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Diurnal variation of cloudiness during southwest monsoon season using INSAT-1B radiance data

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सार — इस शोध पत्र में संवहनी मेघों के दैनिक परिवर्तन का अध्ययन करने का प्रयास किया गया है। इस अध्ययन के लिए वर्ष 1987-89 के मानसून (जून-सितम्बर) के लिए इनसैट-1 बी के 3 घंटेवार पूर्ण विभेदन अवरक्त आंकड़ों का प्रयोग किया गया है। अध्ययन क्षेत्र का विस्तार 35° उ० से 25° द० और 40° पू० से 100° पू० तक है जोकि 2.5× 2 5 अक्षांतर/देशान्तर के लघु क्षेत्रों में उपविभाजित है। प्रत्येक उपक्षेत्र में निर्धारित सीमांत तापमान की अपेक्षा ठंडे मेघों से आच्छादित आंशिक क्षेत्र और माध्य तापमान को इस अध्ययन के लिए प्राचलों के रूप में प्रयोग किया गया है। दो सीमांत तापमानों, नामत: 265°K और 235°K का चुनाव क्रमश: संवहनी मेघों और गहन संवहनी मेघों का प्रतिनिधित्व करने का लिए किया गया है। तीन घंटेवार प्रेक्षणों का प्रयोग करते हुए अधिकतम और न्यूनतम संवहनी गतिविधि की अवधियों का भी पता लगाया गया है। लगभग दोपहर के समय बंगाल की खाड़ी के ऊपर अधिकतम संवहनी गतिविधि का पता चला है जो अधिकतम मध्यरात्रि तक स्थल की ओर पश्चिम दिशा में स्थानांतरित हो गई और सुबह तक पुन: समुद्री क्षेत्र में स्थापित हो गई। यह पूर्व-पश्चिम दोलन भूमध्यवर्ती क्षेत्रों (खुले महासागर) में कम है।

लगभग आधे संवहनी मेघ बंगाल की खाड़ी के उत्तर में और अरब महासागर में गहन संवहन के रूप में विकसित होते हैं जबकि स्थल और भूमध्यवर्ती हिन्द महासागर के निकट यह प्रतिशत कुछ हद तक कम है।

ABSTRACT. An attempt has been made to study the diurnal variation of convective clouds. For this study 3 hourly full resolution, infrared data of INSAT-1B have been used for the monsoon season (Jun-Sep) of 1987-89. The area of study extends from 35°N to 25°S and 40°E to 100°E, which is subdivided into small areas of 2.5 × 2.5 Lat./Long. Mean temperature and the fractional area covered by clouds colder than a given threshold temperature over each sub area are the parameters used for this study. Two threshold temperatures, namely 265°K & 235°K are chosen to represent convective clouds and deep convective clouds respectively. Using the three hourly observations, times of maximum and minimum convective activity are also obtained. Maximum convective activity is observed over head Bay of Bengal at about noon and this maximum migrates westward onto land till midnight and swings back to oceanic area by morning. This eastwest oscillation is less over equatorial regions (open ocean).

