Mausam, (1992), **43**, 1, 59-64

551.557.2 : 551.513 : 551.507.362.2

Satellite observations of interaction between tropics and mid-latitudes

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(*Received 1 May 1989*)

सार — निश्चित ऋतुओं और निश्चित स्थानों पर मध्य - अक्षांश पछुवा हवायें उपोष्ण और उष्ण कटिबंधी क्षेत्रों में छा जाती हैं। व्यापक मध्य-अक्षांश पछुवा हवाओं में गतिमान लघु तरंग क्षोभ, दीर्घ तरंग द्रोणियों को बढ़ाते हैं जिसके कारण अपेक्षाकृत दक्षिण अक्षांशों में नए बेरोक्लिनिक क्षेत्रों का सृजन होता है। ये बेरोक्लिनिक क्षेत्र निम्न अक्षांश के साथ मिल कर एक दूसरे को प्रभावित करते हैं । इस प्रकार नए संचरण ढरें का विकास होता है जिसमें निम्न तल पूर्वी हवाएं उत्तर की ओर प्रायद्वीप, मध्य और उत्तर-पश्चिम भारत में बढ़ती हैं । इस शोध पत्र में उष्णकटिबंधों और मध्य-अक्षांशों के बीच अन्योन्यक्रिया में लघु तरंगों की भूमिका की व्याख्या की गई है और कुछ अनुक्रमों के उपग्रह आंकड़ों को प्रस्तुत किया गया है, जिसमें ऐसी अन्योन्यक्रियायें वास्तव में घटित हुई हों।

ABSTRACT. In certain seasons and over certain locations, the mid-latitude westerlies invade subtropical and tropical areas. Short wave perturbations moving in the broad mid-latitude westerlies amplify the long wave troughs creating new baroclinic zones in relatively southern latitudes. These baroclinic zones interact with the low-latitude circulations thus leading to development of new circulation pattern in which low level easterlies extend northward over the Peninsula, central and northwest India. The paper describes the role of short waves in the interaction between tropics and mid-latitudes and presents satellite data of a few sequences in which such interactions have actually taken place.

Key words — Satellite imagery, Subtropical jet, Monsoon trough, Westerly trough & Tropical cyclone.

1. Introduction

Tropics in general are characterised by low level easterly flows and are insulated from the mid-latitudes by the subtropical high pressure belt. Circulation in the mid-latitudes north of subtropical anticyclones is characterised by westerly flows. Generally speaking Hadley type symmetric meridional circulation should prevail between the equator and subtropics. But the degree of activity in tropical weather systems is altered by the passage of the large amplitude troughs in the westerlies. Extensives sheets of mid and high level clouds in the sub-tropics are often related to maxima in the subtropical jet (STJ), as described by Hill (1963). The mobile cloud systems associated with short waves (SW) on the STJ amplify the long wave troughs leading to larger sway of mid-latitude westerlies over subtropical and lower latitudes. The extension of troughs into lower latitudes has distinct manifestation of cloud evolution in the satellite imagery showing long extensive bands of clouds surging northeastward from the tropics. These cloud surges which owe their existence to the interactions between tropics and mid-latitudes (ITML) are important weather producers in the sub-tropics and further north. Mobile cloud systems associated with SWs on the STJ interact with the south Pacific convergence zone resulting in the subtropical cyclogenesis (Revell 1985). The intensification of a western disturbance (WD) is seen generally accompanied with incursion of warm moist air from the Bay of Bengal or the Arabian Sea into a low pressure induced by development in westerlies. ITML leads to development of thunderstorm and oscillation of monsoon trough. It also leads to shearing (weakening), movement and in certain cases development of tropical cyclones (Sen 1959). This paper describes the sequence of events leading to ITML and their manifestation in cloud and precipitation. Section 2 describes the role of mobile SWs in the amplification of long wave troughs and the characteristic cloud patterns produced as a result of ITML processes that influence the low-latitude weather and circulation. The actual changes in weather and circulation under different synoptic settings are presented in Section 3 from satellite data.

