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Interannual variation in the sea surface temperature threshold for the deep convection over north Indian ocean

D. S. PAI

India Meteorological Department, Pune – 411 005, India

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सार – उत्तरी हिंद महासागर (0–25°उ., 50°पू.–100°पू.) में गहन संवहन और समुद्र सतह तापमान (एस.एस.टी.) के मध्य संबंधों का पता लगाने के लिए वर्ष 1984–90 की अवधि के मानसून ऋतु (जून–सितंबर) के मेघ प्राचलों के अंतर्राष्ट्रीय उपग्रह मेध जलवायु विज्ञान परियोजना (आई.एस.सी.सी.पी.) के मासिक आँकड़ों का उपयोग किया गया है। ~25.2°से. से ऊपर एस.एस.टी. में मानसून ऋतु के दौरान एस.एस.टी. सहित उच्च मेध की मात्रा (एच.सी.ए.) में क्रमिक रूप से वृद्धि हुई है। 27.6°से. के एस.एस.टी. अवसीमा (एस.एस.टी.-टी.एच.) में जिस समय गहन संवहन की घटना की संभावना ≥50 प्रतिशत हो जाती है उस समय एस.एस.टी. सहित एच.सी.ए. में तेजी से वृद्धि होती है। तथापि, बहुत उष्ण एस.एस.टी. की स्थिति में (29° से. से ऊपर एस.एस.टी.) एस.एस.टी. की वृद्धि के साथ एच.सी.ए. में उल्लेखनीय रूप से कमी होती है। उत्तरी हिंद महासागर में एच.सी.ए. – एस.एस.टी. संबंधों में महत्वपूर्ण रूप से स्थानिक विविधता है। बंगाल की खाड़ी में, जैसा कि एस.एस.टी. हमेशा उच्च रहते हैं गहन संवहन के विकास और विविधता को नियंत्रित करने में ऊपरी परिसंचरण की महत्ता एस.एस.टी. की अपेक्षा अधिक रहती है। उत्तरी अरब सागर में अवस्थित उपरितन वायु अवतलन गति गहन संवहन को बढ़ने नहीं देती है। दक्षिणी अरब सागर में गहन संवहन एस.एस.टी और ऊपरी परिसंचरण दोनों से ही प्रभावित रहते हैं। उत्तरी महासागर के एस.एस.टी.-टी.एच. वस्तुतः दक्षिणी पूर्वी अरब सागर की एस.एस.टी. के समान ही पाए गए हैं। वर्ष 1984–90 के दौरान एस.एस.टी.-टी.एच. से उल्लेखनीय अंतः वार्षिक (1.2°से.) भिन्नता पाई गई है। इस अवधि की मानसून ऋतुओं में वर्ष 1987 में 28.8° से. के उच्चतम एस.एस.टी.-टी.एच. पाए गए हैं।

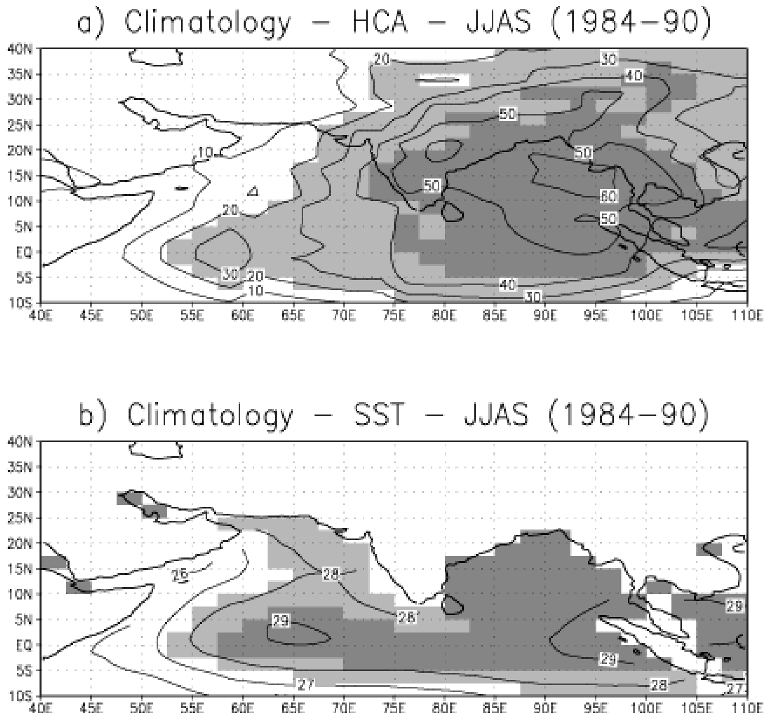
ABSTRACT. International Satellite Cloud Climatology Project (ISCCP) monthly data of cloud parameters for the monsoon season (June-September) for the period 1984-90 are used to examine the relationship between deep convection and sea surface temperature (SST) over the north Indian ocean (0°-25° N, 50° E-100° E). During the monsoon season, at SSTs above ~25.2° C, the high clouds amount (HCA) increases systematically with SST. At the SST threshold (SST_{Th}) of 27.6° C when the probability of occurrence of deep convection becomes ≥ 50%, the increase of HCA with SST is rapid. However, at very warm SSTs (SSTs above 29° C), the HCA decreases significantly with increase in SST. The HCA-SST relationship over north Indian ocean has significant spatial variation. Over Bay of Bengal, as the SSTs are always high, the overlying circulation has the greater importance than SSTs it self in controlling the development and variation of deep convection. Over north Arabian sea, persistent upper air subsidence motion suppresses development of deep convection. In south Arabian sea, the deep convection is influenced by both SSTs and overlying circulation. The SST_{Th} for the north Indian ocean found to be, in effect, equal to that for the southeast Arabian sea. During 1984-90, the SST_{Th} shows significant interannual (1.2° C) variation. Among the monsoon seasons of this period, the highest SST_{Th} of 28.8° C was observed during 1987.

