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Ocean-atmosphere interaction on a seasonal scale over north Indian Ocean and Indian monsoon rainfall and cyclone tracks — A preliminary study

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ABSTRACT. A preliminary study of synoptic sea surface temperature (SST) measurements made by ships plying over the north Indian Ocean has revealed the existence of an interesting Ocean-atmosphere interaction. Large scale monsoon failures over India during 1965 and 1966 caused increase in SST in the Arabian Sea and Bay of Bengal. The warm seas are the likely cause of a persistant anti-cyclone which formed in the upper troposphere over the Indian seas immediately after the 1966 monsoon and persisted there till the monsoon of 1967 which was a normal monsoon. Following this monsoon, SST over the Arabian Sea registered a fall. Conditions again became favourable for monsoon failure. Intensity of upwelling over the coastal waters of Somalia and Arabia (which is apparently regulated by the strength of the monsoon) is a factor with major role in this interaction. These large scale changes are found to affect the cyclone tracks also. This mechanism could, therefore, be the cause of the three year oscillation in sub-tropical westerlies/tropical easterlies over south Asia, Indian monsoon rainfall and tracks of the post-monsoon severe cyclones of the Bay of Bengal observed during the decade 1965 to 1974 and reported by Joseph (1975, 1976).

While in the sub-Saharan areas of Africa (like Sahel) there was large rainfall deficit during every year from 1966 to 1974 (with the year 1972 having the largest deficit), in India the generally bad monsoon decade 1965 to 1974 was broken by a normal monsoon once every three years, *i.e.*, 1967, 1970 and 1973. In the past also this area of Africa had similar long runs of dry spells (Kraus 1977), but an examination of Indian rainfall of 100 years has shown that no interval between successive good monsoon years has exceeded 4 years. This difference in African and Indian rainfall series must be due to the newly found ocean-atmosphere interaction, occurring over the Arabian Sea and Bay of Bengal.

1. Introduction

1.1. The circulation systems of the atmosphere and the ocean are strongly coupled through interactions at the air-sea interface. Some of the important features of this coupling and the feedback processes operating have been described by Gate (1977) and Hasselmann (1977).

1.2. Climatic records show that during some epochs, Indian summer monsoon rainfall has shown large year to year variations, with large scale monsoon failures occurring in some years. The tracks of the severe cyclones of the Bay of Bengal occurring during the post-monsoon season also have shown large inter-annual variability. One such epoch is the decade 1965 to 1974 (Joseph 1975, 1976).

1.3. In this paper a preliminary study of the interaction between the Indian Ocean, north of Lat. 15 deg. S, and the overlying atmosphere has been made. Sea surface temperature (SST) measurements made at synoptic hours by ships plying over north Indian Ocean have been used in this paper in the form of monthly mean values over selected areas.

2. Annual variation of monthly mean SST

2.1. WMO Congress-IV in 1964 decided to apportion the world sea/ocean areas among nine member countries for processing the large number

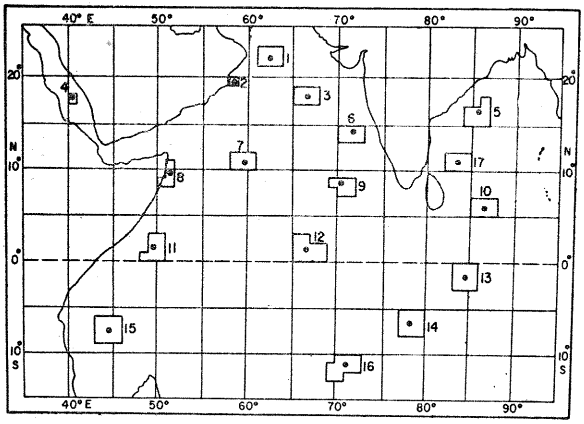

Fig. 1. The 17 "selected representative areas" of Indian Ocean north of 15°S

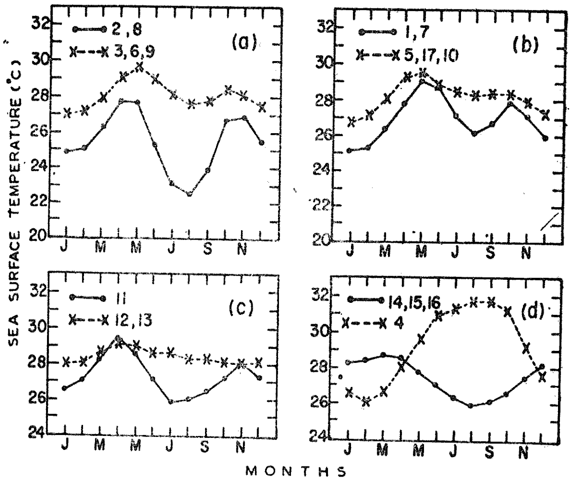

Fig. 2 (a-d). Annual variation of monthly mean SST(°C)

