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See breeze like cloud-free zones during monsoon months

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सार — दक्षिण-पश्चिम मानसून महीनों के दौरान समुद्र सतह, सतह वायु तापमानों तथा सिनॉप्टिक स्थिति के साथ इन्सैट मेघ बिम्बावलियों द्वारा प्रेक्षित विभिन्न मेघ-मुक्त क्षेत्रों के अभिलक्षण तथा भारतीय तटों पर दिन-प्रतिदिन उनके विकास का विश्लेषण किया गया है। यह एक क्षीण या व्यवधान वाली मानसून परिस्थिति थी। प्रस्थायित्व अनुकूल सतह पवन तथा ठंडे पानी में वायु के धीमे-विन्यास से बनाए गए उत्प्रवाह से समुद्र सतह तापमान में धीरे-धीरे कमी आने से भारतीय, प्रायद्वीप तटों के किनारे पर प्रातः काल के स्पष्ट क्षेत्र का आविर्भाव होता है। दिन चढ़ने के साथ ही जल में स्पष्ट क्षेत्र का विस्तृत विस्तार, जहां कि वह अकस्मात् समाप्त होता है और वाताग्र-समान थलीय क्षेत्र, प्रतिरूपी समुद्र-समीर के समान प्रकट होता है। यह अभिग्रहित किया गया है यह प्रभाव समुद्र समीर संचरण तथा ठंडे पानी पर वायु के सिकुड़ने से है। यह परिणाम निकाला गया है कि समय-समय पर इस प्रकार की परिघटना प्रायद्वीप पर मानसून में अधिक क्षीणता या व्यवधान का सूचक है।

ABSTRACT. Characteristic features of distinct cloud-free zones and their day to day evolution along Indian coasts as observed in INSAT cloud imageries during southwest monsoon months have been analysed and discussed along with sea surface and surface air temperatures and synoptic situation. It was a weak or break monsoon condition. Appearance of early morning clear zone just off shore along Indian Peninsula coasts is attributed to the gradual lowering of sea surface temperature due to upwelling caused by persistent favourable surface wind and slow-setting of air above colder water. With the advance of the day, wide extension of clear area over water where it ends abruptly and propagation of front-like zone inland manifest as a typical sea breeze. It is postulated that this is the effect of sea breeze circulation and shrinking of air above colder water. It is inferred that time to time appearance of such phenomenon may be an indication of longer weak or break monsoon over the Peninsula.

Key words — See breeze, Cloud free zones, Monsoon months, INSAT, Cloud imageries, Break monsoon.

1. Introduction

The land-sea breeze circulation is one of the most interesting meso-scale atmospheric phenomena observed in coastal regions during fair weather period. The existence of it has been acknowledged by meteorologist for many years and for obvious observational reasons, the inland penetration of sea breeze is better documented part of this circulation. But its region of influence was considerably under estimated until observations were made from satellite (Anderson *et al.* 1974).

The surface winds at a coastal station are characterised by well marked sea and land breezes. Of these, the sea breeze is relatively stronger and specially pronounced in tropics during summer months. It has profound effects on the distribution of pollution in coastal areas and it tends to bring welcome relief from high pollution level over the city.

Numerous investigations of these breezes show that many factors such as location, temperature difference between land and sea surface, the strength and direction of large scale gradient wind flow, stability of the airmasses, topography, friction and earth's rotation influence land and sea breezes. In India, studies of these winds have been made by many authors, but most of them are excluding monsoon months. Theoretical models of sea breeze circulation under different synoptic conditions are also available.

During southwest monsoon months, June to September, sea and land breezes along west and east coasts of India respectively, are masked by seasonal winds. Besides, humidity content of the air is high, and land and sea are more or less covered by clouds. Creation of local pressure gradient by differential heating over land and coastal water mass which is the basic cause of land and sea breezes is not prominent. However, during weak or break monsoon condition, sometimes, they may be distinctly observed in cloud picture. During such a monsoon condition in 1986, we observed a few cases of characteristic cloud pattern with distinct cloud-free zones and sea breeze fronts along the coastal areas of Peninsular India in INSAT visible cloud pictures. During the study of sea breeze at Ahmedabad, Sajnani (1956) noticed sea breeze on

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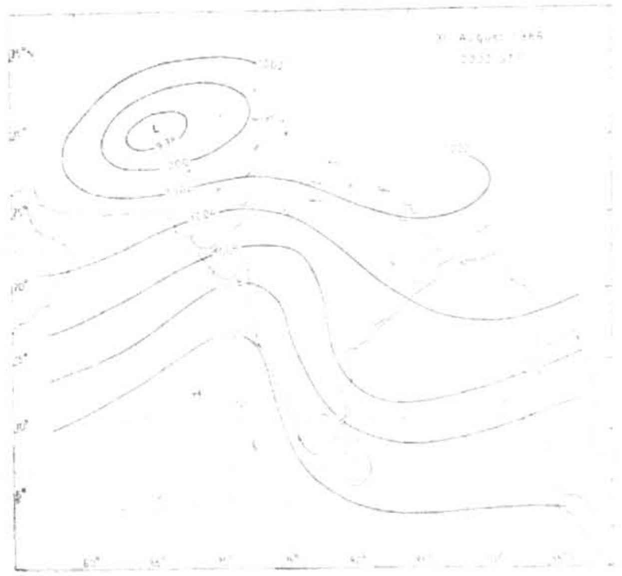

Fig. 1. 00 UTC surface pressure and wind (at 300 m) distributions of 31 August 1986

a few days of weak monsoon condition; although, these were not so marked as in summer months.

