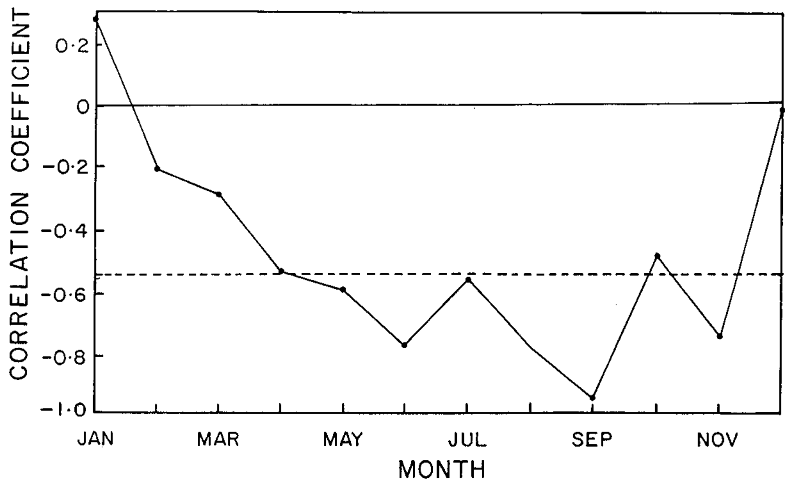


Figure 6. Simultaneous CC (January–December) between the monthly OLR for region A and the monthly all-India rainfall. Horizontal dashed lines show CC significant at the 1% level

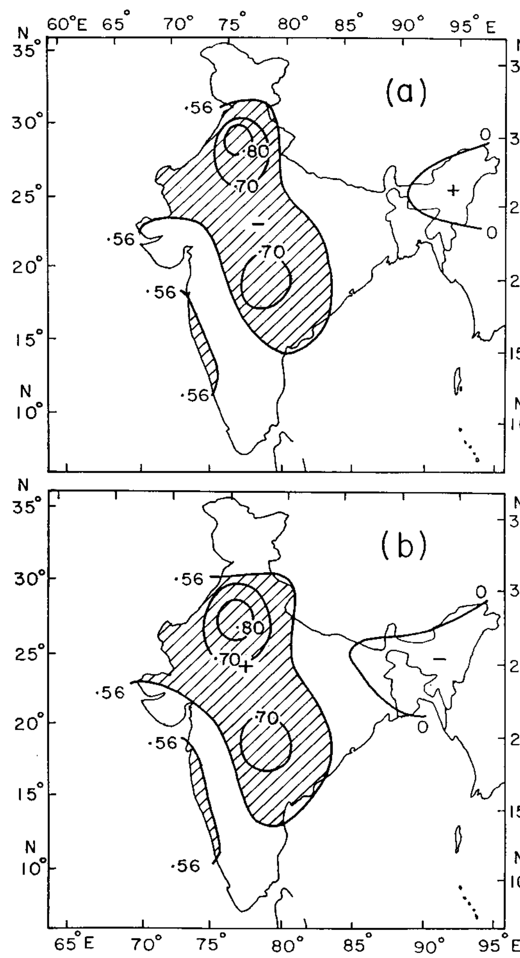


Figure 7. CCs of the summer monsoon rainfall of each of the meteorological subdivisions of India with (a) index A and (b) all ISMR. Hatching shows CC significant at the 1% level

 

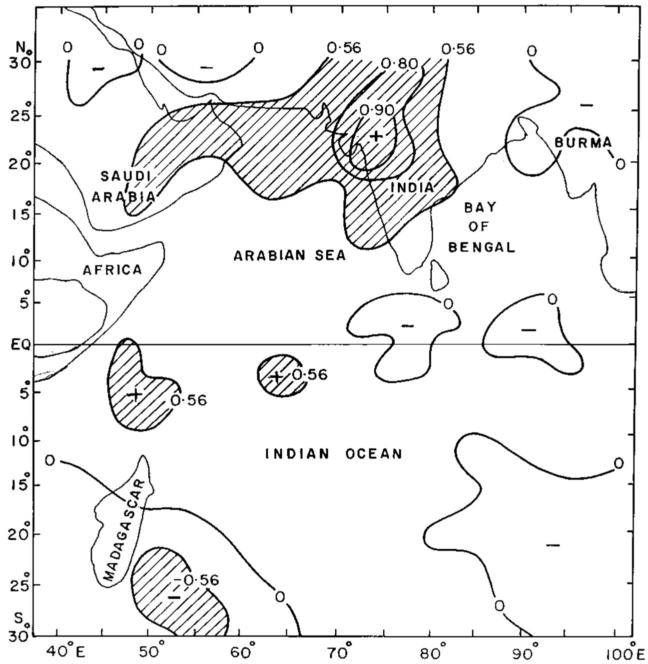


Figure 8. CCs of index A with OLR (averaged for June–September) at each of 2.5° latitude/longitude grids over tropical Asia. Hatching shows CC significant at the 1% level

