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Satellite derived sea surface temperature distribution over the north Indian Ocean during the southwest monsoon season

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ABSTRACT. Sea surface temperatures derived from spectral radiance data in infra-red window region obtained from NOAA-5 and TIROS-N meteorological satellites for 3 years have been utilized to study their distribution over the north Indian Ocean during the southwest monsoon season. It is observed that in a normal monsoon season in the Arabian Sea, cold waters with sea surface temperature (SST) less than 28 deg. C start moving from equatorial region towards north or northeast by the early May, forming the southwest monsoon current. Simultaneously SST's off Somali coast start falling, marking the beginning of Somali current. These cold currents get well organized in June and continue through monsoon months till they disintegrate during September. Frequently, the axis of the cold current extends upto the west coast of India and shows forking over the Arabian Sea, similar to that observed by Findlater (1971) in the low level wind field. The lowest SST's in the season are about 22 deg. C, observed off Somali coast during July and August. On the other hand, the delayed onset of monsoon and subsequent weak monsoon activity over India in the year 1979 were associated with delay in the appearance of cold waters off Somali coast, and the delayed and weaker Somali current. Also, SST's off Somali coast were 2-3 deg. C higher than those prevailing in the normal monsoon seasons. In the Bay of Bengal SST's generally fall with the advance of monsoon, leaving a flat temperature distribution. Complex SST patterns, apparently dominated by transients, were observed during the monsoon season. Generally, warmer SST's prevailed over the north Bay with colder waters at lower latitudes.

1. Introduction

The temperature distribution over the sea surface is the result of a combination of factors like effective solar radiation absorbed by sea, air-sea interaction resulting in sensible heat loss and evaporation cooling at the sea surface, depth of ocean mixed layer, vertical and horizontal advection of water, and wind-induced circulation. The cooling of Arabian Sea surface during the summer monsoon season stands out in contrast with the warming of other tropical sea areas during the summer, and has not been fully understood.

The upwelling of cold sub-surface water off Somali coast during the southwest monsoon season, and its advection over the Arabian Sea as Somali current, has been reported by several workers (Swallow & Bruce 1966; Warren *et al.* 1966; Bruce 1970). Somali current is an unsteady ocean current driven by the frictional stress caused by the low level southwesterly winds crossing the equator (Lighthill 1969). It flows northward along the coast from the neighbourhood of equator to about 9 deg. N, where it separrates from the coast. The Somali current achieves its maximum speed within a month from the onset of the forcing (Lighthill 1969), a short time scale consistent with Leetma (1972). At the same time, the cold waters of the south equatorial current in the western Indian Ocean cross the equator and flow into the Arabian Sea as southwest monsoon current, at times merging with the Somali current. Saha (1970) has concluded that the cold waters brought to surface by upwelling off Somali coast spread eastward in the Arabian Sea with the advance of southwest monsoon season.

The earlier studies were based on sea surface temperature (SST) observations obtained from ship reports which were sparse both in space and in time. The measurements of representative sea surface temperature, maintaining essentially a continuity in space and time, have been possible

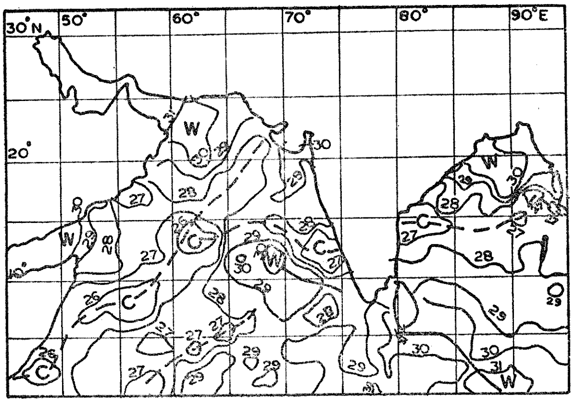

Fig. 1. Satellite derived sea surface temperature distribution on 21 June 1977, showing the Somali current and further spread of cold waters northeastwards, with the axis of cold waters forking out east of Long. 60 deg. E

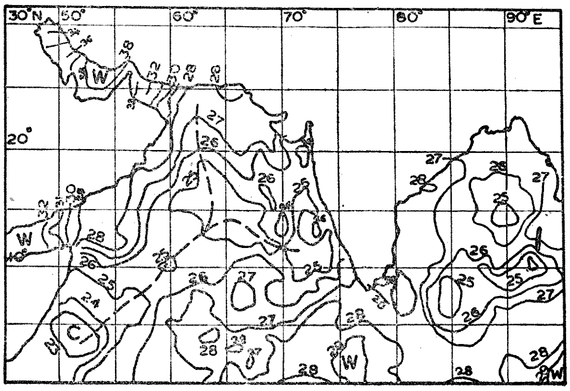

Fig. 2. Satellite derived SST distribution on 26 July 1977 showing well organised Somali current with coldest SST's of 23 deg. C, and spread of cold waters upto the Indian coast

for the first time only after the advent of meteorological satellites employing infrared radiometers. The present paper discusses the distribution of satellite-derived sea surface temperatures over the north Indian Ocean and the Indian seas during southwest monsoon season and their relationship with the monsoon activity over India.