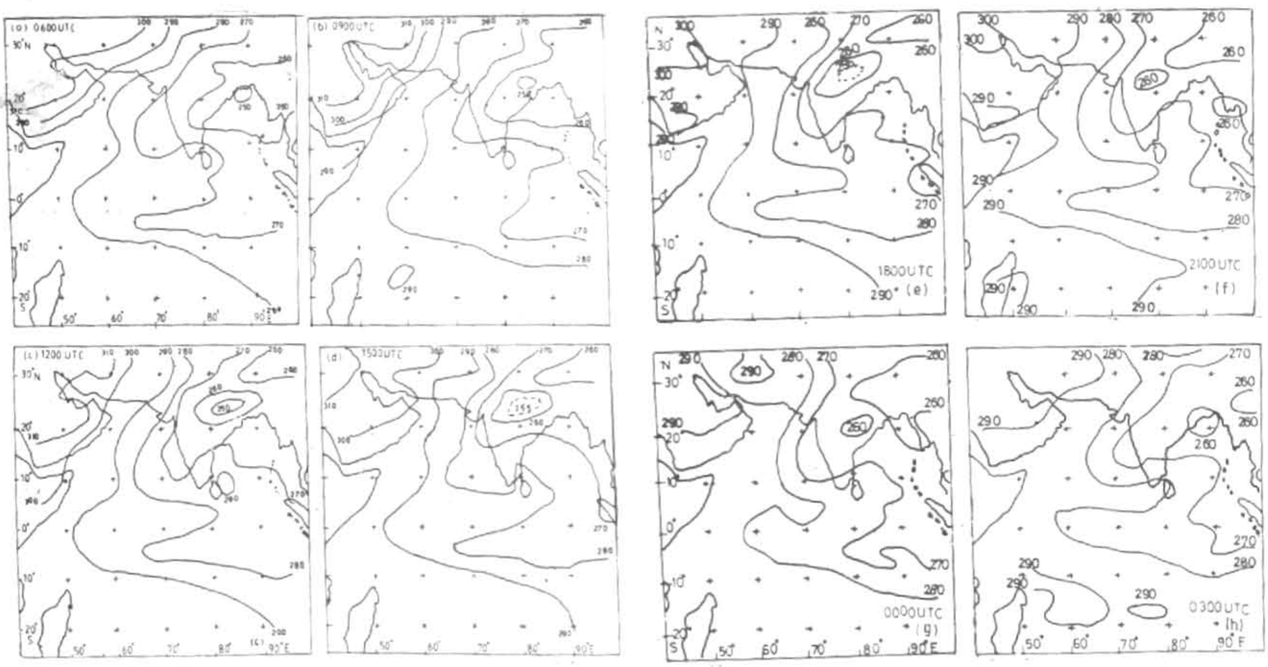
Nearly half of the convective clouds develop into deep convection over the north Bay of Bengal and Arabian Sea while the percentage is slightly less over the land near equatorial Indian Ocean.

Key words — Convective clouds, Diurnal variation, SW monsoon, Grey shade.

1. Introduction

1.1. Clouds are the visible manifestation of the atmospheric circulation. Changes in the large scale development, distribution and variation of cloudiness gives an insight into the changes in the large scale circulation patterns. While this is true everywhere, in general, the dominance of the convective precipitation in the tropical regions, makes it imperative to a tropical forecaster to have the knowledge of the distribution and variation of convective clouds in the region of his interest. Apart from the large scale changes, cloudiness particularly convective cloudiness, exhibits diurnal changes also. In the tropics the diurnal cycle, together with the large scale temporal variations accounts for most of the variation in the weather, including precipitation.

1.2. The important role played by the latent heat release during convective precipitation in acting as a forcing mechanism of large scale tropical and extratropical circulations is of interest of current research (Gill 1980, Weickmann *et al.* 1985). While the understanding of the relationship between the time mean circulation and condensational heating is getting better, the role of the transient part of the thermal forcing, which may be due to the diurnal cycle of the tropical convection, is not yet well understood. It is in this context that the study of the diurnal variation assumes



Figs. 1 (a-h). Mean temperature (°K) for July

importance for a numerical modeller while its knowledge places an operational forecaster in a better position to improve his forecasts. This is particularly useful, over oceanic areas where conventional observations are too scanty. The fishing and the oil exploration operations can beneficially be conducted if the diurnal variations of the hazardous weather associated with the convective activity is known. In this context the above information over oceans and coastal areas is of practical utility. With the availability of 3 hourly data from Indian National Satellite (INSAT), it is now possible to attempt a comprehensive study of the diurnal cycle that the tropical convective clouds exhibit.

1.3. Earlier studies attempted by the Indian scientists, on cloudiness variation are based on the twice daily polar orbital satellite observations and are confined to various case studies. Srinivasan (1968) studied the mean cloudiness pattern over Indian Ocean during southwest monsoon season and presented average cloud distribution during selected epochs of the monsoon. He concluded that the southwest monsoon field is not uniformly clouded but has zones of maximum or minimum cloudiness. Ramaswamy (1971) discussed the mean cloud distribution during the periods of late and normal onset of monsoon, break monsoon and early and late retreat of monsoon conditions. In their study, Bedi and Sikka (1971) related the 6-day mean brightness and 700 hPa mean flow pattern during different stages of the monsoon and found that the brightness maximum coincided with the stream line trough at 700 hPa or had a slightly southward shift and the brightness minimum coincided with the position of the sub-tropical ridge. Thiruvengadathan and Jambunathan (1971) calculated mean cloud cover over 2.5° grids over Arabian Sea for the monsoon season. They found a cloud maximum over northern parts of central Arabian Sea about 500-700 km away from the west coast and this maximum is restricted to north of 15° N during 'break monsoon' conditions while it extends to over entire west coast during normal or active monsoon conditions. Nene (1971) undertook a similar study for Bay of Bengal (for the monsoon season). His results indicated maximum cloudiness north of 10° N, particularly over Orissa-Bengal and Myanmar (Burma) coasts and the minimum between 6° and 9° N, with mean cloudiness to be lesser in August than in July. All these studies are related to the spatial variation of the total cloudiness and no attempts to distinguish convective clouds were made. It was also not possible to study diurnal cycle with twice daily observations.