Key words – Interannual variability, SST threshold, Deep convection, North Indian ocean.

1. Introduction

Cloudiness is one of the important parameters, which not only expresses local weather conditions but also indicates local circulation features. During the monsoon season, large-scale deep convective cloud systems form over the warm oceans surrounding the Indian region, which subsequently propagate on to the heated main land and produce abundant rainfall. Thus, the cloudiness and precipitation over the land are linked to the cloudiness over the ocean. The formation of deep convection over the ocean on the other hand depends on the sea surface temperature (SST).

There are many studies, which examined the relationship between SST and tropical deep convection (Bjerkness 1966, Webster 1972, Lindzen and Nigam 1987, Neelin & Held 1987, Zhang 1993, Rajeevan 2001). One of the important findings of such studies is that the frequency of occurrence of tropical convection increases dramatically at a SST threshold value of about 27°C to 28°C. The threshold SST value represents the approximate large-scale surface temperature required to provide necessary moist static energy to the near surface layer in order for saturated air parcels to ascent into the high troposphere and for deep convection to occur. Gadgil *et al*. (1984) found that over the north Indian ocean during



Figs. 1(a&b). Spatial distribution of mean monthly (a) HCA and (b) SST averaged over the monsoon season (June-September) for the period 1984-90. In (a) contour interval is 10% and grid boxes over which monthly HCA values are ≥20% in all the occasions (≥ 50% occasions) of the data period are shaded dark (light). In (b) contour interval is 1°C and grid boxes over which monthly SST values are ≥ 27.6° C in all the occasions (≥ 50% occasions) of the data period are shaded dark (light)

the monsoon season, this SST threshold value is 27.5° C. Lau *et al*. (1997) and Bony *et al*. (1997) have observed that the large-scale atmospheric circulation has strong influence on the relationship between SST and tropical deep convection. They observed that in the SST range of 27°-28° C, the rate of increase of tropical deep convection with SST under the conditions of strong ascending motion is 2-3 times more than that under conditions of weak large-scale circulation.

The main objective of this study is to analyse the relationship between deep convection and SST over north Indian ocean during the monsoon season using International Satellite Cloud Climatology Project (ISCCP) monthly cloud data and find out the interannual variability in the SST threshold values. This aspect was not examined in any of the earlier studies. In examining large-scale cloud systems, satellite observations of clouds have the advantage of larger spatial view and reduced errors resulting from subjective cloud identifications and sampling variability. However, surface observations are available for a longer time period and provide ‘bottom up’ view that is complementary to the satellite ‘top down’ view.

2. Data and methodology

The measurements of cloud parameters utilized in this study are taken from ISCCP C-2 data set, which provides the monthly averages of cloud cover parameters at a spatial grid of 2.5° × 2.5°, latitude × longitude (Rossow and Shiffer 1991). These data are based on observations by the global network of geostationary weather satellites and atleast one polar orbiting NOAA satellite. Over Indian region, the ISCCP C-2 cloud data are based on observations by GMS, METEOSAT and NOAA satellites. The data set however does not include the data from the INSAT, which is a limitation on the completeness of the data set. In this study, mainly four cloud parameters, *viz*., cloud amount, cloud optical depth, cloud top pressure and cloud albedo are used. The ISCCP clouds are broadly divided into three types. High clouds (Cirrus, Cirrostratus/Cirrocumulus and Convective clouds) have cloud tops above the 440 hPa level. Middle clouds (Nimbostratus and Altocumulus/Altostratus) have cloud tops located between pressure levels of 440 hPa and 680 hPa. Low clouds (Stratus and Cumulus/ Stratocumulus) have cloud tops below 680 hPa level.

Pai and Rajeevan (1998) has shown that over Indian ocean region during the monsoon season, the ISCCP C-2 high cloud amount (HCA) can be used as a proxy for deep convection. They found that the HCA and outgoing long wave radiation (OLR), which is a well known proxy for deep convection have a reciprocal relationship and that the HCA of 20% approximately represents OLR of ~240 Wm^{-2}. Therefore, high clouds over grid boxes with monthly HCA ≥ 20% are assumed to be mainly of the deep convective type.

The other data set used in this study is the National Centre for Environmental Prediction (NCEP) SST data set (Reynolds 1988). The SST data set is derived by blending separately analysed *in situ* (ship & buoy) and satellite measurements of SST (Reynolds 1988). The analysed data provides monthly mean SST on a $2° \times 2°$ spatial grid with a reported accuracy of 1° C. For the purpose of this study, the SST values are interpolated to overlap into $2.5° \times 2.5°$ grids of ISCCP data. The cloud and SST data used in this study are taken from the GEDEX CD-ROM obtained from the Langley Research Center, NASA, USA. The spatial domain selected for this extends from equator to 25° N latitude and 50° E to 100° E longitude with grid spacing of $2.5° \times 2.5°$. After removing the grid points over the land areas of the domain, each month provides data at 129 grid points making a potential total of 3612 points for analysis. Both the data sets are used for the monsoon season (June to September) for the period 1984-90.

