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# Variability of surface fields in different branches of monsoon

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**सार** — टोगा सी० डी० - रॉम (1990) से प्राप्त एफ० एस० यू० आंकड़े और ई० सी० एम० डब्ल्यू० एफ० मॉडल द्वारा विश्लेषित आंकड़ों का प्रयोग करते हुए, 1985 और 1986 के सतही क्षेत्रों के लक्षणों, उदाहरणार्थ गुप्त प्रतिबल सूडोस्ट्रेस के अक्षांशीय एवं रेखांशिक (मेरीडियोनल) घटक, सतही दाब गुप्त एवं संवेध ऊष्मा फ्लक्स, समुद्र सतही तापमान (एस० एस० टी०) और वायु को तापमान का अध्ययन किया गया। सतही दाब और गुप्त ऊष्मा फ्लक्स में मानसून की तीन शाखाएं (*i*) अरब सागर, (*ii*) बंगाल की खाड़ी और (*iii*) दक्षिणी चीन सागर मे दृष्टिगोचर हुई। तथापि अन्य तीन सतही क्षेत्रों में मानसून की शाखाएं दिखाई नहीं देती।

दक्षिणी चीन सागर की शाखा की तुलना में अरब सागर और बंगाल की खाड़ी की शाखाएं, मानसून परिवर्तिता के साथ-साथ सतही क्षेत्रों के परिवर्तिता के प्रबल संकेत देती हैं। यह दृष्टिगोचर हुआ कि अरब सागर में गुप्त प्रतिबल (सूडोस्ट्रेस) और गुप्त ऊष्मा फलक्स अंतरण के प्रबल संकेत मिलते हैं जबकि बंगाल की खाड़ी में सतही दाब का मान निम्नतम है। मानसून की तीनों शाखाओं की तुलना में दक्षिणी हिन्द महासागर में सतही दाब में उल्लेखनीय परिवर्तिता देखी गई। बेहतर मानसून सक्रियता से संबंधित प्रमुख लक्षण है, मई से जून तक गुप्त ऊष्मा फलक्स में अचानक वृद्धि होने के अतिरिक्त गुप्त प्रतिबल की प्रबल धन प्रवणता, तथा 1985 में मानसून-पूर्व (मार्च से अप्रैल) वायुदाब में कमी (एस० एस० टी०) के अन्तरवार्षिक परिवर्तिता पूर्णतः स्पष्ट नहीं है, परन्तु तीनों शाखाओं में एस० एस० टी० की विभिन्नताएं उल्लेखनीय हैं।

**ABSTRACT.** Characteristics of the surface fields, such as zonal and meridional components of pseudostress, surface pressure, latent and sensible heat fluxes, sea surface temperature (SST) and air temperature for the years 1985 and 1986, are studied using ECMWF model-analysed data and FSU data obtained from TOGA CD-ROM (1990). Three branches of monsoon, *viz.,* (*i*) Arabian Sea; (*ii*) Bay of Bengal and (*iii*) South China Sea are observed in pseudostress, surface pressure and latent heat flux. However, the other three surface fields do not reflect the branching phenomenon.

The Arabian Sea and Bay of Bengal branches depict strong signals of variability in the surface fields in association with the monsoon variability compared to the south China Sea branch. Arabian Sea branch is observed to have the strongest signals in the pseudostress and latent heat flux transfer whereas surface pressure is having the lowest value over the Bay of Bengal. Southern Indian Ocean shows significant variability in surface pressure in comparison to the three branches of monsoon. Strong positive gradient of pseudostress in association with sudden increase of latent heat flux from May to June, and the pre-monsoonal pressure drop (March to April) in 1985 are the most prominent features associated with better monsoon activity. Interannual variability in sea surface temperature (SST) is not well marked but differences in SST amongst the three branches are significant.

**Key words** — Variability, Surface fields, Pseudostress, Pressure gradient, Trade wind, Cross-equatorial flow, Meridional circulation, Branching phenomenon.

## 1. Introduction

The variability of the Indian monsoon rainfall is well documented, but not much work has been done on the interannual variability of the monsoon circulation and surface features such as wind stress, sensible and latent heat fluxes and surface pressure over the Indian seas. During the last decade, the internannual variability of surface fields over the Indian Ocean and tropical Pacific have been studied by Wylie and Hinton (1982), Fu *et al.* (1983), Cadet and Diehl (1984), Meehl (1987) and Mohanty and Ramesh (1993). The results of these studies are very encouraging. Wylie and Hinton (1982) analysed the wind stress pattern over Indian Ocean using 1979 FGGE data. They found that a possible phase oscillation exists between the two hemispheres, the strengthening of the southern hemisphere trade occurs when the Somali jet weakens and *vice-versa.* Using 110 years of surface marine data over Indian and west Pacific region, Fu *et al.* (1983) revealed an important feature of monsoon circulation. They showed that the monsoon current coming from the southern hemisphere has three branches : (1) Arabian Sea; (2) Bay of Bengal and (3) South China Sea. Each of these branches has its own characteristics and is distinct from the other, and influences the rainfall in south Asia. Cadet and Diehl (1984) studied the interannual variability of surface fields over the Indian Ocean and showed that weaker trade winds in Southern Hemisphere and stronger zonal wind along the east African coast, weaker than normal cross equatorial flow and high SST are associated with weak monsoon



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activity, whereas, almost a reverse trend occurs in case of good monsoon years. Meehl (1987) analysed the SST, surface pressure and precipitation and suggested that processes in the Indian-Pacific region are continually evolving from one cycle to the next and are part of the dynamically-coupled ocean-atmosphere system. Recent study by Mohanty and Ramesh (1993) showed that wind field exhibits distinct characteristics over the Indian seas in contrasting monsoon years. However, SST and sea level pressure (SLP) do not show any significant variability over the Indian seas but variability is observed over Southern Hemisphere in association with the monsoon activity over India.

Few sensitivity studies have been reported which indicate any relation between the behaviour of the wind field over the Arabian Sea and the monsoon rainfall over India (Krishnamurti *et al.* 1976). Meehl (1989) compared the coupled model simulated results for the period June-August with the observed ECMWF wind field (1979-1986) and found that the coupled model simulates weaker south westerlies and SST over the Arabian Sea than the observed ones. As a result, the precipitation belt shifts southwestwards in case of the model simulation, whereas, the observed rainfall is more over the Indian continent. The interannual variability of monsoon rainfall over India and its relation with SST have also been well documented, both from observed studies (Mooley & Shukla 1987) and sensitivity studies (Fennessy& Shukla 1988 and Rao & Goswami 1988).

There is an indication of eastward propagation of the anomaly fields (Barnett 1984, Yasunari 1987) from Indian Ocean towards eastern Pacific along the equator and southern tropics. This eastward propagation originates over the Indian monsoon region during northern summer and shifts southeastward in the course of seasonal march from northern summer to winter (Meehl 1987) and is believed to be driven by the release of latent heat associated with precipitation anomalies that are phase-locked to wind anomalies. Emanuel (1987) argued that the source of energy maintaining the eastward propagating Kelvin waves comes from air-sea interaction and gave a conceptual model of the Evaporation-Wind (E-W) feed back.