The objective of this study is to analyse and examine as to how, day to day evolution of such phenomenon can be identified in satellite cloud picture and up to what extent different characteristics of the sea breeze not at a particular place, but along the entire coasts of Indian Peninsula can be assessed from INSAT cloud pictures and also try to explore dominant physical factors involved in such cases. Though, our studies concern mainly with satellite cloud pictures, we have also considered available synoptic and sea surface temperature data.

2. Synoptic situation and sea surface temperature

2.1. *Synoptic situations*

A depression crossed north Orissa coast on 20 August 1986, and on 22nd it weakened into a low over Bihar Plateau and adjoining north Orissa. As a result, monsoon became vigorous over Orissa on 20th. On 23rd, it was fairly active only over Bangladesh and moderate over north Bay, and on 24th it was active over east U.P. From 25th to 31st, the axis of the seasonal trough on sea level chart lay close to the foot hills of Himalayas. Then, till 8 September, there was no significant situation. On 21 August, in INSAT cloud picture (not shown) there was indication of anticyclonic flow in lower level over north Arabian Sea, and from 22nd rainfall over Peninsular India started to decrease rapidly. By 26th, the anticyclonic flow in lower level over north and central Arabian Sea started to become prominent, and on 31st it became more distinct. Sea level pressure pattern and stream line at 300 m on 31st at 00 UTC are shown in Fig. 1. On that day at 00 UTC, a weak anticyclonic circulation between 3.6 km and 500 hPa prevailed over the Peninsula south of 20° N. A trough in westerlies in middle and upper tropospheric levels with its axis at 300 hPa, lay roughly along 68° E and north of 30° N. Over India, the maximum wind at 250 hPa was 117°/29 kt over Aurangabad, and that at 200 hPa 105°/42 kt, and at 150 hPa 100°/63 kt, both over Trivandrum. Table 1 shows that the winds between 850 and 600 hPa over the Peninsula are very light.

2.2. *Sea surface temperature*

Table 2 shows air and sea surface temperatures from available ship observations on alternate days from 22nd to 28th, and on every day from 28 to 31 August 1986. On 22nd, the difference of air and sea surface temperature at 40 km and far away from west coast were 0.8° and 0.5° C respectively. On 24th, within 40 - 55 km from southern parts of west coast, the difference lay between 1.2° and 1.5° C, while at far away, it was small; at 25 km south of Sri Lanka, it was 1.0° C. On 26th, at 60 km southwest of Sri Lanka, it was 3.0° C; but about 20 km southeast, it was 2.5° C. On 28th, at 60 km from southern tip of the Peninsula, the difference was 1.2° C, while at the same distance from southern parts of west coast it was 3.5° C (appears high); and at 120 km practically no difference. On 31st, at a distance of 420 km southwest of Trivandrum the difference was 1.0° C. Nearest observation on east coast was at a distance of 120 km (on 29th) which shows practically no difference. From 26th to 31st, a ship was anchored at high sea (9° N/67° E), and observations show practically no difference.

During the period, the range of sea surface temperatures within 90 km from west coast was within 24.8° and 27.0° C, except one (24° C); but in the region to the south of India and west of Sri Lanka, it was as low as 22.7° C. In the east coast it was within 28° and 29° C.

Temperature differences over land and water along west and east coasts at 09 UTC on 31 August, were measured from INSAT-IR data on DAID (Data Analysis and Interactive Display) using in-built computer device and the differences were found to lie in the range of 2°-3° C. Though, in this technique, there are some intrinsic errors in actual values, these may not be so effective in differences.

3. INSAT cloud picture analysis

As scatterly distributed thin low clouds are very difficult to identify in IR-picture, and its resolution is also four times inferior to visible one, so only the visible pictures have been used. Picture at 12 UTC has also been excluded as its quality was very poor due to low sun angle.

On 25 August 1986, in 09 UTC picture (Fig. 2) a narrow clear zone more or less of uniform width over water along west coast south of 20° N is clearly noticed which merges with broad clear area to the south of the Peninsula. To the north of 15° N, it extends inland with a comparative thick line of clouds ahead of it. Sun-glint over south central Arabian Sea, and cloud features clearly indicate low level anticyclonic flow over the sea. An extensive area along and off east coast is cloud free. Even at 03 UTC, ill-defined clear area could be easily recognised to the south of 15° N. On 26th, this feature became less marked; though its existence could be identified southward at 06 UTC and