2. Initiation of ITML

While observing satellite images on a regular and routine basis, one finds some kind of surge in the cloud activity in the tropical and subtropical regions. The surges in the cloud activity are either temporary or change with time. A close analysis reveals that regions where significant change is going on are the baroclinic zones where cloud motions are routinely undergoing

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accelerations (or deaccelerations). As a speed maximum an SW, moves with in the STJ, the speeds increase as the speed maximum forms, then immediately decrease. The word surge seems to apply to this kind of behaviour. Weldon (1979) has summarised the changes that occur in the region infront of — or downstream from — an intensifying speed maximum or surge :

(*i*) A large area infront of the speed maximum is affected.

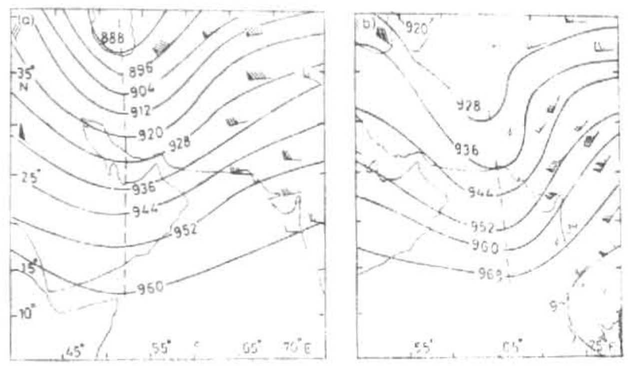
(*ii*) Exactly what changes occur depends upon what is already there.

(*iii*) A general change that occurs is that baroclinic zones are produced or intensified in an orientation that is transverse to the baroclinic zone of the speed maximum or "Surge".

(*iv*) Cloud systems in the region tend to elongate into an orientation parallel to the stretching axis of the deformation. Weak troughs, ridges, highs and lows, pre-existing in the region tend to become elongated, shear-out in an orientation parallel to that axis.

Once the westerly jet maximum moves ahead of the westerly trough, the cloud pattern seen has an "S" shaped back edge in the cirrus field along which the jet stream runs. This is so called baroclinic leaf pattern studied by Weldon (1975, 1979), Bell (1985) and Young *et al.* (1987) in which the cloud appears as a leaf aligned along the deformation zone. In the next section it will be shown that such patterns are frequent in tropical and subtropical latitudes . "S" shaped back edge is the characteristic of a "Comma" cloud in its ascent stage and as the subtropical cyclogenesis proceeds, the comma cloud evolves further. The comma cloud systems associated with the SWs are embedded in the baroclinic leaf and as it evolves beneath this cirrus topped cloud pattern, the leaf becomes more anticyclonically curved. Quite often it is the anticyclonic turning which is seen in the satellite imagery and the vorticity comma associated with SW in the cold air is not seen in the lower latitudes. The typical vortical cloud patterns associated with the westerly developments through ITML processes in which tropical intrusions are sharpening baroclinicity in the middle and upper troposphere are seen occasionally over north India and adjoining Pakistan area.

In the tropical latitudes over India, the important synoptic entities are ITCZ, monsoon depressions and tropical cyclones. When the large amplitude troughs in subtropical westerlies impinge on low-latitude synoptic disturbances, the first sign of ITML is the deformation of clouds northeastward from the lower latitudes. That does not automatically lead to any significant development for which a complete coupling between an SW, large scale westerly flow in the middle and upper troposphere and low latitude lower troposphere easterly flow is required. The ITCZ is not continuous all over the globe. There are regions of enhanced convection interspersed with clear areas. At times it does not appear at all over large areas like the Bay of Bengal or the Arabian Sea. It gets activated wherever and whenever perturbations in easterlies develop and move. As a result of extension of westerly troughs in lower and