To allow for non-linearity in the relationships, a binning method is used to examine the relationship between cloud parameters and SST. In this method, mean and standard deviations of each of the cloud parameters are computed for different SST ranges of equal interval (0.4° C) of SST. The standard deviation of a variable in respect of a given SST range represents the variation in the values of the variable within that SST range. A curve passing through the mean values of a cloud variable (*e.g.*, high cloud amount) plotted against the centre values of respective SST ranges represents the average relationship between the cloud variable and SST.

3. Results and discussion

3.1. *Climatology of HCA & SST*

Figs. 1 (a&b) shows the climatology of HCA and SST distribution over the Indian monsoon region for the monsoon season (June-September) obtained by averaging the grid point monthly data for the period 1984-90. In Fig. 1(a), it is seen that in the oceanic region, over the entire Bay of Bengal and over belt of about 5° off the west coast of the Indian main land, the mean HCA values are ≥40% with maxim (≥60%) over northeast Bay of Bengal. The area of maximum mean HCA approximately corresponds to the centre of the climatological upper level divergent outflow (Krishnamurti *et al*., 1989). Over Arabian Sea, west of 65° E, the mean HCA values are less than 20% except in the regions close to equator, where HCA values are 20-30%. Over the region close to the coasts off Africa and Arabia, mean HCA reduces to below 10%. The low values of HCA over the north Arabian Sea are due to the persistent large-scale subsidence motion associated with the climatological upper air anticyclone over the region. The anticyclonic flow also brings dry warm continental air over the Arabian Sea. The confluence of the continental air with the relatively cool moist air of oceanic origin results in the thermal inversion in the lower level over Arabian Sea (Sen and Das 1986). Sen and Das (1986) has reported the presence of low level inversion over the Arabian Sea even during the established phase of the southwest monsoon.

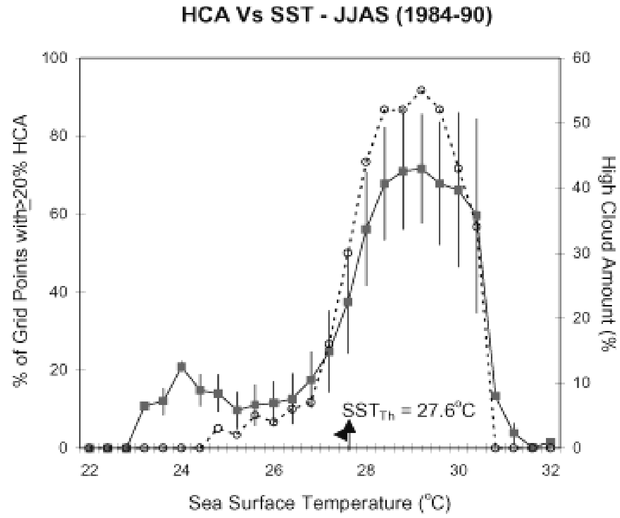
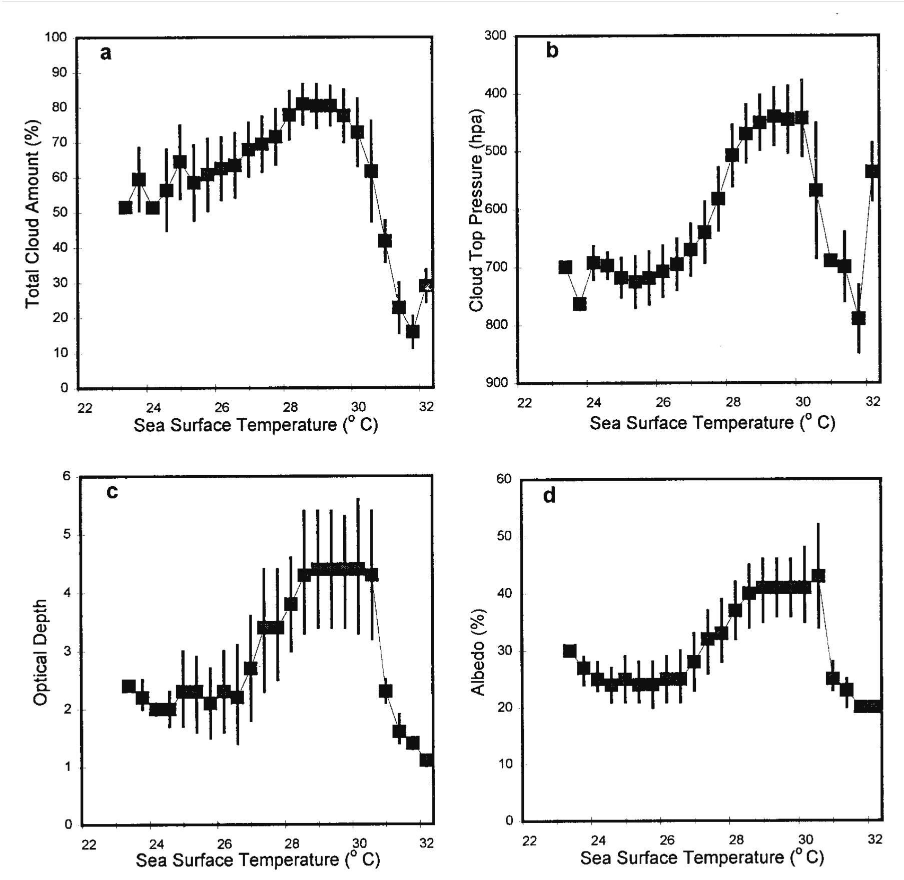