The main objectives of this study are :

(*i*) to examine the surface fields, such as, pseudostress (*u* and *v* components), surface pressure, latent heat flux, sensible heat flux, SST and air temperature and to identify the fields which reflect branching phenomenon from their distinct characteristics; and

(*ii*) to look into the variability of surface fields over the three different branching regions in association with the monsoon variability over India.

## 2. Data

The data used in this study are obtained from TOGA CD-ROM (1990) which contains data on various surface fields, such as, *x* and *y* components of wind and wind stress, surface air pressure, latent and sensible heat fluxes, SST, air temperature etc. TOGA CD-ROM also provides 12-year (1977-88) monthly mean climatological pseudostress field and the monthly mean fields for 1985 and 1986 over the Indian and Pacific Ocean analysed by Florida State University (FSU) at a resolution of 1° × 1°.

The zonal and meridional components of the pseudostress are computed from the daily wind fields of ECMWF given at a grid mesh of 2.5° and then monthly means are calculated. These are analysed in comparison with the monthly mean fields of FSU in 1985 and 1986. The anomalies of pseudostress from the 12-year mean climatology of FSU are also computed. Monthly mean fields of surface pressure, latent heat and sensible heat fluxes, SST and air temperature are analysed at a grid mesh of 2.5° from the daily ECMWF model-analysed data. Model-analysed ECMWF pressure fields are compared with the UKMO observed ship data which show very good coherence.

The rainfall data for 32 sub-divisions of India have been collected for the period 1985 and 1986 from Weekly Weather Reports (WWR) published by the India Meteorological Department.

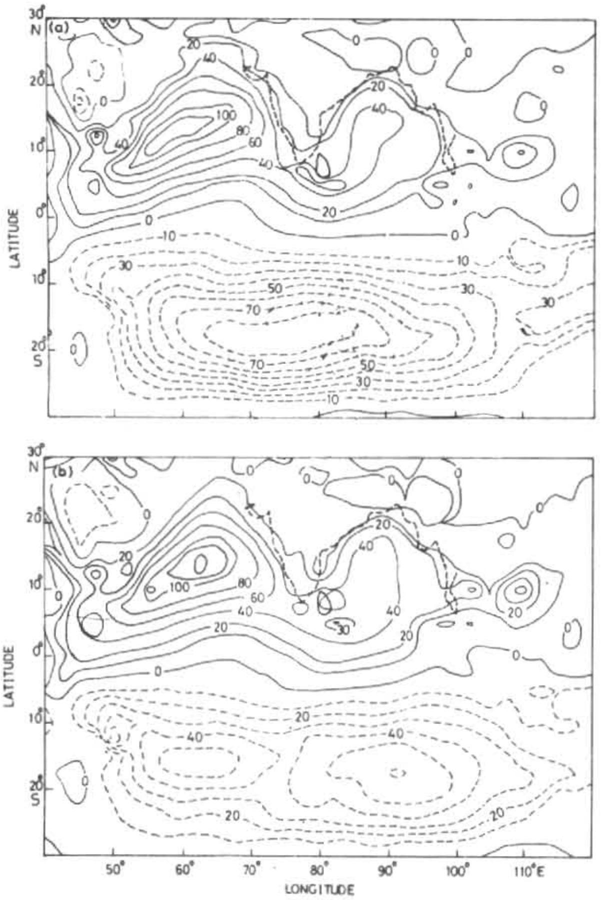
## 3. Results and discussion

The results are presented in two parts; (*i*) the branching phenomenon, and (*ii*) the variability of the surface fields during 1985 and 1986.

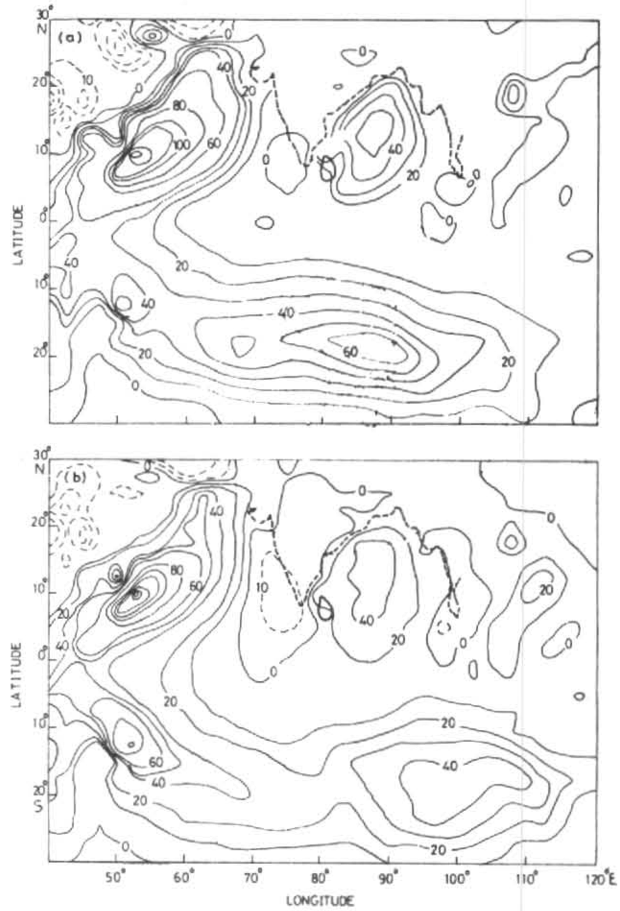
### 3.1. *Branching phenomenon*

The tropical oceans, particularly the Indian and Pacific Oceans, play an important role in the monsoon circulation. They serve as the reservoirs of enormous heat which drive the monsoon circulation and the differential heating between land and sea also influences the circulation features to a greater extent.

In this paper, we have analysed six surface fields such as, pseudostress, surface pressure, latent and sensible heat fluxes, SST and air temperature at 2 m height in order to examine the signals of branching phenomenon. Pseudostress, latent heat flux and




Figs. 1 (a & b). Zonal components of pseudostress ($m^2/s^2$) in July: (a) 1985 and (b) 1986



