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Cloud climatology of the Indian Ocean based on ship observations

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सार – हिंद महासागर की ऋतु संबंधी और वार्षिक मेध जलवायविकी तैयार करने के लिए 1951 से 1998 तक ही अवधि के स्वैच्छिक प्रेक्षण जलपोतों (वी.ओ.एस.) द्वारा किए गए सिनॉप्टिक प्रेक्षणों के आधार पर तैयार किए गए सतह मेध आँकड़ों का उपयोग किया गया है। यह विश्लेषण, समय की प्रत्येक 5°×5° ग्रिड की मासिक श्रृंखलाओं की मेघ विसंगति में से दीर्घ अवधि की प्रवृत्तियों तथा दशकीय और अंतवार्षिक घटकों को पृथक करके किया गया है।

संपूर्ण और निम्न मेघावरण के अधिकतम क्षेत्र मानसून वर्षा ऋतु के दौरान भूमध्यरेखा से भारत के उत्तरी भागों की ओर चले जाते हैं। मानसून वर्षा ऋतु (जून से सितंबर) के दौरान बंगाल की खाड़ी के उत्तरी भाग के ऊपर अधिकतम संपूर्ण मेघावरण 70% से भी अधिक और निम्न मेघावरण 50% से भी अधिक पाया गया है। भूमध्यरेखा के समीप और दक्षिणी गोलार्द्ध में संपूर्ण और निम्न मेधावरण के अधिकतम मानक परिवर्तन देखे जाते हैं। एनसो घटना के दौरान अरब सागर तथा भूमध्यरेखा के समीप हिंद महासागर के ऊपर संपूर्ण और निम्न मेधावरण दोनों को कम होते देखा गया है। किन्तु फिर भी बंगाल की खाड़ी के ऊपर मेधावरण में घट बढ़ एनसों की घटना के साथ नहीं होती है। 1980 के बाद अंतःदशकीय पैमाने पर निम्न मेघावरण निम्न क्षेत्र से उच्च क्षेत्र की ओर बढ़ते हैं जो कि 1970 के दशक के उत्तरार्द्ध के दौरान उत्तरी हिंद महासागर पर समुद्र सतह तापमानों के अंतःदशकीय परिवर्तनों के सदृश्य ही हुआ है।

ABSTRACT. Surface cloud data based on synoptic observations made by Voluntary Observing Ships (VOS) during the period 1951-98 were used to prepare the seasonal and annual cloud climatology of the Indian Ocean. The analysis has been carried out by separating the long-term trends, decadal and inter-annual components from the monthly cloud anomaly time series at each 5° × 5° grids.

Maximum zone of total and low cloud cover shifts from equator to northern parts of India during the monsoon season. During the monsoon season (June-September), maximum total cloud cover exceeding 70% and low cloud cover exceeding 50% are observed over north Bay of Bengal. Maximum standard deviation of total and low cloud cover is observed near the equator and in the southern hemisphere. Both total and low cloud cover over Arabian Sea and the equatorial Indian Ocean are observed to decrease during the ENSO events. However, cloud cover over Bay of Bengal is not modulated by the ENSO events. On inter-decadal scale, low cloud cover shifted from a "low regime" to a "high regime" after 1980 which may be associated with the corresponding inter-decadal changes of sea surface temperatures over north Indian Ocean observed during the late 1970s.

Key words – Cloud climatology, Indian Ocean, Summer monsoon, Decadal variation.

1. Introduction

Cloudiness is one of the most important variables influencing the earth's radiation budget. The cloud field is dynamic because of its relationship to the atmospheric circulation. Due to the complexity of the distribution and multi -scale variations of cloudiness and its radiative properties, our understanding of the role of cloudiness in the climate system and future climate change is very limited. Considering the large impact that cloudiness has on the climate system, it is essential to have accurate cloud cover climatology and document inter-decadal variability and long term trends in the cloudiness. The satellite cloud data sets such as the International Satellite Cloud Climatology Project (ISCCP) (Rossow and Schiffer 1991) have records too short to examine inter-decadal variability and long term trends. For these reasons, studies involving surface cloud observations are important.

Most studies of inter-decadal variability in cloud cover have examined total cloud cover over land regions (Angell 1990, Henderson-Sellers 1992). Some studies have examined cloud amount and type over the ocean basins (Warren *et al.* 1988, Norris *et al.* 1998, London *et al.* 1991,Parungo *et al.* 1994, Bajuk and Leovy 1998, Norris 1999). The results of the ocean studies indicate significant trends in low cloud cover in some oceanic basins during the recent decades. But Nicholls *et al.*(1996)

Area of Study and Average Ship Reports Per Month

78	60	0	12	86	84	1	0	0	0	0	0	0	0
0	234	0	0	2	167	144	62	9	0	0	13	4	0
0	83	168	0	69	193	69	129	96	0	35	69	25	2
0	0	119	248	229	175	81	52	136	33	96	46	28	9
0	0	0	12	126	44	67	112	141	271	262	196	199	116
0	0	4	73	66	20	26	23	15	34	33	56	45	40
0	0	37	86	29	20	16	21	35	17	64	30	6	6
0	2	55	74	14	15	10	15	52	68	12	16	10	8
0	0	100	32	20	8	12	48	33	6	16	15	25	18

30N 25N 20N 15N 10N 5N EQ 5S 10S 15S

30E 35E 40E 45E 50E 55E 60E 65E 70E 75E 80E 85E 90E 95E 100E

Fig.1. The area of the study and average number of observations per month during the period 1951-98

raised questions as to whether these trends are real or spurious because these data are dominated by observational artifacts. Artifacts in observational data sets in surface-based cloud cover can arise from three broad sources (Norris 1999): (*i*) changes in observing practice. (*ii*) incorrect archiving of individual observations and (*iii*) biases introduced by improper data reduction.

Cloud climatology of the Indian Ocean based on few years of marine data was prepared by UK Meteorological office (1949) and U.S. Navy (1976). The cloud atlas of the UK Met Office (1947) was prepared with the data prior to 1940. The atlas of the US navy was prepared using the data up to 1973. However, the data flow from the Voluntary Observing Ships has been increased drastically after 1960s (Woodruff *et al.* 1987).

The present study is designed to prepare the cloud climatology of the north Indian ocean and document the inter-annual, inter-decadal and long term trends using a larger (1951-98) and updated data set. For this study, we have used a data set of marine surface observations recorded by the Voluntary Observing Ships (VOS) in the Indian Ocean with more than 3.8 million records and updated up to 1998. In section 2, the details of the data used and the method of analysis are presented. In section 3, the mean patterns of cloud cover and the relationship of cloud cover with Indian summer monsoon and El Nino/Southern Oscillation (ENSO) phenomenon are discussed. In section 4, the long-term trends in cloud cover over the Indian Ocean and their possible reasons are discussed. In section 5, the inter-decadal variations of cloud cover in the north Indian Ocean are discussed and in section 6, the conclusions are given.