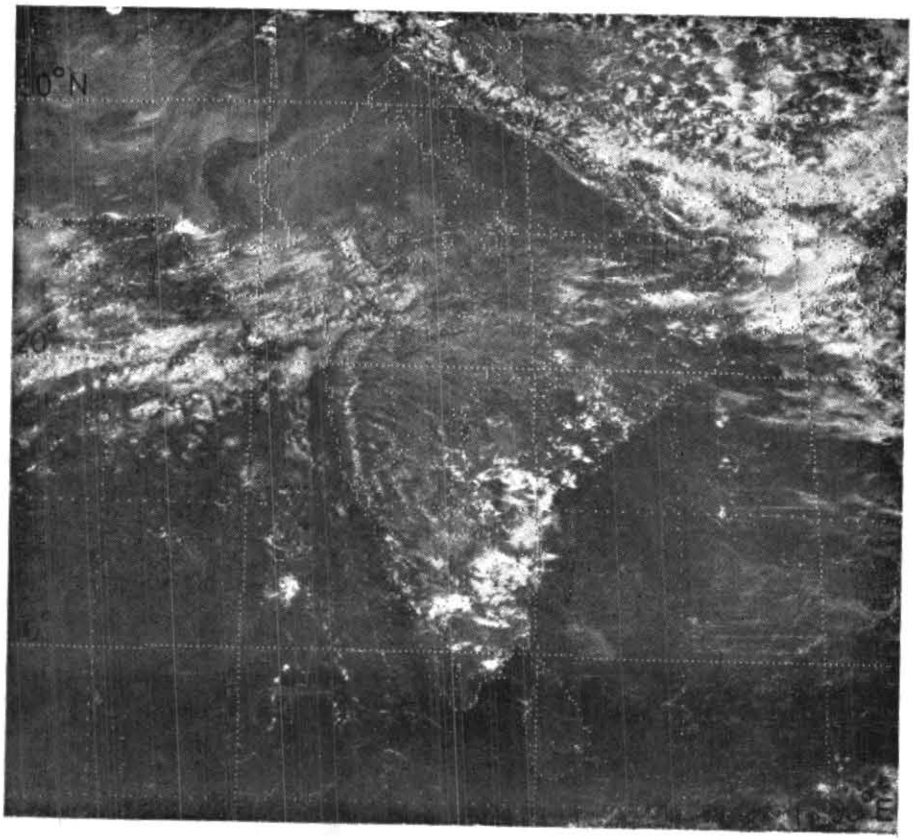

Fig. 2. 09 UTC INSAT cloud picture (visible) of 25 August 1986

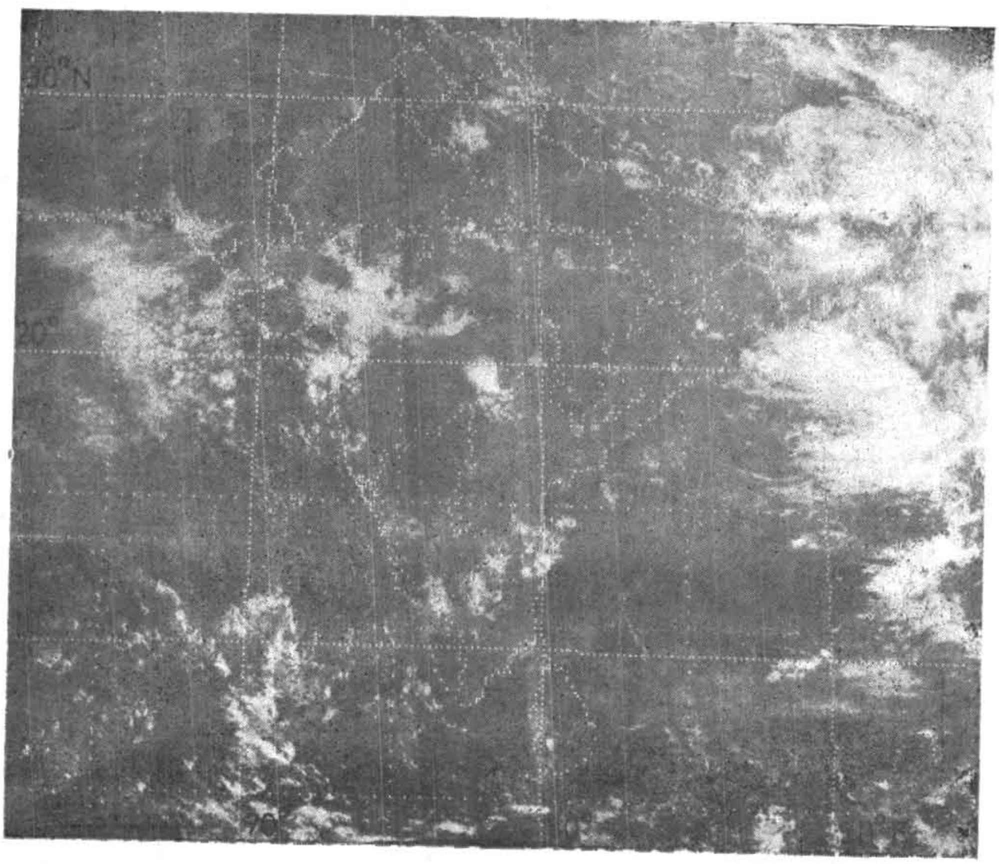

Fig. 3. 03 UTC INSAT cloud picture (visible) of 30 Aug ıst 1986

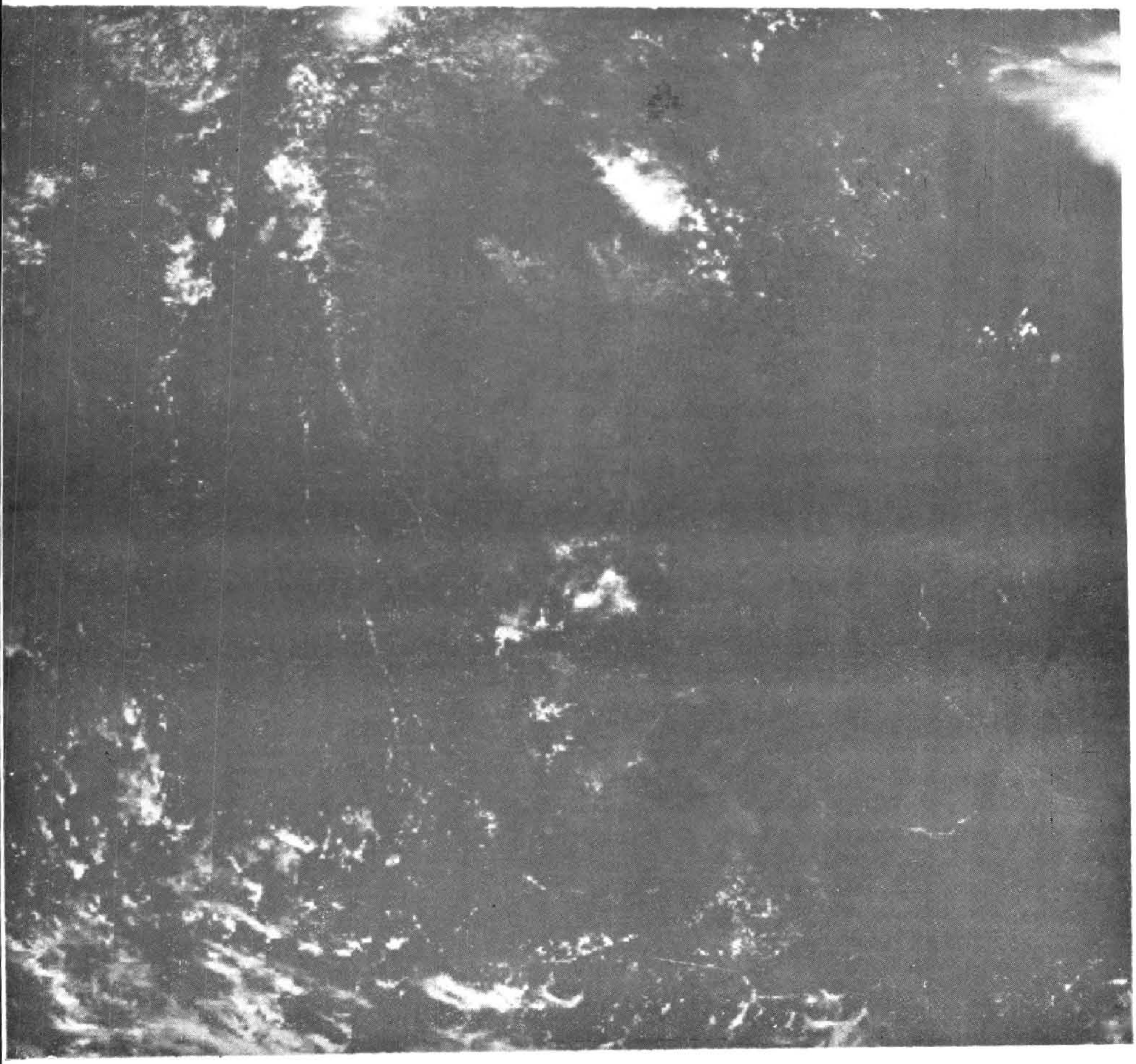

Fig. 4. 06 UTC INSAT cloud picture (visible) of 31 August 1986

TABLE 1

Upper air winds (m/sec) at 00 UTC on 31 August 1986

Station	850 hPa	800 hPa	750 hPa	700 hPa	650 hPa	600 hPa
Bombay	248/07	235/07	246/03	235/03	193/03	245/05
Goa	307/05	295/07	337/03	328/02	274/04	272/03
Mangalore	317/09	325/05	237/02	150/02	225/02	268/03
Trivandrum	008/05	095/05	310/07	005/03	035/02	356/03
Bangalore	315/05	010/05	021/03	232/03	220/03	239/03
Amini	338/09	334/07	335/05	338/02	360/03	302/03
Minicoy	327/09	327/11	321/08	322/05	308/04	—
Visakapatnam	291/03	313/04	319/07	303/05	276/01	289/01
Machilipatnam	250/04	280/05	275/06	273/03	244/11	240/04
Aurangabad	270/07	217/05	180/07	208/05	190/03	188/04
Jagdalpur	320/05	326/03	310/04	326/03	302/02	290/02
Karaikal	237/02	126/01	330/03	360/03	047/05	037/05
Madras	300/01	005/04	360/07	035/04	290/01	272/03
Bhubaneswar	315/07	316/05	012/03	350/03	330/05	274/04
Hyderabad	315/05	299/06	297/05	303/03	222/07	211/05