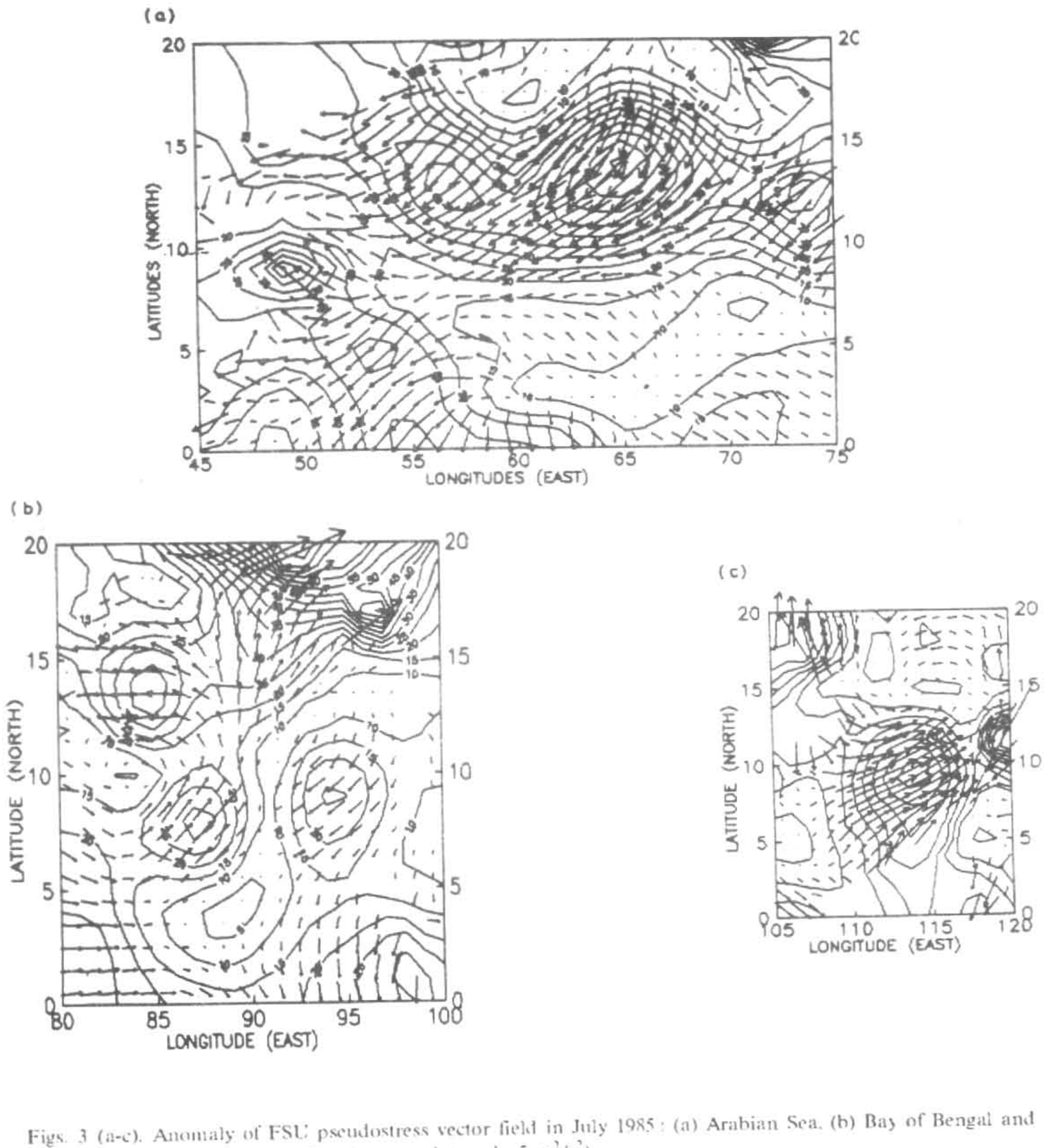

Figs. 2 (a & b). Meridional components of pseudostress ($m^2/s^2$) in July: (a) 1985 and (b) 1986

surface pressure give clear signals of the three branches which are discussed below. However, the other three fields do not reflect the branching phenomenon.

3.1.1. *Pseudostress* — Fig. 1 shows the zonal component of the pseudostress during 1985 and 1986. In both the years there are three regions of strong westerlies over the west Arabian Sea, Bay of Bengal and south China Sea. The intensities decrease from west to east. Meridional component of pseudostress also exhibits three regions of strong southerlies for both the years with intensity decreasing from west to east Figs. 2 (a & b). The maximum pseudostress over west Arabian Sea decreases from 180 $m^2/s^2$ in 1985 to 160 $m^2/s^2$ in 1986 followed by Bay of Bengal and south China Sea. The meridional components in all the three branches are dominant compared to the zonal components. The three regions of maxima seen in 1985 and 1986 are in agreement with the branching phenomenon of the southwest monsoon described by Fu *et al.* (1983).

Figs. 3 (a-c) shows the anomaly (1985-climatology) FSU pseudostress vector fields for 1985 July over the three regions, *viz.*, Arabian Sea (0°-20°N, 50°-70°E), Bay of Bengal (0°-20°N, 80°-100°E) and south China Sea (0°-20°N, 105°-120°E) and Figs. 4 (a-c) shows the anomaly (1986-climatology) fields for 1986 July. Comparison of these two figures brings out the difference in circulation over the three regions. In both 1985 and 1986 July over Arabian Sea [Figs. 3(a) & 4(a)], generally, there is weakening of the southwesterlies except over the north Arabian Sea in 1986 where the flow is seen to strengthen. Over Bay of Bengal, there are positive anomalies in the southwesterlies in both 1985 and 1986 [Figs. 3(b) & 4(b)] except over east central Bay of Bengal in 1985 where there is weakening of southwesterlies. Over the southern Bay the anomaly is stronger in 1986 than in 1985. In case of south China Sea in both 1985 and 1986, the anomaly patterns are similar except near the equator in the east where the wind weakens in 1985 and strengthens in 1986.

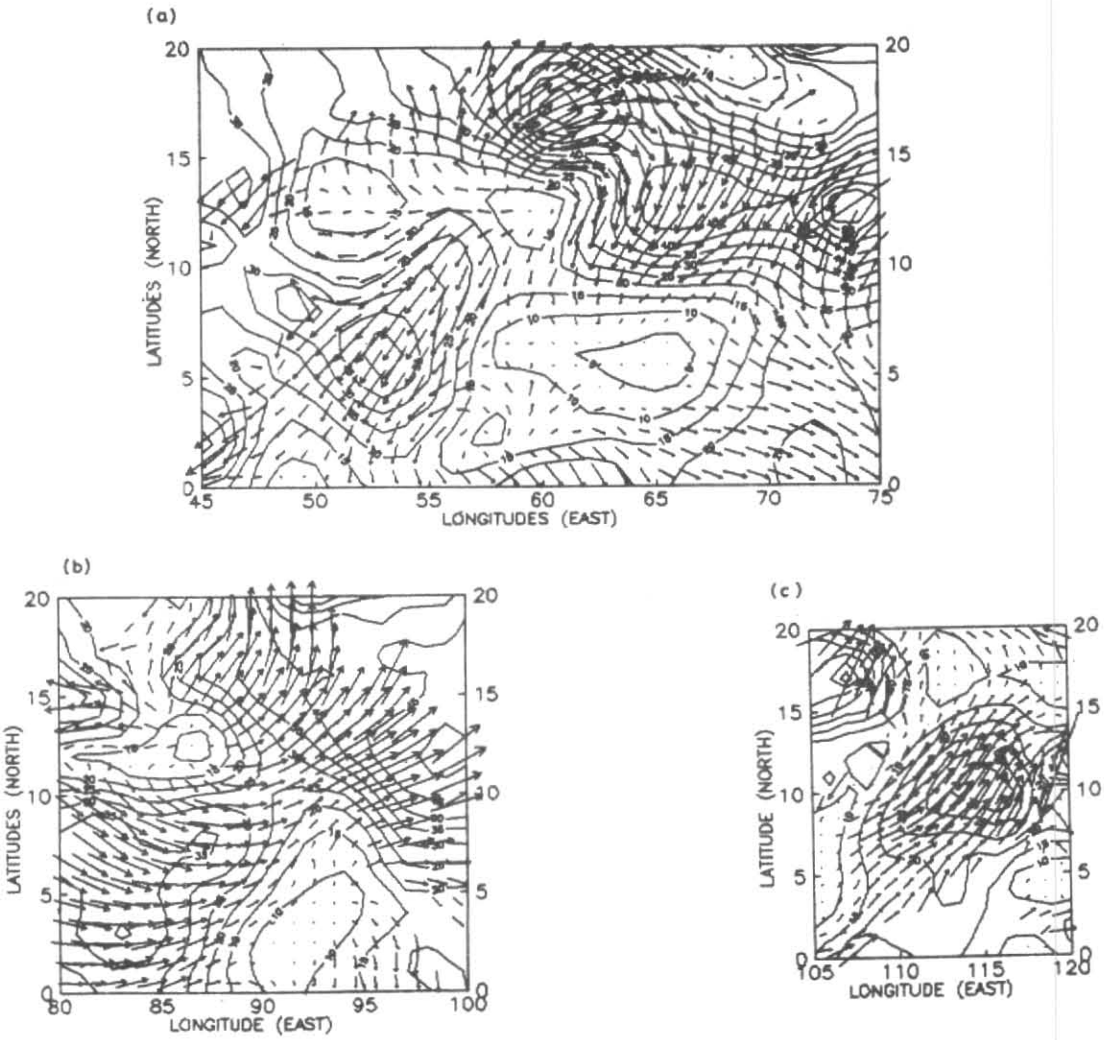
The branching phenomenon is also reflected in the cross-equatorial flow (Fig. 5). The flow entering the northern hemisphere during summer monsoon months is concentrated at three regions at about 45°-55°E, 80°-90°E and 100°-120°E; corresponding