2. Data used and method of analysis

The greatest source of long-term cloud information over the global ocean are synoptic reports primarily provided by Volunteer Observing Ships (VOS) which are reported according to World Meteorological Organization (WMO) code (WMO 1974). Total cloud cover (TC) is estimated to the nearest okta (eigth), where TC=0 is clear sky and TC=8 is overcast. When the sky is obscured,

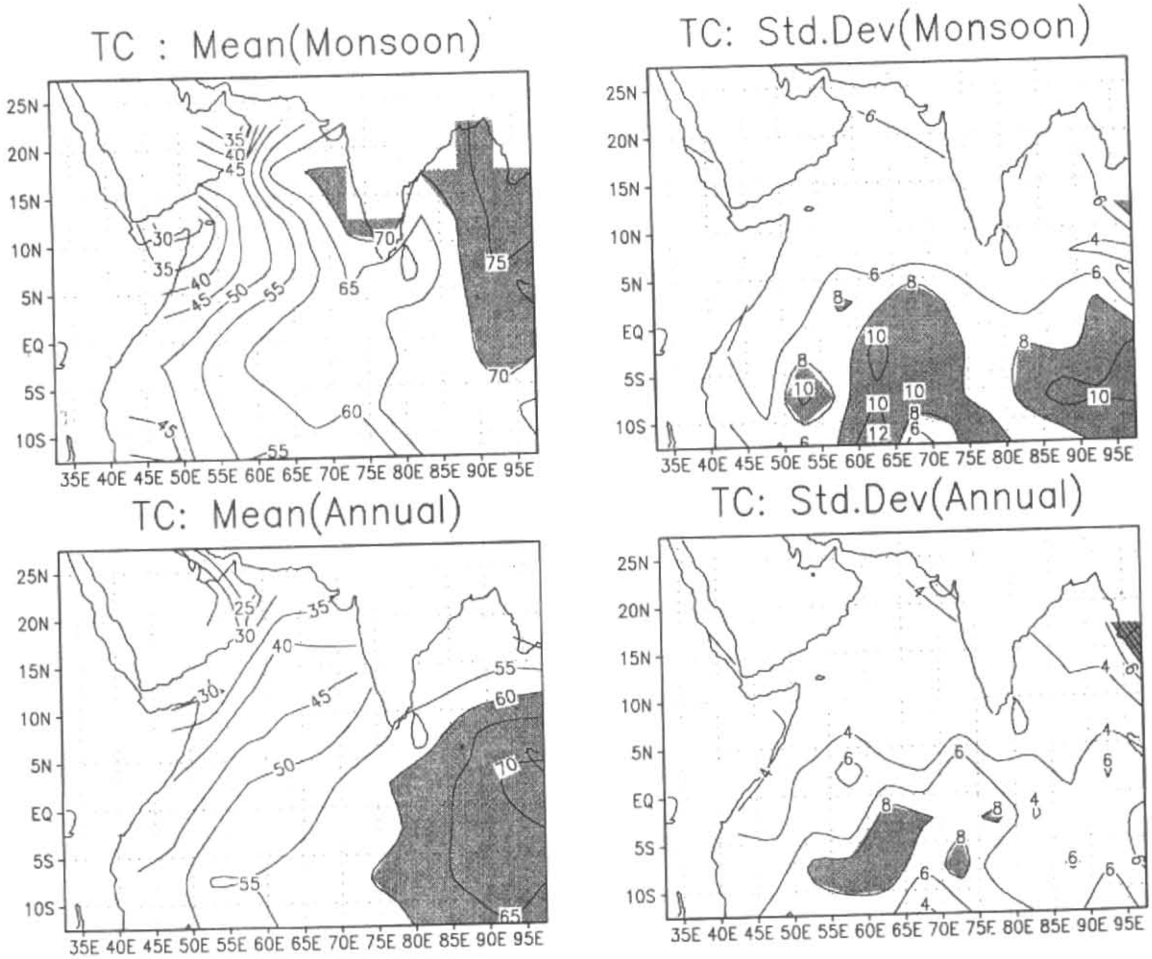


Fig. 2. Mean and standard deviation (S.D.) of total cloud cover for monsoon season (top panels) and annual (bottom panels) in percentage. Period: 1951-98. Interval: Mean: 5% and S.D: 2%. Areas with mean cloud cover more than 70% for TC and 60% for LC are shaded. S.D. more than 8% are also shaded

TC=9 is reported. Cloud cover by low clouds (LC) is similarly estimated, where LC=0 is no low cloudiness and LC= 8 is overcast low cloudiness. If no low clouds are present which is a rare occurrence over open ocean, observers are instructed to report LC as cloud cover by middle clouds.

The synoptic observations from these volunteer ships are being collected, processed and archived after carrying out the prescribed quality controls by the India Meteorological Department (IMD) who is responsible on behalf of WMO for the preparation of Marine Climatological data. The area of responsibility, the region between 15° S to 30° N, 30° E to 100° E is shown in Fig.1. These data are further exchanged with other responsible countries. We have used these ship observations which are archived at the National Data Centre (NDC) of the India Meteorological Department. In all, we have used 38,36,624 synoptic observations recorded during the period 1951-98 in the Indian Ocean. We have found that comparatively, few marine observations are available prior to 1950.

The comprehensive ocean-atmosphere data set (COADS) (Woodruff *et al.* 1987) contains total cloud cover prior to 1951. Low cloud cover data is not included in this data set. However, basic synoptic observations prior to 1950 are available in the COADS data set. But major changes in the rules for reporting low clouds introduce large inhomogeneities into the data set prior to 1950 (Conway Leovy, 2000, Personal Communication). It would be very difficult to reconstruct credible marine cloud variation records prior to 1950s. Moreover, scanty observations available during the First and Second World Wars may cause additional data discontinuity. Therefore, we have not made any attempts to extend the data set before 1950. It is to be mentioned that 48 years of data are sufficient for preparing cloud climatology and to examine

