

# Role of low level flow on the summer monsoon rainfall over the Indian subcontinent during two contrasting monsoon years

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## ABSTRACT

The summer monsoon rainfall over the Indian subcontinent shows 1 large inter-annual variability in three important aspects, namely, the onset date, quantum of monsoon rainfall and the monsoon activity within the monsoon (June - September) period. In the present study, we look into the role of the low level flow during two contrasting monsoon years, viz., 1987 (deficit) and 1988 (excess) using the daily data from the National Centre for Environmental Prediction (NCEP) Reanalysis and European Centre for Medium range Weather Forecasting (ECMWF).

We have further classified the daily data into different pentads (5 day means) to look into the role of the low level flow over the tropical Indian Ocean on the monsoon activity, during different phases such as break, weak, moderate and active rainfall conditions over the Indian subcontinent. The strength of the low level flow into the Indian subcontinent (equatorial Indian Ocean (EIO) region) is significantly higher during active and moderate (break and weak) monsoon conditions. The low level flow and moisture transport were studied using the surface pressure, surface winds, 850 mb winds and integrated columnar precipitable water during different periods ranging from break to very active conditions in the monsoon activity. The present study, thus, clearly brings out the importance of low level flow into the Indian subcontinent (Equatorial Indian Ocean) during the excess (deficit) monsoon years.

## INTRODUCTION

The monsoon is a global phenomenon affecting a large part of Asia, Africa and northern Australia. The fundamental driving mechanism of the monsoon cycle is the cross-equatorial pressure gradient resulting from differential heating of land and ocean modified by the rotation of the earth an exchange of moisture between ocean, atmosphere and land.

The Indian summer monsoon (from June to September) rainfall is of great importance to India's agriculture and economy as 60-90% of annual rainfall is received during this season. Severe flood and drought conditions over the Indian subcontinent are the result of intraseasonal oscillations within the monsoon period. The onset, activity during the season and the withdrawal of the southwest monsoon are also subject to large variations. The interannual variability of Indian Summer Monsoon (ISM) has been studied by several authors since the pioneering works of Blanford 1884; Lockyer & Lockyer 1904; Walker 1910. The above studies explain partially the trends and periodicities in ISM rainfall, but failed to explain the causative factors of the interannual variability. This could be due to the non availability of good quality controlled data on higher spatial and temporal scale. Several studies have been carried out on the role of air-sea interaction processes over the Indian Ocean (Cadet & Diehl 1984; Shukla & Mishra 1977; Weare 1979; Joseph & Pillai 1984; Ramesh Kumar et al.1986; Shukla 1987; Rao & Goswami 1988; Mohanty & Ramesh 1993. These studies are

mainly concentrated on the relationship between sea surface temperature anomalies over Arabian Sea and summer monsoon rainfall over India. Studies of Shukla & Misra (1977) showed a weak positive correlations between monthly SST over the Arabian Sea and rainfall over India. Weare (1979) analysis revealed the opposite; a warmer Arabian Sea is associated with decreased ISM rainfall. Shukla (1987) found that heavy (deficit) rainfall is followed by negative (positive) SST anomalies, but the magnitude of the SST anomalies for the premonsoon months is small and insignificant. Joseph & Pillai (1984) obtained the same results. On the contrary, the studies of Rao & Goswami (1988) suggest that SST in the southeast Arabian Sea during the premonsoon season are significantly correlated with ISM rainfall. The study of Ramesh Kumar et al. (1986) indicated that large negative anomalies off the Somali and Arabian coasts are associated with good monsoon rainfall over India. The relationship between the SST in the Eastern Equatorial Indian Ocean (EEIO) and monsoon rainfall was studied by Sadhuram (1997). Their study indicated that SST anomaly during October and November in the EEIO is useful for monsoon rainfall prediction. Also, the remote forcing of SST anomalies during February affects the broad scale monsoon circulation via the teleconnection through the East or North Pacific, while the forcing in October and November months play important role in monsoon rainfall via the teleconnection through the West Pacific and North-Australia-Indonesia region ( Sadhuram & Wells 999). Recendy, Clark Cole & Webster (2000) found that

in boreal fall and winter preceding the summer Indian monsoon, SST throughout the tropical Indian Ocean correlates positively with subsequent monsoon rainfall. Negative correlation occurs between SST and the AIRI (All India Rainfall Index) in the subsequent autumn in the northern Indian Ocean. These studies have provided conflicting results on the relationship of SST with monsoon activity.

The origin and amount of moisture being transported to the Indian subcontinent during the southwest monsoon season was also studied by many investigators. Pisharoty (1965) utilizing the data collected during IIOE, examined the moisture budget and found that evaporation from Arabian Sea to be the main contributor for summer monsoon rainfall. Saha & Bavadekar (1973) using additional upper air data concluded that 70% of moisture flux from the south Indian ocean accounts for the bulk of moisture needed for summer monsoon rainfall. The intraseasonal variations of moisture budget have also been examined by several scientists (Ramamurty, Jambhunathan & Sikka 1976; Ghosh, Pant & Dewan 1978; Howland & Sikdar, 1983; Cadet & Reverdin 1981a, Sadhuram & Ramesh Kumar 1988). While the importance of evaporation over the Arabian Sea is suggested by Ghosh, Pant & Dewan 1978; Murakami, Nakazawa & He 1984, the role of cross equatorial flux has been emphasized by Cadet & Reverdin 1981a,b, Howland & Sikdar 1983; Sadhuram & Ramesh kumar, 1988; Ramesh Kumar & Sadhuram, 1989; Ramesh Kumar, Shenoj & Schluessel 1999. Most of these studies suggest that the cross equatorial moisture flux provides an important source of moisture for the ISM rainfall though the evaporation from the Arabian Sea is quite significant.

Most of the above mentioned studies have used only limited data sets as no long term observation were available. Now with the availability of daily and twice daily reanalysis results from NCEP/NCAR project various aspects of monsoon can be studied in detail which can throw more light on the different phases of monsoon activity. In the present study, an attempt is made to understand the role of low level flow on the ISM rainfall. We have analysed the windfield (surface and 850 mb), surface pressure and precipitable water with an objective to understand the influence of these parameters in relation to extreme monsoon activity over the Indian subcontinent during two contrasting monsoon years 1987 and 1988. As the activity of monsoon depends on the amount of moisture transported to the Indian subcontinent, moisture transport during the period June to September also has been computed to have a better understanding of the contrasting behaviour of monsoon of 1987 and 1988.

#### DATA USED

The study uses twice daily zonal (u) and meridional (v) winds at 10m height and at 850 mb and total columnar water vapour

derived from National centre for Environmental Prediction (NCEP) reanalysis project for the years 1987 and 1988. The NCEP reanalysis project uses a frozen state of art analysis system (the Global Data Assimilation System, GDAS), using past data, from 1957 to 1998. This project involves the recovery of land surface, ship rawin sonde, pibal, aircraft, satellite and other data; quality controlling and assimilating these data with a data assimilating system that is kept unchanged over the reanalysis period 1957-96. This eliminates perceived climatic jumps associated with changes in data assimilating system. The NCEP 40 year reanalysis is a research quality dataset suitable for weather and short term climatic research (Kalnay et al. 1996): This dataset have been extensively used by several authors for a variety of studies. The data are on a T62 Gaussian grid (192 long. X 94 lat.). In order to compute the moisture transport into the Indian subcontinent, NCEP daily specific humidity data are also used for the years 1987 and 1988. Twice daily surface pressure fields for the above period has been extracted from the European Centre for Medium range Weather Forecasting (ECMWF) Reanalysis (ERA). A full description of ERA is available in Gibson, Kalberg & Uppala (1996). ERA was performed using a version of the ECMWF operational data assimilation system, which includes a spectral T106 forecast model with 31 hybrid vertical levels and a fully three-dimensional semi-Lagrangian advection scheme.

#### METHODOLOGY

The years 1987 and 1988 were chosen for the present study because of their contrasting monsoon activity as reported earlier (Krishnamurti, Bedi & Subramaniam 1989; 1990; Ramesh Kumar & Shluessel 1998 and Ramesh Kumar, Shenoj & Schluessel 1999). 1987 was a major drought year in India; 1988 India had more than normal rainfall during the monsoon season June to September. Fennessy & Shukla (1994) give the daily rainfall as a percentage of normal for the four month period of 1987 and 1988. Ramesh Kumar & Schlusel (1998) classified these data into very weak, weak, moderate, active and very active conditions. In order to have a better picture of the contrasting behaviour of monsoon of 1987 and '88, we have further divided the monsoon period from June to September into 24 pentads (five day means) and these pentads are classified according to Ramesh Kuamar & Schlusel (1998) criteria as shown in Table 1. All the daily values of wind speed, pressure, columnar precipitable water were further averaged to five day pentads for the present study.