Figs. 3 (a-c). Anomaly of FSU pseudostress vector field in July 1985 : (a) Arabian Sea, (b) Bay of Bengal and (c) South China Sea (contour interval : 5 $m^2/s^2$)

to the three branches of the monsoon. However, the peaks of the flow are at 50°E, 80°E and 105°E. While the region of peak flow in Arabian Sea agrees with that of Fu *et al.* (1983), in Bay of Bengal and south China Sea branch, it shifts about 5° towards west. The flow entering the Southern Hemisphere at the same region as that of northerly flow is also observed during December-February but with lesser intensity. Thus, the branching phenomenon is also reflected in the northeast monsoon. Stronger cross-equatorial flow is also observed over Arabian Sea branch and it weakens over Bay of Bengal and south China Sea branch (Cadet & Diehl 1984).

Figs. 6 (a-c) shows the duration and intensity of the southwest and northeast monsoon over the three different regions. The duration of southwest monsoon is maximum (March-October) over Bay of Bengal but the intensity is maximum (120 $m^2/s^2$) over Arabian Sea. In both Arabian Sea and Bay of Bengal the southwest monsoon is stronger than the northeast monsoon. However, the winter monsoon




Figs. 4 (a-c). Same as in Fig. 3 but for July 1986 (contour interval : 5 $m^2/s^2$)

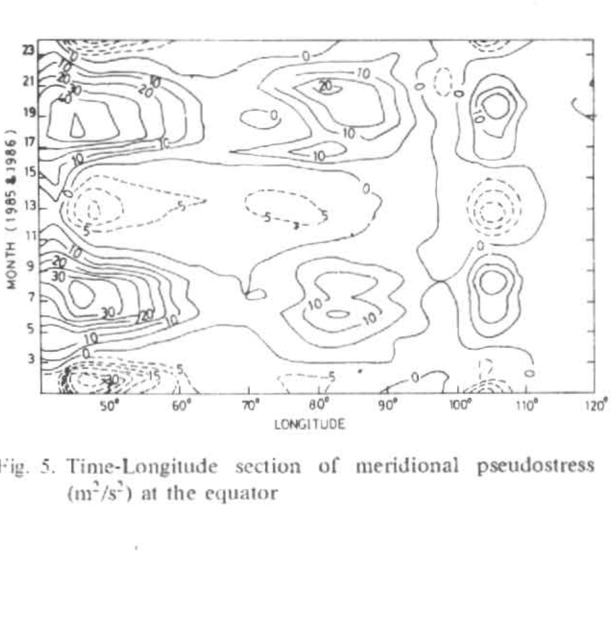
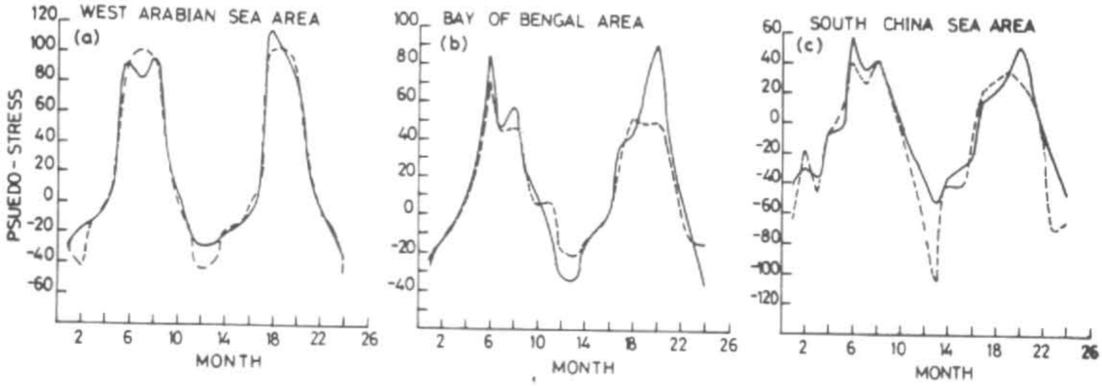


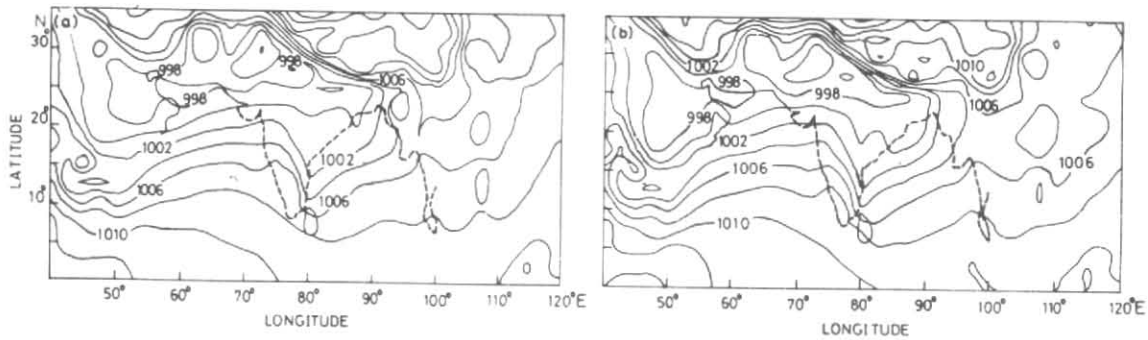

Fig. 5. Time-Longitude section of meridional pseudostress ($m^2/s^2$) at the equator

over Arabian Sea and Bay of Bengal is weaker than that over south China Sea (110 $m^2/s^2$). The duration of the winter monsoon is also maximum over the south China Sea (October-April). Thus, the summer monsoon is intense over Arabian Sea and most active over Bay of Bengal but winter monsoon is most active in the south China Sea.