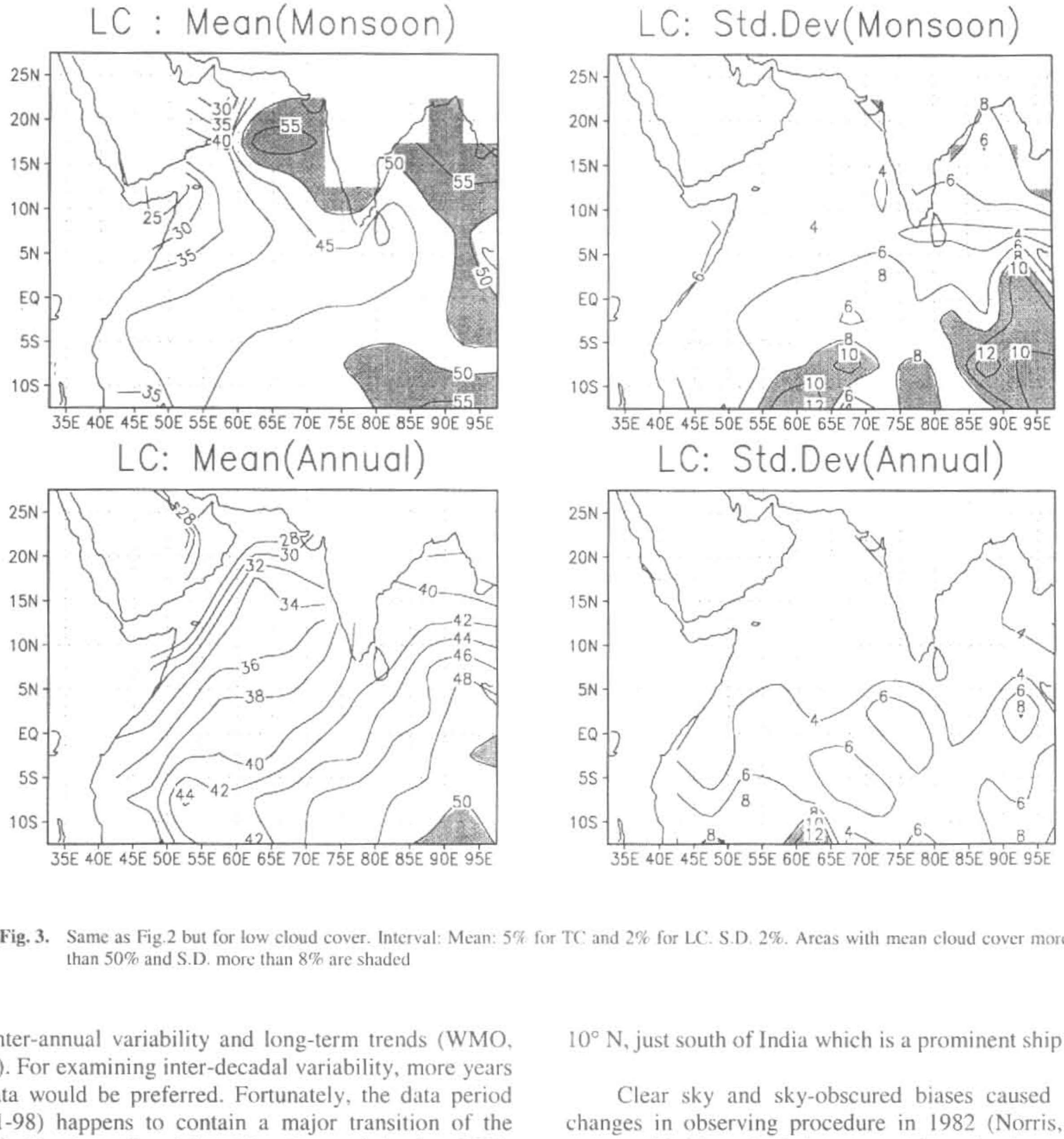


Fig. 3. Same as Fig.2 but for low cloud cover. Interval: Mean: 5% for TC and 2% for LC. S.D. 2%. Areas with mean cloud cover more than 50% and S.D. more than 8% are shaded

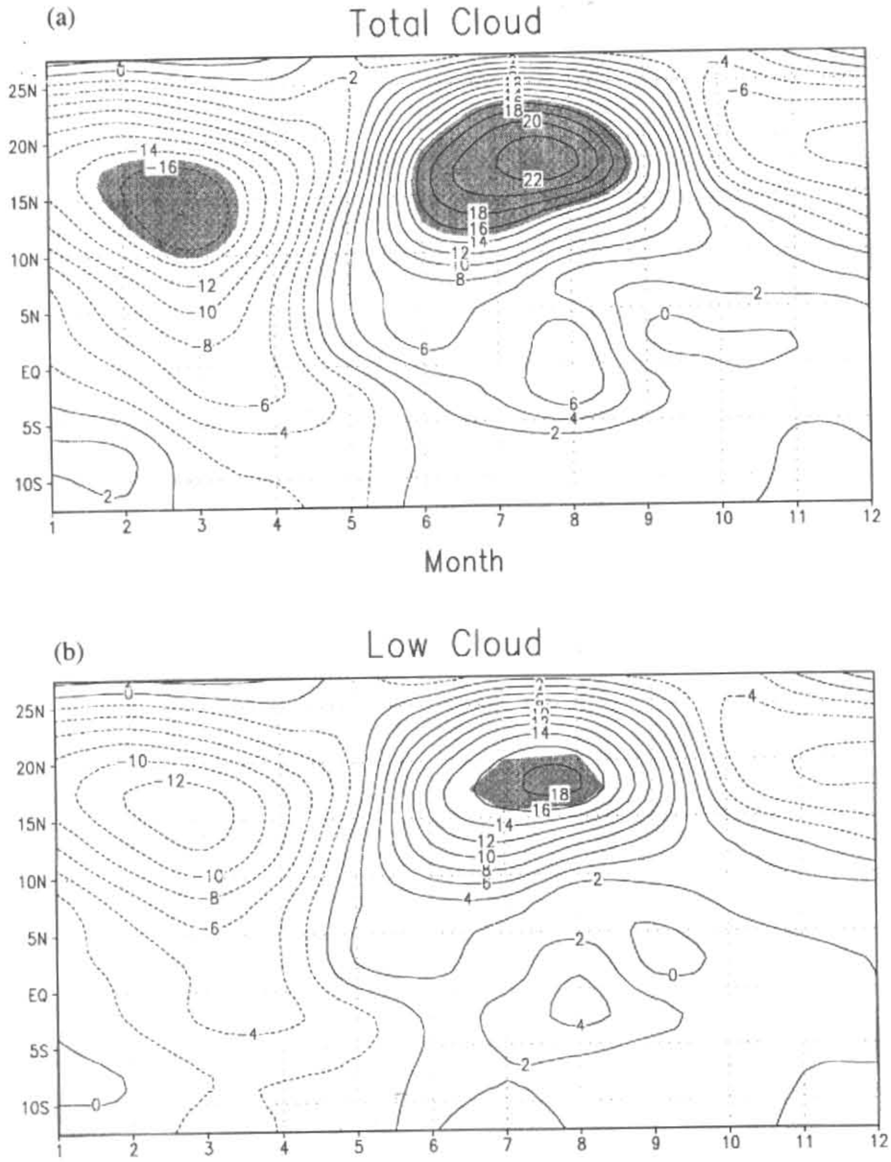
the inter-annual variability and long-term trends (WMO, 1966). For examining inter-decadal variability, more years of data would be preferred. Fortunately, the data period (1951-98) happens to contain a major transition of the ENSO like inter-decadal mode observed in the 1970s (Kachi and Nitta 1997). It is to be mentioned that Bajuk and Leovy (1998) and Norris and Leovy (1994) and Kachi and Nitta (1997) have used less than 50 years of data to study the inter-decadal variations of the global climate system. Norris (1999) and Bajuk and Leovy (1998) used Iow cloud observations available only after 1950.

The synoptic observations archived at NDC were further decoded and total and low cloud cover data were extracted and averaged month wise in 5° × 5° Lat. / Long. grids. The average observations (number of observations / month) in the grids are also shown in Fig.1. Maximum number of observations is for the latitudinal belt 5° N to 10° N, just south of India which is a prominent ship route.