more so at 09 UTC. On 27th, the feature became more clear than previous day, and its clarity increased with the advance of the day. Low clouds over east Arabian Sea were distributed in a scattered manner. Though east coast was covered with clouds, there was an indication of clear area to its southern part. On 28th, it again became less marked. On 29th, clear area along west coast extended further northwards. Low clouds over eastern Arabian Sea started to become aligned in lines nearly parallel to the coast. On 30th, even as early as 03 UTC (Fig. 3), a narrow clear zone along the west coast extends from Bombay to southwest Sri Lanka, while parts north of Bombay are being obscured by advection of clouds from neighbouring areas. On east coast a narrow cloud free area is seen along Andhra and south Orissa coasts. On 31st above features became more distinct and prominent. In 03 UTC, the width of clear zone southward from Goa increased up to the tip of the Peninsula, its boundary over sea was sharp. On east coast it was ill-defined. In 06 UTC picture (Fig. 4), a region remarkably free from clouds around Indian Peninsula skirting the coast line from northern part of west coast to north Orissa coast including west coastal areas of Sri Lanka became noticeable. A line of clouds along the seaward edge of clear zone from northern part of west coast to Sri Lanka can also be seen. With the progress of the day these features became more marked beginning from Kathiawar Peninsula as seen in 09 UTC picture (Fig. 5). The clear area is quite large and ends abruptly over water. Low clouds over eastern part of Arabian Sea are distinctly aligned in lines parallel to the coast. Since 06 UTC, clouding over both land and water has increased appreciably and clear zone continued to expand and pushed further inland and seaward. Landward penetration is of the order of 40-55 km on west and southeastern coasts. This clear zone is not symmetrical about the shore line, extends more over sea than over land. Another feature is that the width of the clear area over water in west coast is not uniform; in the nothern part it is less and gradually increasing southwards, it became as large as 200-250 km between India and Sri Lanka. Clear area over sea in east coast is much more extensive without having any sharp boundary at its seaward edge; though anticyclonic curved lines of low clouds are evident far away. One of the most remarkable features of this development is a front-like zone at the leading edge over land. This zone is commonly referred as a sea breeze front which is distinguishable on east coast also. It has moved rapidly inland within three hours. All these are characteristic features of typical sea breeze noticed in satellite cloud pictures. Convergence of sea breeze over southeast part of Sri Lanka, a small island, is very evident and that over tip of the Peninsula is also discernible.

In 09 UTC picture of 1 September (Fig. 6), the cloud free zones still persists; though not so prominently as on 31 August, along most parts of west coast, between India and Sri Lanka and southern parts of east coast, other parts being obscured by cirrus outflow from convective clouds. Subsequently, this type of phenomenon appeared distinctly on 9 and 18 September, and 2 October 1986 (Fig. 7).

4. Discussions

Starting from 25 August, narrow cloud free zones have been observed at 03 UTC (till early local time)

TABLE 2

Available ship observations

Date (Aug 1986)	Time of obsn. (UTC)	Location Lat. (°N)/ Long. (°E)	Approx. distance (km) from east/west coast	AT (°C)	SST (°C)	AT *minus* SST
22	00	11.0/75.5	40 West	26.4	25.6	0.8
,,	06	11.0/75.5	40 West	26.4	25.6	0.8
,,	06	15.5/67.7	600 West	26.5	26.5	0
,,	06	09.2/67.7	900 West	27.3	27.7	−0.4
,,	12	16.4/68.7	460 West	26.6	26.1	0.5
24	00	10.5/75.2	90 West	25.0	24.8	0.2
,,	00	19.0/68.0	500 West	26.0	26.4	−0.4
,,	00	08.6/76.3	55 West	26.8	25.3	1.5
,,	06	11.6/74.6	90 West	27.7	26.5	1.2
,,	06	21.9/68.9	40 Gujarat	26.2	26.0	0.2
,,	06	05.9/82.6	140 S. Sri Lanka	27.2	27.1	0.1
,,	06	19.0/69.0	300 West	27.2	26.5	0.7
,,	06	05.8/81.0	25 S. Srilanka	27.0	26.0	1.0
,,	06	13.9/85.3	520 East	28.5	28.4	0.1
,,	12	19.0/70.0	300 West	27.2	26.8	0.4
,,	12	05.8/80.0	30 S. Sri Lanka	27.3	27.0	0.3
,,	12	22.8/68.0	90 Kutch	26.2	25.7	0.5
26	00	19.0/70.2	300 West	26.0	26.5	−0.5
,,	06	06.4/79.4	60 SW Sri Lanka	27.0	24.0	3.0
,,	06	06.3/81.7	20 SE Sri Lanka	27.5	25.0	2.5
,,	12	08.3/74.3	250 West	27.3	27.0	0.3
,,	12	05.8/83.3	280 SE Sri Lanka	27.9	27.0	0.9
,,	12	05.8/88.0	700 SE Sri Lanka	28.2	28.1	0.1
28	00	07.5/77.6	60 Southern tip of Peninsula	23.9	22.7	1.2
,,	06	10.1/75.6	60 West	27.5	24.0	3.5
,,	06	16.6/86.3	320 West	29.5	29.0	0.5
,,	12	09.5/75.2	120 West	27.2	27.1	0.1
29	00	12.2/82.8	260 East	28.0	28.0	0
30	12	19.0/67.0	500 West	26.6	26.5	0.1
,,	12	17.6/66.3	720 West	26.3	25.7	0.6
,,	12	24.2/65.9	100 SW of Karachi	27.5	27.0	0.5
31	00	07.3/73.2	420 West	30.0	29.0	1.0
,,	00	15.5/70.9	300 West	27.0	27.0	0
,,	00	19.0/67.0	600 West	25.4	24.9	0.5
,,	06	19.0/67.0	600 West	27.0	26.0	1.0
,,	12	13.5/73.8	100 West	27.5	27.0	0.5
,,	12	19.0/67.0	600 West	26.8	26.6	0.2

AT — Air temperature. SST — Sea surface temperature.