3.1.2. *Surface pressure* — The branching phenomenon is also reflected in the surface pressure field. There are three distinct troughs observed at the southern edge of the monsoon low [Figs. 7 (a & b)] located at the east coasts of the continents. These results agree with that of Fu *et al.* (1983) and indicate the influence of heating due to land and sea. The




Figs. 6 (a-c). Area-averaged pseudostress ($m^2/s^2$) for: (a) Arabian Sea (0°-20°N, 50°-70°E), (b) Bay of Bengal (0°-20°N, 80°-100°E), and (c) south China Sea (0°-20°N, 105°-120°E) (Solid lines: Zonal components of pseudostress, Dashed lines: Meridional components of pseudostress)



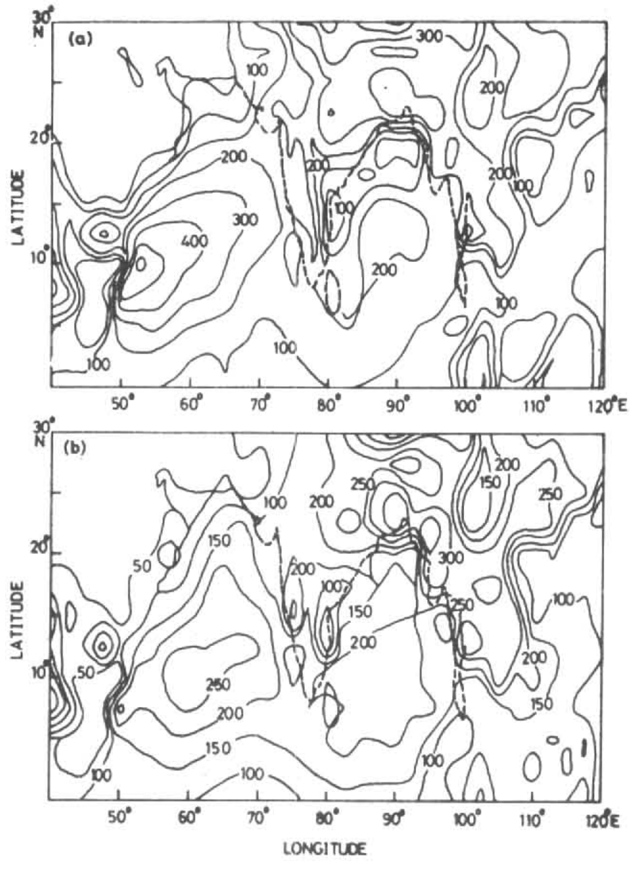

Figs. 7 (a & b). Average surface pressure (hPa) in July: (a) 1985, and (b) 1986 (contour interval: 2 hPa)

wavelength of the pressure wave is observed to be around 30° longitudes and is close to the wavelength (20° longitudes) of moving Rossby wave in middle latitudes (Fu *et al.* 1983). However, these quasi-stationary waves are much shorter than their counterpart in middle latitudes (120°-180° longitude). Three high pressure centres are also located in the extreme northern part during northern winter, positioning themselves around 45°E, 80°E and 110°E. Therefore, the branching phenomenon of winter monsoon is also reflected in the pressure field. Tilting of the position of troughs and ridges takes place in the zonal direction with the advance of the season. The pressure centre over Arabian Sea branch moves westward and that over south China Sea moves eastward, but the troughs over the Bay of Bengal branch remain stationary. This shifting may be attributed to the seasonal land-sea heating contrast. During winter monsoon the high pressure centre is stronger over south China Sea (1027 hPa) and it weakens towards Arabian Sea branch (1019 hPa). Thus, the distinct behaviour of the three branches is also evident from the pressure field.

3.1.3. *Latent heat flux* — Latent heat transfer is observed to be concentrated over the three regions Figs. 8 (a & b), *viz.*, (1) Arabian sea, (2) Bay of Bengal and (3) south China Sea and it confirms to the branching phenomenon of the southwest monsoon as observed in case of pseudostress and surface pressure. The maximum heat loss occurs over the Arabian Sea branch, concentrated at a zone in the southwest Arabian Sea. The heat loss over Bay of Bengal and south China Sea reduces significantly as compared to Arabian Sea. However, flux transfer during winter monsoon does not show centres of maximum transfer zones. Thus, the branching phenomenon is not reflected in the latent heat flux transfer in winter.

3.2. *Variability of surface fields*

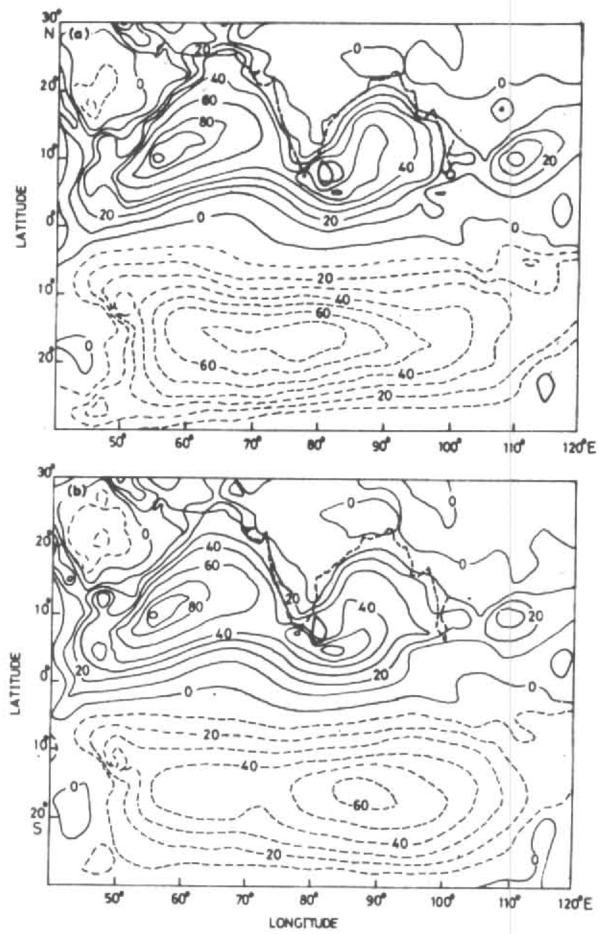
Variability of surface fields during 1985 and 1986 is discussed in relation to the variability in monsoon rainfall over India. The area-weighted rainfall data from June to September, over 32 sub-divisions in India, are used for the purpose. During 1985,




Figs. 8 (a & b). Average latent heat flux (W/m$^2$) in July: (a) 1985, and (b) 1986

8 sub-divisions had more than normal rainfall and during 1986 more than normal rainfall was observed in 3 sub-divisions only. The seasonal (June-September) rainfall was 794 mm in 1985 and 740 mm in 1986 (Thapliyal 1990). Thus, 1985 was a better monsoon year than 1986, although not very contrasting in rainfall. However, definite signals of variability are observed from the characteristics of the surface fields as discussed below.