The amount of moisture being transported into Indian subcontinent is an important parameter influencing monsoon rainfall. We have also computed the moisture transport at various levels into the Indian subcontinent during the different phases of the summer monsoon.

Role of low level flow on the summer monsoon rainfall over the Indian subcontinent during two contrasting monsoon years

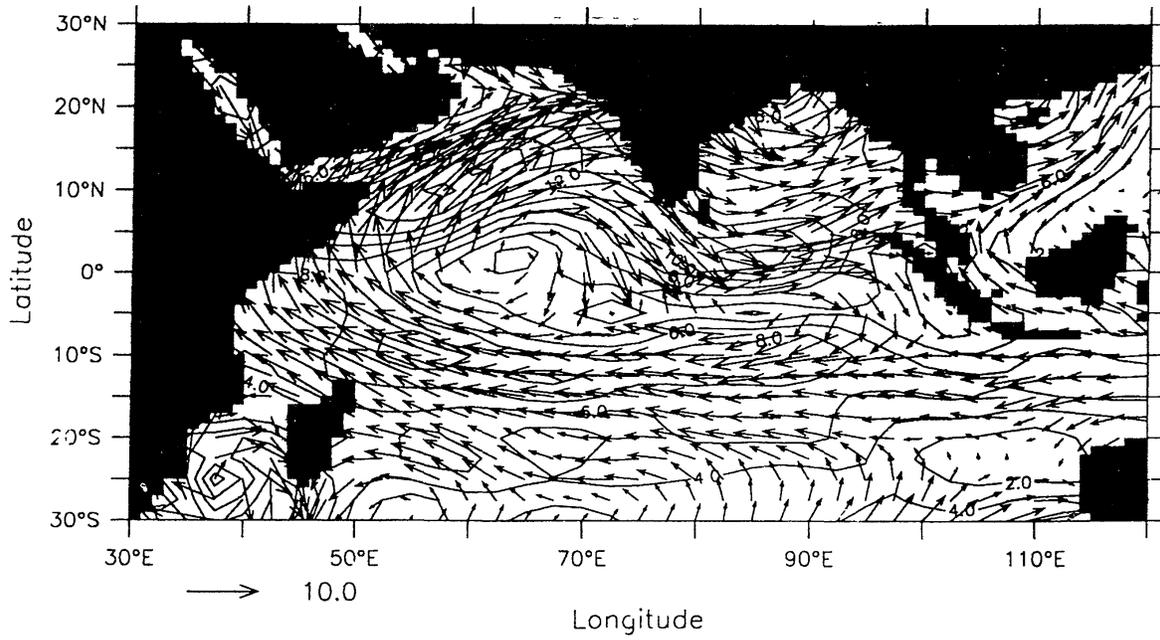
**Table 1**

Days	1987	Classification	1988	Classification
	No. of days in the pentad having above normal rainfall		No. of days in the pentad having above normal rainfall	
Jun 1-5	2	Weak	1	VeryWeak
Jun 6-10	3	Moderate	2	Weak
Jun 11-15	4	Active	1	VeryWeak
Jun 16-20	2	Weak	2	Weak
Jun 21-25	0	Break	2	Weak
Jun 26-30	0	Break	1	VeryWeak
Jul 1-5	2	Weak	2	Weak
Jul 6-10	2	Weak	2	Weak
Jul 11-15	0	Break	3	Moderate
Jul 16-20	0	Break	4	Active
Jul 21-25	0	Break	5	Very Active
Jul 26-30	0	Break	4	Active
Jul 31-Aug4	0	Break	2	Weak
Aug 5-9	2	Weak	3	Moderate
Aug 10-14	1	Very Weak	0	Break
Aug 15-19	2	Weak	2	Weak
Aug 20-24	3	Moderate	4	Active
Aug 25-29	3	Moderate	4	Active
Aug 30-Sep 3	0	Break	3	Moderate
Sep 4-8	1	Very Weak	1	VeryWeak
Sep 9-13	0	Break	3	Moderate
Sep 14-18	0	Break	4	Active
Sep 19-23	0	Break	5	Very Active
Sep 24-28	1	Very weak	5	Very Active

**Table 2**

Classification	1987	1988
Case - I July 21-25	Break	Very Active
Case - II July 26-30	Break	Active
Case-III June 11-15	Active	VeryWeak

21-JUL-25-JUL 1987



21-JUL-25-JUL 1988

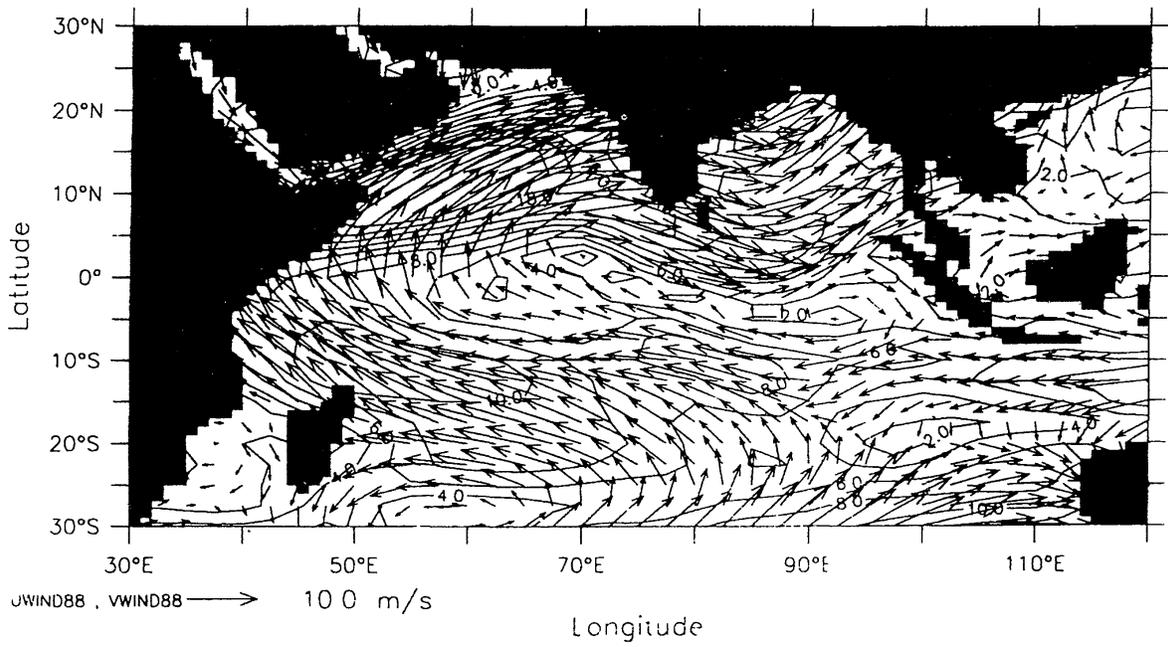
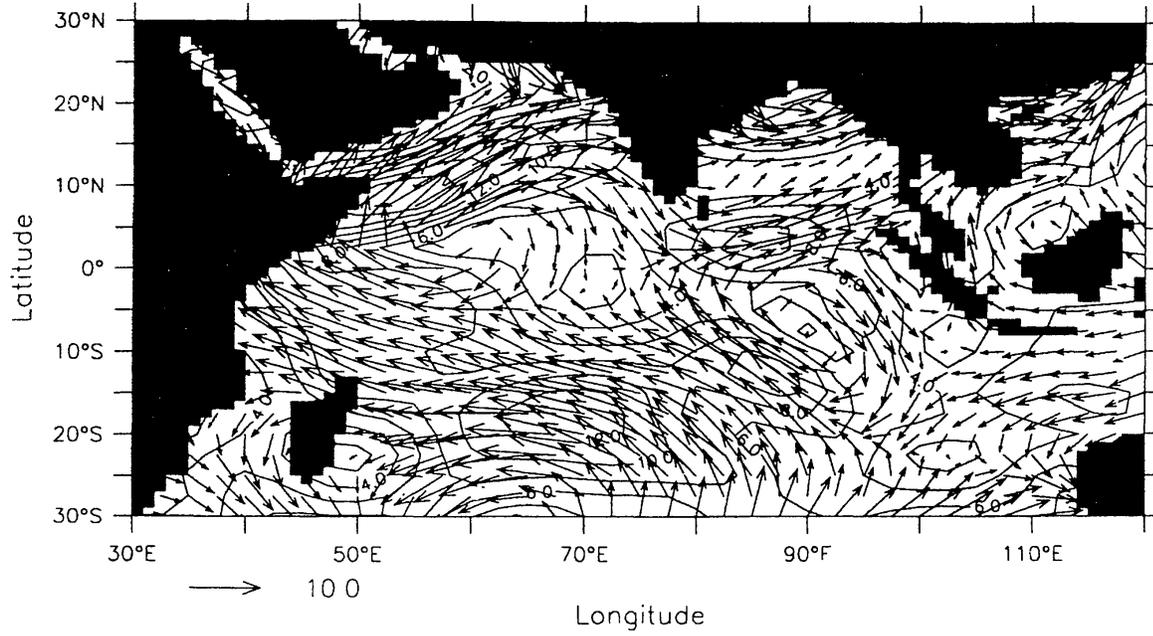


Figure 1(a). Pentad mean winds at 850mb.