1.4. This paper describes the diurnal variation of convective clouds in terms of fractional coverage of cold cloudiness in each area of 2.5×2.5 Lat./Long. over a three year period for monsoon season. In the following section, the data used and the methodology adopted are described. In section 3, the results are discussed. Section 4 summarises the results.

2. Data and method

2.1. *Data used*

2.1.1. The Very High Resolution Radiometer (VHRR) of INSAT-1 satellite operates in two channels, namely, VIS & IR. The resolution in these two channels are 2.75 km and 11 km respectively at the sub satellite point.

The IR sensor can discriminate temperature differences of 1°K of less. Though the satellite is capable of scanning a full earth disc image once in every 30 minutes, under normal circumstances, the data are received once in every 3 hours. The data at this frequency is considered to be adequate for this study as the average cloudiness over an area of 2.5° Lat./Long. is calculated and those averages are used.

2.1.2. The 3 hourly full resolution Infrared (IR) data of INSAT-1 for 3 monsoon seasons (Jun to Sep) for the years 1987-1989 were used to calculate the mean monthly patterns to study diurnal variations. The area considered extends from 35° N to 25° S and 40° E to 100° E, which covers the major portion of the monsoon regime. This area is further subdivided into smaller areas of 2.5° Lat./Long. called 'boxes' over which all the averages are attempted.

2.2. *Method*

Details of the method are described by Rao *et al.* (1989). The parameters used in this study are : (a) mean cloud top temperatures, and (b) fractional area covered by clouds colder than a given threshold temperature called 'fractional cloud cover' (Fc) in each area of 2.5° Lat./Long. boxes over the area mentioned above. Fractional cloud cover for two temperature thresholds (265° K & 235° K) were calculated. While the threshold temperature 265°K, represents all convection, 235° K temperature represents the deep convection during this season. It may be mentioned here that the measurement of cold cloud top temperature (threshold) does not preclude the existence of a warmer cloud layer underneath, as the satellite views the clouds only from above.

2.2.1. The steps involved in the calculation are given below :

(*i*) The grey shade value of each pixel in a box is read and is converted into its corresponding temperature by means of a look up table. Then this pixel is placed in a box appropriate to its position and in one of the classes of the predefined (all clouds whose top temperatures are below freezing level are divided into 15 classes and those with warmer tops are taken as one class) 16-class histogram (Table 1) by virtue of its temperature. At the same time, the average temperature of all the pixels in the box (mean temperature) is also calculated. The whole image is scanned and the histogram classes in each box are thus filled and the mean temperature of each box is also computed.

(*ii*) Step (*i*) is repeated for all the 8 images of the day, starting from 0000 UTC through 2100 UTC. This calculation is repeated for all the days in a month and for all the four months of the season (Jun to Sep) over the 3-year period.

(*iii*) Hourwise monthly mean temperatures of each 'box' are calculated using the data of the three years by calculating the average for each month for a given hour and by taking mean of the three months.

(*iv*) For a given hour, for each box, the frequencies of pixels in each class are accumulated over a given month, using daily values. Then the fractional cloud cover for that hour and for that box is calculated for a chosen threshold temperature using the definition :

$$\frac{\text{No. of pixels colder than the chosen threshold temperature}}{\text{Total number of pixels in that box}}$$

This yields us mean monthly fractional cloud cover for each box pertaining to each time and this is expressed in percentage.

(*v*) Using monthly values, the means for the three months are calculated over each box for all the 8 times separately.

Fractional cloud cover for two threshold temperatures, *i.e.*, 265° K & 235° K are calculated. The times of occurrence of maximum and minimum convection are also calculated. The ratio of convection between the two threshold temperatures is also computed to know the fraction of convection that develops into deep convection.

2.3. *Limitations*

At the threshold temperature of 235°K, there is possibility of cirrus contamination. It is presumed that since the spatial average is taken over the grid box, its effect is considerably reduced.