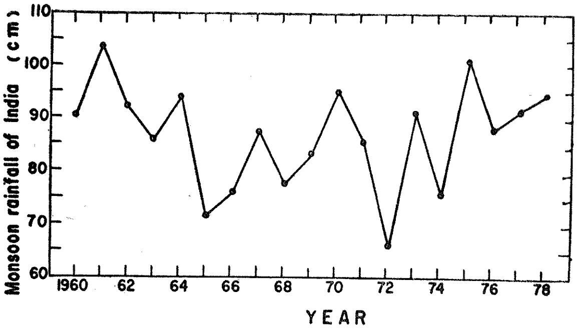

Fig. 3. Area weighted monsoon rainfall of India in cm (1960-1978)

[From Parthasarathy & Mooley 1978]

of ship weather observations made at main synoptic hours by the Voluntary Observing Fleet of about 40 maritime nations. The area of responsibility given to India is shown in Fig. 1. India thus gets meteorological observations from ships, checked by the Meteorological services of these 40 countries, for the area marked in Fig. 1 in the form of punched cards or magnetic tapes. India is responsible for publishing climatological tables for 17 'Selected Representative Areas' marked in the figure. Details regarding this scheme are given by Khorkao and Nene (1972).

2.2. Data in the form of monthly mean values of sea surface temperature (SST) for these 17 locations for the period 1961 to 1967 were made available to the author by the India Meteorological Department. The seven year monthly mean 1961-1967 has been taken to represent the normal in the absence of a longer series. This series contain data of 5 good monsoon years 1961 to 1964 and 1967, and two years of large scale monsoon failure 1965 and 1966. Analysis of the same SST data (1961-1967) has been done by Keshavamurthy *et al.* (1975).

2.3. From the similarity of month to month variation of SST, these 17 areas or locations were grouped into 8 groups and the mean of the SST for these groups are represented in Fig. 2. Locations 2 and 8 represent the regions of upwelling during the summer monsoon. SST rises from January and reaches a maximum in April and May. Thereafter SST falls sharply due to upwelling and reaches lowest temperature in August. The fall of SST from May to August is from 27.7 deg. C to 22.5 deg. C (*i.e.,* 5.2 deg. C). From September onwards SST begins to increase and reaches a second maximum in November. Locations 1 and 7 have similar features. According to Saha (1970, 1974) the cool waters produced over coastal Somalia and Arabia by upwelling spreads, due to ocean currents, to areas 1 and 7, and also to areas 3, 6 and 9. The SST variations at locations 1 and 7 are similar to those at 2 and 8. Here the SST reaches a maximum in May. From May to August there is cooling from 29.1 deg. C to 26.2 deg. C (*i.e.,* 2.9 deg. C). The second maximum is in October. The absolute values of SST are higher at 1 and 7 than at 2 and 8. At locations 3, 6 and 9 the SST lowering from May to August is from 29.7 deg. C to 27.6 deg. C (*i.e.,* 2.1 deg. C). The SST values are higher than those for locations 1 and 7.

2.4. For locations 5, 17 and 10 over the western part of Bay of Bengal, maximum SST is in May. There is a cooling of the sea from 29.7 deg. C in May to 28.3 deg. C in August (*i.e.,* through 1.4 deg. C). The SST is 28.4 deg. C in September and October and thereafter begins the winter cooling. Location 4 shows an area where the effects of pure solar heating is seen. Here upwelling and other monsoon effects are not seen