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26-JUL-30-JUL 1987



26-JUL-30-JUL 1988

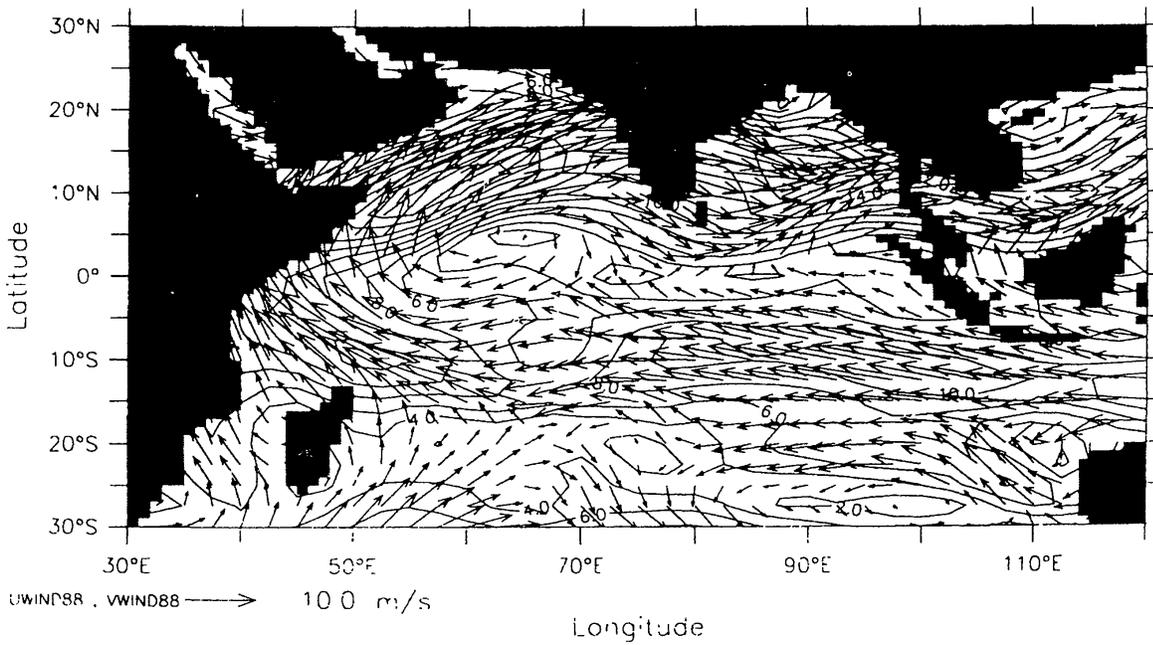
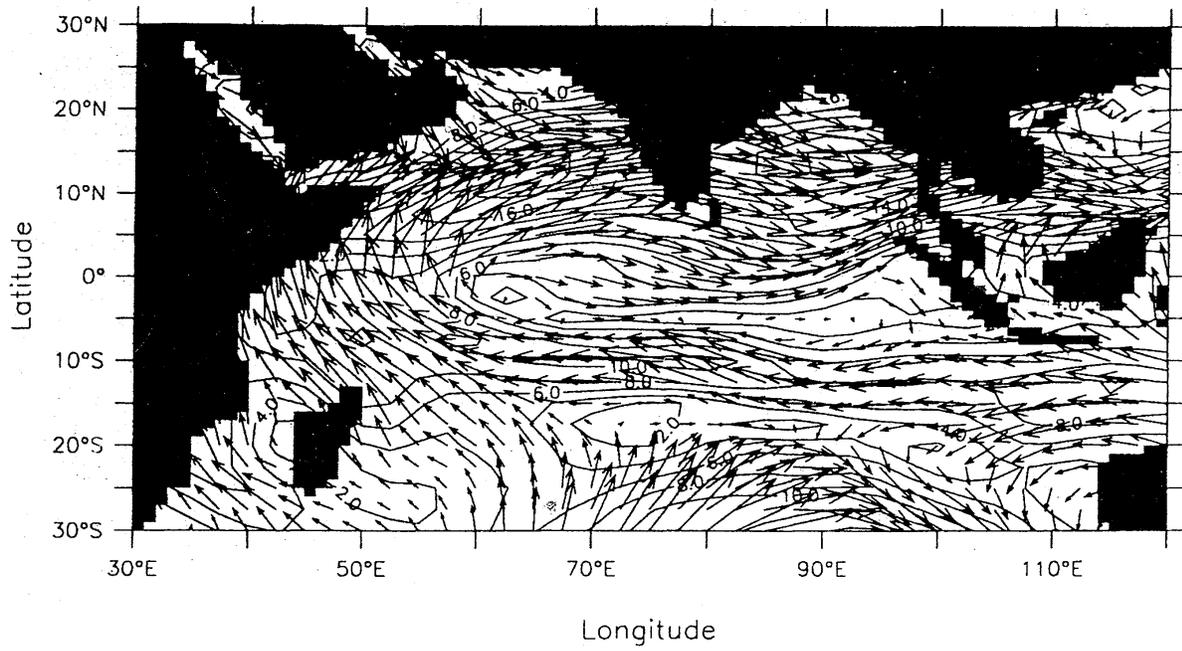


Figure 1(b). Pentad mean winds at 850mb.

11-JUN-15-JUN 1987



11-JUN-15-JUN 1988

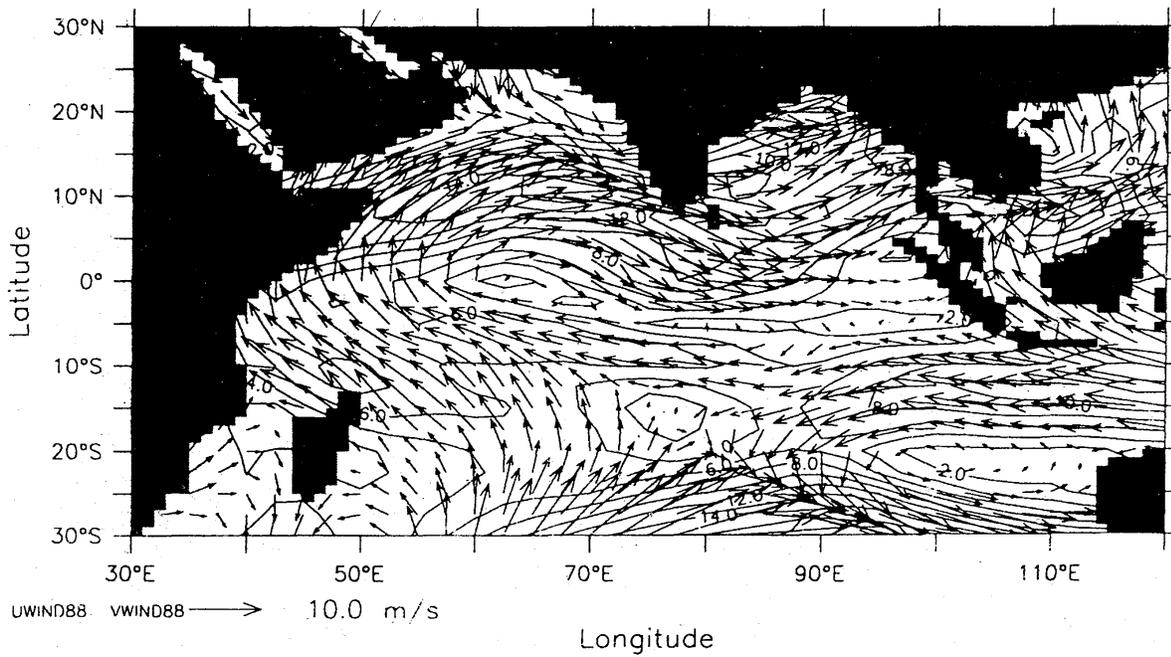


Figure 1(c). Pentad mean vinds at 850mb.

## RESULTS AND DISCUSSION

The importance of low level flow over the Indian subcontinent has been brought out by analyzing the pentads of wind at surface and 850 mb, surface pressure, total columnar water vapour and moisture transport. We have analysed all the phases of the summer monsoon for the above contrasting years, but presenting only three cases (Table 2) which depict contrasting behavior in monsoon activity.