Clear sky and sky-obscured biases caused due to changes in observing procedure in 1982 (Norris, 1999) were avoided by calculating average low cloud cover (LC) only when 1<TC < 8 and then normalizing by the frequency that 1 <TC < 8 *i.e.*,

$$\overline{LC} = \frac{\sum LC}{n_{low}} \times \frac{n_{all} - n_{clr} - n_{obs}}{n_{all}} + \frac{8 \times n_{obs}}{n_{all}}$$

Where the summation is over all observations contributing to n_{low} here n_{low}, is the number of observations when LC is reported and 1<TC< 8; n_{all}, is the number of all observations, n_{clr}, is the number of observations of clear sky (TC=0); and n_{obs}, is the number of observations of sky obscured (TC=9). The right hand term proceeds from the assumption that low cloudiness is

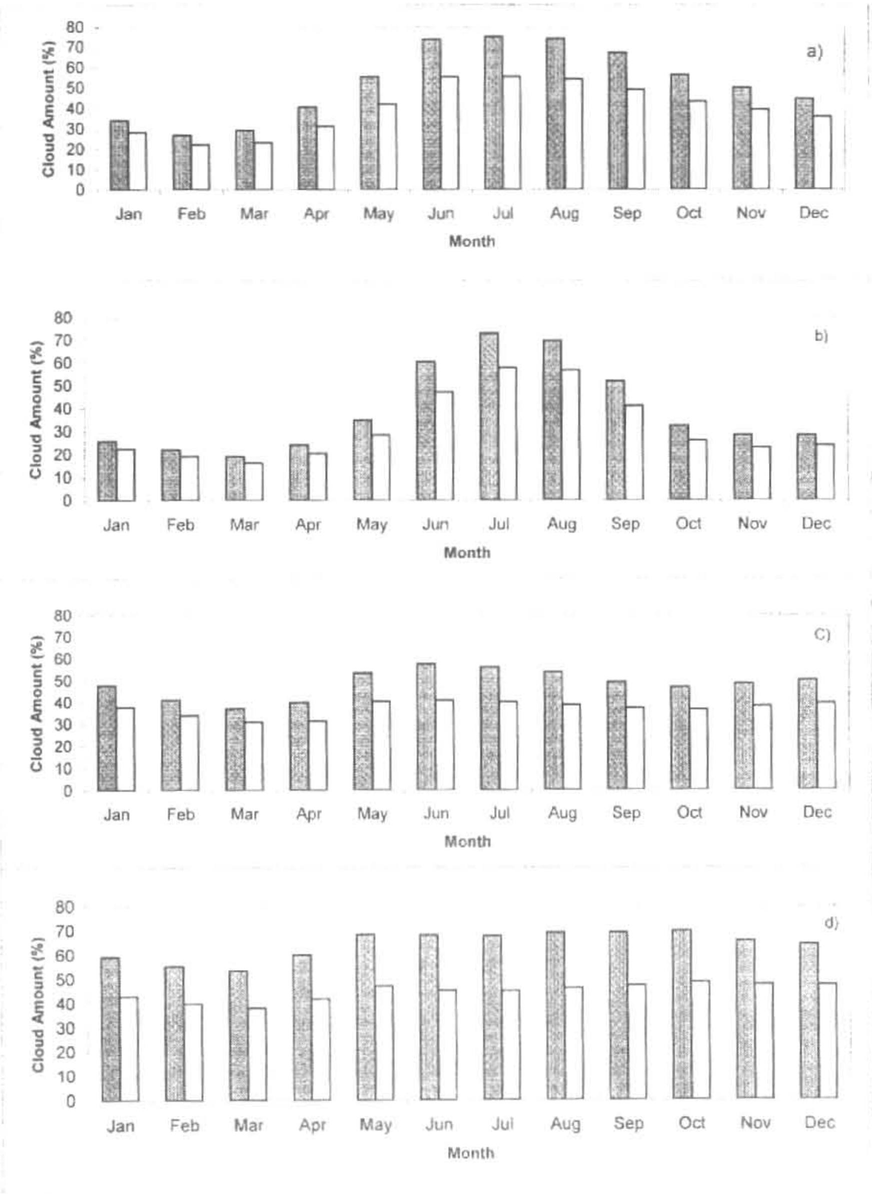


Figs. 4(a&b). Latitude – Month variation of zonally averaged (50° E-100° E) (a) total cloud cover and (b) low cloud cover anomalies subtracted from annual mean. Interval: 2%

overcast when the sky is obscured. In the case that LC is always reported, $n_{low} = n_{all} - n_{clr} - n_{obs}$.

The monthly data were used for calculating the cloud climatologies of four seasons namely winter (January-February), Pre monsoon (March-May), Monsoon (June-September) and Post monsoon (October-December) and for annual (all 12 months).

Using the data of 1951-98, monthly anomalies of total and low cloud cover were calculated at each grid point. In order to separate the decadal variations from longer period variations, a linear trend U_{TR} (t) (t is time) computed by using a least squares method is first removed from the original anomaly time series. Further, to separate the inter-decadal variations $[U_{DC}(t)]$ from the inter-annual variations, we have used an 11- year running mean as a



Figs. 5(a-d). Monthly variation of mean total (shaded vertical bars) and low (open vertical bars) cloud amounts (in %) over (a) Bay of Bengal (b) Arabian Sea (c) West equatorial Indian Ocean and (d) east equatorial Indian Ocean. Period: 1951-98

low pass filter. Since the major inter-annual variability of the regional climate system is associated with the tropical biennial oscillation and the ENSO, this filter effectively eliminates the inter-annual variations. The remaining values are defined as inter-annual components $[U_{IA}(t)]$. Thus, the anomaly time series $U(t)$at each grid can be expressed by

$$U(t) = U_{TR}(t) + U_{DC}(t) + U_{IA}(t)$$

This method of separation of interannual and decadal components is similar to that performed by Kachi and Nitta(1997) and Krishnamurty and Goswami (2000).

In this paper, we have presented only the monsoon season and annual climatologies. In addition, to the climatological parameters like mean and standard deviation, interannual variation of cloud cover and its relationship with Indian summer monsoon rainfall and