Fig. 2. Variation of mean monthly high cloud amount (HCA) for 0.4° C Sea Surface Temperature (SST) bins as function of SST for the north Indian Ocean for the monsoon season (June- September) for the period 1984-90. Vertical bars are standard deviations of the means. The solid curve connects the means. The dashed curve connects the probability of occurrence of grid points with HCA of ≥ 20% expressed in percentage of each 0.4° C SST bins. SST_{Th} is the threshold value of SST for the occurrence of deep convection and is defined in the text

In Fig. 1(b), the maximum mean SSTs (>29° C) are seen over eastern most part and small area around 65° E of equatorial North Indian Ocean. In the Bay of Bengal, the mean SSTs are between 28° C and 29° C. Westwards from the SST maximum over the Northwest Indian Ocean, the mean SSTs reduce to less than 26° C over the upwelling region off the African and Arabian coasts. On comparing both the panels [Figs. 1 (a&b)], it is seen that



Figs. 3 (a-d). Variation of mean monthly Total cloud amount (TCA) for 0.4°C Sea Surface Temperature (SST) bins as function of SST for the north Indian Ocean for the monsoon season (June-September) for the period 1984-90. Vertical bars are standard deviations of the means. The solid curve connects the means. (b), (c) & (d) are same as (a) but for the variation of Total cloud top pressure (hPa), Total cloud optical depth and total cloud albedo respectively against SST

in the Arabian Sea, 20% HCA contour line approximately passes between SST contours of 27° C and 28° C. This suggests that in the region of mean SSTs of less than about 27.5° C, the HCA reduce below 20%. However, the maximum mean HCA values are not observed over the maximum mean SSTs.

In Fig. 1(a), grid boxes over which HCA values are ≥ 20% in all occasions (≥50% occasions) of the data period are shaded dark (light). It is seen that in the Bay of Bengal, all the grid boxes are dark shaded. As HCA of ≥ 20% represents deep convection, this indicates that the major contribution in the HCA over the Bay of Bengal is from the deep convective clouds. In the Arabian Sea off the west coast (south of 20° N) also, there is a small area where the HCA of ≥ 20% is observed in all the occasions. Away from this deep convective clouds dominated region, the contribution of deep convective clouds in the HCA decreases and that of cirrus type clouds increases. Thus, the HCA observed over most of the western part of the Arabian Sea is mainly due to the cirrus type clouds, which are blown to the region by the overlying easterly jet stream. It is also so as this part of the Arabian Sea is dominated by up welling with inversion close to the surface in the boundary layer.

3.2. *HCA vs SST*

Fig. 2 shows the relationship between HCA and SST over north Indian ocean (0° -25° N, 50° E-100° E). It depicts the means and standard deviations of HCA for 0.4° C SST bins against SST obtained using grid point data during the monsoon months (June-September) for the entire period (1984-90). The dashed curve represents the probability of grid boxes having ≥20% HCA expressed as percentage for each SST bin.

The solid curve connecting the mean HCA (Fig. 2) indicates that the HCA and therefore the organised convection increases as the SST increases from around 25.2° C and reaches its peak value of 43.0% at ~29.2° C. In fact, 90% of the total 3612 grid boxes lie between 25.2° C and 29.2° C. After 29.2° C, HCA decreases with increasing SST. At the SST value of 29.2° C, the probability of grid boxes with ≥20% HCA is also maximum (96%). Another aspect is that despite the small sample size at higher SSTs, statistical tests (*t*- test at 99% confidence interval) showed that the adjacent HCA bin means at SSTs of 29.2° C and above are distinct (except points above 31.2° C). Also 72% of the total grid boxes are in the SST range of 28° C - 30° C and in this SST range 75-95% of the grid boxes have HCA ≥20%.

Along the rising portion of the curve (Fig. 2), an SST threshold (SST_{Th}) for the occurrence of the deep convection is defined as the lowest SST value at which the probability of grid boxes with ≥20% HCA reach 50% or more. The SST_{Th} is similar to the one that suggested by Gadgil *et al*. (1984). As seen in the Fig. 2, the value of SST_{Th} is 27.6° C. Using a similar analysis, the SST_{Th} values for the four months of January, April, July and October representing four seasons for the same period (1984-90) (Figures not shown) are found to be 28.0° C, 29.4° C, 27.6° C and 28.4° C respectively (*i.e*. seasonal variation of 1.8° C in the SST threshold value). However, it may be mentioned that in the decreasing portion of the HCA-SST relationship (Fig. 2), above 30.8° C, there are no grid boxes with HCA ≥20% even though the SST is well above the threshold value. These results clearly demonstrate that high local SST is a necessary but not sufficient condition for deep convection. Though a warmer SST increases the buoyancy of the air in the planetary boundary layer, but if this buoyancy is suppressed by factors like subsidence or a stable stratified boundary layer, the deep convection and thus high clouds will not be promoted. It is seen that other cloud properties such as total cloud amount, total optical depth, total cloud top pressure and total cloud albedo etc. have also similar relationship with SST as shown in Fig. 3.

The decreasing portion of the relationship at warmer SSTs can be associated with diminished deep convection. These may be the regions where local or remote forcing are acting to suppress deep convection. Waliser and Graham (1993) addressed this important aspect in which they emphasised the importance of cooling mechanisms associated with deep convection in determining the observed upper limits on tropical SST.