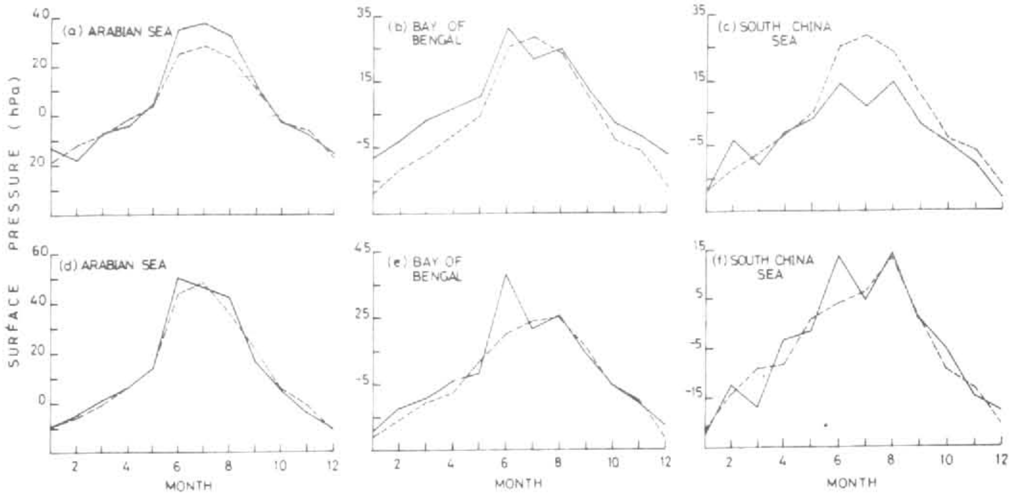
3.2.1. *Pseudostress* — Seasonal averages (June-September) of the zonal components of pseudostress for the years 1985 and 1986 are depicted in Figs. 9 (a & b). In 1985, the easterlies in the Southern Hemisphere are stronger than those in 1986. The Somali jet is also slightly stronger in 1985 than in 1986. The difference of easterlies in the Southern Hemisphere is significant and this emphasises that strengthening of Southern Hemisphere trade is associated with a better monsoon. During pre-monsoon months easterlies over the Arabian Sea in 1985 are slightly stronger than those in 1986 [Figs. 10 (a-f)] and the reverse trend is observed during post-monsoon months (October-December). Over the Bay of Bengal, again a higher monsoonal average is seen in 1985 than in 1986 [Figs. 9 (a & b)]



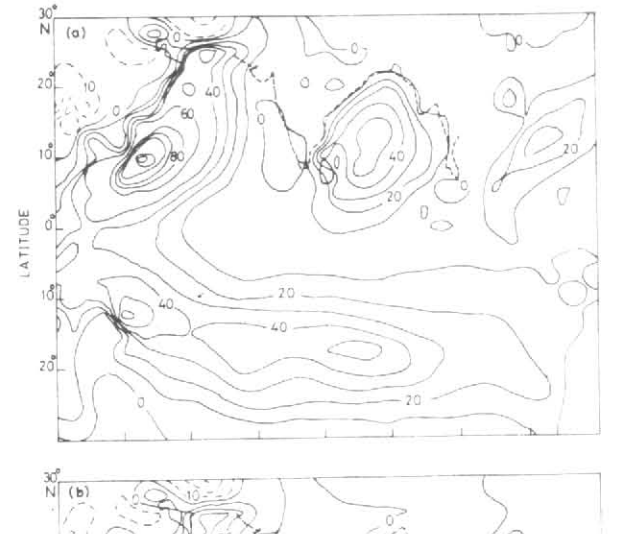

Figs. 9 (a & b). June-September zonal pseudostress (m$^2$/s$^2$): (a) 1985, and (b) 1986

and it is mainly due to the large positive difference in June during 1985. Almost the same trend is observed over the south China Sea also. The easterlies in winter over the Arabian Sea and Bay of Bengal are stronger in 1985 than in 1986. It is, however, irregular in nature over the south China Sea. The variability in easterlies is relatively less as compared to the westerlies.

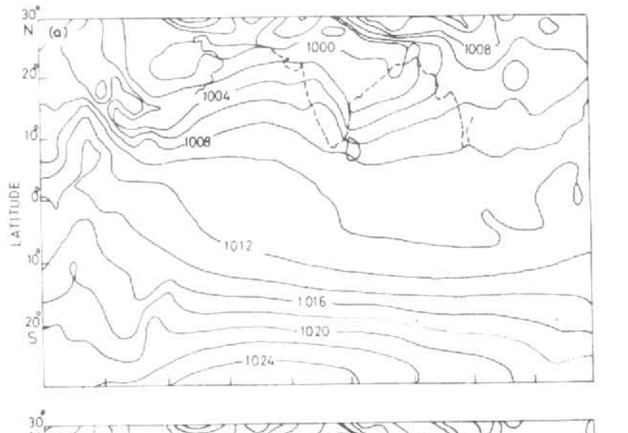
Considering [Figs. 11 (a & b)], it is observed that meridional component during monsoon months (June-September) is stronger in all the branches in 1985 than in 1986. In Bay of Bengal it remains dominant throughout 1985 except in July and May where a little lower values are observed as compared to July 1986 [Fig. 10 (b)]. But in south China Sea, the meridional component is predominant in 1986 [Fig. 10 (c)] except in February. In Arabian Sea, however, a higher value of meridional pseudostress is observed during pre-monsoon months in 1986 and the reverse trend is observed in the subsequent months. Thus, the three branches behave differently as regards to pseudostress.



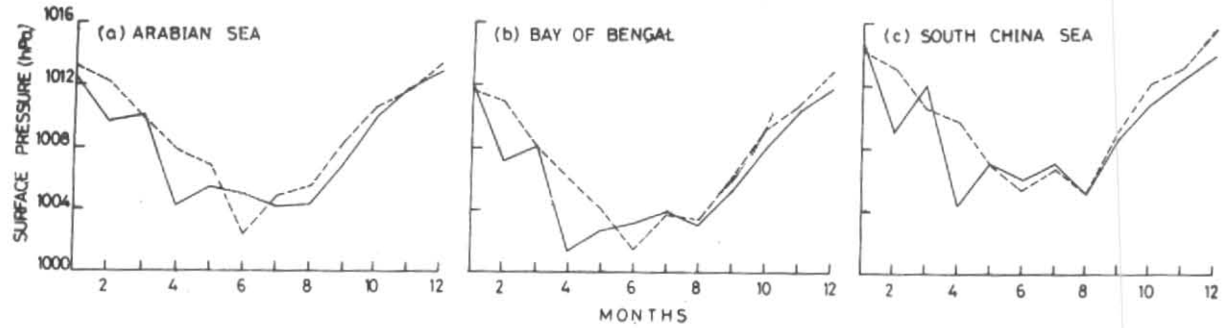

Figs. 10 (a-f). (a-c) Monthly meridional and (d-f) zonal components of pseudostress ($m^2/s^2$) during 1985 (solid line) and 1986 (dashed line) over three branches of monsoon