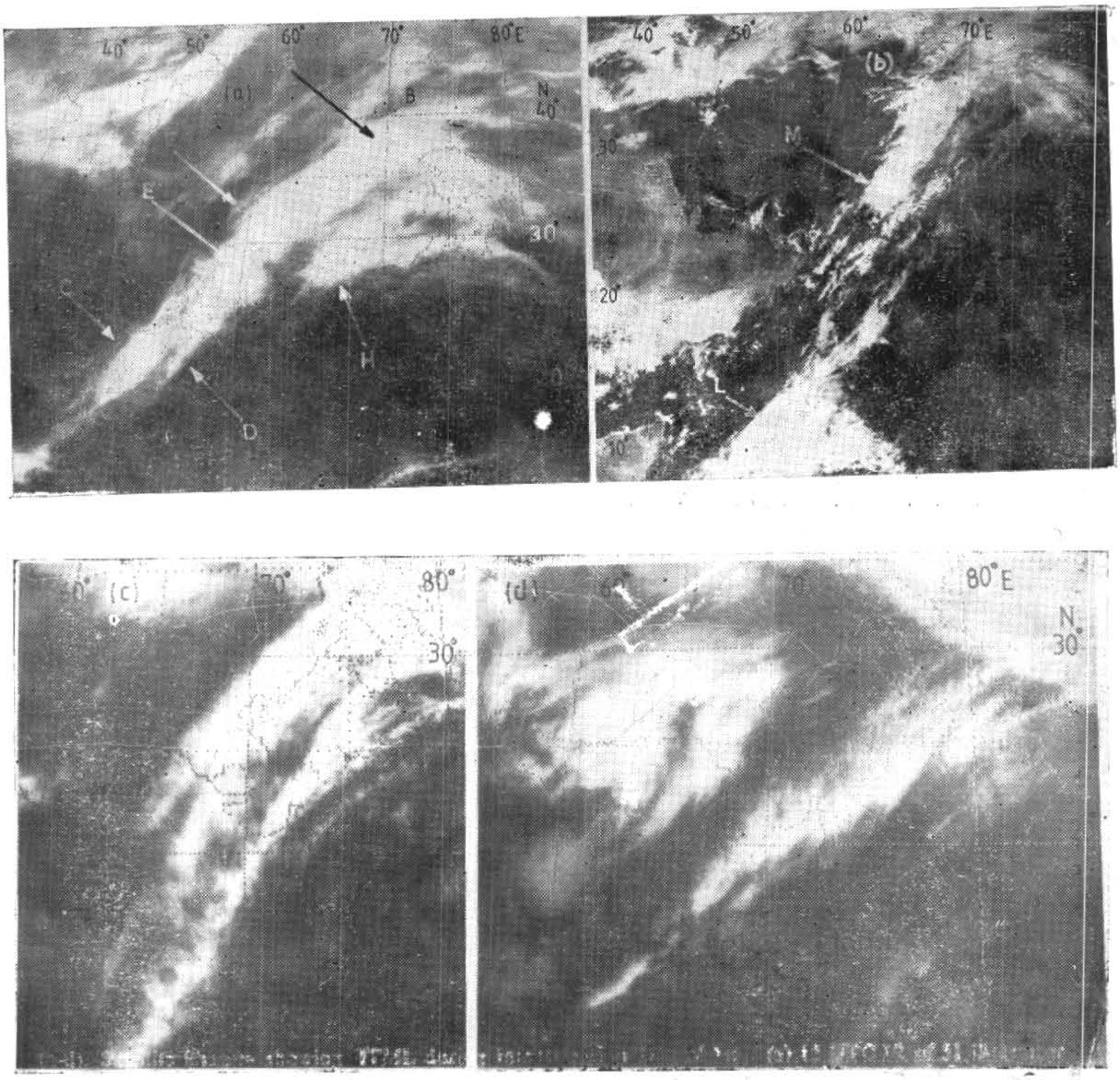
Figs. 1 (a&b). 300 mb trough in westerlies at 00 UTC : (a) 31 December 1987, and (b) 5 January 1988

subtropical latitudes, the low level circulation changes The easterlies extend northward and come under the sway of middle and upper level westerlies in the non-monsoon months. This increases the convective instability of the environment and release of precipitation can enable a growing disturbance, if any, to amplify further. During monsoon season, the western end of monsoon troughs gets deformed as a result of ITML. The poor stability of western end is attributed to ITML. A few cases are presented in the next sections to show how the satellite imagery can improve our understanding of the evolving flow pattern and the associated weather under different sequences of ITML.