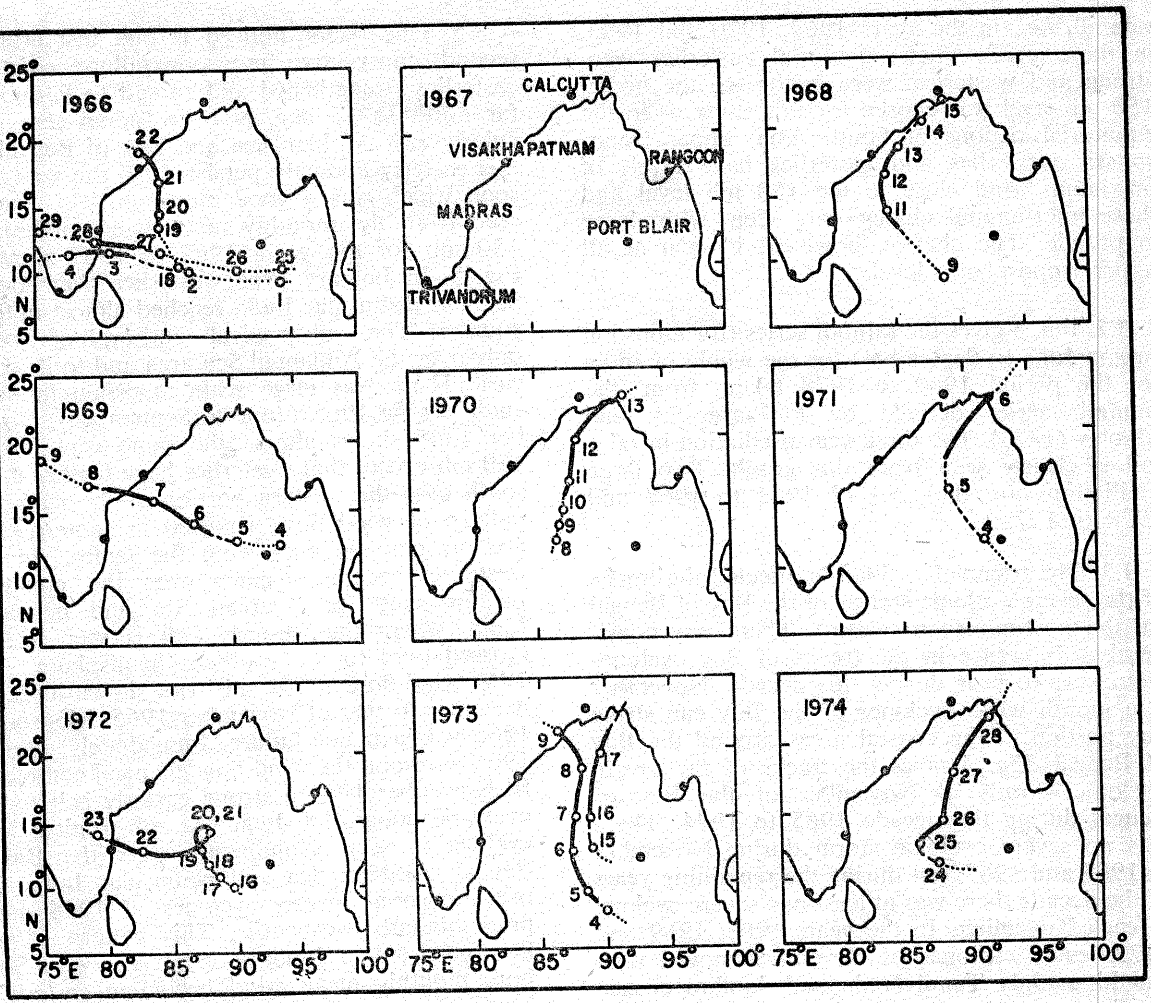

Fig. 4. Severe cyclones of November-Decade (1965-1974)

in contrast to areas discussed earlier. SST continues to increase during the monsoon months also. Location 11 is similar to locations 1 and 7 except that the pre-monsoon maximum in SST is reached in April and not in May. Locations 12 and 13 on the equator have very little annual variation in SST. Locations 14, 15 and 16 in the southern hemisphere Indian Ocean show a single maximum for SST in March and minimum in August as a southern hemisphere station under solar influence only.

2.5. The large contribution from the Arabian Sea to the moisture supply for the Indian summer monsoon have been highlighted by Pisharoty (1965) and Ghosh *et al.* (1978). Pisharoty has also pointed out that small changes in SST have profound influence on the amount of evaporation. From the analysis by Bavadekar and Mooley (1978) of the moisture flux through a wall along west coast of India from Trivandrum to Bombay, from ground level to 450 mb, it is seen that the moisture flux through the wall decreases from July to August. This decrease is most probably caused by the low SST values in August.

3. Three year oscillation over South Asia during decade 1965 to 1974

3.1. From a study of the monthly mean winds of the 150 mb level, Joseph (1975, 1976) found a regular north-south oscillation of the westerly wind belt (and a corresponding oscillation in the equatorial easterlies also) during the decade 1965 to 1974 over the equatorial region of Asia. The period of this oscillation was found to be 3 years. This triennial oscillation was found to be very pronounced over the Arabian Sea and adjoining peninsular India. This oscillation in wind which is described in detail later in this section was found to affect Indian monsoon rainfall. Large deficiencies of rainfall occurred over central and northwest India during the four monsoon months of June to September in the years 1965, 1966, 1968, 1972 and 1974. Minor deficiencies of rainfall occurred in 1969 and 1971. In between at regular intervals of 3 years the country had good rainfall, *i.e.*, in the years 1967, 1970 and 1973, in those years when equatorial easterlies were strong and westerlies were further to the north. 150 mb level was chosen for this study as in the equatorial regions of South Asia, upper tropospheric westerlies and easterlies have levels of maximum wind close to the 150 mb level and these inter-annual changes are seen with large amplitude. The change, however, is seen at all upper tropospheric levels.