8). The CC pattern found in this case resembles the pattern of CCs (Figure 2) obtained by correlating the ISMR with the summer monsoon period OLR at each of the grid points of tropical Asia.

## 4. ESTIMATION OF PRECIPITATION AND OLR

As the CC between index A and the ISMR is found to be quite high, it is logical to develop relationships between them for their quantitative estimates. An attempt has been made to achieve this objective in the following section.

A simple linear regression equation is developed using index A in order to have quantitative estimates of the ISMR. The equation has the form

$$R = a_0 + a_1 X \tag{1}$$

where $a_0$ (constant term) = 3.6474; $a_1$ (coefficient of $X$) = − 11.84; $R$ = estimate of ISMR (in mm) and $X$ = index A (in $\mathrm{Wm}^{-2}$).

Similarly, the equation for a quantitative estimate of index A from precipitation has been developed which has the form

$$X = b_0 + b_1 R \tag{2}$$

where $b_0$ (constant term) = 302.277; $b_1$ (coefficient of $R$) = 0.078; and, as above, $X$ = estimate of index A (in $\mathrm{Wm}^{-2}$) and $R$ = ISMR (in mm).

The scatter diagram relating the observed ISMR ($R$) and that estimated ($R$) through relation 1 (Figure 9(a)) indicates that they are in high agreement with each other. Thus, it appears that ISMR can be computed with a high degree of accuracy through relation 1, using index A. Hence, relation 1 can be used to update the ISMR series. Generally, updating of the ISMR series involves averaging of the area weighted rainfall of 306 stations distributed over India, which is a time consuming process, and can be accomplished only by the middle of November, whereas updating of the ISMR through relation 1 could

 

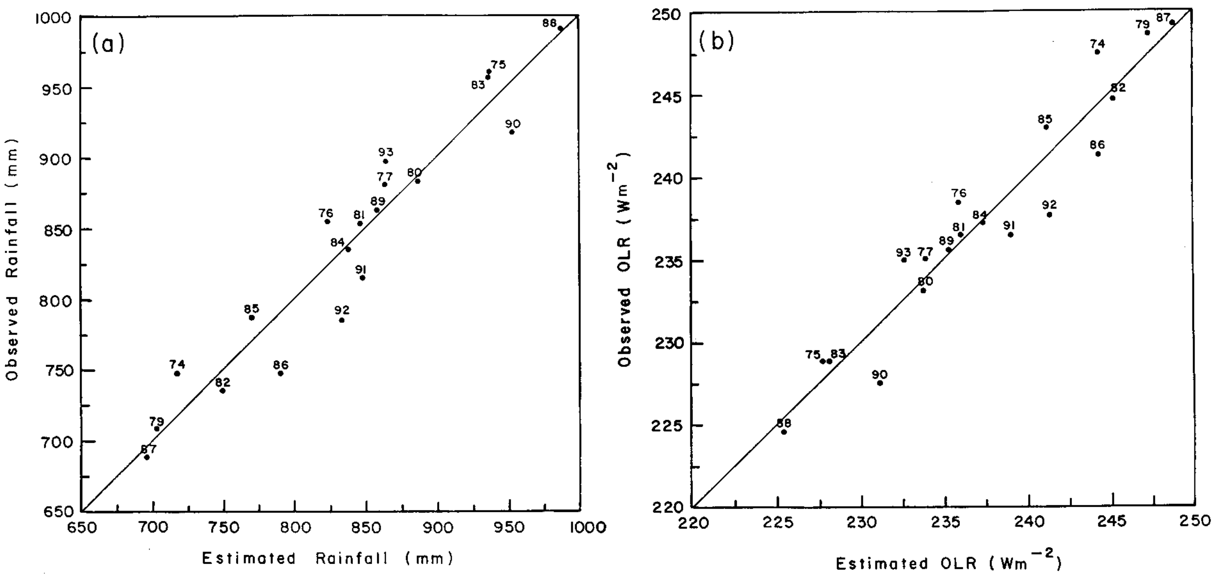


Figure 9. Scatter diagram comparing observed and estimated (a) all ISMR and (b) index A. The estimate of all ISMR and index A is made through Equations (1) and (2), respectively. The data year is also shown in the diagram with the last two digits