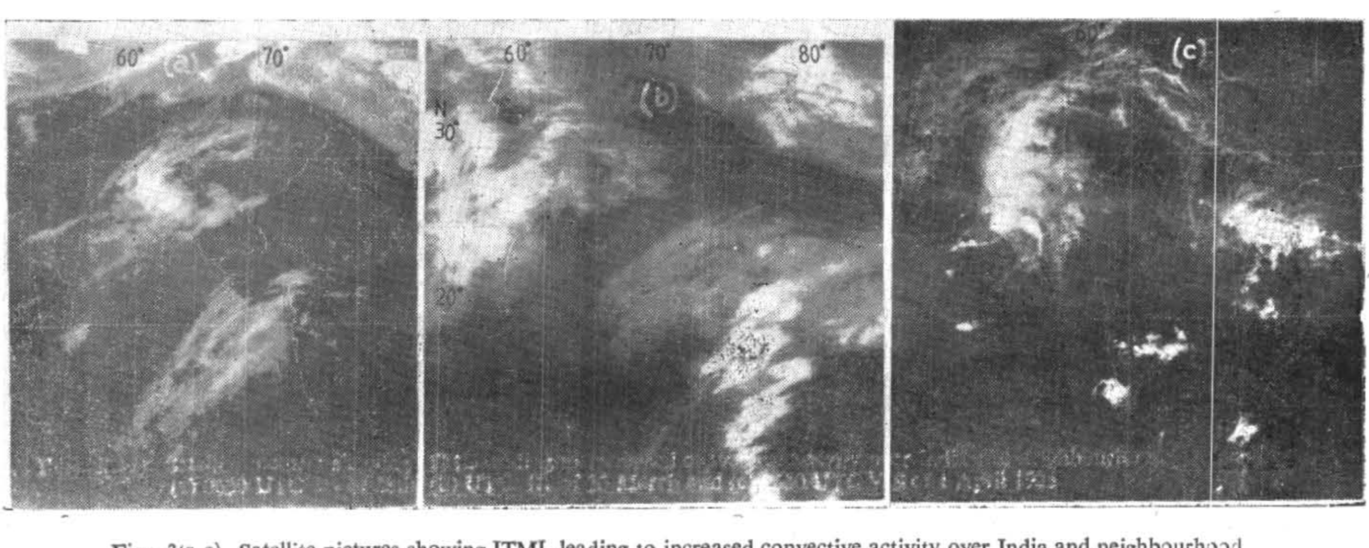
3. Epochs of ITML during different synoptic settings