3.2. Fig. 3 gives the rainfall series (for monsoon season June to September) for the whole of India for the period 1960 to 1978 taken from the rainfall series derived by Parthasarathy and Mooley (1978). The three year oscillation in rainfall is clearly seen from this graph. Two large oscillations are the ones of 1964 to 1967 and 1970 to 1973.

3.3. The triennial oscillation affected the tracks of the severe cyclonic storms of the Bay of Bengal (in the post-monsoon season). There was considerable difference in the tracks of Bay cyclones from year to year during this decade. November is a month when cyclones of the Bay can strike any portion of the coastal areas around the Bay of Bengal. Fig. 4 gives the tracks of the severe cyclonic storms of November of the Bay of Bengal during the decade 1965 to 1974. There was no severe cyclonic storm during November in 1965 and 1967, but during the remaining years of the decade there was at least one severe cyclone in each November. In the years 1966, 1969 and 1972 severe cyclones of November moved west and hit mainly Tamil Nadu and Andhra coasts. In the remaining years of the decate severe cyclones had northerly movement and they affected West Bengal, Bangladesh etc. A three year oscillation in the tracks of the cyclones is clearly seen. The northerly movements of cyclone occurred during the periods when equatorial easterlies were weak and the sub-tropical westerlies intruded southwards into the tropics. Although, in the years 1965 and 1967 there were no severe cyclones in November, the severe cyclones that occurred in October and December in both these years moved northwards only, in accordance with the 3-year oscillation in winds.

3.4. It is seen that the predominantly north or west movement of the Bay severe cyclones is not in the month of November only; the whole post-monsoon season is affected by it. In 1970, 1971 and 1973 the severe cyclones of the months October to December moved northwards whereas in 1972 all the severe cyclones of October to December moved westwards. This persistence in a season is a very interesting aspect of cyclone motion over the Indian seas. It shows that cyclone motion in a given season is not random and there is possibility for evolving schemes for seasonal forecasting of cyclone tracks.

3.5. One factor noticed is that just after the second consecutive monsoon failure, equatorial easterlies strengthened and spread to latitudes as far north as 15 deg. N over Indian seas particularly east Arabian Sea and Bay of Bengal and this easterly anomaly persisted till the next monsoon which was a good monsoon. This may be seen from the monthly mean wind analysis for 150 mb for the years 1965 to 1967 shown in Fig. 5. In January 1965 westerlies over Arabian Sea and peninsular India reached almost upto the equator. The sub-tropical anti-cyclone existed only over the Andaman Sea area and to its southeast. There was large scale monsoon failure in India during 1965 (June to September). November 1965 shows almost the same wind flow at 150 mb except that westerlies have further moved south over the western portion of the map. This pattern of wind flow persisted in January 1966 also as may be seen from the figure. In fact, westerlies became stronger over the equatorial regions south of Arabian Sea and peninsular India, where the westerly belt is seen to have crossed over to the southern hemisphere. April 1966 wind flow at 150 mb (not shown in figure) is similar to that of November 1965. Monsoon of 1966 was a major failure. Immediately after the 1966 monsoon the wind flow changed completely. In November 1966 a strong easterly belt formed over the equatorial area. A sub-tropical anticyclone is seen prominently over the Bay of Bengal. Arabian Sea and peninsular India. The post-monsoon severe cyclones of 1966 moved predominantly westwards. This pattern of wind flow persisted in January 1967 also with Singapore monthly mean wind becoming easterly 45 knots. On many days in January 1967, an easterly jet stream with maximum wind level near 150 mb and with wind speeds of 80 to 100 knots was seen over south Bay of Bengal and southeast Arabian Sea. The monsoon of 1967 was good and immediately after that the wind flow reverted back to the type that existed in 1965. After two consecutive monsoon failures, a major change in the upper tropospheric wind flow occurred and the monsoon of the third year was good. Soon after the good monsoon of the third year the wind flow reverted back. Such a change was noticed during the rest of the decade 1965-74 also.