Table I. Grid no.

| Location | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Latitude | 25.00°N | 25.00°N | 22.50°N | 22.50°N | 20.00°N | 20.0°N |
| Longitude | 72.50°E | 75.00°E | 72.50°E | 75.00°E | 72.50°E | 75.0°E |

be accomplished by the middle of October. A study of Singh (1993) has shown that a maximum of 34 independent rainfall stations are sufficient to estimate the ISMR. The present study utilizes OLR data at six grid points of west–central India to compute index A. Hence, this appears to be a better way to update the ISMR series. The locations of these grid points are shown above (see Table I).

Index A for a particular year can be prepared as discussed in Section 3, and can be used to estimate the ISMR corresponding to that year through relation 1. Similarly, using rainfall (i.e. ISMR) index A can be estimated through relation 2. The estimated series of index A is found to be in high agreement with the observed one (Figure 9(b)). Hence, it appears that index A for a particular year can be estimated with a high degree of accuracy through relation 2. As index A for 1978 could not be computed owing to failure of the satellite during the year, the estimate of index A for 1978 is made through relation 2, which is found to be 231.40 $Wm^{-2}$. Using this value of index A, the estimate of the ISMR for 1978 through relation 1 is found to be 906.76 mm, which agrees quite well with the observed value of 908.00 mm. This also confirms the usefulness of relation 2 in the computation of index A. Further, it appears that similar relationships can be developed to estimate OLR (averaged for period June–September) over the grid points of west–central India and adjoining areas.

## 5. CONCLUSIONS

The OLR estimated from the NOAA polar orbiting satellite has been analysed at each of the 2.5° latitude/longitude grids of tropical Asia for investigating its simultaneous association with the ISMR. The interannual variation of the ISMR is found to be significantly related to the interannual variation of OLR of three regions of tropical Asia. These regions are (a) west–central India, (b) south Equatorial Indian Ocean, and (c) east of Madagascar Sea. The variations of OLR of regions A and B are in the opposite phase with the ISMR, whereas that of region C is in phase with the ISMR. The results appear to be consistent with the fact that variations in OLR of region A and B are owing to variations in the convective clouds associated with the ITCZ and the Equatorial trough, respectively. Hence, low OLR (or high convective activity) of these two regions represents high ISMR. The region C is a cloud free region, and OLR, in this case, appears to be modulated owing to variation in the sea surface temperature. Therefore, high OLR of the region represents high ISMR.

The association of the ISMR is highest with OLR of region A. The CC of the ISMR with OLR averaged for region A (index A) is found to be $-0.96$, which appears to be quite high for any two meteorological variables. Hence, it appears that interannual variation of the ISMR is well represented by interannual variation of index A (with opposite sign).

The all-India rainfall for each of the individual monsoon months (June–September) also shows a significant relationship with simultaneous period OLR averaged for west–central India. However, the relationship appears to be stronger during the latter half (August–September) as compared with the first half (June–July) of the season.

The CC between the ISMR and index A for a 10 year running window is found to be almost constant over the period of analysis and, hence, the relationship between them appears to be stable.

Index A, as well as the ISMR, are correlated in turn with the monsoon rainfall of each of the contiguous meteorological sub-divisions of India. The spatial patterns of CC in both cases are found to be almost similar. This also confirms that interannual variation of the ISMR and index A is in good agreement to each other, and hence, index A can be regarded as a proxy of the ISMR variability with opposite sign.

The ISMR, estimated through a linear regression model using index A, is found to be in high agreement with the observed rainfall. Index A, therefore, can be useful in updating the ISMR series. The updating of the ISMR series requires averaging of area weighted rainfall of nearly 306 stations distributed throughout India, which is a time consuming process, taking nearly 2 months after the summer monsoon season, whereas, using index A, the ISMR can be updated with good accuracy by the middle of October.

The study further demonstrates that index A can be computed with a high degree of accuracy through a simple linear regression model using the ISMR. The relationship can be utilized in filling the OLR data gap for 1978 over west–central India and adjoining areas. Finally, it appears that index A can be used in the study of interannual variability of the ISMR in relation to tropical climate variability of the globe.