Figs. 11 (a & b). June-September meridional pseudostress ($m^2/s^2$) : (a) 1985 and (b) 1986




Figs. 12 (a & b). June-September surface pressure (hPa) : (a) 1985 and (b) 1986 (contour interval : 2 hPa)




Figs. 13 (a-c). Monthly average surface pressure in hPa during 1985 (solid line) and 1986 (dashed line) over three branches of monsoon

Considering the cross-equatorial flow (Fig. 5), it is observed that the flow into the Northern Hemisphere is more by 20 $M^2/S^2$ in 1986 than in 1985 over the Arabian Sea region (around 45°E). The cross-equatorial flow, however, does not show significant variability over Bay of Bengal (around 80°E) and south China Sea (around 105°E). Over Arabian Sea and Bay of Bengal, westerlies strengthen from 1985 to 1986, whereas, over south China Sea, it remains almost the same (Fig. 5). But in case of meridional component, southerlies decrease in strength from 1985 to 1986 over the Bay of Bengal and south China Sea.

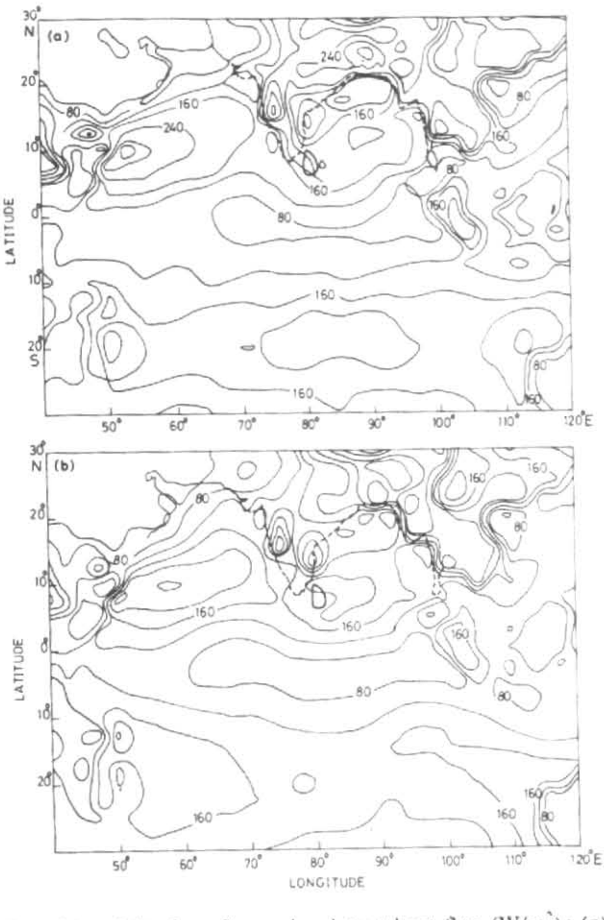
A strong gradient is observed from May to June in zonal as well as meridional components over all the three branches [Figs. 10 (a-f)]. The gradient is more in 1985 than in 1986. The highest is observed over Arabian Sea (38 $m^2/s^2$) and decreases towards south China sea. Surface meridional wind dominates over the zonal component and shows higher variability as compared to the zonal component and agrees with the results of Mohanty & Ramesh (1993). This indicates that the meridional component has a better correlation with Indian monsoon than zonal component and this correlation is positive in nature. The same trends are also observed in case of Somali jet and Southern Hemisphere trades. The latter accumulates and pumps enormous amount of water vapour into the north Indian Ocean, resulting in more precipitation in 1985 than 1986. Results of this study agree with Cadet and Reverdin (1981) who showed that 70% of water vapour that crosses the western coast of India originates from Southern Hemisphere and the rest 30% comes from evaporation over the Arabian Sea.

Considering the three branching regions, it is observed that the variability is maximum in Arabian Sea branch and is little less in Bay of Bengal. However, very little variability is observed in case of south China Sea branch. This may be attributed to the fact that Arabian Sea and Bay of Bengal are to the west of the Indonesian region, which has been considered as the most energetic region in the tropics (Walker cell). Webster (1981) showed that wind anomalies on the western side of the source are stronger than those on the eastern side.

3.2.2. *Surface pressure* — Seasonal pressure averages are presented in Figs. 12 (a & b) which indicate that surface pressure does not show marked variability in the northern Indian Ocean but variability is observed in the southern hemispheric surface pressure. Pressure is relatively high in the southern Indian Ocean (50°-80°E) in 1985 than in 1986, which results in creating more inter-hemispheric pressure gradient in 1985. However, stronger cross-equatorial flow is observed around 50°E (Figs. 5 & 11) and with higher intensity during 1986.

The pressure over the three branches is consistently low in 1985 than in 1986 [Figs. 13 (a-c)] except in June and July over Bay of Bengal and south China Sea and in June over Arabian Sea. It is interesting to observe that during weak monsoon year of 1986, the summer minimum of surface pressure in June rises suddenly in July creating a strong gradient which is not the case in 1985. More intense lows are observed over Bay of Bengal as compared to Arabian Sea and south China Sea during 1985. Another significant feature of pressure field is the rapid fall of pressure from March to April in a good monsoon year. Thus a rapid fall in surface pressure during the pre-monsoon months of March and April indicates the advance of a good monsoon, while a sudden rise in the surface pressure over Indian seas during early months of monsoon (June and July) is associated with a bad monsoon.

From the mean monthly pressure fields for the two years, it is observed that the eastward propagating mode is dominant only over the southern



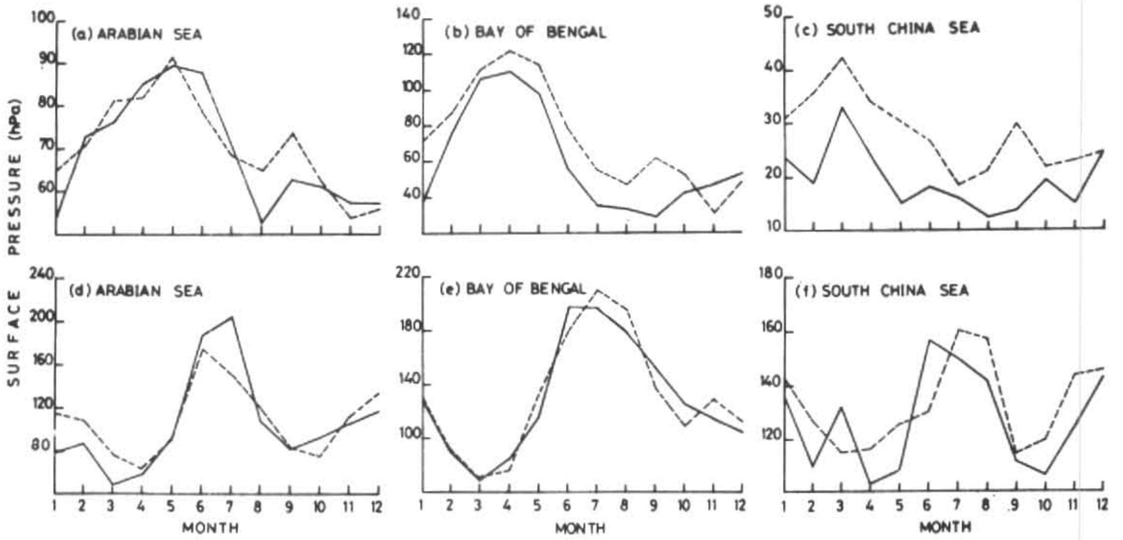

Figs. 14 (a & b). June-September latent heat flux ($W/m^2$) : (a) 1985 and (b) 1986