3.6. 1971 and 1972 were bad monsoon years (1972 had a severe monsoon failure). The wind flow of April 1971, November 1971, January 1972 and April 1972 have common features of prominent westerly winds over Arabian Sea and peninsular India, weak equatorial easterlies and the existence of the subtropical anti-cyclone only over the extreme southeastern portion of the chart. The wind flow pattern changed considerably immediately after the monsoon of 1972. In November 1972 the sub-tropical anti-cyclone is seen over Bay of Bengal, Arabian Sea and peninsular India along with a strong easterly belt near the equator. All the post-monsoon severe cyclones

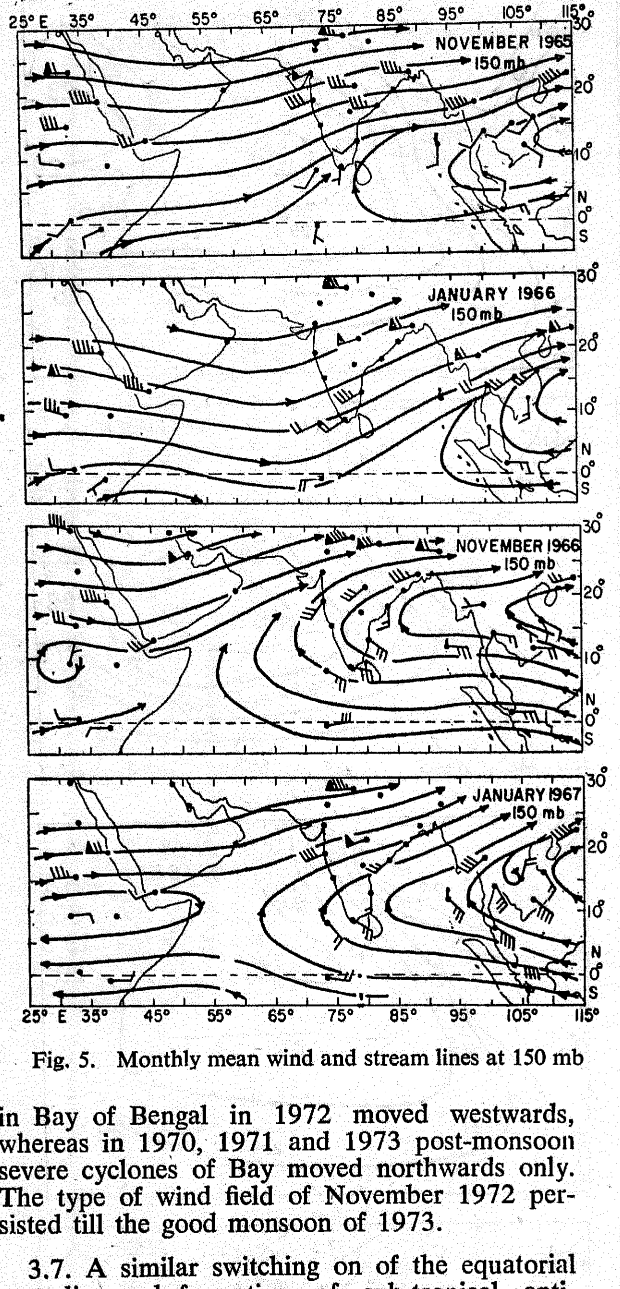

Fig. 5. Monthly mean wind and stream lines at 150 mb

in Bay of Bengal in 1972 moved westwards, whereas in 1970, 1971 and 1973 post-monsoon severe cyclones of Bay moved northwards only. The type of wind field of November 1972 persisted till the good monsoon of 1973.

3.7. A similar switching on of the equatorial easterlies and formation of sub-tropical anticyclone over Bay of Bengal, Arabian Sea and peninsular India is seen in 1969 also, immediately after two consecutive monsoon failures, *i.e.*, 1968 and 1969 monsoons.

4. SST variation during 1964 to 1967

4.1. Monthly values of SST for the 17 climatological locations of north Indian Ocean during May and September of the years 1964 to 1967 are shown in Figs. 6(a-d). Isolines of SST are drawn at 1 deg. C intervals (continuous lines) and occasionally at half degree intervals (broken line). May was chosen as it is the month just before the monsoon season begins and it is the warmest month in SST over Arabian Sea and Bay of Bengal. September shows the accumulated action of the monsoon on SST, particularly the effects of upwelling.

4.2. In May 1964 east Arabian Sea and Bay of Bengal are very warm. Maximum SST over east Arabian Sea is 30.3 deg. C and over Bay of Bengal 30.4 deg. C. The 30 deg. C isoline covers a large area of east Arabian Sea and Bay of Bengal. The upwelling over locations 2 and 8 during the good monsoon of 1964 cooled those areas considerably, particularly location 8. The tongue of cold water is seen extending to the southeast Arabian Sea. In general, the whole Arabian Sea had cooled to varying degrees by September 1964. The surface sea currents over Arabian Sea during May to August may be seen from Saha (1974). Whether the cooling of the Arabian Sea is mainly due to the spreading eastwards of the upwelled cold waters as suggested by Saha (1974) has to be investigated. There is a 29 deg. C isoline over the Bay of Bengal in September 1964. The monsoon cooling of Bay in 1964 has only been slight.