3.1. *Development of WDs*

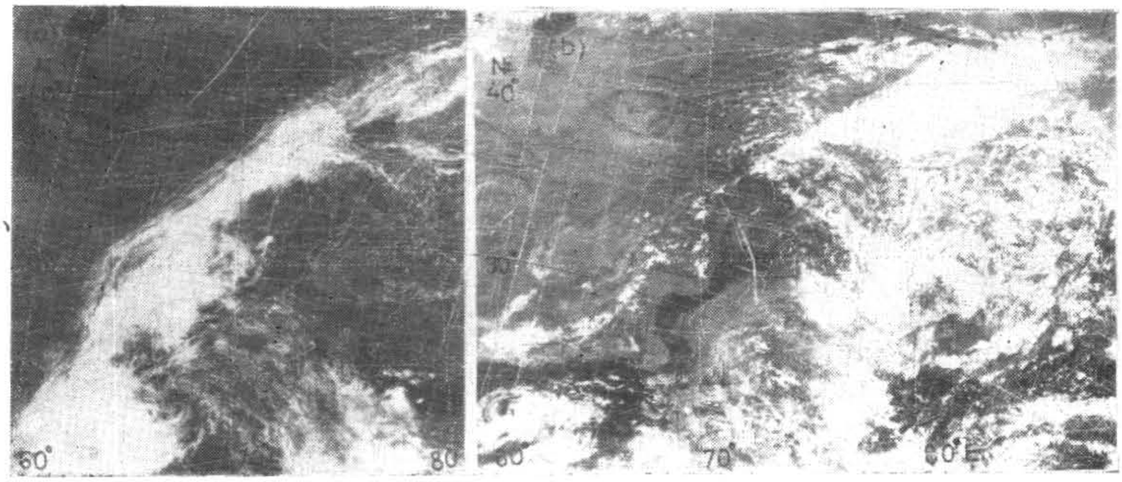
Some of the satellite pictures and the conventional weather charts for the period 31 December 1987-5 January 1988 are shown in Figs. 1 & 2. This epoch is chosen to discuss the development of WDs in relation to ITML. The cloud AB (Fig. 2a) originates at low latitudes and is forced ahead of a large amplitude trough in westerlies (Fig. 1a). A number of SWs are seen submerged in it at C, D, E, F & G due to cirrus filling in between them. Another SW is seen at H, ahead of the main band. The characteristic "S" shaped back edge in respect of most of these SWs is obscured due to large scale baroclinic cirrus but the band AB has "S" shaped back edge parallel to the axis of maximum winds and constitutes the baroclinic leaf. The trough in westerlies moves a little eastward on 1 January 1988. Two separate cloud entities L & M are seen (Fig. 2b) ahead of the trough. The cloud M is far ahead of the trough. According to remarks made in the CAS Working Group Report on Tropical Meteorology (WMO 1988) the cloud band ahead of the trough in westerlies sometimes splits into different masses and that is what has happened on 1 January 1988. The cloud mass L belongs to ITCZ and gets deformed northeastwards along the shear line as a result of ITML. The baroclinic cloud band M owes its existence basically to trough in westerlies in the middle and the upper troposphere which has also induced the extension of low level hot and moist tropical easterly flow (not shown) to northwest India and neighbouring Pakistan where it meets the middle latitude dry and relatively cold westerly flow. Though the temperature contrasts between the two flows are not significant, the humidity contrasts could be



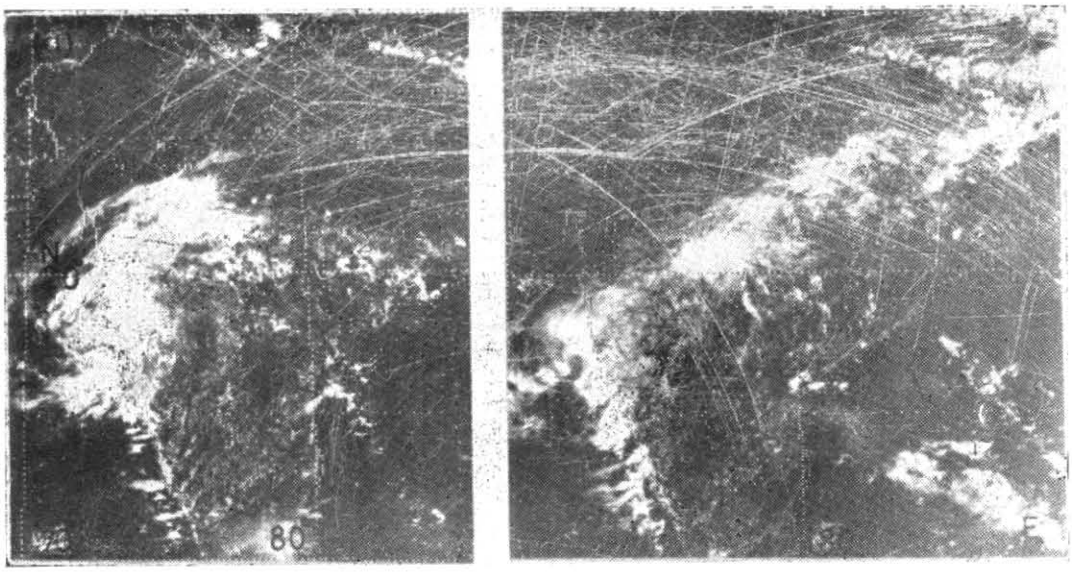
Figs. 2(a-d). Satellite imagery showing ITML during intensification of WDs: (a) 12 UTC IR of 31 December 1987, (b) 09 UTC VIS of 1 January 1988. (c) 12 UTC IR of 2nd and (d) 12 UTC IR of 3 January 1988