2. Data

SST's used in this study have been derived from the spectral radiance in the infrared window channel at 10.5-12.5 μ m wavelength, measured by radiometers on-board the polar-orbiting meteorological satellites NOAA-5 and TIROS-N. SST's are computed once per day using an automated procedure known as Global Operational Sea Surface Temperature Computation (GOSST-COMP) as described by Brower *et al.* (1976) and Walton *et al.* (1976). The procedure includes temperature retrievals from spectral radiance after applying statistical analysis and quality control checks to the data, correction for the effects of atmospheric attenuation by using time coincident measurements derived from Vertical Temperature Profile Radiometer (VTPR), and generation of contoured maps of the analysed sea surface temperature field. The satellite derived SST's are the mean values computed for each block area of about one degree in latitude and longitude. The contoured maps therefore do not show small-scale structure in the SST distribution. The global daily mean difference between satellite-derived SST's and ship reports has been found to vary from -0.9 deg. C to 0.4 C, with RMS variation varying between 1.67 deg. C and 2.23 deg. C most of variance coming from ship observations (Brower 1976). The daily temperature maps for the years 1977, 1978 and 1979 obtained from National Environmental Satellite Service of USA were used as basic data for the present study. The following sections describe the characteristics of sea surface temperature distribution over the north Indian Ocean for the three successive summer monsoon seasons.

3. SST distribution during the summer of 1977

3.1. *Arabian Sea*

3.1.1. During the month of April, the sea waters north of equator started warming up and the SST maximum progressively shifted northward from the equatorial Indian Ocean. In early May, the warmest SST's exceeding 31 deg. C were established over north Arabian Sea and Persian Gulf, with temperatures decreasing southward. SST's off Somali coast were 28-30 deg. C. By the middle of May the cold waters from equatorial region started moving northward indicating the initiation of the southwest monsoon current. Simultaneously SST's off Somali coast started falling and cold waters spread towards northeast. By the end of May 1977 the Somali current became better organised. In the south Arabian Sea, the axis of cold waters was roughly oriented in west to east direction between latitudes 8 deg. N and 11 deg. N.

3.1.2. In June, SST's off Somali coast continued to fall and the Somali current strengthened. The cold waters crossing from the south of the equator at times appeared to merge with it and spread towards northeast and east upto the west coast of India. East of latitude 60 deg. E, the axis of cold water showed a fork-like structure, with one branch extending upto north Gujarat coast, and the other extending up to Karnataka coast and terminating into a cold pool. The SST distribution of 21 June 1977 (Fig. 1) shows these features.

3.1.3. The spread of cold waters from the equatorial west Indians Ocean northeastward continued in July. The cold SST axis ran from south Somali coast upto Gujarat-Maharashtra coast. The forking in the cold water axis along

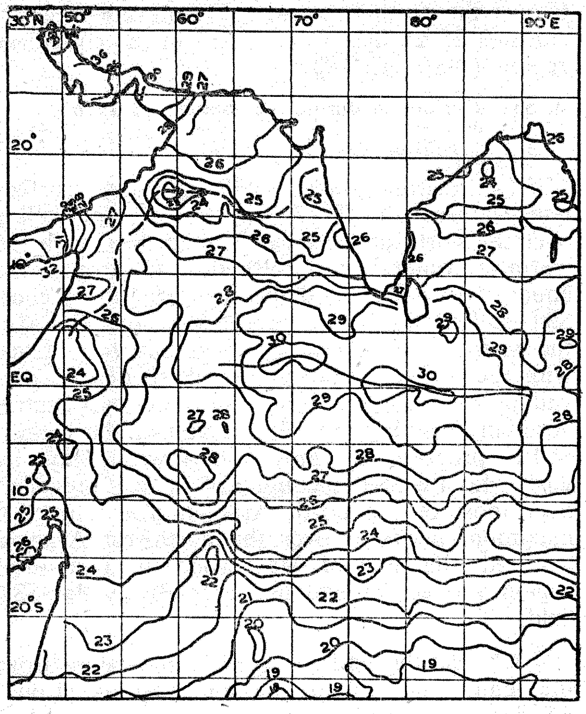

Fig. 3. Satellite derived SST distribution on 30 August 1977 showing the warming of equatorial Indian Ocean, westward shift of the cold current in the Arabian Sea, and a cold pool off Arabian coast