4.3. The effect of the large cooling in the Arabian Sea during the monsoon of 1964 persisted till May 1965. Locations 3 and 6 are colder in 1965 May, than in 1964 May by 0.6 deg. C to 0.9 deg. C. Arabian Sea did not have a 30 deg. C isoline of SST in May 1965. Bay of Bengal continued to be warm in May 1965. The monsoon of 1965 was a failure. A bad monsoon is likely to have weaker surface winds over the Indian seas and therefore reduced upwelling. This contention which remains to be verified is indirectly supported by Krishnamurthy *et al.* (1976). They find that in the drought year of 1972 the seasonal mean Somali low level jet as shown by the 850 mb wind of Mogadiscio (Somalia) was much weaker than that of the near-normal rainfall year of 1973.

4.4. That weaker upwelling took place in the monsoon of 1965 may be inferred from the temperature change from May to September 1965 in Arabian Sea particularly at location 8. Locations 3 and 6 showed slight cooling in September 1965, but west and southeast Arabian Sea were warmer than in September 1964; Bay was slightly colder in September 1965.

4.5. In May 1966 east Arabian Sea continued to be cold as in May 1965. Bay of Bengal is considerably colder than May 1965; maximum temperature in the Bay is only 29.3 deg. C. Monsoon of 1966 was again a major failure. By the end of this monsoon the whole of the Arabian Sea and Bay of Bengal warmed considerably. The progress of the warming at locations 8 and 7 from September 1964 to September 1965 to September 1966 is interesting to see. In Septem-