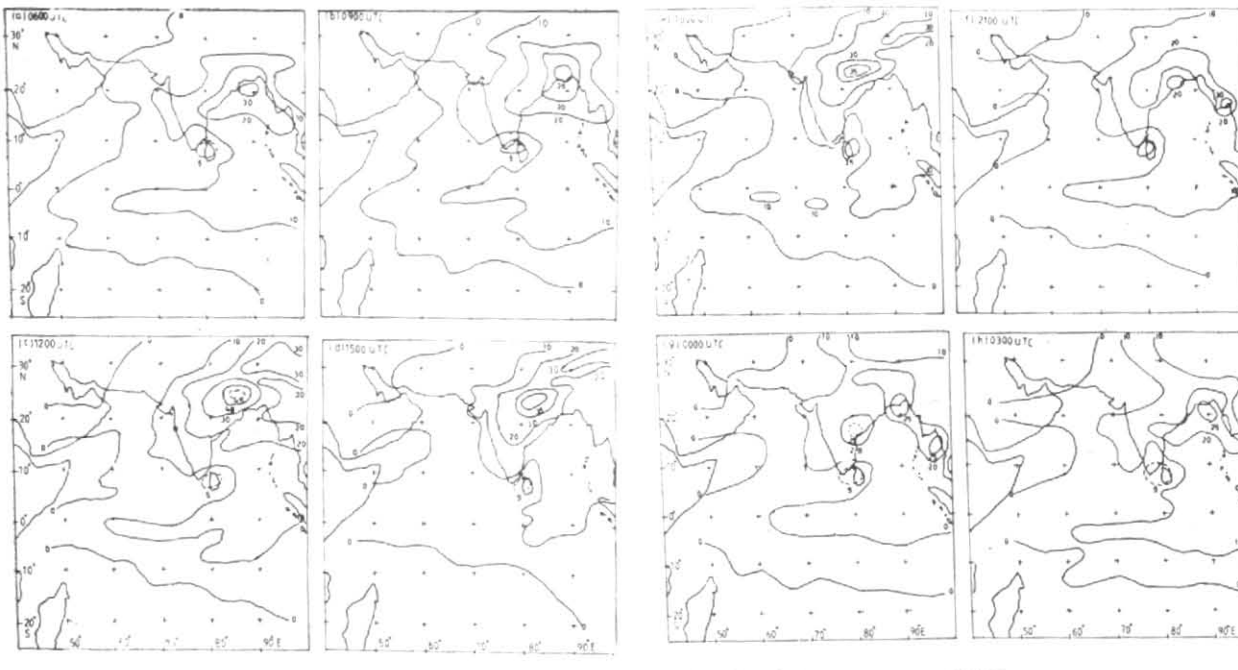
3. Discussion of results

3.1. *Mean temperature pattern*

From the IR data of the satellite, cloud top temperatures can be obtained as mentioned earlier. This in turn gives an idea of the height of the cloud tops, thus the mean temperature of a 'box' gives information of the mean height of the clouds in that 'box' at that hour, except in cloudless areas where naturally, the temperature shows the surface (land or ocean) radiative temperature. Since the information about the cloud height is derived from the temperature data, 'mean cloud height' means the average of the tops of the clouds prevailing in the given area and does not refer to the average of the base and top of the clouds. Though this gives an average height of the clouds, in that area, individual clouds may extend to still higher levels. The mean temperature patterns for the representative month, *i.e.*, July, are presented in Figs. 1 (a-h).

3.1.1. Lowest temperatures (indicated by 250° K isopleth) indicating maximum convection, are found at 0600 UTC over head Bay of Bengal with increasing temperature westwards and northwestwards This area of lowest temperature moves westwards inland upto 1800 UTC and swings back to head Bay of Bengal by 0300 UTC. This indicates that the convection is maximum over the oceans in the morning hours and this moves over to land as the day advances. Similar observations are made by Meisner and Arkin (1987). Rao and Raman (1958) while discussing the diurnal variations of rainfall, observed that the central India receives more than 50% of the daily rainfall during the night time, *i.e.*, between 1730 and 0830 IST. The migration of cloudiness maximum to the land during the night time is in agreement with the above observation.