### WINDS

#### At 850 mb

One of the most interesting feature of the ISM is the low level jet centred around 850 mb, originating in the southern Indian Ocean near Madagascar, penetrates inland over low lying areas of Kenya, Ethiopia and Somalia and emerges in the Arabian Sea and flows across the central parts to coasts of India. The low level jet stream was first identified by Bunker (1965) off Somalia during the IIOE period (1962-1966). Joseph & Raman (1966) found that the low level jet stream exists over Peninsular India on a large number of days during July with a core speed of 40 to 60 knots near 1.5 Km asi. Studies of Findlater (1969,71) showed that the low level jet plays a major role in the monsoon activity over the Indian subcontinent. The strength and location of the low level flow into the Indian subcontinent thus plays an important role in determining the strength of the monsoon activity.

With an objective to identify the role of low level jet on monsoon activity, we have analysed 850 mb winds for the monsoon period Jun-Sept for the years 1987 and 1988. The analysis showed that the wind speeds are high over the western Arabian Sea as compared to central Bay of Bengal and the southern Indian Ocean. Western Arabian Sea shows great contrast, where wind speeds are about 2m/s higher in 1988 than in 1987. Wind vectors with the speed contoured for 1987 and 88 for different pentads are shown in Figs 1 (a) -(c)

Another important feature observed is the relative strength of the low level jet over the Indian subcontinent. During the active monsoon periods, the core of the jet is directed to Indian subcontinent producing heavy rainfall over India. But during the break period the core of the low level jet is directed south of Indian peninsula leading to break monsoon condition over India. This was reported earlier in the studies of Vinaychandran, Sadhuram & Ramesh Babu (1989) and Sijikumar et al. (2000). They referred to this as a split in the low level jet during the break period.

#### Case -I

July 21-25 is a very active period for '88 and a break period for '87. During this period, wind speeds are higher over the central Arabian Sea for 1988 (by about 6m/s). The core of the low level jet is directed to Indian subcontinent producing heavy rainfall over India. Whereas in 87, the flow is diverted towards equator resulting break monsoon condition over India.

#### Case -II

The pentad July 26-30 is an active period for '88 and break period for '87. Similar to the above case, the wind speeds are higher over central Arabian Sea for '88 and the core of the low level jet is directed to Indian subcontinent.

#### Case-III

June 11 -15 is an active period for '87 and a very weak period '88. Wind speeds over the central Arabian Sea are about 2 m/s higher for '87 and the flow is directed to Indian subcontinent. In '88 wind speeds are relatively low and most of the flow is diverted to equatorial region leading to very weak rainfall condition over Indian subcontinent.

### SURFACE WINDS

Surface winds are also generally higher over the central Arabian Sea for the year 88 than 87. Highest contrast is observed for the month of July as shown in Fig.2 Wind speeds are higher for the active periods than the break and weak conditions.

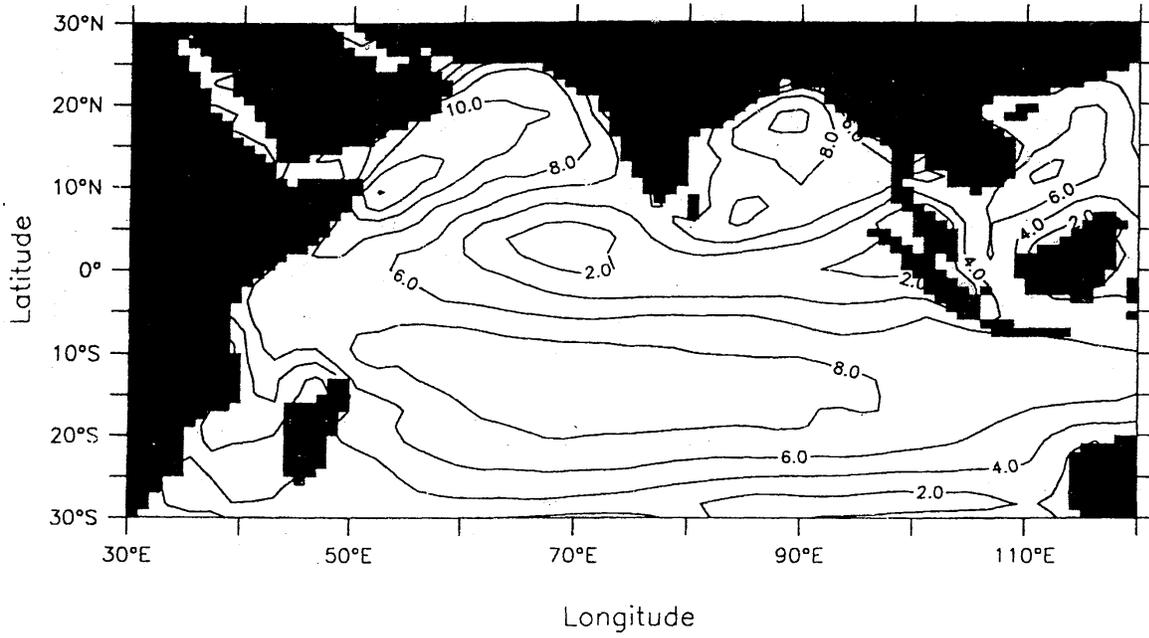
### SURFACE PRESSURE

Surface pressure has been found to play an important role in the monsoon activity over India (Ramesh Kumar & Sadhuram 1989). The fundamental driving mechanism of the monsoon circulation are the pressure difference between the Mascereene high and head Bay of Bengal. This pressure difference induces strong cross equatorial flow of winds leading to heavy rainfall over India. The surface pressure fields averaged for different pentads for the period Jun to Sept. are shown in Figs 3(a)-(c). Higher cross equatorial pressure gradients are observed for excess rainfall pentads. Cross equatorial pressure gradient is 2 mb higher for the period July 21-25 for 88 than for 87. For June 11-15 cross equatorial pressure gradient is 4 mb higher for 87 than for 88. Another interesting feature is the drop in pressure along the west coast of India, which is higher for the excess rainfall periods. The presence of an offshore trough is clearly seen from the Fig.3 (b) for the pentad 26-30 July 88.

### TOTAL COLUMNAR PRECIPITABLE WATER

Figs 4(a)-(c) show the difference in total columnar precipitable water of 1988 and 1987 for different pentads. The positive values of precipitable water over the Arabian Sea for a particular pentad shows the availability of moisture for precipitation is more for that pentad leading to excess rainfall over the Indian subcontinent. For July 21-25, 12 units of excess precipitable water is available over the Arabian Sea producing very active rainfall over Indian subcontinent. Also for July 26-30, the precipitable water content is high for '88 than '87. For 11 to 15 June, negative values indicates the deficiency of precipitable water for 88 producing weak rainfall over India for 88 and active rainfall period for 87.