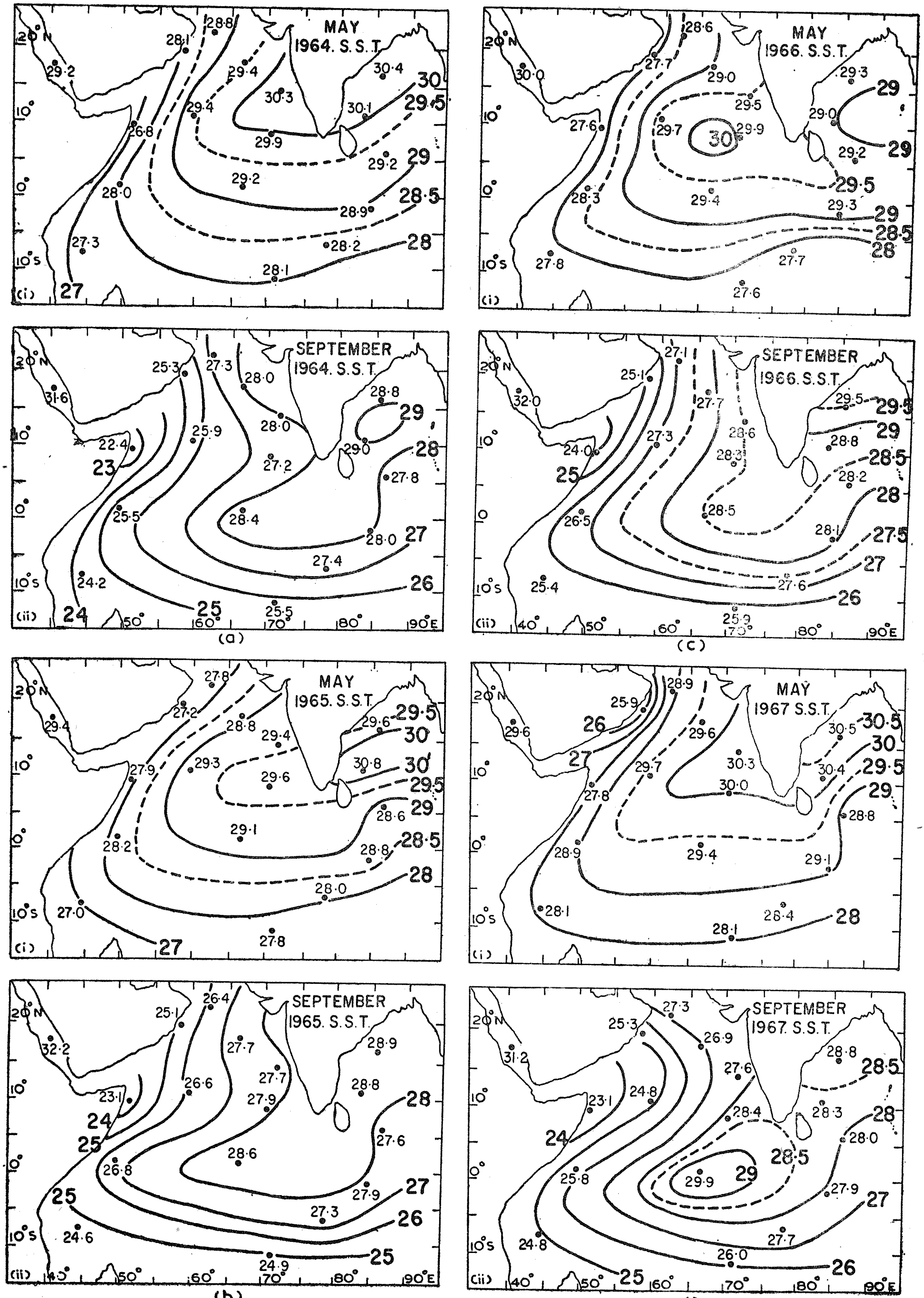

Fig. 6 (a-d). Monthly mean SST (°C) at "selected representative areas" and the SST isotherms of May and September, 1964 to 1967 ber 1966 east Arabian Sea and the whole of Bay of Bengal and the adjoining equatorial ocean areas are above 28 deg. C, Bay of Bengal being considerably more warm. This warmth of the sea areas is the most likely cause for the development of the strong equatorial easterlies and the prominent sub-tropical anti-cyclone seen over the Indian seas in November 1966 and January 1967 in Fig. 6b. In May 1967 east Arabian Sea and the Bay of Bengal were covered by 30 deg. C isoline of SST as in 1964 May. 1967 monsoon was a good monsoon. This good monsoon again cooled the Arabian Sea as may be seen from the SST in September 1967. The cold tongue has covered a vast area of Arabian Sea in 1967 monsoon and locations 8, 7 and 3 cooled maximum (from September 1966 to September 1967).

SST data obtained from ship observation published in *Indian Daily Weather Reports* were studied for the period 1970-1973. 1970 and 1973 were good monsoon years. In 1971 monsoon rainfall was slightly below normal and 1972 had a severe monsoon failure. It was found from the available SST observations that the Arabian Sea and Bay of Bengal had warmed considerably by September 1972.

5. Discussion

5.1. From sections 3 and 4 the following inferences may be drawn.

(a) There was an unmistakable three year oscillation in the large scale monsoon rainfall of India and the tracks of post-monsoon severe cyclones of the Bay of Bengal during the decade 1965 to 1974.

(b) The overall picture of 150 mb wind flow over south Asia during the decade 1965 to 1974 is that the westerly wind belt intruded to very low latitudes. In fact, in 1966, 1968 and 1972 in winter months, northern hemisphere sub-tropical westerlies had even crossed over to the southern hemisphere over Arabian Sea longitudes. In most of these years equatorial easterlies were weak. This may be compared to the strong mean equatorial easterlies near the equator during the epoch of good Indian monsoon 1958 to 1964 (Newell *et al.* 1972).

(c) The deeper intrusion of westerlies into south Asia is responsible for the large scale monsoon failures India experienced many times during the decade 1965 to 1974. It was also responsible for the preferred northward movement of the severe cyclones of the Bay of Bengal of the post-monsoon season (Joseph 1978b).

(d) Two monsoon failures in succession warmed the entire Arabian Sea and Bay of Bengal. The exact cause of the warming is under investigation. It is seen that upwelling during monsoon over Arabian and Somali coastal areas has a big control on the temperature over the Arabian Sea. Whether Sea currents have a role in spreading the warmth due to reduced upwelling as far as Bay of Bengal, has to be critically studied. Other factors like surface wind and associated vergence, evaporative cooling, cloud cover over the area etc have also to be studied.

5.2. Increased convection over the warm set areas of Arabian Sea and Bay of Bengal (*see* Bjerknes 1969) may be responsible for the formation of a persistent anti-cyclone over the Indian seas and peninsular India immediately after two consecutive monsoon failures. There is considerable support for this from a recent numerical study for the tropical Pacific Ocean by Julian and Chervin (1978). Imposing a 1-2 deg. C EL-Nino caused warm SST anomaly over the tropical east Pacific on the normal SST values used in the NCAR 5 deg. grid global atmospheric model, they found that the warm SST anomaly generated a strong easterly wind anomaly over the area of SST anomaly, with simultaneous westerly wind anomalies to the north and south, in effect anomalous anti-cyclones formed to the north and south of the warm SST anomaly.