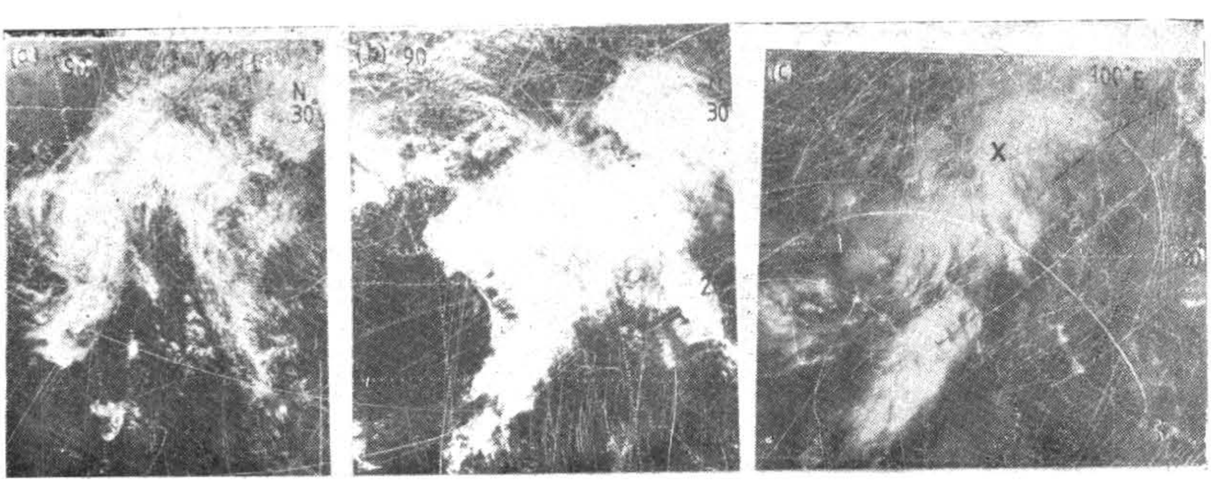
Figs. 3(a-c). Satellite pictures showing ITML leading to increased convective activity over India and neighbourhood (a) 0630 UTC IR of 28th, (b) 12UTC IR of 30 March and (c) 0630 UTC VIS of 1 April 1985