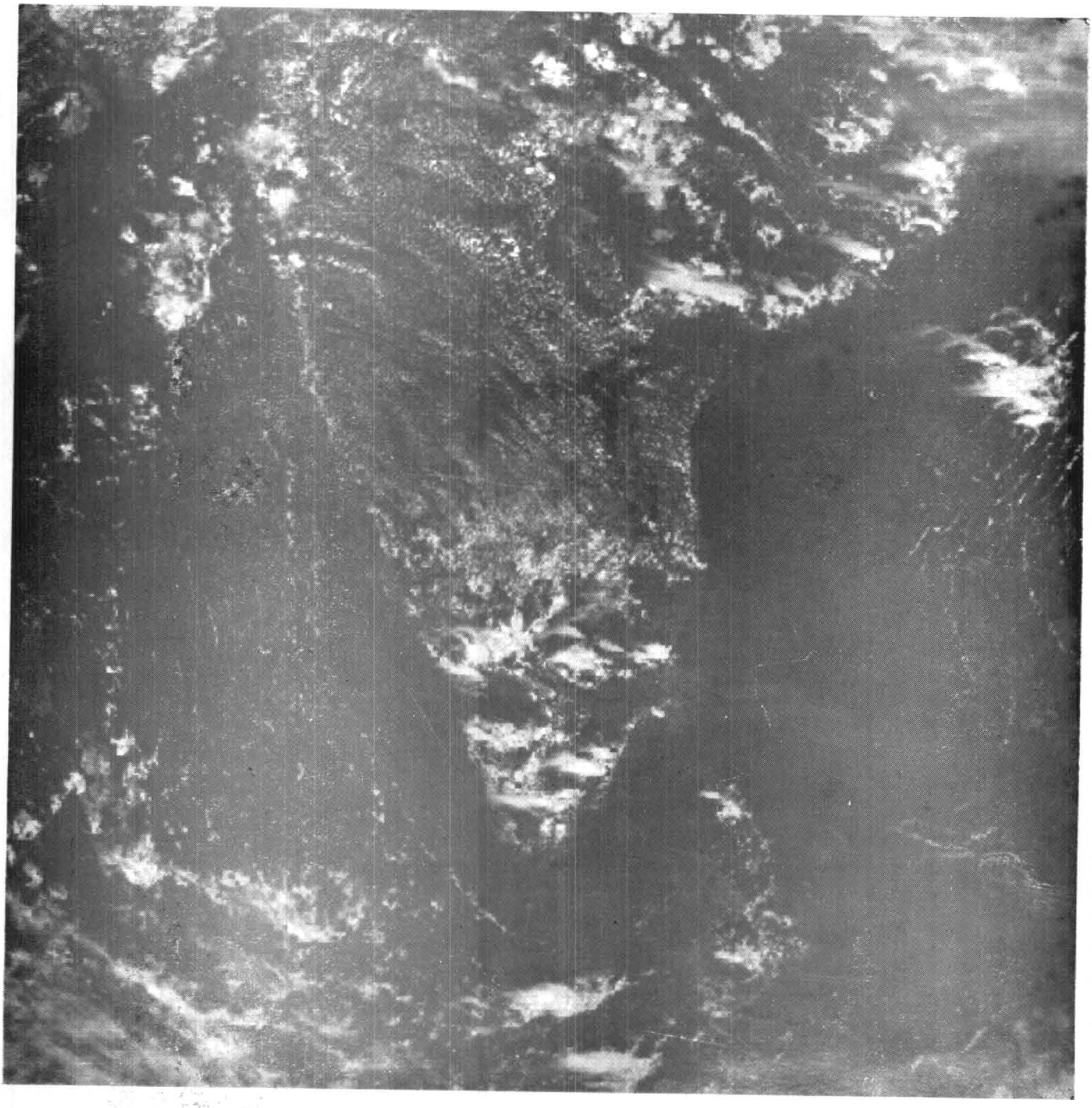

Fig. 5. 09 UTC INSAT cloud picture (visible) of 31 August 1986

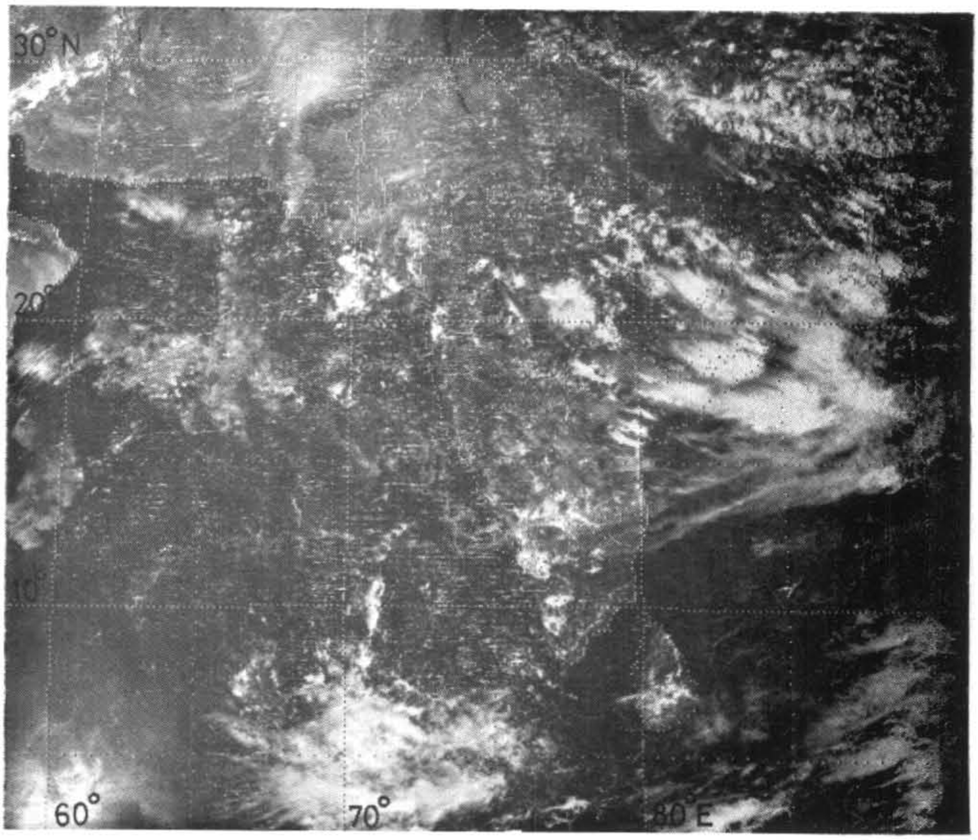

Fig. 6. 09 UTC INSAT cloud picture (visible) of 1 September 1986

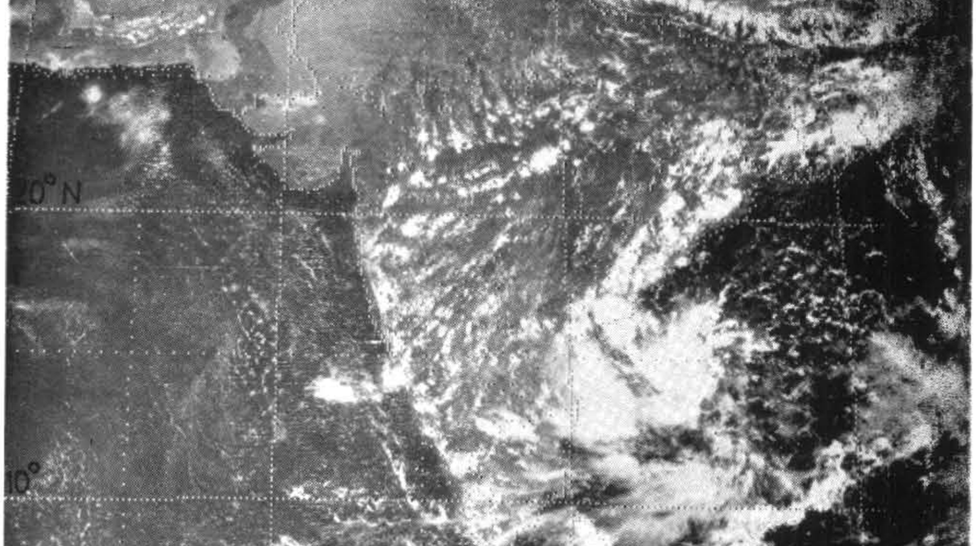

Fig. 7. 09 UTC INSAT cloud picture (visible) of 2 October 1986

along west coast on several days and in the region to the south of India and west of Sri Lanka on most of the days. This can not be attributed to sea breeze circulation.

Coastal upwelling may influence the low level atmosphere circulation depending on the orientation of the coast line. If the surface wind is not very light and blows for a period of time, it produces stress on the light surface water and drift it away as wind driven current. As soon as this types of current sets in, deflecting effect due to earth's rotation comes into play and in the northern hemisphere, this deflection may be as much as 45° to the right of the direction of wind that produces them. Thus, even if the wind blows keeping the land on its forward left side and makes an angle of 45° or less with it, upwelling can take place. On the other hand, if the wind has a component away from the coast, upwelling may be enhanced depending on its angle with the coast. Further, if the slopping of the sea bed is not steep upwelling will be more effective. Yoshida (1967) has shown that in shallow seas upwelling can occur over a larger area. Generally, upwelling region is confined to a distance of about 100-150 km from the coast; but in more favourable conditions cold water may be observed as far as 400 to 500 km away from the coast. Evidently, the coldest temperature will be found very near the coast in every case.