with the cold pool in northeast Arabian Sea persisted till mid-August although with considerable variations in location and intensity. In July, SST's along the equator were 24-25 deg. C off Somali coast, and 27-29 deg. C in the region east of 65 deg. E. These features are seen in the SST chart of 26 July 1977 (Fig. 2). In July and early August, the location of the southwest monsoon current, *i.e.*, the cold water axis, had the Arabian Sea gyre south of Lat. 10 deg. N.

3.1.4. By early August warming of sea waters was observed in the equatorial region between longitudes 60 deg. E and 95 deg. E as also in southeast and central Arabian Sea. The associated SST ridge got progressively organised in east-west direction, pushing the cold water axis westward closer to Arabia coast by the mid-August. Simultaneously a cold pool formed off Arabia coast around 17 deg. N. This upwelling off Arabia coast lasted only for 2 weeks during the second half of August, and had lowest SST of 23 deg. C associated with it on 30 August 1977 (Fig. 3).

3.1.5. The SST off Somali coast fell progressively from 28 deg. C in the middle of May till the end of July. They fell to 27 deg. C by the May end, 24 deg. C by the June end, and 23 deg. C by the July end. They were 23-24 deg. C in August. The Somali current, which had got organised by the end of May, started disintegrating by the beginning of September and disappeared after two weeks when SST's rose to 26 deg. C. In the sea area off Somali coast, the lowest temperatures prevailed near the equator. Their variations during the monsoon months (Table 1) show the intensity of the Somali current.

TABLE 1

Lowest sea surface temperatures (°C) prevailing off Somali coast between equator and 5 deg. N

Year	Apr	May	Jun	Jul	Aug	Sep	Oct
1977	28	27	24	23	23	25	26
1978	27	25	25	24	22	24	26
1979	27	27	26	25	25	26	26

TABLE 2

Lowest sea surface temperatures (°C) off Kerala coast

Year	Apr	May	Jun	Jul	Aug	Sep	Oct
1977	28	27	27	25	26	26	27
1978	28	29	27	26	26	26	27
1979	28	28	28	27	27	27	27

3.1.6. In September the west to east SST gradient was progressively reduced, but the warm SST ridge in the equatorial regions east of 60 deg. E continued to be significant. By early October, northeast Arabian Sea warmed upto 31 deg. C so that an east-west oriented cold water axis was formed in the central Arabian Sea. This axis moved southward to 5 deg. N by the month end.

3.1.7. Upwelling was observed off Kerala coast from the middle of May till the end of July. The resulting cold waters had the lowest SST of 25 deg. C towards the end of July 1977 (Table 2).

3.2. *Bay of Bengal*

3.2.1. In April the warm SST ridge moved from equatorial region northward. By the beginning of May the highest SST's of 30 deg. C were established over the north Bay of Bengal with temperatures decreasing southward. The cold water axis, having the lowest SST's of 27 deg. C, was oriented roughly along Lat. 10 deg. N. The warm SST's in north Bay continued till the middle of July. The cold water axis shifted northward upto about 16 deg. N by the June end. This pattern of SST distribution is seen in Fig. 1.

3.2.2. In July there was a general fall of SST's and the warm temperatures over the north Bay disappeared after the middle of the month (Fig. 2). The lowest SST of 24 deg. C was observed in south Andaman Sea. Cold SST's of 24-26 deg. C were also observed off Andhra-Orissa coast from mid-August to mid-September. However during the period July-September complex patterns were observed in the Bay, without any systematic changes.