In order to study the variation in the SST-deep convection interaction during the monsoon season over various parts of north Indian ocean, the north Indian Ocean is divided into five important domains and HCA-SST relationship is examined separately over each of the domains. These domains are (*i*) North Bay of Bengal (15° N –25° N, 80° E–100° E), (*ii*) South Bay of Bengal (0° –15° N, 80° E–100° E), (*iii*) North Arabian Sea (20° N–25° N, 50° E– 70° E), (*iv*) Southwest Arabian Sea (0°–20° N, 50° E–65° E) and (*v*) Southeast Arabian Sea (0°–20° N, 65° E–80° E). Fig. 4 depicts five panels corresponding to HCA-SST relationship over the five domains of the north Indian ocean. The important features of each of the panels are discussed below.

In the north Bay, during the data period, there are 224 grid boxes. In the corresponding panel in the Fig. 4, it is seen that, the centre values of all the SST bins are more than 27.6° C (SST_{Th} value for the north Indian ocean) and are between 28° C and 30.4° C. The HCA means varied from 56% to 67%. From Figs. 1(a&b) it is also clear that, over all the grid boxes of this domain during the entire data period, HCA values are ≥ 20% and SSTs are ≥ 27.6° C. In Fig. 1(b), grid boxes over which SST values are ≥ 27.6° C in all the occasions (≥50% occasions) of the data period are shaded dark (light). In Fig. 4, it is also seen that in general HCA increases with increase in SST. All these above features indicate that in this domain, the HCA is generally high and it is dominantly contributed by deep convection. During the monsoon season, the eastern tip of the monsoon trough over the Indian mainland extends over this domain. Therefore, during normal or strong monsoon conditions, the atmospheric conditions over this region are generally conducive for the genesis of low pressure systems and hence the development of deep convection. As the SSTs are also always high (≥ 27.6° C), the variation in the HCA over this region could be mainly due to the variation in the atmospheric circulation pattern over this region.

In south Bay, there are 1120 grid boxes and like north Bay, centre values of all the SST bins are ≥27.6° C (between 27.6° C & 30.4° C) and almost all the grid box HCA values are ≥ 20%. However, mean HCA values of various bins are about 10% less than that over north Bay and they vary between 46% & 56%. The oceanic tropical convergence zone (TCZ) over tropical Indian ocean (Pai, 1996) normally develops over this region and extends westwards up to the southwest Arabian Sea. During the normal and active oceanic TCZ, the conditions are conducive for the development of deep convection over this region. There is however a competitive inverse interaction between activity of oceanic TCZ and monsoon trough (which generally extends from the Indian main land to the northwest Pacific through north Bay). As such, the HCA-SST relationship over south Bay is almost similar to that over north Bay.