Satellite pictures and synoptic data indicate that the low level flow over Arabian Sea became predominantly anticyclonic since 22 August, and as a result, west coast came under the influence of persistent north westerly to northerly surface wind. With the progress of time, this wind became more oriented along the coasts. There is sufficient reason to believe that persistent wind, orientation of coast line, bathymetry of sea near the coast, favoured to cause upwelling phenomenon which acted to reduce the near shore sea surface temperature. Within the limit of accuracy, it also appears from temperature data that near the coast, sea surface temperature started to become colder than air temperature even before 22 August.

When the sea surface water is cooler than the air above it, heat is transported from air to the sea, and due to turbulent mixing, this cooling process extends to some extent of the atmosphere. This process leads to the progressive cooling and shrinking of the lower level of the atmosphere. Schroeder *et al.* (1967) pointed out that during the warm half of the year upwelling water just offshore along the Pacific coast of the United States are effective in cooling a shallow over laying layer of atmosphere. Raghavan (1969) contends that this cooler and heavier air moves sideways to the warmer region and warmer air from warm region comes above colder air as a counter current and subsides. Shallow inversion may also form over it. Both these effects inhibit cloud formation. It appears from temperature data that the sea surface temperature was not so low as to inhibit low cloud formation over a narrow zone, if it was not cooler than the air temperature above it. It is most likely that upwelling and above mechanism are responsible for early morning cloud-free area just near the coast. Most probably, orientation of coast line, persistence and turning of wind, and divergence of overturned water brought about more effective upwelling in wide area to the south of India and west of Sri Lanka and as a result, lowest sea surface temperature was recorded in this sector (Table 2), and in consequence of it, cloud-free area was large and more or less persistent.

Close to the east coast there is no ship observation. Winds along this coast are off shore which may increase the upwelling; on the contrary, it might have increased the spreading of cold water far into the sea, thereby hindered the lowering of sea surface temperature and creation of its sharp gradient near the coast which is necessary for distinct boundary of clear area.

To designate the situation of 31 August, as a sea breeze, apparently, it may be felt necessary to identify the existence of the return current from conventional data. But as expected by continuity requirement, the speed of the return flow which is approximately twice the depth of the sea breeze is about half of that of the sea breeze. Return current predicted by theory has not always been observed (Atkinson 1981). Even, Fisher (1960), and Frizzola and Fisher (1963) in their carefully set up experiment found that the return flow was difficult to detect; particularly, if there was gradient wind. In the present case, it is practically impossible to detect the return current from conventional data. However, return current may exist as the gradient winds are very light between 850 and 600 hPa (Table 1). Moreover, if the Figs. 4 and 5, are compared with other studies of sea breeze where satellite pictures were used (Anderson 1974), it will be clear that the sea breeze is fully reflected in cloud pattern with many distinct characteristic features including its evolution.

Further, it is difficult to be convinced that the cooling and shrinking of overlaying air due to upwelling phenomenon is only the physical factor to turn a very narrow clear zone of early morning along the coasts to the extent of a large and distinct sea breeze circulation (as in this study) within such a small period.

In studying an Oregon sea breeze from synoptic data, Johnson and O'Brien (1973) observed that persistent northerly component in the local surface wind creates coastal upwelling phenomenon which acts to reduce near shore sea surface temperature and unique combination of intense heating inland and cold sea surface produce very high coastal thermal gradient which leads to the development of strong sea breeze circulation.

It is most likely that decrease of clouds and rainfall and steady high temperature over the Peninsula and gradual cooling of near shore sea surface water due to upwelling created sufficient thermal gradient across the coast (maximum in the afternoon) resulting in the development of a strong sea breeze circulation, in which both the shrinking process and return current were coupled together.

From 25 August, day to day fluctuation of the narrow coastal clear zone were noticed. It is likely that a weak sea breeze might have formed in the afternoon on those days when clear areas over land were also seen (*e.g.*, Fig. 2). This fluctuation was markedly noticed in situation from 31 August to 1 September. On 1 September, the features were much more weak than those of previous day. It is likely that after fully grown up stage of sea breeze, a rapid influx of marine air and associated moisture in the valley leads to the sudden decrease in heating and diminishes the thermal forcing necessary to maintain a sea breeze as well as northerly gradient flow. It may even lead to a relaxation of coastal upwelling due to reduced wind speed which would further reduce coastal thermal gradient and sea breeze forcing.

5. Remarks

Monsoon current over west coast became weak even before 22 August 1986, and continued to remain so during whole month of September. Subsequently, similar types of clear zones appeared thrice. After 31 August, isolated heavy rain from convective clouds occurred twice over southern Peninsula. Eastern coast, northeastern and eastcentral parts of India got rainfall during this period only due to two depressions formed over the Bay of Bengal. Time to time, ridge in lower level over Arabian Sea became prominent. The effect of upwelling along coastal India has not yet drawn much attention. Break or weak monsoon in August and September sometimes exists for shorter period, sometimes longer period, and sometimes it becomes so prolonged that it terminates to complete withdrawal. Lower layer of the atmosphere close to the sea is very important; since it is solely responsible for transporting moisture and heat to the higher atmosphere. The sea breeze in an upwelling regime may represent an important feed back mechanism between major atmospheric and meteorological process on a large scale. Appearance of clear zone in the early morning along west coast of India and subsequent development and extension of sea breeze as seen in cloud pictures may provide an additional clue in determining, whether weak or break monsoon condition will be of shorter or longer duration. It requires intensive investigation.

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