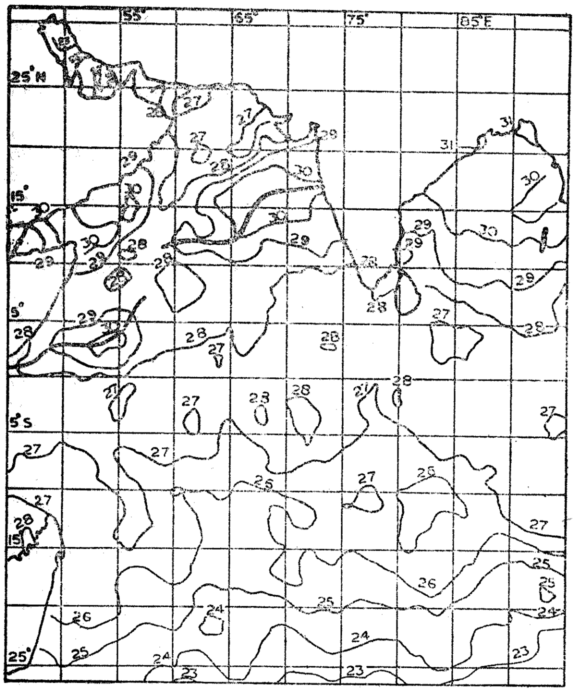

Fig. 4. Satellite derived SST distribution on 11 April 1978 showing the *in-situ* warming of sea surface north of equator

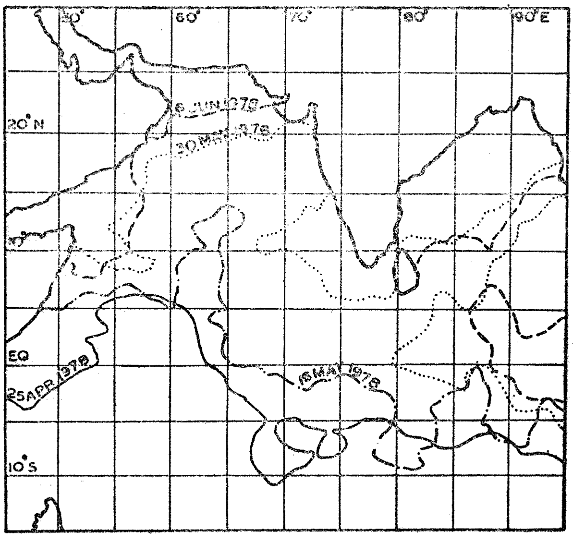

Fig. 5. Northward spread of cold waters as seen by the movement of 28° C SST isotherm from 25 April 1978 to 6 June 1978. The 28°C isotherm on different dates is shown as :

25 April 1978 ————————
16 May 1978 —— . —— . ——
30 May 1978 ....
6 June 1978 — — — — — — —

3.2.3. In October, SST's again rose to 30 deg. C over the north Bay and cold waters with temperatures 25-26 deg. C prevailed in the equatorial region (0-10 deg. N).

4. SST distribution during the summer of 1978

4.1. *Arabian Sea*

4.1.1. During March 1978 cold sea surface temperatures of 25-27 deg. C were prevailing over the north and central Arabian Sea, with the warmest waters of 29-30 deg. C around the equator. In early April the region of the highest SST shifted northward across the equator. Also the *in-situ* warming of Arabian Sea took place with the highest temperatures of 30 deg. C prevailing off Somali coast and in east-central Arabian Sea (Fig. 4). The region of the highest SST's progressively moved northward, any by early May the SST maximum of 31 deg. prevailed over most of the north Arabian Sea. The SST maximum persisted over the northwest Arabian Sea till the end of May while the equatorial region was colder and had a relatively flat SST field.

4.1.2. By the end of April, cold waters from the equatorial Indian Ocean west of Long. 65 deg. E started moving towards north and northeast. This is shown by the progressive movement of 28 deg. C SST isotherm from 25 April 1978 to 6 June 1978, till it reached Lat. 22 deg. N upto north Gujarat coast (Fig. 5). This incursion of cold waters northward upto 15 deg. N is shown by the SST chart of 16 May 1978 (Fig. 6). The cold waters had spread over practically whole Arabian Sea by early June. The axis of cold water, *i.e.*, the lowest SST's, showed intermittently a fork-like structure over the east and central Arabian Sea from early June till the middle of August.

4.1.3. A pool of cold waters in southeast Arabian Sea off Kerala coast persisted from 27 June to 18 July when cold waters spreading from southwest Arabian Sea eastward reached the Kerala coast. It had the lowest temperature of 26 deg. C during July (Table 2).

4.1.4. Upto 16 May 1978, SST's of 27-30 deg. C prevailed off Somali coast, with the temperatures decreasing equatorward. Subsequently the temperatures started falling. They fell to 26 deg. C by the end of May, 25 deg. C by the end of June, 24 deg. C by the early July, and 22 deg. C by the end of August (Table 1). The low temperatures off Somali coast were accompanied by well organised Somali current and further incursion of cold waters northeastward upto Gujarat coast, as seen in the SST chart of 29 August 1978 (Fig. 7).