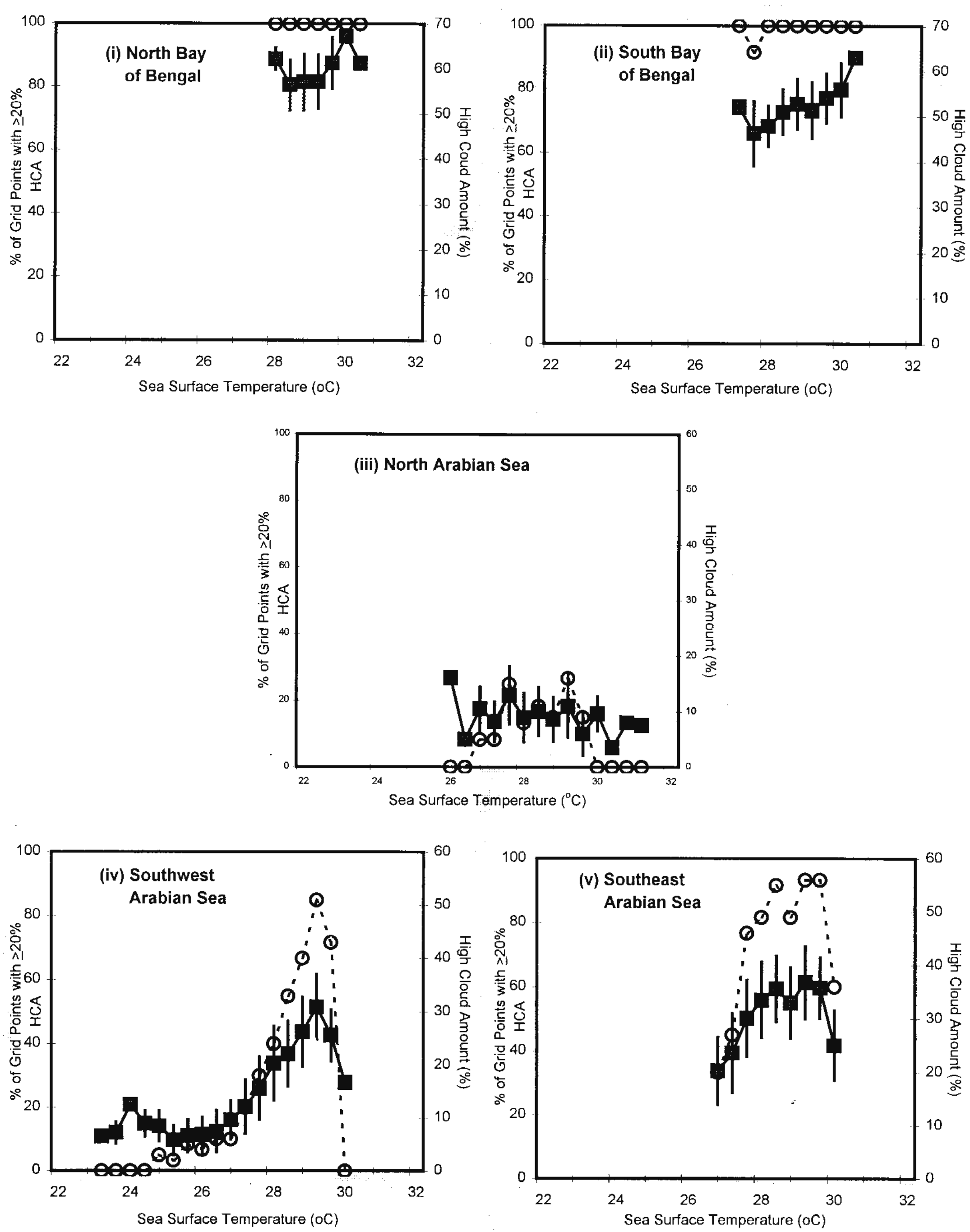


Fig. 4. Same as Fig.2, but for five different spatial domains of North Indian Ocean. These domains are (*i*) North Bay of Bengal (15° N –25° N, 80° E–100° E) (*ii*) South Bay of Bengal (0°–15° N, 80° E–100° E), (*iii*) North Arabian Sea (20° N–25° N, 50° E– 70° E), (*iv*) Southwest Arabian Sea (0° –20° N, 50° E–65° E) and (*v*) Southeast Arabian Sea (0°–20° N, 65° E–80° E)

The discussions in the last two paragraphs, therefore, indicate that the rising portion of the consolidated HCA-SST curve above SST of 27.6° C and its peak (Fig. 2) is a reflection of HCA-SST interaction over Bay of Bengal.

In the north Arabian Sea, during the data period, there are 168 grid boxes with centre values of SST bins varying between 26.0° C & 31.2° C. Irrespective of the SST values, the HCA values (particularly at high SSTs) are small (about 10%). In all the SST bins, the percentage of grid points with ≥20% HCA are very small. At and above 30° C, it is zero. The reason for the suppression of deep convection over this region could be the large-scale subsidence zone extending over this region and centered at the heat low region over the neighbouring land region. The dry air of continental origin that penetrates over this region is also responsible for the same. In the HCA-SST curve in Fig. 2, the effect of including data of north Arabian Sea is, therefore, to reduce the mean HCA values in all the SST bins (with SST centre values of ≥ 26° C), particularly at bins of higher SSTs.

In southwest Arabian Sea, there are 1064 grid boxes with centre values of SST bins varying between 22.2° C and 30.0° C. About 54% of these grid boxes have SSTs ≤ 27.6° C. It is seen that (Fig. 4) above 26.0° C as the SSTs increases, the mean HCA also increase. The maximum mean HCA of 31% was observed at 29.2° C. Above this SST value, the mean HCA reduces with increase in SST. It is also seen that in the rising portion of the HCA-SST curve, the percentage of grid boxes with HCA ≥20% also increases rapidly indicating that SST is clearly an important factor for the development of deep convection over this region. The SST_{Th} for the deep convection over southwest Arabian Sea obtained according to the earlier definition is found to be 28.4° C, which is 0.8° C more than the SST_{Th} for the deep convection over north Indian ocean (27.6° C) considered in total.

In southeast Arabian Sea, there are 784 grid boxes with centre values of SST bins varying between 26.8° C and 30.0° C. In this case, it is seen that the mean HCA values of all the SST bins are ≥20% and increase with SST until the peak mean HCA (37%) is observed at SST of 29.2° C. Above this, the HCA showed decrease with SST. On further examining it is found that, most of the grid boxes pertaining to the decreasing portion of the HCA-SST curve over both western and eastern parts of south Arabian Sea are from the northern portion adjacent to north Arabian Sea. The SST_{Th} for deep convection over southeast Arabian Sea is found to be 27.6° C, which is same as that for the north Indian ocean considered in total. Along the rising portion of HCA-SST curve over this region, the percentage of grid points with HCA ≥20% increases and becomes close to 100% near the peak. This indicates that over this domain also like over southwest Arabian Sea, SSTs are an important factor in the development of deep convection. However, peak of the HCA-SST curve over southeast Arabian Sea is broader and higher than that over southwest Arabian Sea.

From the above discussions, the important features of the spatial variability of HCA-SST relationship over north Indian ocean can be summarised in the following two paragraphs.

In the Bay of Bengal, as the SSTs over all the grid boxes are always high (above the threshold value), the circulation has the greater control over the development and the variation of deep convection over the region. In the north Arabian Sea, due to the persistent subsidence motion and penetration of dry continental air, the deep convective clouds generally do not develop. Due to relatively clear sky conditions, the warmest SSTs of the season are generally observed over some pockets of the north Arabian Sea. In the south Arabian Sea above normal 29.2° C, the HCA decreases with SST. Most of the grid boxes pertaining to the decreasing portion of the relationships over south Arabian Sea are mainly from the northern portion closer to north Arabian Sea. Thus, the decreasing portion of the consolidated HCA-SST curve of Fig. 2 can be related to the depressed convection over the northern parts of Arabian Sea.

In this study most of the grid boxes with SST ≤ 27.2° C pertain to the southwest Arabian Sea dominated by upwelling with low level inversion close to the surface in the boundary layer. In this SST region [(Figs. (2&4)] the HCA values are very small and are mainly contributed by cirrus type clouds. Above around 27.2° C, in the south Arabian Sea (both southwest and southeast), both HCA & probability for the occurrence of deep convection increase with increase in SST. This indicates the strong dependence of the deep convection over this domain (particularly in the southeast Arabian Sea) on the SST. However, the deep convection - SST coupling can be modified by the overlying atmospheric circulation. Thus over south Arabian Sea, both SSTs and circulation features are important in the development and variation of the deep convection. The SST_{Th} for the entire North Indian ocean is found to be, in effect, the SST_{Th} for the southeast Arabian Sea (discussed in the next section also).