1-JUL-30-JULY 1987



1-JUL-30-JULY 1988

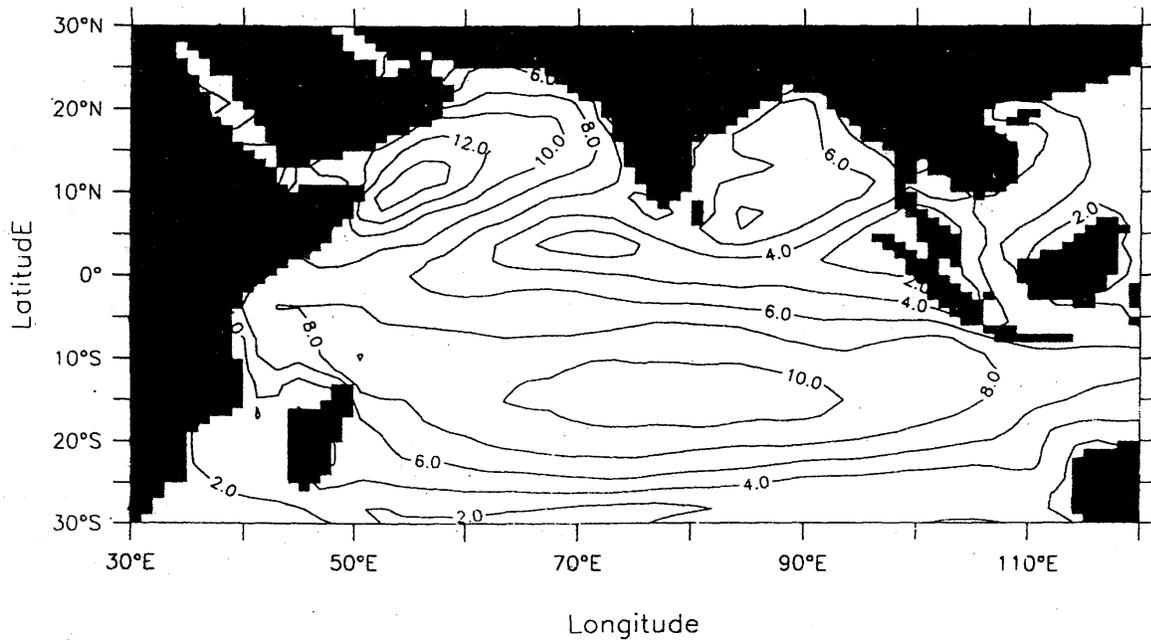
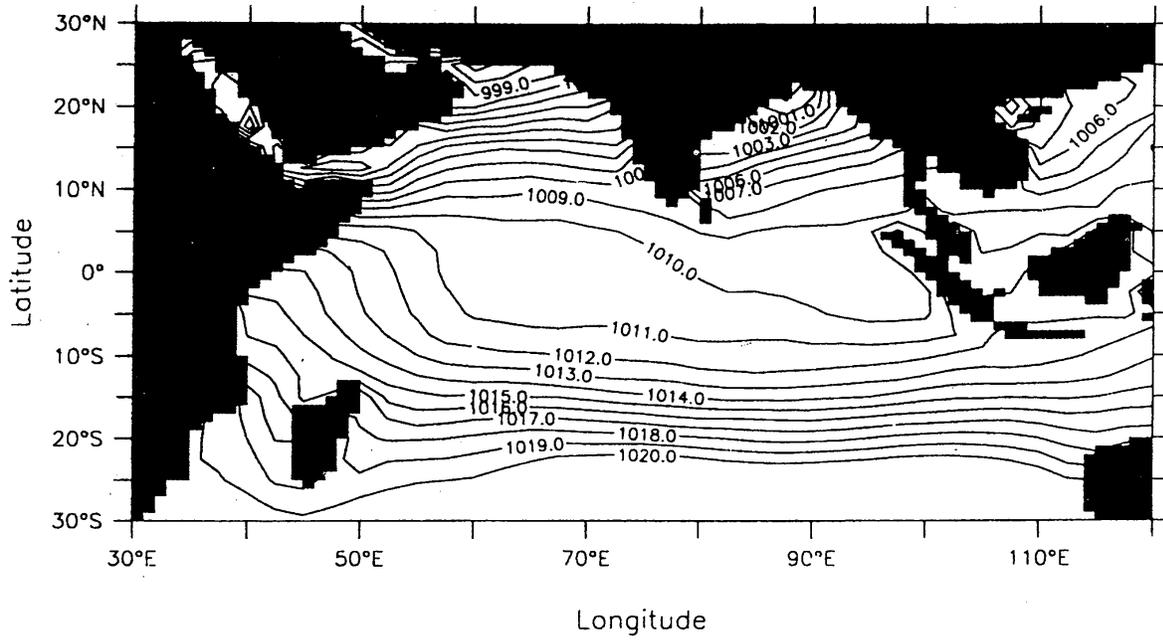


Figure 2. Mean surface windspeed (m/s) for July

21-25-JUL 1987



21-25-JUL 1988

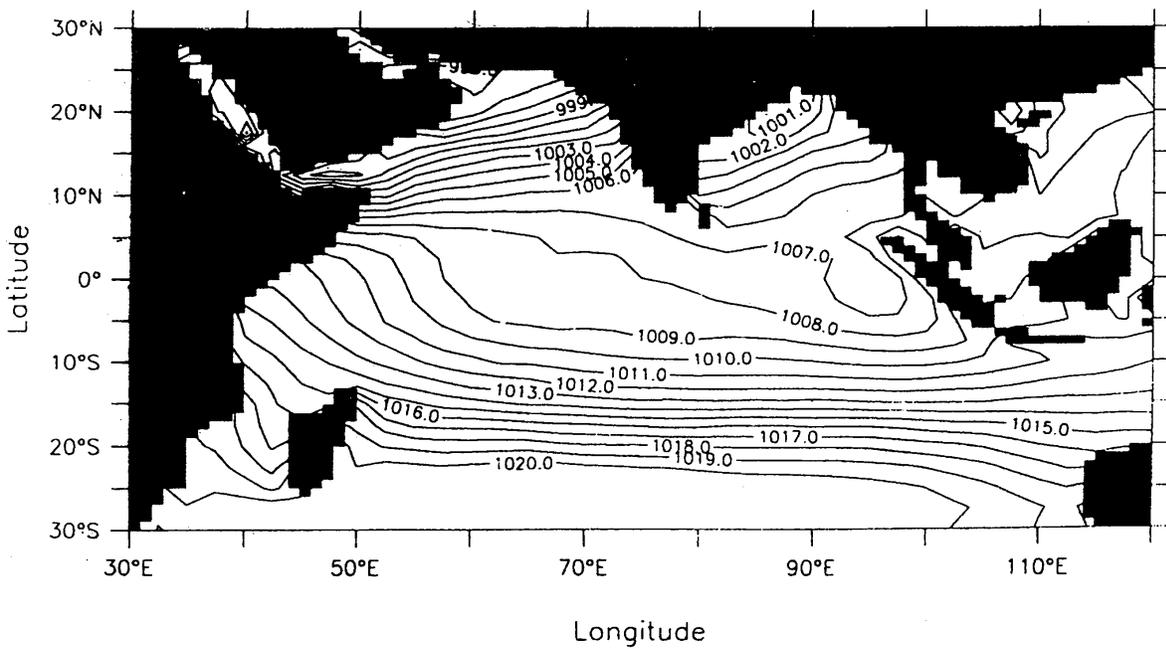
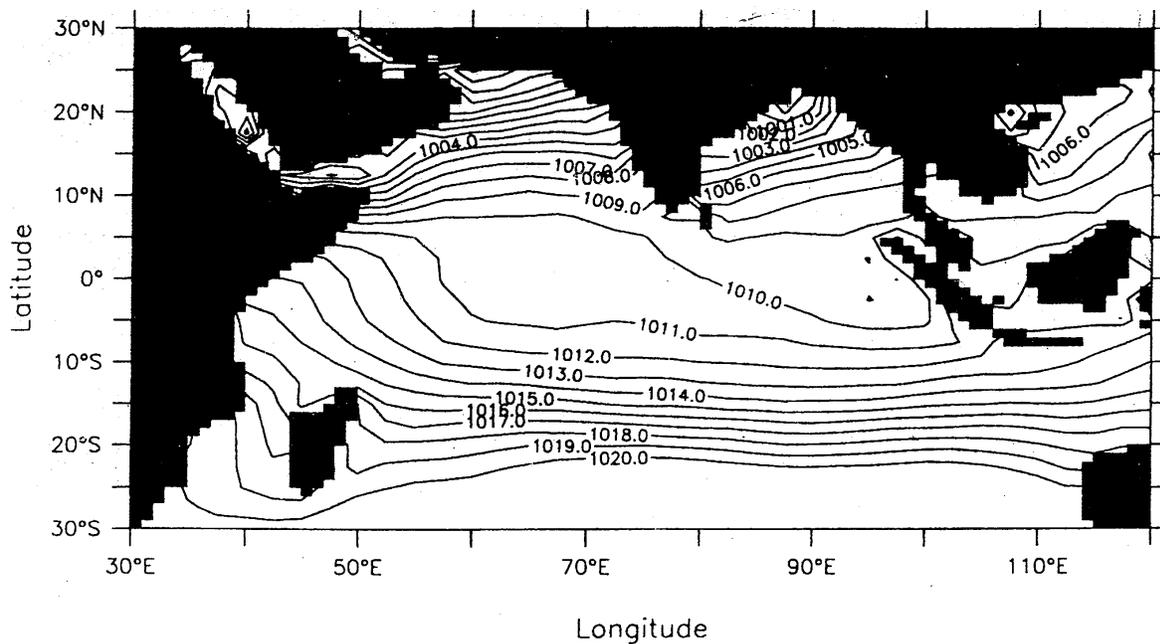


Figure 3(a). Pentad mean surface pressure (mb)