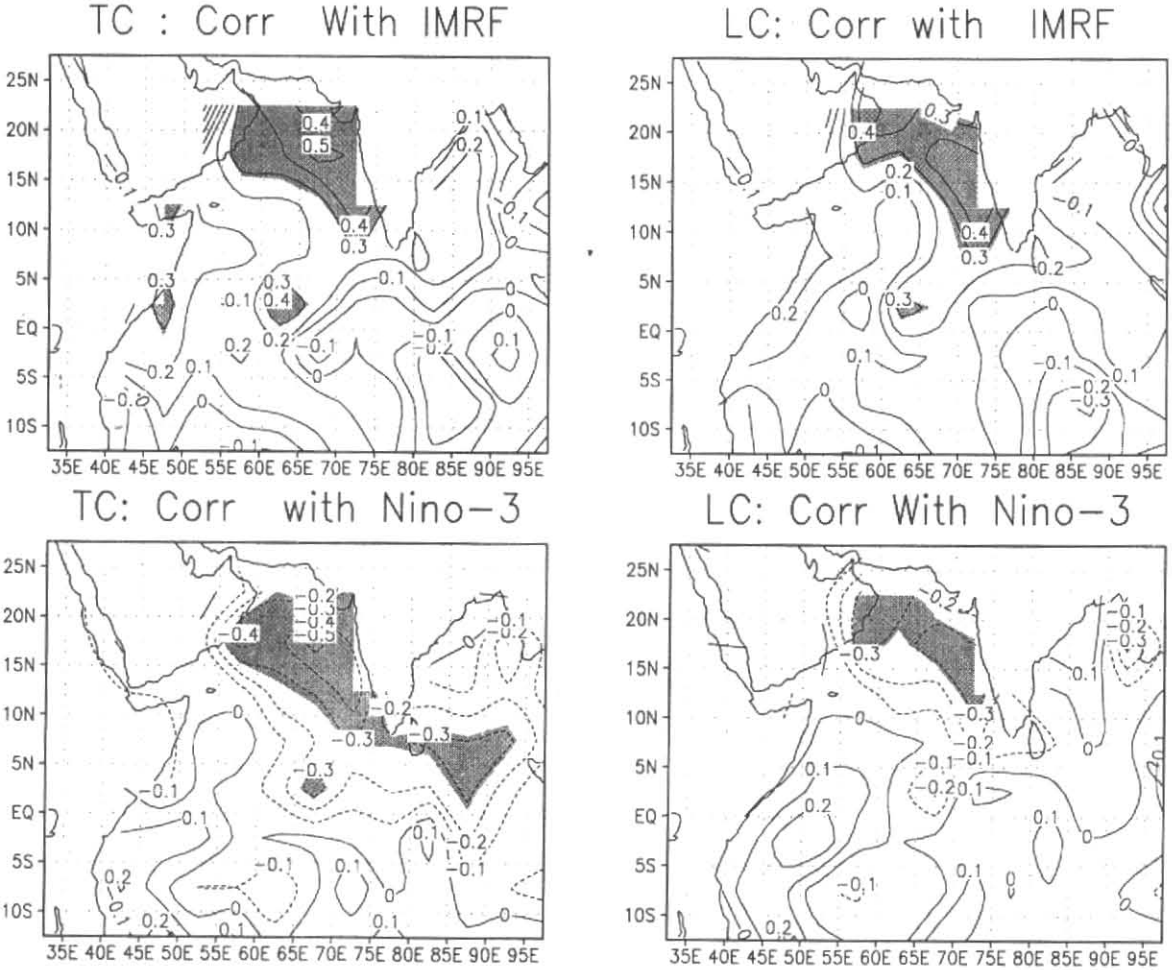


Fig. 6. Correlation coefficients of total and low cloud cover during the monsoon season with Indian Summer Monsoon Rainfall (top panels) and with Nino-3 SST anomalies. (bottom panels). Period: 1951-98. Interval: 0.1. Areas with positive (negative) CCs more than 0.28 (-0.28) are shaded

ENSO phenomenon are also examined using the correlation methods. The long-term trends of low and total clouds are also examined and possible causes for the long-term trends are discussed. The trends are estimated using linear regression method. The linear regression has the following form :

$$Y_t = a + bt + \varepsilon_t$$

Where, Y_t is the cloud cover anomaly, a is the intercept, b the slope and ε_t is the residual. Using the least square method, the trend (slope) can be estimated as

$$\hat{b} = \frac{\sum_{t=1}^{n} (t - \bar{t}) Y_t}{\sum_{t=1}^{n} (t - \bar{t})^2}$$

Where n is the number of observations. Assuming that the residuals are independent and normally distributed with mean zero and variance σ^2, the estimated standard error of b is

$$\mathrm{SE}(\bar{b}) = \left[\frac{\sum_{t=1}^{n} (Y_t - \bar{a} - \hat{b}t)^2}{(n-2) \sum_{t=1}^{n} (t - \bar{t})^2} \right]^{1/2}$$

The hypothesis H_0,: $b = 0$ is tested based on the fact that b/SE(b) is distributed as Student's t with n-2 degrees of freedom when the null hypothesis (H_0) is true.

In addition, the sea surface temperature data taken from the updated version of the Meteorological Office

Historical Sea Surafce Temperature (MOHSST6) which contained *in situ* observations (Parker *et al.* 1995), also have been used.

3. Climatology of cloudiness in the Indian Ocean

3.1. *Mean and standard deviation*

The mean and standard deviation of total cloud (TC) cover calculated using 48 year (1951-98) of data for monsoon season (June-September) and annual are shown in Fig.2. The same details for low cloud cover are shown in Fig.3.

During the monsoon season, maximum TC exceeding 75% are observed over Bay of Bengal. Along the west coast of south peninsula TC exceeds 70%. Over the west Arabian Sea, TC is less than 40%. Maximum standard deviation exceeding 8% is observed near the equator and over southern hemisphere which may be related to the fluctuations in the oceanic convergence zones. Over NE Bay of Bengal also, the standard deviation exceeds 5%. Over other parts of Indian Ocean, it is less than 5%. Annual total cloud cover shows maximum exceeding 70% over equatorial east Indian Ocean. TC decreases towards northwest. Over the coast of Arabia, TC is less than 30%. The standard deviation of annual TC is more than 5% mainly over S.H and north east Bay of Bengal. Comparatively, annual standard deviation is less than the standard deviation of the monsoon season.

During the monsoon season, low cloud cover (LC) exceeds 50% over Arabian Sea and north Bay of Bengal. LC decreases systematically towards west. Over west equatorial Indian ocean, LC is less than 40%. Over west Arabian Sea it is less than 30%. The standard deviation of LC during the monsoon season is maximum near the equator and Southern hemisphere. Over both these regions, it exceeds even 10%. Over the Arabian Sea, it is less than 6%. Annual low cloud cover again shows maximum over the equatorial east Indian Ocean where it exceeds 50%. Over the coast of Arabia and northwest Arabian Sea, it is less than 34%. Large standard deviations exceeding 4-5% are observed near the equator.

3.2. *Annual cycle*

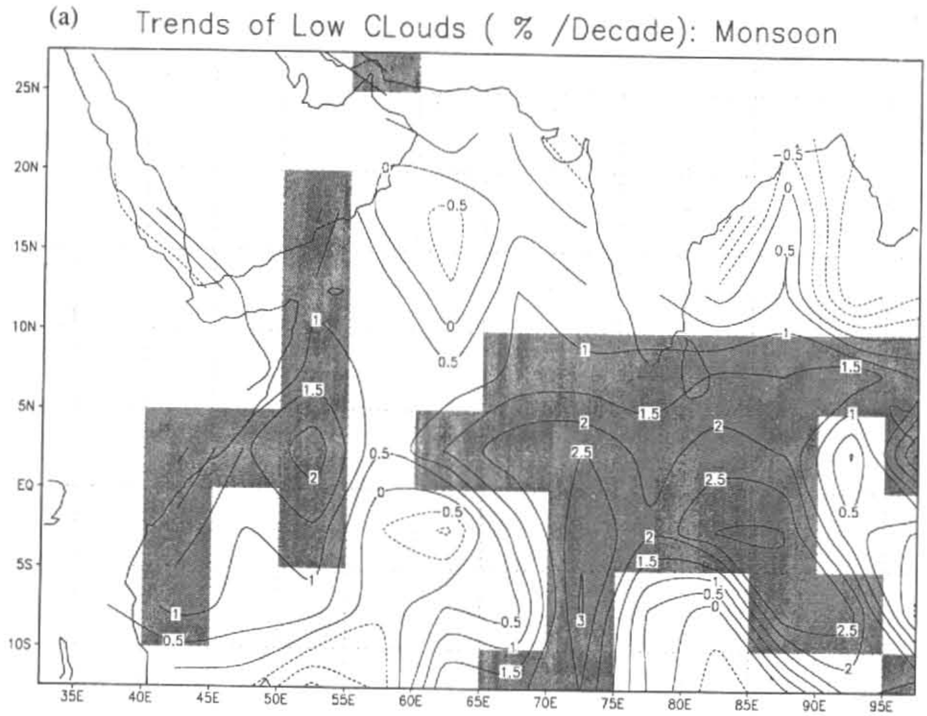
The annual cycle of zonally averaged (between 50° E – 100° E) total and low cloud cover anomaly (subtracted from the annual mean) is shown in Fig.4. In the southern hemisphere the anomalies in TC are positive during January and February and again from June to December. Over the Indian region, large positive anomalies exceeding 20% are observed during the monsoon season. Similar pattern is also observed in case of the annual cycle of low clouds. Positive cloud anomalies associated with the mid-latitude (due to western disturbances) activity over NW India during winter and pre-monsoon months also can be noted. It is also interesting to note that during July to September months, positive low cloud cover anomalies are observed over S.H. along 5° S, which are associated to the Southern Hemispheric Equatorial Trough (SHET).