The temperatures off Somali coast started rising in early September and the Somali current disintegrated shortly afterwards.

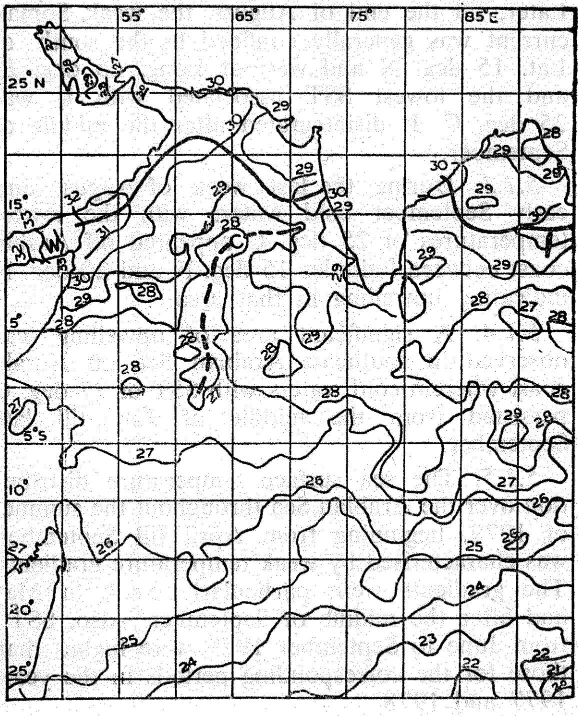

Fig. 6. Satellite derived SST distribution on 16 May 1978 showing the advance of cold waters in the Arabian Sea

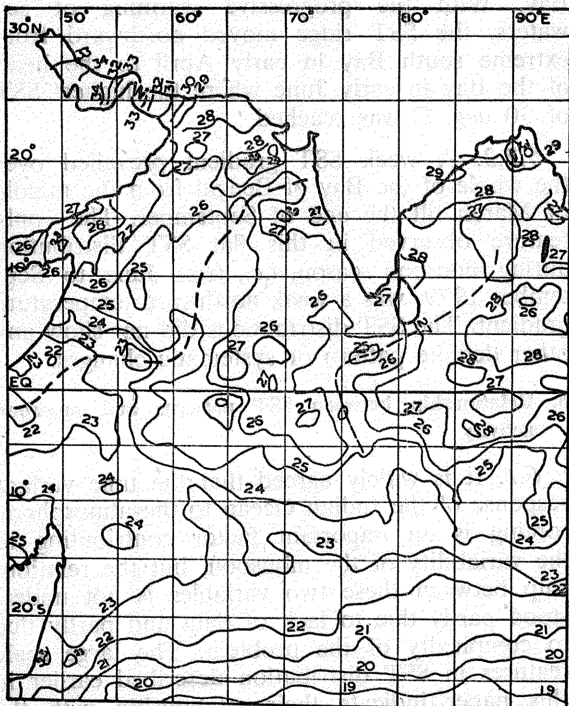

Fig. 7. Satellite derived SST distribution on 29 August 1978 showing the advection of cold water upto Maharashtra coast in the Arabian Sea, and into the Bay of Bengal

4.1.5. In October, a flat SST field of 26 28 deg. C prevailed over whole of the Arabian Sea. SST's rose over the north Arabian Sea later in the month.

4.1.6. No evidence of a cold SST pool and hence that of large-scale coastal upwelling was observed in the sea area off Arabia coast during the monsoon season of 1978.

4.2. *Bay of Bengal*

4.2.1. During March 1978 cold waters of about 27 deg. C prevailed over the north and central Bay of Bengal and warm waters of 29-30 deg. C around the equator. In April, *in-situ* warming of the north and central Bay took place so that the SST gradient was reversed (Fig. 4). In May the warm SST ridge lay over the central Bay and was generally oriented along west to east direction. In June the SST ridge reached its northernmost position at the Head Bay, where the highest temperatures of 30-31 deg. C existed. The incursion of cold water from the equatorial Indian Ocean between longitudes 75 deg. E and 85 deg. E and its spread northeastward into the Bay of Bengal and Andaman Sea was indicated in the month of June.

4.2.2. From July to September flat SST field with weak temperature gradients prevailed in the Bay. The SST distribution showed complex patterns and no systematic changes were noticed.