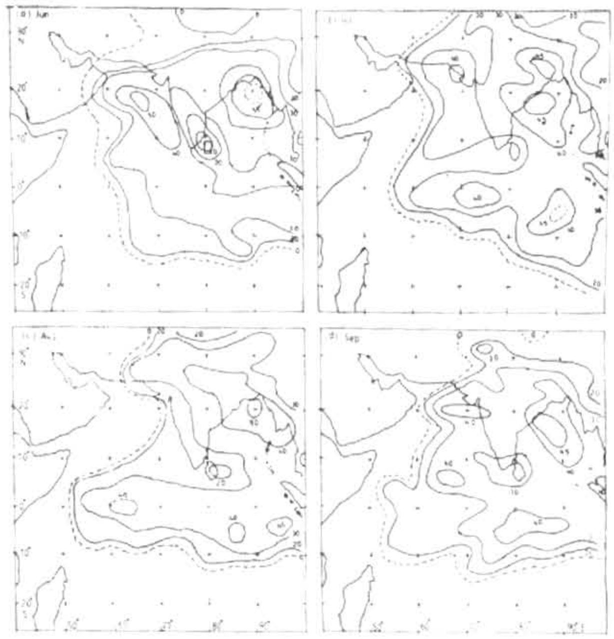
3.1.2. The pattern of mean temperature indicates an axis of minimum temperature extending from head Bay of Bengal to southeast Arabian Sea, through southern



Figs. 2 (a-h). Fractional cloudiness (%) for July (threshold temperature 235°K)

TABLE 1

Class	Temperature range (°K)
1	>270
2	270-266
3	265-261
4	260-256
5	255-251
6	250-246
7	245-241
8	240-236
9	235-231
10	230-226
11	225-221
12	220-216
13	215-211
14	210-201
15	200-190
16	<190

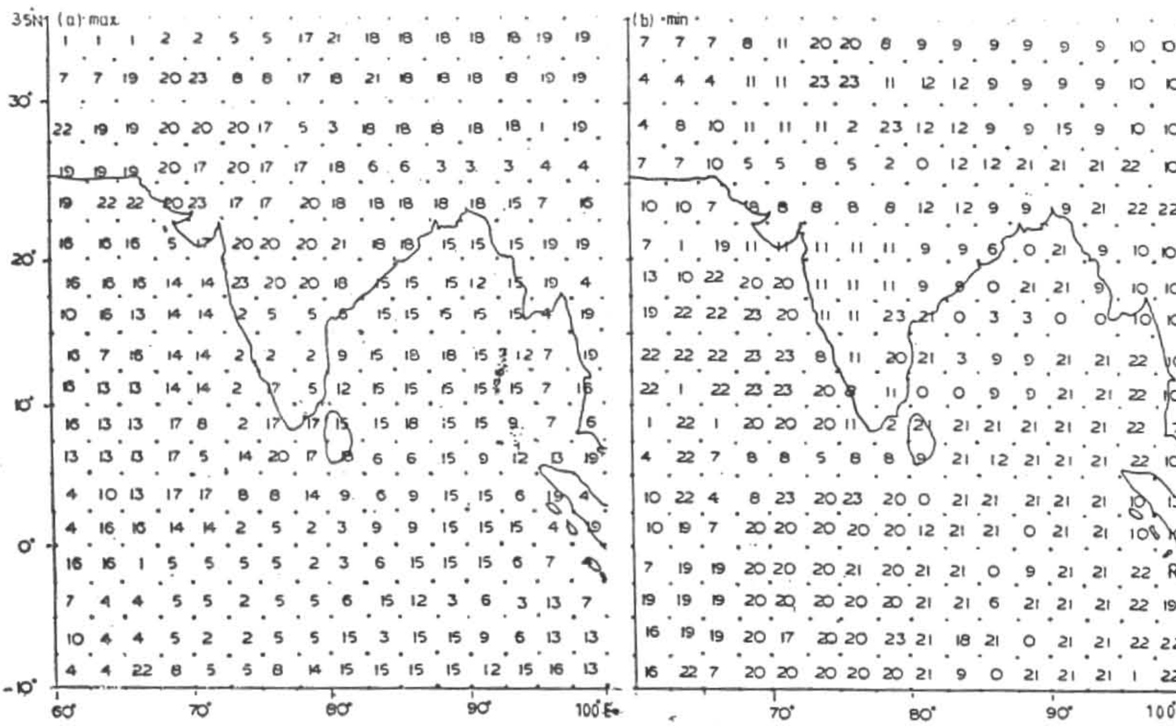


Figs. 3 (a-d). Ratio of 235°K and 265°K

peninsula and another east-west axis of minimum temperature is seen just south of the equator which coincides with the mean position of Southern Hemisphere Equatorial Trough (SHET). The diurnal variation of convection in the SHET region is small as indicated by the absence of large temperature changes.