26-30-JUL 1987



26-30-JUL 1988

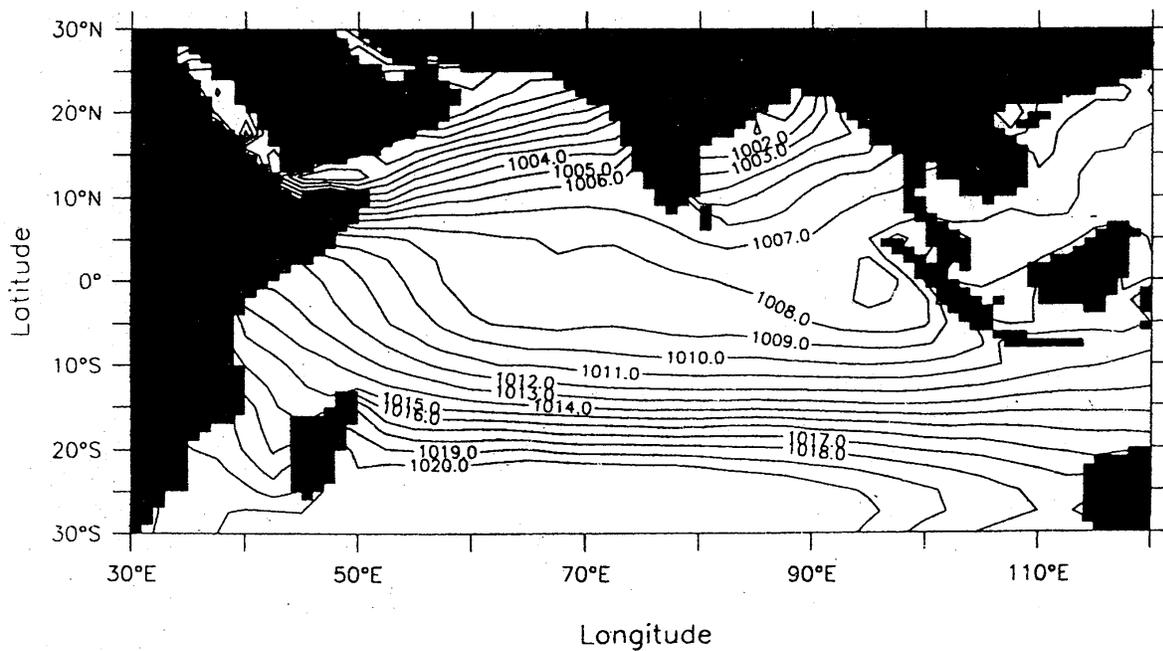
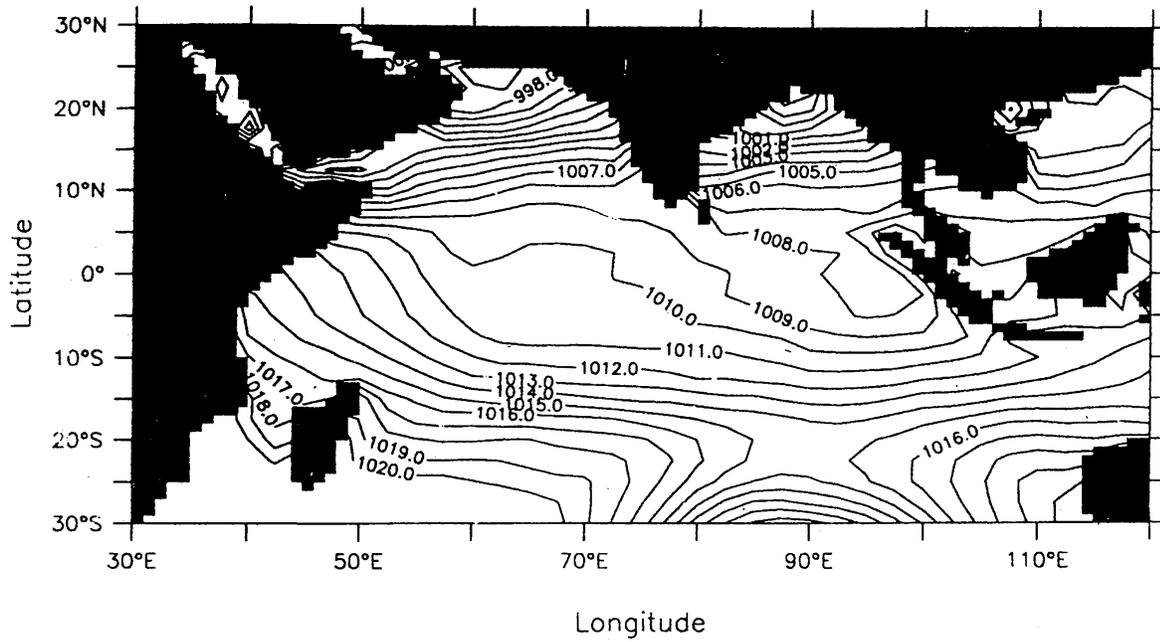


Figure 3(b). Pentad mean surface pressure (mb)

11-15-JUN 1987



11-15-JUN 1988

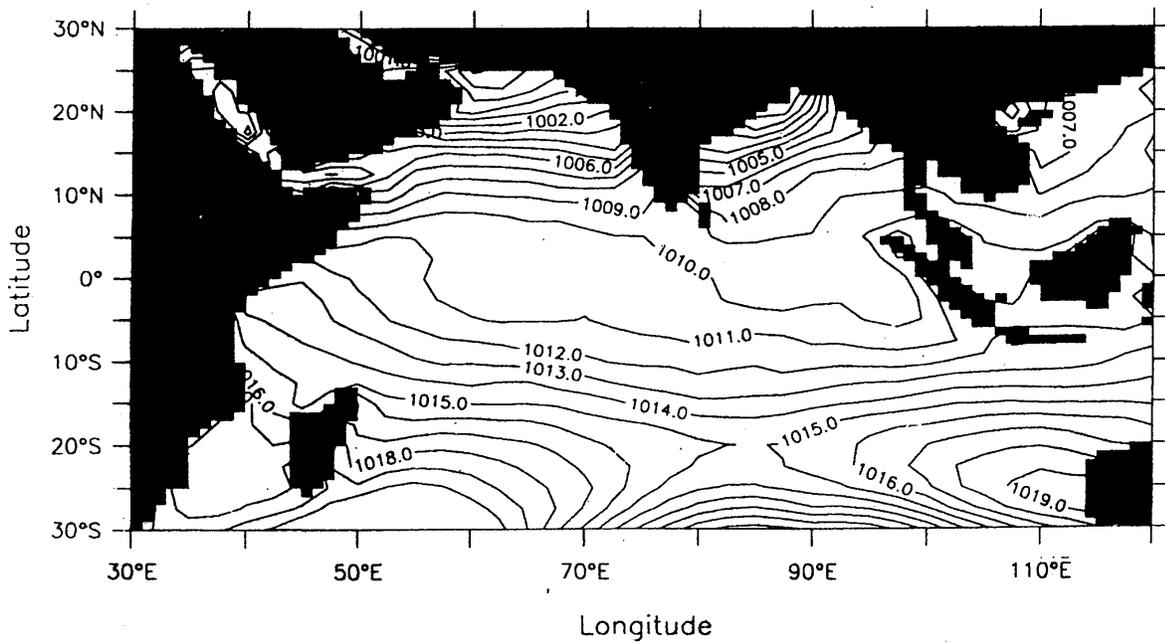
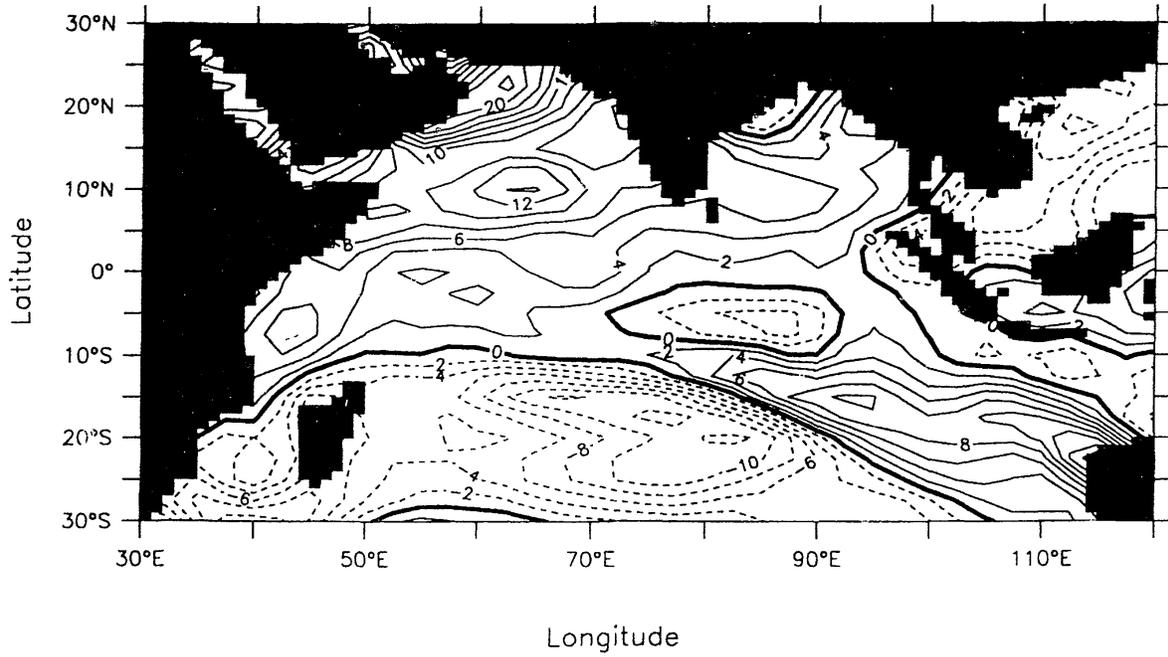