3.3. *Interannual variation of SST_{Th}*

Fig. 5 depicts the HCA-SST relationship over the north Indian ocean for the monsoon season (JJAS) for the individual years during the period 1984-90. Table 1 presents the SST threshold values at which the probability for the grid points with HCA ≥20% becomes 75%, 50% and 25% for further analysis. Table 1 also shows the interannual variation of SST corresponding to peak HCA and SST with highest grid point frequency. It is clearly seen that both these SSTs are higher than the corresponding SST threshold values. In the last column of the Table 1, the C.C. between SST & HCA obtained by using all the grid point values of the respective monsoon

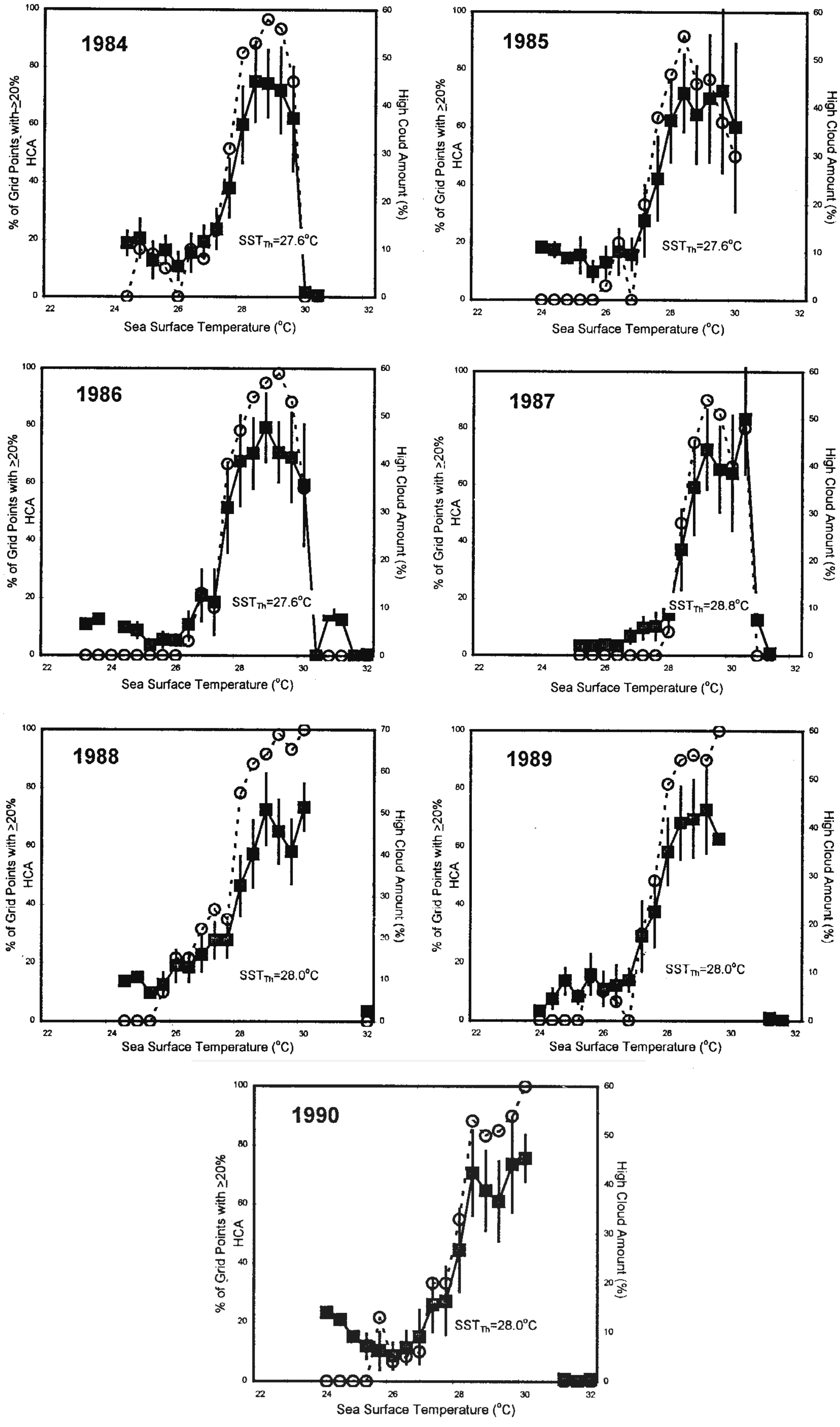


Fig. 5. Same as Fig.2, but for individual years from 1984 to 1990

TABLE 1

Interannual variation of SST threshold for deep convection over North Indian Ocean during the monsoon season (June-September) for the period (1984-90)