3.1.3. Over southeast Peninsula and Sri Lanka, warm temperatures (>270° K) prevail, indicating that over this region low clouds, with tops below freezing level prevail which explains the receipt of less rainfall over the region during this season.

3.1.4. The temperatures over west Arabian Sea are warmer at all the hours. Since the temperature is a measure of the height of the clouds, warmer temperature means either very little cloudiness or the existence of clouds of small thickness like fair weather cumulus.



Figs. 4 (a-b). (a) Time of maximum convection for July — Local time (to nearest hour), and (b) time of minimum convection for July — Local time (to nearest hour)

3.1.5. South Indian Ocean south of 10°S experiences little cloudiness as indicated by warmer mean temperatures.

The mean patterns for the other three months are similar to those of July.

3.2. *Fractional cloudiness patterns*

3.2.1. As mentioned earlier Fractional Cloudiness (Fc) is calculated for two threshold temperatures, namely, 265°K and 235°K. Since the variation in both the threshold temperature patterns are similar, the patterns for the month of July for the threshold temperature 235°K are only presented. The patterns for the other months are also discussed.

3.2.2. *July pattern* — Figs. 2 (a-h) depict the mean pattern of fractional cloudiness for the month of July at all the eight synoptic hours of the day. Following points are noted :

(*i*) At 0600 UTC, the maximum lies over head Bay of Bengal, which starts moving towards the land as the day advances. Initially the maximum of convection moves northwards towards Bihar plateau by 1200 UTC with an increase in the maximum. In fact the whole pattern shows a westward shift towards the land with the advance of the day. Maximum westward shift of convection occurs over land at about midnight. The maximum starts shifting towards east after that time and the pattern swings back to its original position by 0600UTC. Along the west coast and over the land areas (especially north of 20°N) the convective activity increases towards midnight and decreases thereafter.

(*ii*) Another band of convective activity is seen roughly along 3°S, in the region of SHET. There does not seem to be much diurnal variation in this trough as seen by the position of 10% isopleth.

(*iii*) Convection is practically absent in the western Arabian Sea as indicated by the envelop of zero isopleth at all hours. It is minimum over southeast peninsula and adjoining Sri Lanka. Convective activity is also absent in the region of south of 10°S throughout this season.

(*iv*) Over the west coast, where heavy rainfall occurs only 10-15% of the area is covered by clouds whose tops are colder than 235°K, as indicated by the isopleths. This again suggests that practically all the rainfalls from warm top clouds only, over the region thus highlighting the importance of the orographic lifting in the rain processes.

(*v*) The diurnal variations in the monsoon trough region is more than in the near equatorial trough (SHET). This may be due to the fact that the latter lies always over a homogeneous surface.

3.2.3. The diurnal variation of convective activity shows similar variation in all the three months. However, the main differences which were observed are described below. The patterns are not presented for want of space.

3.2.3.1. *June* — Two maxima of convective activity are observed over east central Bay off Arakan coast and the other over southeast Arabian Sea off Kerala and Karnataka coast, with minimum cloudiness over southeast peninsula and Sri Lanka. While the maximum over east central Bay moves northwestwards to north Bay by 1500 UTC another maximum develops over east M.P. and adjoining Bihar. By midnight both the maxima coincide and extend westwards while the southeast Arabian Sea maximum moves closer to the coast. By 0000 UTC the land maximum decreases and the maximum activity zone is confined to the oceanic areas only, which moves towards Arakan coast by 0600 UTC. The maximum in the southeast Arabian Sea shifts westwards.

3.2.3.2. *August* — The diurnal cycle of convective activity is more or less similar to that in July during this month. The only difference is that the maximum of convective activity moves further westwards up to east Rajasthan during August. The diurnal oscillations cover more longitudes than those in July. Further, SHET occurs more towards north near about equator during this month with slight increase in the over all convective activity all along its location.