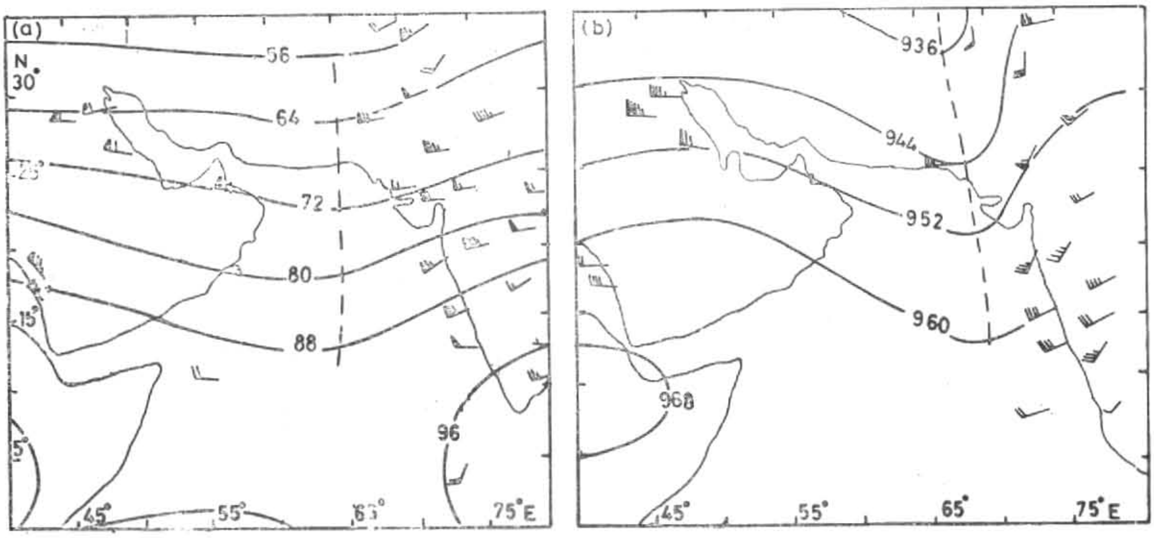
Figs. 4(a-b). Satellite imagery showing deformation of monsoon circulation as a result of ITML : (a) 0600 UTC VIS of 10th and (b) 0900 UTC VIS of 12 August 1986



Figs. 5(a-b). 0600 UTC VIS Satellite imagery showing development of monsoon depression (a) 3rd and (b) 5 October 1987



Figs. 6(a-c). VIS Satellite imagery showing deformation of cyclones (a) 0600 UTC of 19 October 1988, (b) 0600 UTC of 4 February 1987 and (c) 0300 UTC of 16 November 1988



Figs. 7(a & b). Upper air flow showing trough in westerlies

striking. The SWs seen on 31 December in the cloud band AB lose their individual identity on 1 January. So though the cloud masses L & M owe their existence to different forcing mechanisms, the SWs are involved in their development. The poleward edge of the cloud M is sharp in the IR image (not shown). It is the baroclinic leaf pattern which is associated with a surface trough of low pressure. In the actual synoptic charts, a cyclonic circulation is seen between 850 and 700 hPa over north Pakistan and neighbourhood on 1 January. The cloud band M cannot be forced by this circulation. On the other hand, it is possible that sharpening of baroclinicity across this band is leading to strengthening of winds (not much data from that area) and in the left exit region of jet, the circulation is being induced. The cirrus cap confirms the presence of positive vorticity advection (PVA) over the same area. The cloud masses L & M move eastward on 2 January and again show merger at times. In association with these developments light to moderate precipitation was reported on 2 January 1988 from many stations in J & K. An SW is again seen over the north Arabian Sea & neighbourhood (Fig. 2d) on 3 January and it moves to south and central Pakistan on 4 January (Figure not shown). Meanwhile, though the large scale trough becomes flat on 3 January, it again gets amplified after 4 January. A low level circulation gets induced over northwest India on 5 January. But this time the depth of tropical easterly flow feeding into northwest India is shallow. This may be due to the smaller number of SWs noticed in the second half of this sequence. Though another circulation is induced on 5 January as already pointed out, the associated cloud and precipitation as seen on 6 January chart (not shown) are very innocuous. But the weekly precipitation in J & K was normal for the week ending 6 January 1988.

In this entire epoch, the SWs are seen moving in the large scale flow, influencing it by amplifying troughs and inducing circulations and also leading to ITML. But the rapid intensification of SW manifesting into characteristic spiral pattern is not seen. The evolution of vertical motion field is, therefore, very slow particularly in the second spell in which the depth of easterly flow feeding into northwest India is very shallow. These developments also lead sometimes to very intense subtropical cyclogenesis as what happened on 7 January 1989 when moderate to rather heavy rain was reported from many parts of NW India. This case is being studied separately.