5. SST distribution during the summer of 1979

5.1. *Arabian Sea*

5.1.1. In the month of March cold waters with temperatures of about 25 deg. C prevailed over the north Arabian Sea, with SST's increasing towards south and southeast. By the end of March, the sea area north of equator gradually warmed up and the east-west oriented SST ridge shifted northward from equator to about 15 deg. N. The ridge practically maintained this position till early May and the gradual warming of sea water north of equator continued. During May a flat SST distribution of 28-30 deg. C with very weak temperature gradients set in whole of the Arabian Sea. Temperatures in the Persian Gulf and the Gulf of Aden were higher than 30 deg. C, and those off Somalia coast were 28-29 deg. C (Fig. 8).

5.1.2. Sea surface temperatures off Somali coast started falling by mid-June, forming a feeble tongue of cold waters with temperatures 26-27 deg. C along the coast. SST's in this region fell to 25 deg. C by 10 July 1977 and the cold waters started spreading northeastward as Somali current (Fig. 9). However, weak temperature gradient prevailed over most of the Arabian Sea. The cold Somali current weakened thereafter. In whole of the monsoon season of 1979, it appeared to be most intense around 10 July 1979.

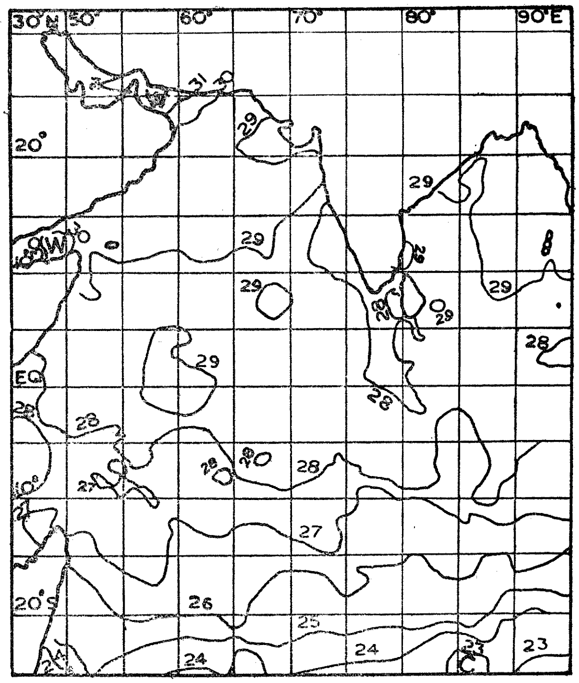

Fig. 8. Satellite derived SST distribution on 29 May 1979 showing a weak SST gradient north of Lat. 5°S

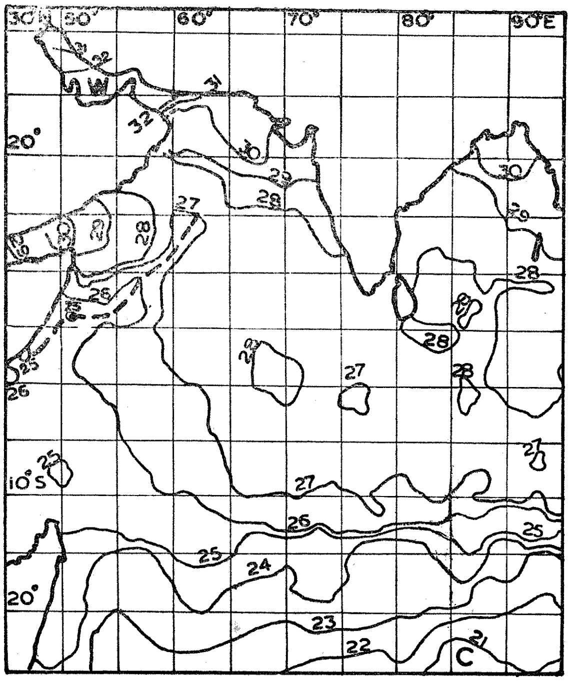

Fig. 9. Satellite derived SST distribution on 10 July 1979 showing weak Somali current during the monsoon season of 1979

Later, till the end of August, the weak Somali current was generally confined to the south of Lat. 15 deg. N and west of Long. 65 deg. E, and the lowest SST associated with it was 25 deg. C. It disintegrated after the middle of September.

5.1.3. During the last week of August and early September cold waters with the lowest temperatures of 25 deg. C appeared off Arabia coast between latitudes 15 deg. N and 20 deg. N indicating upwelling in that area.

5.1.4. A significant area of upwelling was observed in southeast Arabian Sea off Kerala coast wherein cold waters with SST of 27 deg. C persisted from the middle of July till late September.