Year	SST at which HCA peak (^{0}C)	HCA peak (%)	Centre value of SST range having max. number of grid points (^{0}C)	SST (^{0}C) at which probability of grid points with HCA ≥ 20% becomes			C.C. between HCA and SST
				≥ 75%	≥ 50%	≥ 25%	
1984	28.4	45.0	28.4	28.0	27.6	27.6	0.61
1985	28.4	43.1	28.4	28.0	27.6	27.2	0.48
1986	28.8	47.6	28.8	28.0	27.6	27.6	0.58
1987	29.2	43.5	29.2	28.8	28.8	28.4	0.52
1988	28.8	50.9	29.2	28.0	28.0	26.8	0.47
1989	29.2	43.7	28.4	28.0	28.0	27.2	0.53
1990	29.6	44.2	28.8	28.0	28.0	27.2	0.52

season is shown. During all the years, the C.C. is found to be statistically significant with maximum during 1984 (0.61) and minimum during 1988 (0.47). Another important aspect is that the SST_{Th} values for the north Indian ocean in each and every year are found to be equal to the SST_{Th} values for the southeast Arabian Sea (not shown in the Table 1). As seen in the last section the same is the case with SST_{Th} determined using data of all the years together. The year to year variation of SST_{Th} shows that during all the years except 1987, when SST is in the range of 27.6^o C to 28.0^o C, the probability for deep convection to occur is 50% or more. *i.e.*, SST_{Th} varies from 27.6° C to 28.0° C. During 1987, an ENSO year with weaker than normal Indian summer monsoon, the SST_{Th} is 28.8° C, which is 1.2° C more than the normal SST_{Th} (Fig. 2). This indicates that during the period of 1984-90, the SST_{Th} has an interannual variation of 1.2° C.

In general during the monsoon season, due to the presence of a huge upper air divergent flow over the Indian monsoon region centered on north Bay of Bengal, the atmospheric conditions over this region are generally favourable for the development of deep convection. The large-scale monsoon circulation has also large interannual variation and is influenced by both local and remote forcing. The strong local ascending/ descending motion caused by local forcing can cause descending/ascending motion over areas far away through the remote forcing mechanism (the monsoon-ENSO coupling). Such variation in the vertical motion can influence the development of deep convection significantly, which could be the reason for both the seasonal and the interannual variation observed in the SST_{Th}.

In 1987, over equatorial areas of north Indian Ocean, the SSTs were persistently above normal during most of the monsoon season. The warm anomalies were centered over south Bay of Bengal. However, over other areas of north Indian ocean, SSTs were normal or below normal during early part of the season. This warm SST anomaly over south Bay of Bengal and associated increased deep convection were found to be one of the reasons for the weakening of monsoon circulation in 1987 (Krishnamurti *et al*. 1989). Krishnamurti *et al*. (1989) also found northward progression of a counter monsoon circulation anomaly in the lower levels and southeastward shifting of upper level anticyclone from its normal position. As a result there was general weakening of Arabian Sea circulation and upper level tropical easterly jet. These features explains the relatively higher value for SST_{Th} (28.8° C) over southeast Arabian Sea and hence over north Indian ocean.

In the Table 1, it is also seen that during most of the years, the SST at which the probability of deep convection becomes ≥ 25% is ~27.2° C - 27.6° C. However, for 1987 & 1988 (a La Nina year of excess Indian summer monsoon rainfall), the corresponding SST values are 28.4° C & 26.8° C respectively (*i.e.* an interannual variation of 1.6° C). At the same time, except for 1987, for all the other years, at 28° C, 75% or more of the grid boxes showed deep convection. For 1987, this is observed at a higher SST value of 28.8° C. In 1988, the SSTs over the areas surrounding the Indian subcontinent and the Indian ocean were near normal to somewhat above normal for almost the whole monsoon season (Krishnamurti *et al*. 1990). However, the HCA values over Indian monsoon region were in general more in 1988 in compared to that in 1987. The major differences were over north Bay of Bengal and southeast Arabian Sea. The HCA values over these two regions during 1988 were more by 10-20% and 5-10% respectively in comparison with that during 1987. Krishnamurti *et al*. (1990) found that, in 1988, the low level flows over the Arabian Sea were near normal and the upper level easterly jet was stronger than normal. Also in 1988, the upper level divergent flow centered at its normal position over the north Bay of Bengal was stronger than normal. So these observations once again suggest the possible influence of large-scale circulation on the HCA-SST relationship.

4. Conclusions

From the analysis of the HCA-SST relationship over north Indian ocean during the monsoon season, the following conclusions can be drawn.

(*i*) When the SST is ≥25.2° C, the HCA shows gradual increase with SST. The peak value of HCA (43%) is observed at SST of 29.2° C. However, at SSTs above 29.2° C, the HCA shows decrease with SST.

(*ii*) Along the ascending branch of the HCA-SST relationship, at SST_{Th} value of 27.6° C, when the probability for the occurrence of deep convection is ≥50%, the increase in HCA with SST is relatively rapid.

(*iii*) There is significant spatial variation of HCA-SST relationship over north Indian ocean. As the SSTs over the Bay of Bengal are always high (≥27.6° C), the overlying circulation features are more important than SSTs in controlling the development and variation of deep convection that region. Over north Arabian Sea, the persistent subsidence motion associated with the overlying upper air anticyclone generally suppresses the deep convection. Over south Arabian Sea, both SSTs and circulation are important for the development and variation of deep convection.

(*iv*) During all the monsoon seasons of the period 1984-90, SST_{Th} for north Indian ocean was found to be, in effect, equal to that for southeast Arabian Sea (which is only a part of north Indian ocean).

(*v*) The SST_{Th} for the deep convection shows both the seasonal (1.8° C) and interannual (1.2° C) variations, which can be attributed to the changes in the HCA-SST interaction caused by the variation of the overlying circulation. Among the various monsoon seasons of the period 1984-90, highest SST_{Th} was observed during the year 1987 (28.8° C).

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