Figure 3(c). Pentad mean surface pressure (mb)

21-JUL-25-JUL



26-JUL-30-JUL

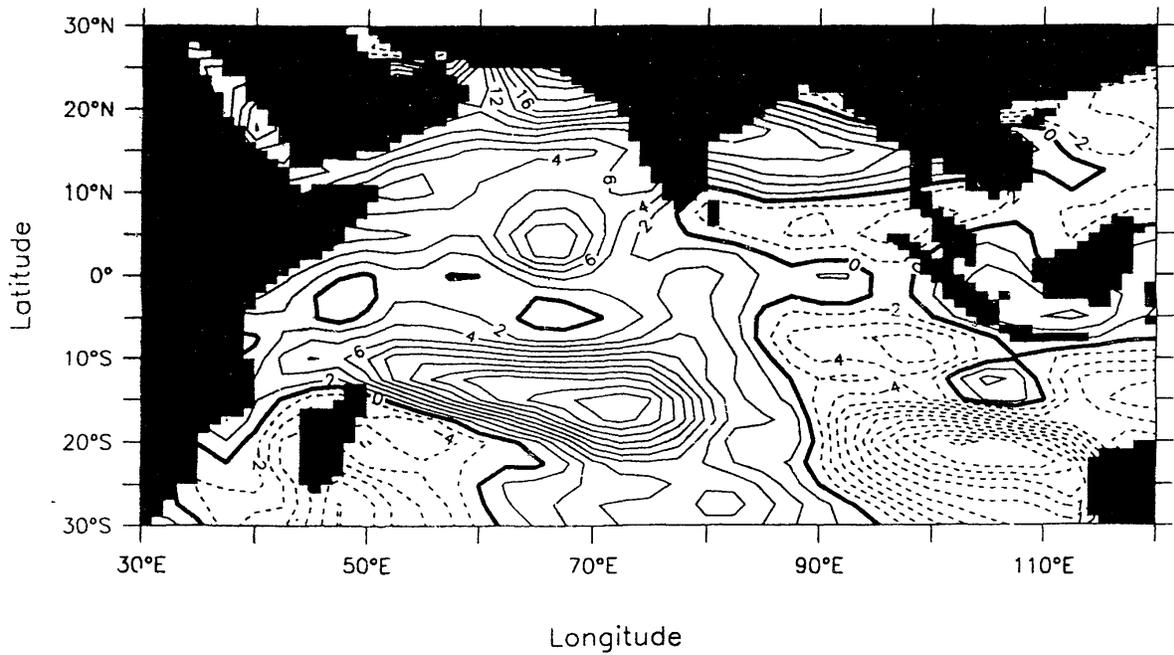
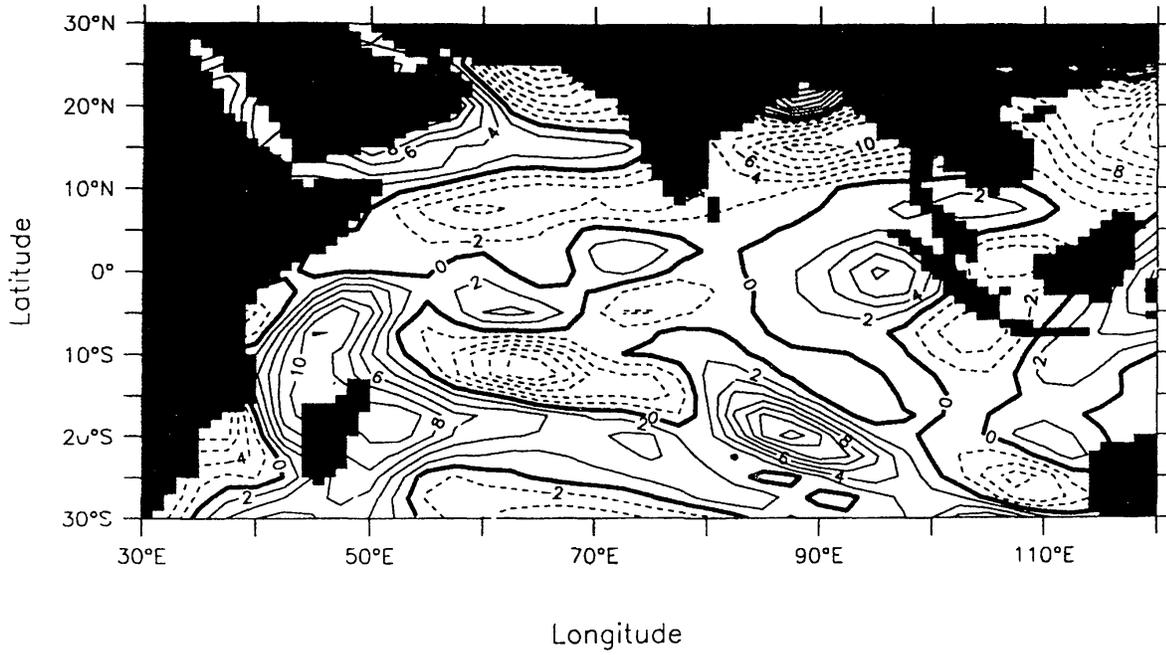


Figure 4(a). The difference of pentad mean total columnar precipitable water (kg/m<sup>2</sup>) for the years 1988 and 1987.

11-JUN-15-JUN



16-JUN-20-JUN

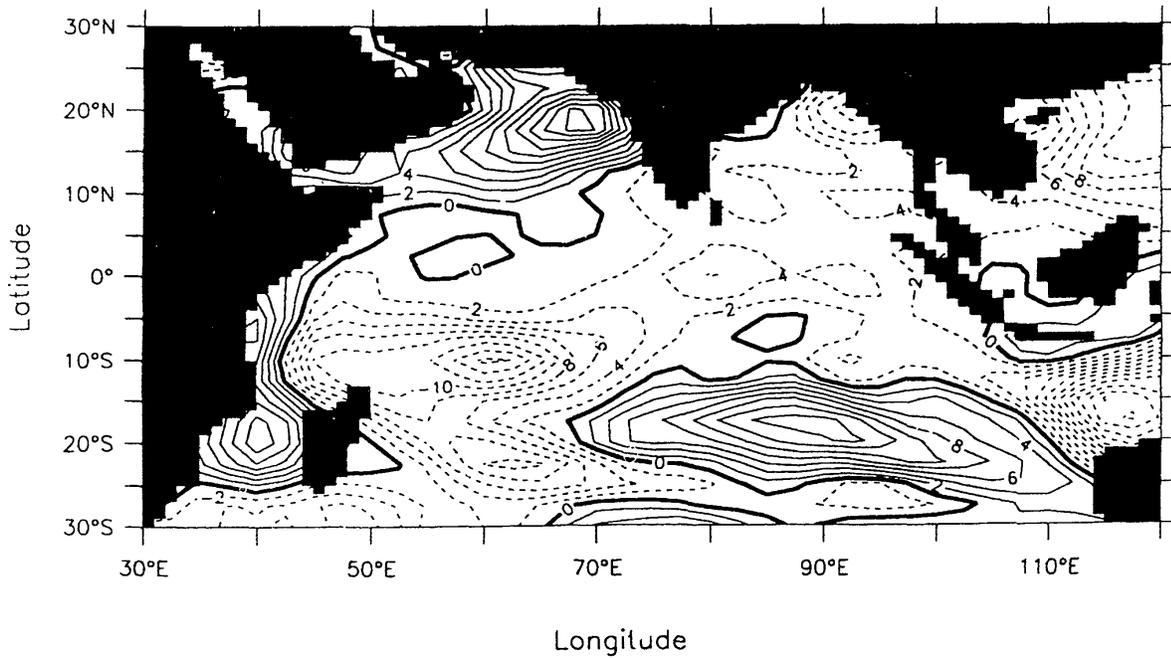


Figure 4(b). The difference of pentad mean total columnar precipitable water (kg/m<sup>2</sup>) for the years 1988 and 1987.

## MOISTURE TRANSPORT

The amount of moisture being transported to the Indian subcontinent during different pentads of the monsoon season is of great importance to the monsoon activity. In order to study the amount of moisture transport we have taken three sections (Section-I: 5°S to 5°N; 75°E, Section-II: 5°N to 15°N; 75°E and Section III : 15°N to 25°N; 75°E). The moisture transport through each section is presented in Table 3. The amount of moisture transported through Section -II is more compared to other sections. During the active phases of the monsoon, more moisture is transported to the Indian subcontinent through Section-II, producing strong monsoon activity over the Indian subcontinent. During the break and weak monsoon conditions, more moisture is transported to the equatorial section (Section-I) or through Section-III producing below normal rainfall over the Indian subcontinent. Even though we have computed the moisture transport for both years, we are presenting only the results of 1987.