5.1.5. The sea surface temperature distribution over the Arabian Sea throughout the summer of 1979, beginning from April till September, was characterised by weak temperature gradients. The gradients were particularly weak in May and after the middle of September. Also, SST's from June to September 1979 were higher than those for the corresponding periods in the years 1977 and 1978.

5.2. *Bay of Bengal*

5.2.1. In March SST's of 27 deg. C prevailed over the north Bay of Bengal with warmer waters of 29 deg. C around the equator and in south Bay. With the progressive warming of sea waters, the SST ridge moved northward from extreme south Bay in early April to the head of the Bay in early June where the highest SST of 30 deg. C was reached.

5.2.2. A week SST gradient prevailed over the whole of the Bay of Bengal from the middle of March till the end of September. The only feature observed in this flat SST distribution during monsoon season, *i.e.*, from June to September 1979, was a weak northward temperature gradient. The SST distributions did not show any other definite pattern or systematic changes.

6. Relationship between SST patterns and monsoon activity

6.1. It is widely agreed that the time variant response of the Indian Ocean to the atmospheric forcing is an important factor contributing to the variability of the monsoon, but the relationship between these two variables is not understood partly due to lack of data and partly due to complexity of the problem. The large scale features in SST distribution described earlier in this paper indicate their relationship with the activity of southwest monsoon. The years 1977 and 1978 had very good monsoon activity over India and neighbourhood. On the other hand, 1979 had a bad monsoon season, characterised by: (*i*) 10-12 days delay in the onset of monsoon over the Peninsula, eastern and central India, (*ii*) only 3 monsoon depressions forming over the Head Bay and moving along the axis of monsoon trough, and (*iii*) breaks in monsoon; the first occurred during 20-28 July, and the second occurred from the middle of August, after which the monsoon did not revice, and practically ended in withdrawal. The characteristics of SST distribution based on the 3 years data are described below.

6.2. In March the warmest sea surface temperatures of 29-30 deg. C prevailed around the equator with the coldest waters in northern parts of Arabian Sea and Bay of Bengal. During April there is *in-situ* warming of the ocean surfaces north of equator. By early May the warm SST ridge, with temperatures greater than 30 deg. C, progressively shifts northward to north Arabian Sea and the north Bay. The SST gradient is reversed from March to May in the sea areas north of the equator.

6.3. *SST distribution over the Arabian Sea shows the following characteristics in a good monsoon season*

(*i*) In early May, cold waters with SST less than 28 deg. C start moving from the equatorial region towards north and northeast. At about the same time, SST's off Somali coast start falling and this marks the beginning of Somali current.

(*ii*) The northeastward advection of cold waters from equatorial Indian Ocean off Somali coast upto the west coast of India becomes more organised in June and continues through monsoon months till early September. Frequently, the axis of Somali current extends upto the west coast of India, and shows forking over the Arabian Sea, similar to that observed by Findlater (1971) in the low level wind field. In early monsoon season, *i.e.*, in June and July, the cold waters occasionally move eastward upto Kerala coast, terminating into a cold pool off the coast.

(*iii*) Sea surface temperatures off Somali coast start falling from early May onwards, and lowest temperatures of 22-23 deg. C are observed close to the equator during July and August. By the end of September, SST's off Somali coast rise and Somali current disintegrates, leaving a flat SST distribution over northwest Indian Ocean and Arabian Sea. SST variations off Somali coast between the equator and Lat. 5 deg. N, where the lowest temperatures prevailed, indicate the intensity changes of Somali current (Table 1).

6.4. During 1979 monsoon season, characterised by delayed onset of monsoon and subsequent weak monsoon activity over India, fall of SST off Somali coast started by 19 June. A weak Somali current started organizing by early July. The current was weak in July and it did not extend upto the west coast of India. SST's off Somali coast were generally 2-3 deg. C higher than those prevailing in the normal monsoon years. The delayed onset of monsoon and subsequent weak monsoon activity over India in 1979 were associated with delay in the appearance of cold waters off Somali coast, and the delayed and weaker Somali current. The poor monsoon season was also characterized by weak SST gradients and warmer waters in the Arabian Sea.

6.5. In the Bay of Bengal SST's generally fell with the advance of monsoon, leaving a flat temperature distribution. Complex SST patterns, apparently dominated by transients, were observed during the monsoon season. Generally, warmer SST's prevailed over the Head Bay with colder waters at low latitudes.