3.2.3.3. *September* — There is a general decrease in the convective activity during the month particularly so over northwest India and over the region west of 80°E and north of 20°N. The diurnal migration of convective activity maximum occurs in northnorthwest direction compared to westnorthwest direction during the earlier months of the season. Pattern of diurnal oscillation is similar. The activity in the SHET region is around 2°S and occurs more to the east with maximum occurring near Sumatra islands with little variation in its location during the day.

3.3. *Ratio of Fc between* 235 *and* 265°*K*

In order to know what fraction of convection becomes deep convection, in each box, a ratio of the fractional cloudiness between the two threshold temperatures, namely, 235° K and 265° K are computed. The Fc values are averaged over all hours for each month for the threshold temperatures and the mean ratio for the month is computed and the isopleths are drawn. The results are presented in Figs. 3 (a-d) for the month of June, July, August and September respectively.

3.3.1. *June* — About 55% of the clouds attain temperatures of 235°K or lower over north Bay of Bengal and about 50% attain similar temperature over central Arabian Sea. Over land, about 30% of the clouds attain these heights indicating only 30% of the total rainfall, during this month, over this region, is from deep convective clouds. Over Sri Lanka and adjoining Tamil Nadu the cloud top temperatures attained 235° K or less in less than 10% of the occasions. As the total cloudiness is itself very low over these regions, this can be interpreted that the clouds are mainly of warm top and do not extend to very high level. Over west coast, where the rainfall is very heavy, only 30% of the clouds attain the temperature 235° K or less indicating the importance of orographic lifting in causing heavy falls. Over SHET also the convection on majority of the occasions, does not extend to higher levels.

3.3.2. *July* — With the establishment of monsoon over most parts of the country by the beginning of July there is general increase of convective activity throughout the country. Maxima of 45% are located over west central Bay off Andhra coast and over Gangetic West Bengal and Bihar plateau. Minimum activity continues to prevail over Sri Lanka and adjoining southeast peninsula. In the SHET regions, the convective activity shows appreciable increase from June and over 40% of the area the convection becomes deep.

3.3.3. *August and September* — The pattern is not much different from that of July in August while it shows a marginal decrease in convective activity during September over northwest India. The deep convection shows an increase over Sri Lanka and adjoining areas from July to September. The activity in the SHET region remains more or less the same.

3.4. *Hours of maximum and minimum convective activity*

Though Fig. 1 gives a rough idea of the diurnal variation of deep convection, it is of interest to know the exact hours at which it is maximum and minimum over different areas. For the purpose, the fractional clouding was averaged for each month over the three years at every hour and the hour of maximum and minimum cloudiness is picked up. In Fig. 4, the hour of maximum and minimum convective activity is presented for the month of July.

The deep convection is maximum over head Bay of Bengal around noon, while it occurs 3 hours later in the central Bay of Bengal. Near the coastal regions early morning maximum is seen. Over land, north of 17° N the maximum occurs in the evening or early night while it occurs in the hilly regions of Assam and J & K near about 3 A.M. Along the west coast also the maximum convection, though small in percentage, occurs at about 2 A.M. In the Arabian Sea the maximum convection takes place over large areas in the afternoon. In the SHET region the maximum convection occurs in the early hours of the morning.

Time of occurrence of minimum convection also shows variation over Bay of Bengal. It occurs at about 8 P.M. over major portions of Bay of Bengal except over the central regions, where the minimum convection occurs near 8 A.M. Over the land between the 15° N and 25° N, the minimum convection occurs in the morning hours. Punjab, Haryana and Himachal Pradesh experience the minimum convection at about midnight. In the hilly areas of J & K and Assam the preferred time for minimum convection is at early night. Over Arabian Sea the minimum convection takes place between 8 and 11 P.M. In the SHET region (open ocean) the minimum occurs in the early night.

For the other months of the season (not shown), brief description of the occurrence of maximum and minimum convection is given below :

June

Over Bay of Bengal, the time of occurrence of maximum varies from south to north as the process of onset of monsoon is in progress during this month. In the southern portions of the Bay, the maximum occurs in the morning, while it occurs in the afternoon over central and head Bay of Bengal. Over the land, it is more uniform occurring in the early night over the region south of 25° N. Over the northern portions of this latitude the maximum occurs in the evening as this region is still unaffected by the monsoon current. Over Arabian Sea and west coast (hills), it occurs between late night and early morning. Over the region of SHET early morning maximum is observed.