Monthly variation of area averaged total and low cover over 4 representative regions has been prepared. The four regions are Bay of Bengal (10° N to 25° N, 80° E - 95° E), Arabian Sea (10° N - 25° N, 60°E - 75° E), west equatorial Indian Ocean (0° N- 10° N, 50° E - 75° E) and east equatorial Indian (0° N - 10° N, 75° E - 100° E). The results are shown in Fig. 5. Over Bay of Bengal and Arabian Sea there is an appreciable annual cycle of total and low cover with maximum during monsoon season and minimum during winter. Total (low) cloud cover increases by about 50 % (40 %) from winter to monsoon season. Over the equatorial Indian Ocean, there is little variation from month to month. The variation in total cloud cover is around 10 % and in low cloud cover it is hardly 5 %.

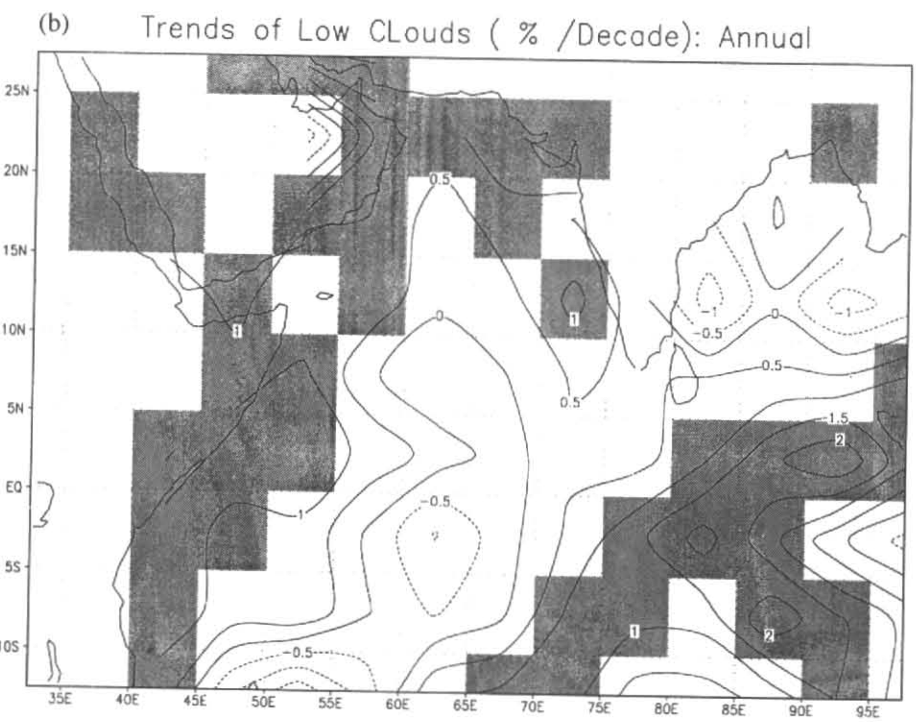
3.3. *Relationship with Indian summer monsoon activity and ENSO*

Summer monsoon rainfall over India exhibits large inter-annual variability associated with large scale circulation anomalies. Similarly, the El Nino/Southern Oscillation phenomenon (ENSO) influences Indian summer monsoon circulation on inter-annual time scale (Sikka 1980, Ropelewski and Halpert 1987). In this section, using the inter-annual time series of cloud cover anomalies, U_{IA}, (t), the inter-annual variation of total and low cloud cover associated with Indian summer monsoon activity and ENSO is examined. Even though one can visualize that in deficient monsoon and ENSO years, cloud cover over the Indian Ocean will be suppressed, the spatial pattern and strength of the relationship have not been documented. We have therefore calculated linear correlation coefficients of cloud over anomalies during the-monsoon season with Indian summer monsoon rainfall (ISMR) and Nino 3 – Index during the summer months. In Fig. 6, the top panels show the correlation coefficients (CCs) of total and low clover during the monsoon season with Indian summer monsoon rainfall during the 48 year period, 1951-98. Both the total and low cloud cover over the Arabian Sea and equatorial north Indian Ocean show significant positive relationship with Indian summer monsoon rainfall which implies that more than normal clouds are observed over these regions during the excess monsoon years. Comparatively, total cloud cover is more strongly correlated with Indian monsoon rainfall than the low cloud cover. Over Bay of Bengal the relationship is

(a)



(b)



Figs. 7(a&b). Trends (Percentage / Decade) of low cloud cover during (a) Monsoon season and (b) Annual. Interval: 0.5%/decade. Areas where the trends are statistically significant at 95% level of significance are shaded