7. Ocean response to varying windfield

7.1. The fall in SST's in the west Indian Ocean south of Lat. 5 deg. N and rapid northward advance of a tongue of cold waters in the Arabian Sea were initiated around 16 May in the summer of 1978 (Figs. 5 and 6). Further fall of temperatures off Somali coast and the formation of Somali current followed later in the month. The monsoon current reached the west coast of India by early June. Simultaneously with these changes at the sea surface, significant changes occurred in the low level wind field over the west Indian Ocean, as seen in the wind vectors derived from the half hourly data of the geostationary meteorological satellite METEOSAT (Fig. 10). On 10 May a sharp wind discontinuity existed around the equator with generally weak westerlies to the north of 2 deg. N, strong southeasterlies in the southern hemisphere, and a weak cross-equatorial flow. By 16 May, the cross-equatorial southerly jet (Findlater 1969) got organised around the equator. Also the southwesterlies over the southwest Arabian Sea were markedly strengthened with maximum wind speed of 40 kt associated with them. These changes corresponded to the rapid northward advance of cold waters in the Arabian Sea. These SST changes qualitatively indicate the dynamic response of the ocean to changes in wind stress patterns generated over the equatorial west Indian Ocean during the onset phase of the

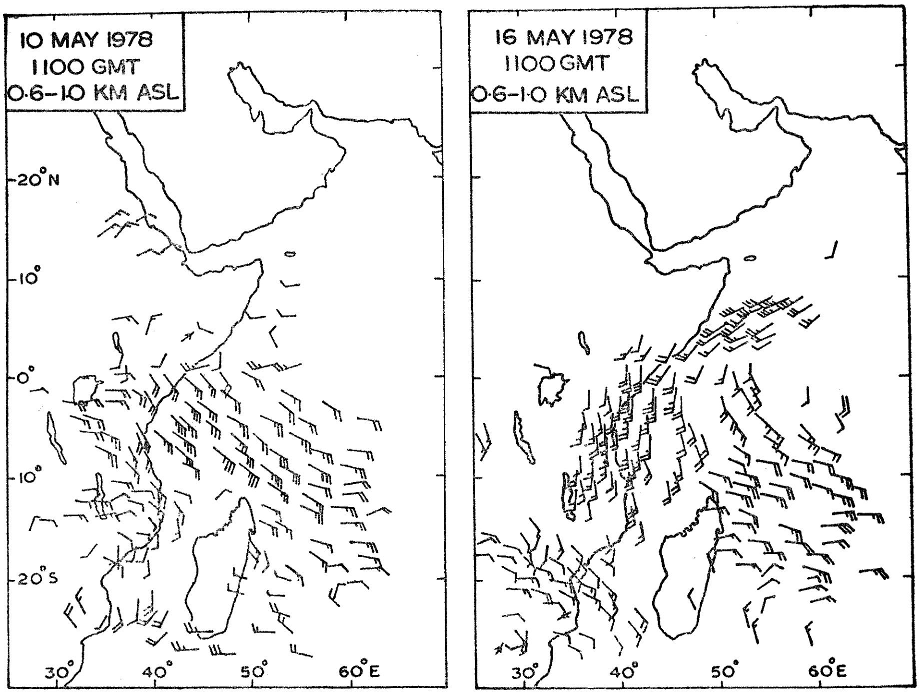

Fig. 10. Low level wind vectors derived from METEOSAT satellite imagery showing the strengthening of southwesterly winds between 10 and 16 May 1978

monsoon. They agree with Lighthill (1969) that the Somali current gets organised at most within a month after the winds over the north Indian Ocean change to the southwest monsoon pattern.

7.2. Findlater (1969, 1971) has shown that this intermittent low level jet flows through Madagascar, Kenya, Somalia and thence to the west coast of India and bifurcates into two axes over the Arabian Sea. This pattern was reflected in the axis of the cold waters extending upto the Indian coast, and the SST axis showing variable fork-like structure from June to mid-August during the years 1977 (Figs. 1 and 2) and 1978. This supports the observation of Saha (1974) that the path of the low-level high-speed air current more or less coincides with the axis of the minimum SST in the Arabian Sea during the southwest monsoon season.

8. Conclusions

Although the satellite-derived SST data are available for a short period only, they do indicate the following important features :

(*i*) The reversal of sea surface temperature gradient over the Arabian Sea and Bay of Bengal with the advance of the northern summer from March to May;

(*ii*) the advection of cold waters from the northwest Indian Ocean into the Arabian Sea, the upwelling off Somalia coast, and the organisation of the Somali and the southwest monsoon sea currents in the Arabian Sea which frequently extends upto the Indian coast, during a good southwest monsoon season and

(*iii*) the delayed and weaker Somali current, weaker SST gradients and warmer sea waters in the Arabian Sea during a poor southwest monsoon season.

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