Indian Ocean, however, its time of evolution is difficult to predict. The propagation starts little earlier in 1985 than in 1986 and the intensity of pressure is towards lower side in pre-monsoon months of 1985 than in 1986. The zonal gradient starts strengthening around December and continues upto April when the meridional gradient is weak. The reverse trend is observed from May onwards and continues till September. Thus, the inverse coupling of the zonal and meridional circulation (Barnett 1984) is observed.

3.2.3. *Latent and sensible heat fluxes* — The latent heat transfer during the monsoon months (June-September) is dominant in the southwestern sector of the Arabian Sea [Figs. 14 (a & b)] in 1985 (360 $W/m^2$) as compared to 1986 (240 $W/m^2$) and may be attributed to stronger Somali jet. However, other two branches do not show significant variability between 1985 and 1985. It is also observed that the latent heat transfer in the Southern Hemisphere trade wind region is relatively more in 1985 than in 1986 and may be due to the stronger southern hemisphere trade wind during 1985. Figs. 15 (d-f) show that the latent heat transfer over Arabian Sea during pre-monsoon months is less in 1985 than in 1986 and the reverse trend is observed during monsoon months. Thus, the role of wind stress in controlling the latent heat transfer is clearly evident. Over Bay of Bengal and south China Sea, the flux transfer is more during monsoon months in 1986. During the post-monsoon period the south China Sea branch behaves differently from the other two, having a secondary maximum in the month of December which may be associated with the notion given by Meehl (1987), which says that the condition of strong convection over India and southeast Asia during summer monsoon persists over the Indonesian maritime continent and Australian monsoon region in the succeeding autumn. The interesting feature observed in the latent heat flux transfer is the sudden increase of heat flux from May to June establishing a higher positive gradient in 1985 than in 1986.

Sensible heat flux over the Bay of Bengal and south China Sea [Figs. 15 (a-c)] is consistently more in 1986 than in 1985 and also maintains a higher average over the Arabian Sea during 1986. This sensible heat flux over the trade wind zone is considered as the vital force in driving the local meridional cell by creating "Pressure head" (Malkus 1962), although its magnitude is very less as compared to latent heat flux. Thus, higher transfer of sensible heat flux in 1986 reduces the contrast in meridional circulation between 1985 and 1986 which would have been more otherwise.

3.2.4. *SST and air temperature* — Although interannual variability in SST in association with the monsoon variability has been reported (Cadet and Diehl 1984, Mooley and Shukla 1987, Rao and Goswami 1988), the present result (Fig. 16) does not show significant variability between 1985 and 1986. But a distinct difference is observed in magnitude from one region to the other. Highest SST is observed over Arabian Sea branch followed by Bay of Bengal and south China Sea. Arabian Sea, however shows little higher SST (0.7°C) during monsoon months (June-September) in 1985. Although small in magnitude, this higher seasonal SST in 1985 may be related to the maximum variability of pseudostress and latent heat flux in Arabian Sea as compared to the other two branches. The prominent feature observed in SST is the steep rise which starts in February and continues till May to reach the maximum, in almost all the three branches. Then the SST decreases in the monsoon and post-monsoon




Figs. 15 (a-f). (a-c) Monthly average sensible heat flux, and (d-f) latent heat flux in W/m[2] during 1985 (solid line) & 1986 (dashed line) over three branches of monsoon

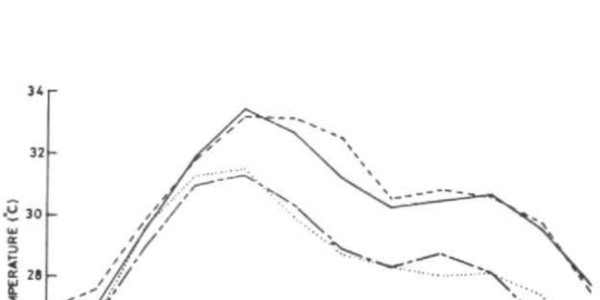



Fig. 16. Monthly average SST (°C) in three branches of monsoon

months over Arabian Sea and Bay of Bengal. However, south China Sea behaves in a different way, where the May SST is almost maintained throughout the monsoon season and the decreasing trend starts only after October.

Air temperature at 2 m height follows the same trend as SST over all the three branching regions. This indicates the influence of the surface layer of the ocean over the moist marine boundary layer existing immediately above it and the importance of the surface fields also. A significant difference in SST and air temperature is observed in the pre-monsoon months and this contributes to the higher sensible heat transfer in these months.

## 4. Conclusions

From the analysis of surface fields the following conclusions are made in this study:

(*i*) Three distinct branches of the southwest monsoon, *viz.* (1) Arabian Sea, (2) Bay of Bengal and (3) south China Sea are observed from the characteristics of zonal and meridional components of pseudostress, surface pressure and latent heat flux. However, other three surface fields, such as SST, sensible heat flux and air temperature do not reflect the branching phenomenon. Cross-equatorial flow also shows the three branches of the monsoon.

(*ii*) Arabian Sea branch has the strongest signal in the pseudostress and latent heat flux and shows significant variability in association with the monsoon rainfall variability in 1985 and 1986.

(*iii*) Meridional components of pseudostress are stronger than the zonal components and are positively related to the Indian monsoon rainfall.

(*iv*) Strengthening of the Southern Hemisphere trade, the Somali jet, and more inter-hemispheric pressure gradient are associated with a better monsoon (in 1985) and thus play an important role in deciding the activity of monsoon over India.

(*v*) Steep gradient in zonal and meridional components of pseudostress in association with the sudden increase of latent heat flux from May to June and the rapid fall of pressure from March to April, in all the three branches of monsoon, are the most prominent features associated with a better monsoon year (in 1985).

(*vi*) Variability in SST is not well marked. However, differences in SST from one branch to the other are significant with Arabian Sea having the highest SST.

(*vii*) Since the characteristics of the surface fields obtained in this study based on two less contrasting years of monsoon are very interesting, the study on the inter-annual variability of all the surface fields over the three branches of the monsoon and the southern Indian Ocean are being carried out over a longer period of time (1985-1990) in order to document the strong signals of the surface fields associated with monsoon variability.

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