## CONCLUSIONS

The daily analysed fields of NCEP/NCAR reanalysis data is thus able to bring out the contrasting monsoon activity for the years 1987 and 1988 over the Indian subcontinent. The present analysis could clearly bring out the importance of low level flow on the monsoonal activity over the Indian subcontinent. The monsoon activity is directly linked to the amount of moisture is transported to the Indian subcontinent during the monsoon period. Active periods of rainfall are characterised by stronger low level flow directed to Indian subcontinent transporting more moisture in to the Indian subcontinent between latitudes 5°N to 15°N. During break and weak rainfall periods, the low level flow is diverted to equator and hence the moisture is transported south of the Indian peninsula, leading to below normal rainfall over India.

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## REFERENCES

- Blanford, H.F., 1884. On the connexion of the Himalaya snowfall and seasons of drought in India, Proc. Roy. Soc. London, 37, 3-22.
- Bunker, A.F., 1965. Interaction of the summer monsoon air with the Arabian Sea, '(Preliminary analysis)', Proc. Symp. Met. Results International Indian Ocean Expedition, Bombay, 22-26 July 1965.
- Cadet, D.L. & Reverdin, G., 1981a. Water vapour transport over the Indian Ocean during summer 1975, *Tellus*, 33, 476-487.
- Cadet, D.L. & Reverdin, G., 1981b. The monsoon over the Indian Ocean during summer 1975, Part.I, Mean fields, *Mon. Wea. Rev.*, 103, 148-158.
- Cadet, D.L. & Diehl, B.C., 1984. Interannual variability of surface fields over the Indian Ocean during recent decades, *Mon. Wea. Rev.*, 112, 1921-1935.
- Clark, O.C., Cole, J.E. & Webster, P.J., 2000. Indian Ocean SST and Indian summer rainfall; predictive relationships and their decades variability, *J. Climate*, 13, 2503-2519.
- Fennessy, M.J. & Shukla, J., 1994. GCM simulations of active and break monsoon periods, Proc. International Conf. on monsoon variability and prediction, Int. Centre for Theoretical Physics, Trieste, Italy, 9-13 May 1994, Vol. II, WCRP-84, WMO/TD-No 619.
- Findlater, J., 1969. A major low level air current near the Indian Ocean during northern summer, *Quad. J. Roy. Met. Soc.*, 95, 362-380.
- Findlater, J., 1971. Mean monthly airflow at low levels over the western Indian Ocean, *Geophysical memories*, No. 115, HMSO, London 53pp.
- Ghosh, S.K., Pant, M.C. & Dewan, B.N., 1978. Influence of the Arabian Sea on the Indian summer monsoon, *Tellus*, 30, 117-125.
- Gibson, J.K., Kalberg, P. & Uppala, S., 1996. The ECMWF Reanalysis (ERA) project, ECMWF Newsletter No.73, ECMWF, Reading, United Kingdom, 7-17.
- Howland, M.R. & Sikdar, D.N., 1983. The moisture budget over the N.E. Arabian Sea during pre-monsoon and monsoon onset, 1979, *Mon. Wea. Rev.*, 111, 2255-2268.
- Joseph, P.V. & Pillai, P.V., 1984. Air-sea interaction on a seasonal scale over north Indian Ocean, Part I: Interannual variations of sea surface temperature and Indian summer monsoon rainfall, *Mausam*, 35, 323-330.
- Joseph, P.V. & Raman, P.L., 1966. Existence of low level westerly jet-stream over peninsular India during July, *Indian J. Meteorol. Geophys.*, 17, 407-410.
- Kalnay, E., Kanamitsu, M., Kisder, R., Collins, W, Deaven, D, Gandin, m., Saha, S., White, G, Woollen, J, Zhu, Y, Chelliah, M., Ebisuzaki, W, Higgins, W, Janowiak, J., Mo, K. C.,Ropelewski, C., Wang, J., Leetma, A., Reynolds, R., Roy Jenne & Dennis Joseph, 1996. The NCEP/NCAR 40 year re - analysis project, *Bull. Amer. Met. Soc.*, 77, 437-471.
- Krishnamurti, T.N., Bedi, H.S. & Subramaniam, M., 1989. The summer monsoon of 1987, *J. Climate*, 2, 321-340.
- Krishnamurti, T.N., Bedi, H.S. & Subramaniam, M., 1990. The summer monsoon of 1988, *Meteorol. Atmos. Phys.*, 42, 19-37.
- Lockyer, N. & Lockyer, W.J.S., 1904. The behavior of the short-period atmospheric variation over the earth's surface, *Proc. R. Soc. London*, 73, 457-470.

- Mohanty, U.C. & Ramesh, K.J., 1993. Characteristics of certain surface meteorological parameters in relation to the interannual variability of Indian summer monsoon, *Proc. Indian Acad. Sci. (Earth Planet. Sci.)*, 102,1,73-87.
- Murakami, T., Nakazawa, T. & He, J., 1984. On the 40-50 day oscillation during the 1979 northern hemisphere summer, Part.II, Heat and Moisture budget, *J. Meteor. Soc. Japan*, 62.
- Pisharoty, P.R., 1965. Evaporation from the Arabian Sea and the Indian southwest monsoon, In: *Proceedings of the symposium on meteorological results of the IIOE*, Bombay, India Meteorological Department, 43-54.
- Ramamurty, K., Jambhunathan, R. & Sikka, D.R., 1976. Moisture distribution water vapour flux over the Arabian Sea during active and weak spells of southwest monsoon, 1973, *Ind. J. Met. Hydrol. Geophys.*, 27(2), 127-140.
- Ramesh Kumar, M.R., Sathyendranath, S., Viswambharan, N.K. & Rao, L.V.G, 1986. Sea surface temperature variability over North Indian Ocean- A study of two contrasting monsoon seasons, *Proc. Indian Acad. Sci. (Earth Planet. Sci.)*, 95, 3,435-446.
- Ramesh Kumar, M.R. & Sadhuram, Y, 1989. Evaporation over the Arabian Sea during two contrasting monsoons, *Meteorol. Atmos. Phys.*, 41, 87-97.
- Ramesh Kumar, M.R. & Schluessel, P., 1998. Air-sea interaction over the Indian Ocean during the two contrasting monsoon years 1987 and 1988 studied with satellite data, *Theor. Appl. Climatol.*, 60, 219-231.
- Ramesh Kumar, M.R., Shenoi, S.S.C. & Schluessel, P., 1999. On the role of the cross equatorial flow on summer monsoon rainfall over India using NCEP/NCAR reanalysis data, *Meteorol. Atmos. Phys.*, 70, 201-213.
- Rao, K.G. & Goswami, B.N., 1988. Interannual variations of sea surface temperature over the Arabian Sea and the Indian Monsoon: A new perspective, *Mon. Wea. Rev.*, 116,558-568.
- Sadhuram, Y, 1997. Predicting monsoon rainfall and pressure indices from Sea Surface Temperature, *Curr. Sci.*, 72, 3, 166-167.
- Sadhuram, Y & Ramesh Kumar, M.R., 1988. Does evaporation over the Arabian Sea play a crucial role in moisture transport across the west coast of India during an active monsoon period? *Mon. Wea. Rev.*, 116, 307-312.
- Sadhuram, Y & Wells, N.C, 1999. Role of the Indian Ocean in the southern oscillation, atmospheric circulation indices and monsoon rainfall over India, *The Global Atmosphere and Ocean System*, 7, 47-72.
- Saha, K.R. & Bavadekar, S.N., 1973. Water vapour budget and precipitation over the Arabian Sea during the northern summer, *Quart. J. Roy. Meteor. Soc*, 99, 273-278.
- Sijikumar S., Sathiyamoorthy, V., Anu Simon., Prince K Xavier, Sajith, V. & Joseph, P.V., 2000. Does the low level jet stream split into two branches over the Arabian Sea?, *Tropmet 2000: Ocean and Atmosphere*, 167-172.
- Shukla, J., 1987. Interannual variability of monsoons, in : *Monsoons*, pp.632, (eds) Fein, J.S., Stephens, P.I., New York, John Wiley & Sons.
- Shukla, J. & Mishra, M., 1977. Relationship between sea surface temperature and wind speed over the central Arabian Sea and monsoon rainfall over India, *Mon. Wea. Rev*, 105, 998-1002.
- Vinaychandran, P.N., Sadhuram, Y, & Ramesh Babu, V., 1989. Latent and sensible heat fluxes under active and weak phases of summer monsoon of 1986, *Proc. Ind. Acad. Sci.*, 98, 2, 213-222.
- Weare, B.C., 1979. A statistical study of the relationship between ocean surface temperature and the Indian monsoon, *J. Atmos. Sci.*, 26, 2279-2291.
- Walker, G.T., 1910. *IMD.Mem. XXI Pt. II*, 22-25.

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