5.3. Increased warmath of the Arabian Sea could increase the moisture supply to the monsoon heat engine considerably as may be seen from the study of Saha and Bavadekar (1977). They computed moisture flux across west coast of India from Trivandrum to Bombay from 1000 mb to 450 mb during the monsoon months of June to September of 1964 to 1972. This data along with the rainfall series given by Parthasarathy and Mooley (1978) are given below :

	Year		
	1964	1965	1966
Total flux of water vapour*	356.24	307.44	248.88
Monsoon rainfall of India**	94.32	71.81	76.54
	1967	1968	1969
Total flux of water vapour*	383.08	372.10	333.06
Monsoon rainfall of India**	87.57	78.12	83.72
	1970	1971	1972
Total flux of water vapour*	420.90	356.24	294.02
Monsoon rainfall of India**	95.56	86.56	66.29

*Unit of flux is 10^{10} tons

**Unit of rainfall is cm

The SST values of Arabian Sea are not yet available for the whole series 1964 to 1972. But from the warm SST over Arabian Sea in May 1964 and May 1967 and the cold SST in 1965 May and 1966 May as seen from section 4, it may be inferred that Arabian Sea has a considerable role in the making of a good monsoon or a monsoon failure, through moisture supply alone.

5.4. Angell and Korshover (1978) and Yamamoto and Hoshiai (1979) find a three year oscillation in global temperature of the tropics during the decade 1965 to 1974, the former in the troposphere where a 0.3 deg. C amplitude is seen and the latter in the surface temperature where the amplitude is 0.1 deg. C. These authors have postulated different causes for the 3 year oscillation which is considered distinctly different from the familiar quasi-biennial oscillation. It is suggested that the 3 year oscillation in temperature observed by them may also be partly due to the large 3 year oscillation of the Asian monsoon caused by the ocean-atmosphere interaction described in this paper.

6. Difference between sub-Saharan African and Indian rainfall

7.1. According to Winstanley (1973) the altitude of the 500 mb surface along latitude 40 deg. N between longitudes 110 deg. W and 70 deg. E began decreasing since 1960 and it signified an increase in the southward extent of the troughs in westerlies. These westerly intrusions according to him, reduced the summer monsoon rainfall of the areas to the south of Sahara and in southwest Asia (including northwest India). Jagannathan and Khandekar (1962) found high positive correlation between 500 mb altitude of Jodhpur and Delhi in March with subsequent monsoon rainfall. Joseph (1976) found the 500 mb height variations of Jodhpur, Delhi and Nagpur of January to March almost paralleling the variations of April and May (*See* Van de Boo Gard 1977). There has been a change of radiosonde type in 1968 at these 3 Indian stations, but the temperature changes due to this change of instrument type is very small at lower tropospheric heights. Moreover, the change is at around the lowest point of the graph). In the decade 1965 to 1974, 500 mb values are low, which could be taken as an index of intrusion of sub-tropical westerlies into lower latitudes. Thus this study supports Winstanley's picture. Keshavamurthy and Awade finds low thickness field (300 mb to 1000 mb) over southern USSR as the cause of the 1972 monsoon failure. This also forms part of the same picture.

6.2. The sub-Saharan region of Africa (areas like Sahel) experienced deficit rainfall during every year from 1966 to 1974 (with the year 1972 having the largest deficit) as seen from the rainfall analysis of Kraus (1977). The semi-arid regions of India also experienced drought during the same period. But there is a major difference between the droughts of these two areas. While the drought of Sahel and other sub-Saharan areas was year after year from 1966 to 1974, in India the generally bad monsoon decade of 1965 to 1974 was broken by normal monsoon once every three years 1967, 1970 and 1973. According to Kraus (1977) such long runs of dry and wet years have occurred in Sahelian belt earlier also, but a study of Indian monsoon rainfall of 1875 to 1974 by Banerjee and Raman (1976) has shown that no interval between successive good monsoon years has exceeded 4 years. Thus long runs of dry (deficient monsoon) years have not occurred in India. According to Kidson (1977) low rainfall of Sahel has been paralleled by a weakening of the northern hemisphere circulation. Therefore, this difference between the recent series of droughts in India and Sahel, pointed out by Joseph (1978 a), could be due to the ocean-atmosphere interaction described in this paper, a blessing indeed for India.

7. Conclusions

In this study using the available SST data, the phenomenon of ocean-atmosphere interaction over north Indian Ocean affecting Indian monsoon and cyclones has been studied. Since SST at a few points far apart were only available, the analysis of SST presented in Fig. 6 has not brought out small scale features. It is also a qualitative and a preliminary study on the subject. A quantitative study using 5 degrees square averaged values of sea surface temperature, sea level atmospheric pressure, air temperature, cloudiness, wind velocity etc using ship data of the period 1964 to 1973 over the north Indian Ocean is being made. However, this preliminary study has been able to bring out the great importance of air-sea interaction on a seasonal scale in relation to Indian monsoon rainfall and cyclone tracks.

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