Over south Bay of Bengal the minimum occurs at about 8 P.M., while it is at midnight over north Bay of Bengal. Over the central Bay, the preferred time is in the morning. The convection is minimum over the country south of 25° N in the morning, while early morning minimum occurs north of this region. Over Arabian Sea the minimum occurs around midnight. Over the SHET region the minimum convection occurs in the early night.

August

During this month, when the monsoon is at its peak, the time of occurrence of maximum convection is more uniform over all the regions of Bay except in the central parts of Bay of Bengal. The maximum occurs in the afternoon and that over central Bay occurs in the early morning. Over land the maximum convection occurs in the evening while it occurs 3 hours later over western India. Over south Peninsular India it occurs in the night. Afternoon maximum is also predominant over Arabian Sea. Over SHET region, there is an east to west variation in the time of occurrence of maximum convection. In the eastern parts it is in the afternoon while the preferred time is early morning in the central region of SHET.

The minimum convection is noticed before midnight over major parts of the Bay, while it occurs in the morning hours over central region. Minimum cloudiness occurs in the morning/night over land. Late night minimum occurs over Arabian Sea except in the north Arabian Sea where it occurs in the early morning. In the SHET region minimum occurs in the early night.

September

The time of maximum convection over the Bay in this month is in the afternoon, as in August. Over the central Bay it is in the early morning. Over the land the maximum occurs in the evening, occurring 3 hours later over western region. Over major portion of Arabian Sea, the maximum occurs in the afternoon or evening, except off the west coast where it is early in the morning. SHET convection shows east-west variation in this month also in its time of occurrence. Over the central parts it occurs in the afternoon while the western parts experience maximum, early in the morning.

The minimum occurs in the early night over Bay except over central parts where it occurs in the morning. Over the land the minimum is noticed in the morning. Over Arabian Sea, over large area the preferred time is around midnight. Minimum convection is noticed in the early night over SHET region.

The present observation is an apparent contradiction to the land/sea breeze theory which explains the occurrence of rainfall over land and sea purely by radiative argument as stated by Ramage (1971). But during monsoon season the present observation of about maximum/minimum convective clouds suggests that purely radiative processes are not the only dominating force but large scale dynamic effects may be important. It is possible that the head Bay of Bengal is a zone of large convergence during this season and this convergence may also show a diurnal variation attaining a maximum value at noon which may explain the observed maximum convective cloud development. Similar observations were made by Gruber (1976) and McGarry and Reed (1978).

4. Summary and conclusions

Two parameters, namely, the mean temperature and the fractional cloudiness colder than a given threshold temperature over each area of 2.5 × 2.5 Lat./Long. were used to study the diurnal variation of convection over India and neighbourhood. Two threshold temperatures, namely, 265° K (cloud tops about 6 km) and 235° K (cloud tops about 9-10 km) were selected to study the total convective and deep convective clouds. Mean values for each synoptic hour, over three monsoon seasons are calculated and the patterns were studied. Due to similarity of the patterns for all the monsoon months (except minor variations), those for July only are presented. The hours of maximum and minimum convection were also presented.

The following conclusions are drawn from the patterns of mean temperature and fractional cloudiness:

(*i*) The convection is maximum over the head Bay of Bengal around noon and this maximum exhibits east-west diurnal oscillation. Interestingly such migration of convection to this extent is not seen over open oceans as inferred from the small changes in the SHET region. This difference may be due to the interface of land and ocean near the north Bay of Bengal.

(*ii*) There is practically no convection over western Arabian Sea.

(*iii*) The convection is minimum over southeast Peninsular India and adjoining Sri Lanka and this region experiences less rainfall during this season.

(*iv*) Both the patterns of mean temperature and fractional cloudiness reveal that the deep convection is very less over the west coast. Occurrence of heavy rainfall during monsoon season, inspite of the absence of deep convection reveals the importance of orographic effects.

(*v*) About half of the convective clouds become deep over Bay of Bengal and Arabian Sea, while only 1/3 of the clouds attain such heights over land during June. Marginal increase in the deep convective activity is seen over land till August. Over equatorial regions the percentage of convective clouds becoming deep, increase with the advance of the season.

(*vi*) Noon time maximum and night minimum convection are noticed over the Bay and the Arabian Sea, while it is maximum in the evening/early night and minimum in the morning over land. The times of occurrence of maximum and minimum of the convection over the central parts of the Bay are different than over the rest of the Bay. The reason for this is not understood. Over the equatorial regions early morning maximum and late night minimum are observed.

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