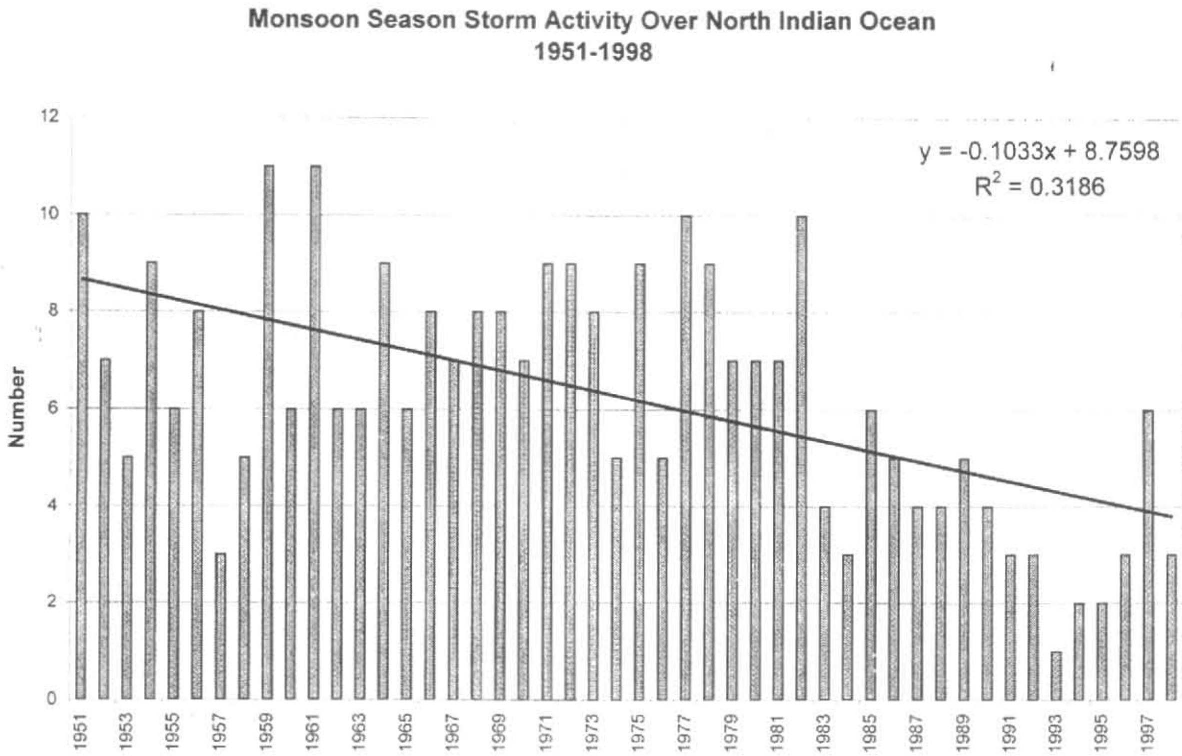


Fig. 8. The time series of number of storms (depressions and above) during the monsoon season from 1951-98. The continuous line is the least square fit of the trend line. The trend equation and square of correlation coefficient (R^2) are indicated

statistically not significant. Significant CCs are also observed in case of low cloud cover over the east African coast / west Indian Ocean. This may be explained as follows. Strong cross equatorial current from the south hemisphere during the strong monsoon years causes above normal upwelling off the east African coast. This enhanced upwelling leads to large negative sea surface temperature anomalies off the east Indian coast. These negative SST anomalies can cause above normal low cloud cover as marine stratus cloudiness is negatively correlated to SSTs on inter- annual time scale (Norris and Leovy 1994). Over the equatorial southern hemisphere, CCs are found to be negative. This may be due to the observed out of phase relationship between the continental TCZ over the Indian region and the southern hemisphere equatorial trough (SHET) (De *et al.* 1995).

The correlation coefficients with Nino-3 Index (SST anomalies of July, August and September, averaged over the region: 5° S - 5° N, 150° W – 90° W) are shown in Fig.6 (bottom panels). For both low and total cloud cover, the pattern of CCs with Nino-3 Index is almost similar to the monsoon rainfall anomalies but with opposite sign. Over Arabian Sea and the equatorial Indian Ocean, the CCs are significantly negative which implies that warm events in the eastern Pacific suppress cloudiness in these regions. Over equatorial west Indian Ocean, positive CCs are also observed. Over Bay of Bengal, insignificant CCs are observed which implies that cloud cover over this region is not modulated by the ENSO events.

4. Long term trends of cloud cover

During the recent years, there have been many studies highlighting significant trends in global surface air temperatures and many other meteorological parameters both over land and ocean (Jones 1994 and Karl *et al.* 1994). The long term linear trends of low cloud cover in this study were estimated using linear regression analyses of the data 1951-98. The significance of the trends was estimated using the Students t - test with (n-2) degrees of freedom. Figs. 7 (a&b) show the spatial distribution of the trends of monsoon season and annual low cloud cover respectively. The grid points where the trends are

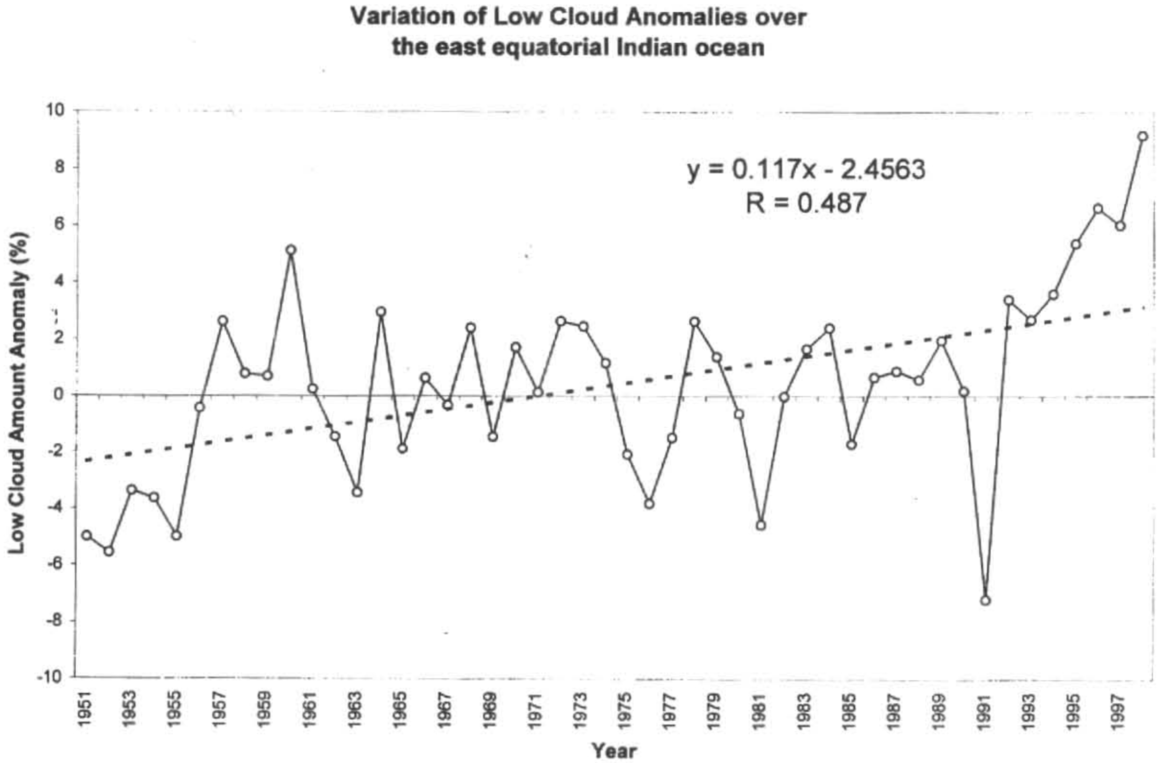


Fig. 9. The yearly variation of low cloud amount anomalies averaged during the monsoon season over the equatorial Indian Ocean (10° S – 10° N, 70° E– 100° E). The dotted line indicates the trend line fitted with the least squares method

significant at 95% significance level are shaded. The annual low cloud cover exhibits increasing trends over most of the Indian Ocean, north of 15° S. Two areas with significant increasing trends observed are the west equatorial Indian Ocean off the east African coast and the east equatorial Indian Ocean. Over these regions, low cloud amount trends exceed 2% per decade. Over Bay of Bengal, however, there is a decreasing trend. These decreasing trends in low cloud cover may be associated with the decrease in monsoon storm (depressions and above) activity over Bay of Bengal observed during the recent decades (Srivastava *et al.* 2000). Earlier, De and Joshi (1995) reported decadal oscillation in the number of cyclonic disturbances in the north Indian Ocean for the period 1891-1990. The yearwise frequency distribution of cyclonic storms (depressions and above) over Bay of Bengal during the period 1951-98 is shown in Fig.8. About 32 % of variance in the variation of storm activity is explained by the linear trend and the trend is statistically significant. During the period 1951-98, the trend is statistically significant. During the same period, storm activity during the monsoon season is decreased at the rate of 1 storm/ decade.