## ACKNOWLEDGEMENTS

The authors are grateful to Dr G.B. Pant, Director, and Dr S.S. Singh, Head, Forecasting Research Division, Indian Institute of Tropical Meteorology, Pune, for encouragement and providing the necessary facilities. Thanks are also due to the unknown referees and Dr Glenn R. McGregor, Editor, for their valuable comments which helped improve the text of this paper.

## REFERENCES

Arkin P, Rao AVRK, Kelkar RR. 1989. Large-scale precipitation and outgoing long-wave radiation from INSAT-1B during the 1986 southwest monsoon season. *Journal of Climate* **2**: 619–628.

Banerjee AK, Sen PN, Raman CRV. 1978. On forecasting southwest monsoon over India with midtropospheric circulation anomaly of April. *Indian Journal of Meteorology and Hydrological Geophysics* **29**: 425–431.

Bhalme HN, Rahalkar SS, Sikdar AB. 1987. Tropical quasi-biennial oscillation of the 10 mb wind and Indian monsoon rainfall—implications for forecasting. *Journal of Climatology* **7**: 345–353.

Hastenrath S. 1987. On the predication of Indian monsoon rainfall anomalies. *Journal of Climate and Applied Meteorology* **26**: 747–857.

Hahn DG, Shukla J. 1976. An apparent relationship between Eurasian snow cover and Indian monsoon rainfall. *Journal of Atmospheric Science* **33**: 2461–2462.

Heddinghaus RH, Krueger AF. 1981. Annual and interannual variation in outgoing longwave radiation over the tropics. *Monthly Weather Review* **109**: 1208–1218.

 

Horel JD, Hahmann AN, Gezsler JE. 1989. An investigation of the annual cycle of the convective activity over the tropical Americas. *Journal of Climate* **2**: 1388–1403.
Janowiak JE, Arkin PA. 1991. Rainfall variation in the tropics during 1986–1989, as estimated from observations of cloud-top temperature. *Journal of Geophysical Research* **96**: 3359–3373.
Mooley DA, Paolino DA. 1988. A predictive monsoon signal in the surface level thermal field over India. *Monthly Weather Review* **116**: 339–352.
Motell CE, Weare BC. 1987. Estimating tropical pacific rainfall using digital satellite data. *Journal of Applied Meteorology* **26**: 1436–1446.
Muthuvel C, Arkin P. 1992. Large-scale interannuvariability of monthly outgoing longwave radiation over the global tropics. *Journal of Climate* **5**: 371–389.
Parthasarathy B, Sontakke NA, Munot AA, Kothawale DR. 1987. Drought/flood in the surnmer monsoon season over different meteorological subdivisions of India for the period 1971–1987. *Journal of Climatology* **7**: 57–70.
Parthasarathy B, Rupa kumar K, Sontakke NA. 1990. Surface and upper air temperatures over India in relation to monsoon rainfall. *Theoretical and Applied Chmatology* **42**: 93–110.
Prasad KD, Verma RK. 1985. Large-scale features of satellite-derived outgoing long-wave radiation in relation to monsoon circulation over the Indian region. *Journal of Climatology* **5**: 297–306.
Prasad KD, Singh SV. 1988. Large scale features of the Indian summer monsoon rainfall and their association with some oceanic and atmospheric variables. *Advances in Atmospheric Sciences* **5**: 499–513.
Prasad KD, Bansod SD, Sabade SS. 2000. Forecasting Indian summer monsoon rainfall by outgoing longwave radiation over Indian Ocean. *International Journal of Climatology* **20**: 105–114.
Sikka DR. 1980. Some aspects of the large-scale fluctuation of summer monsoon rainfall over India in relation to fluctuations in planetary and regional scale circulations patterns. *Proceedings of the Indian Academy of Science (Earth Planetary Science)* **89**: 179–195.
Singh N. 1993. Optimizing a network of rain-gauges over India to monitor Indian monsoon rainfall variations. *International Journal of Climatology* **14**: 61–70.
Yoo J, Carton JA. 1988. Spatial dependence of the relationship between rainfall and outgoing longwave radiation in the tropical Atlantic. *Journal of Climate* **1**: 1047–1054.
Xie P, Arkin P. 1998. Global monthly precipitation estimates from satellite observed outgoing longwave radiation. *Journal of Climate* **11**: 137–164.

 