Trends in low cloud cover during the monsoon season contribute very significantly to the annual trends. During the monsoon season, trends in low cloud cover exceed 2.5% / decade over the east equatorial Indian Ocean. Over the west Indian Ocean, the trends exceed 2.0 % / decade. Low cloud cover over Bay of Bengal showed negative trend. Total cloud cover also showed increasing trends over these regions (not shown but are of smaller magnitude. The fact that low cloud trend is greater than the total cloud trend suggests that the increase in low cloud cover may be largely responsible for the increase in total cloud cover. Further, we have seen that the geographical pattern of the long-term trends of cloud cover is similar to that of sea surface temperature (not shown) which suggests the long term trends of cloud cover may be attributed to the long term trends of sea surface temperatures observed over the Indian Ocean (Jones 1994).

The inter-annual variation of low cloud cover anomalies during the monsoon season, averaged over the equatorial Indian Ocean is shown in Fig. 9. In this time series, the decadal component [$U_{DC}(t)$] is removed. It can

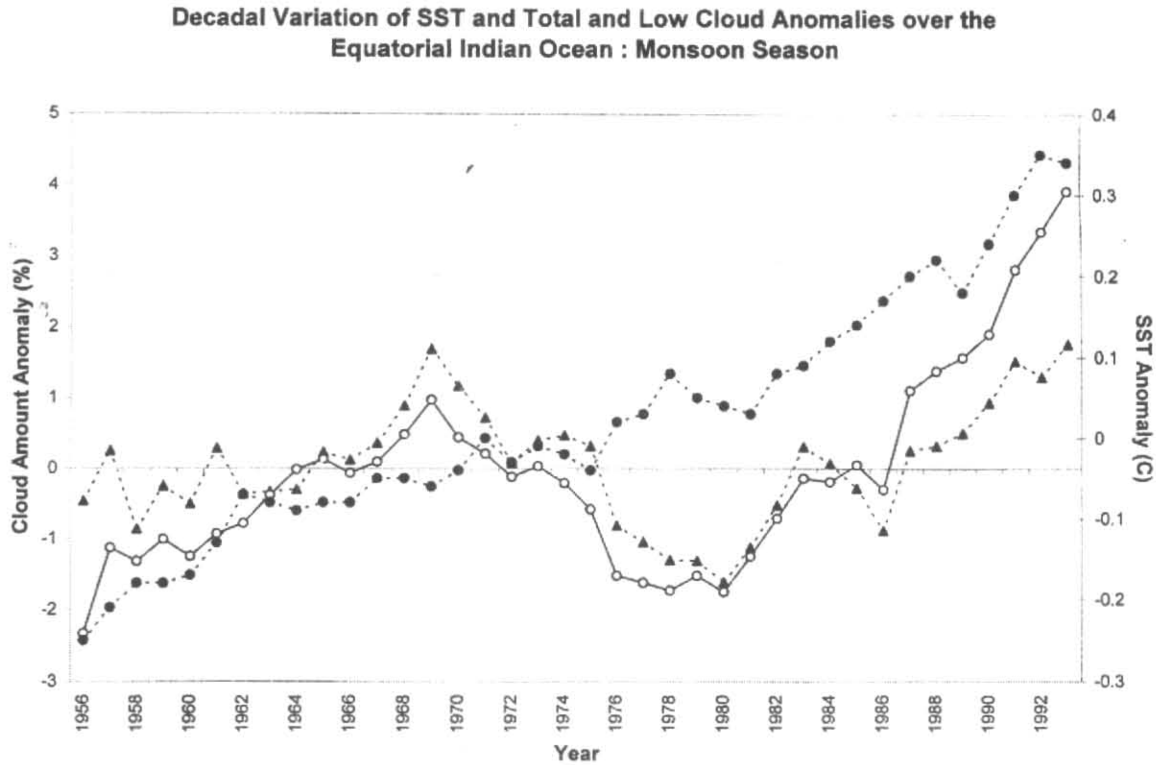


Fig. 10. The decadal component of SST (dashed line with filled circles) and total (dashed line with filled triangles) and low (continuous line with open circles) cloud anomalies over the equatorial Indian Ocean (10° S- 10° N, 50° E-100° E). The year indicates the central year of the 11-year period

be seen that low cloud cover increased systematically since 1951 at the rate about 1.2% per decade. The trend is statistically significant at 99% level. Annual variation of area averaged low cloud cover (not shown) also exhibits similar pattern. Chu and Wang (1997), Waliser and Zhou (1997) have examined recent climate change in tropical convection in the western Pacific and Indian Ocean using Outgoing Longwave Radiation (OLR) data. These studies revealed a significant decrease in OLR over the tropical central-western Pacific and a large portion of the Indian Ocean which is consistent with increased cloud cover reported in this study.

5. Decadal variations

Chu and Wang (1997) have speculated that monsoon convection over tropical western Pacific and the Indian Ocean has undergone a change in the climate mean state, probably on a decadal timescale. In this section, we examine the decadal variation of cloud cover in the north Indian Ocean and its simultaneous variation with SST. In Fig. 10, the variation of the decadal component $[U_{DC}(t)]$ of total and low cloud cover over the east equatorial Indian Ocean (10° S-10° N, 70° E-110° E) is shown. The decadal component is the 11-year running mean of cloud amount anomalies after removing the long-term trend. In the same diagram, the decadal component of SST anomalies averaged over the same area is also shown. It can be noted that till early 1980s, both low and total cloud cover anomalies were negative or close to zero which became positive after early 1980. Thus on decadal scale, cloud cover in the equatorial Indian Ocean exhibited a change from a low cloud cover "regime" to a high cloud cover "regime". On inter-decadal scale, SSTs have entered into a positive phase after 1976 Similar "regime " shift was noted for sea surface temperatures of tropical oceans (Nitta and Yamada 1989). They have observed such a "regime" shift in tropical SSTs during late 1970s. The inter-decadal change in the cloudiness observed in the equatorial Indian Ocean may be therefore related to the decadal scale shift observed in tropical SSTs as positive SST anomalies can cause more convection and more low cloud cover. However data in the future years would confirm or otherwise this decadal scale fluctuations in the near - equatorial Indian Ocean cloudiness.

6. Conclusions

Data set (1951-98) of surface cloud observations collected by the Voluntary Observing Ships was used to prepare the climatology of low and total cloud cover of the north Indian Ocean. The geographical and seasonal variations of cloud cover in the Indian Ocean have been examined. ENSO events suppress the cloud cover in these regions. However, cloud cover over the Bay of Bengal is not modulated by the ENSO events. Low and total cloud cover over most of the Indian Ocean exhibited positive trends which are statistically significant. The rate of increase of low cloud cover is 1.2 % per decade. There is also an indication that cloud cover in the equatorial Indian Ocean exhibited a fluctuation on inter- decadal time scale, from a low cloud cover regime to a high cloud cover regime which may be associated to the decadal scale change in tropical SSTs observed during late 1970s.

In this study, we have included all types of low clouds for estimating the low cloud cover. It may be interesting and useful if the analysis is carried out separately for different low cloud types like convective clouds (cumulus and cumulonimbus) and stratiform clouds (stratus). Such an analysis will reveal further the mechanisms (dynamical or thermodynamical) causing the observed changes in cloud cover on inter-annual and decadal timescales.

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