3.2. *ITML during pre-monsoon season*

A case study is presented to show how ITML leads to increased convective weather activity during the period 28 March-2 April 1985. The satellite pictures for this period are shown in Fig. 3. Some of the upper air charts for this epoch are given in Fig. 7. A westerly trough in the sub tropical westerlies seems to have not only amplified but also undergone some oscillation in its location over the Arabian Sea during this period. The presence of the trough was revealed through the bands of medium/high clouds forming ahead of the westerly trough from 27 March onwards. The NE-SW medium/high cloud band in the east central and northeast Arabian Sea on 28 March (Fig. 3a) is the baroclinic cloud mass ahead of the trough and its straight western edge shows that it may be a deformation band ahead of an upstream wind maximum. There is no upper air-data available over vast areas of west Arabian Sea and adjoining Arabian peninsula but isolated reports of strong winds over Arabia suggest a northwesterly wind maximum over Arabia and neighbouring Arabian Sea. Such a feature (a wind maximum or an SW is missed even in US upper air network (Weldon 1975). SWs are generally not seen even in the satellite imagery when these are embedded in the upper air subsiding northwesterly branch and make their appearance felt after their arrival on the forward side of the trough. But deformation band type clouding is generally seen ahead of the wind maximum.

There was not much upper air data available to delineate precisely the axis of the trough in the upper air charts. The axis was drawn keeping in view the position of clouds over India, Pakistan and Arabian

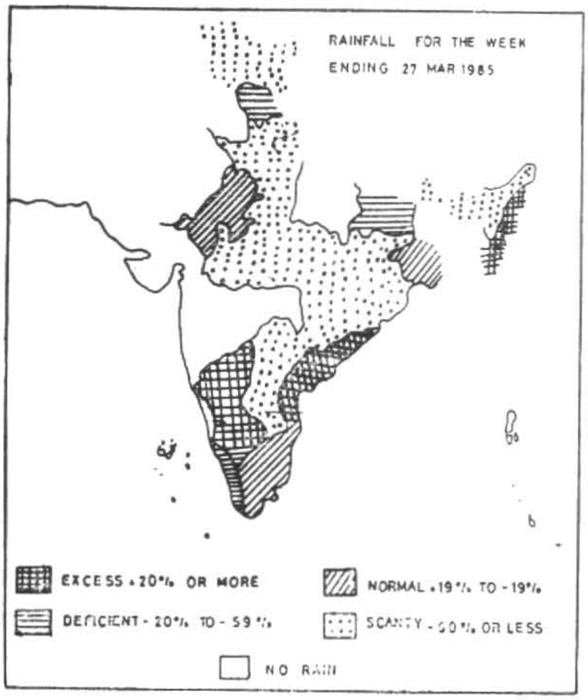


Fig. 8. Precipitation

Sea, along 65° E on 29 March at 250 hPa (Fig. 7a). An SW is also seen on 28 March (Fig. 3a) over south Pakistan. This moves northeastwards and triggers convective developments on 29 March over Pakistan and neighbouring parts of India. As the upper air trough approaches the west coast, the convective activity increases in the afternoon over land areas on 30 March (Fig. 3b). The low level easterlies (charts not shown) are confined to south Peninsula. A very intense SW is seen in the northwest Arabian Sea on 31 March (Figure not shown) which can be traced back as a part of a well organised cloud system southwest of the Caspian sea on 29 March (not shown). The SW induced persistent cloud mass over the north Arabian Sea moves around and re-organises. A typical SW induced subtropical cyclogenesis occurs over south Pakistan at 0630 UTC of 1 April (Fig. 3c) where a comma cloud system is seen under the influence of the development. The low level southeasterlies have invaded central India on 31 March itself and in response to the new development associated with evolution of SW, have a complete sway over northwest India on 1 April in association with shift of subtropical high at 850 hPa from west central Bay to northwest Bay. The subtropical westerly trough retrogrades in accordance with the new development. If the subtropical cyclogenesis had taken place on the front side of the trough, it would have been very intense. The amplified westerly trough again moves to the east and is along 70°E on 2 April (Fig. 7b).

Meanwhile, the low level moist southeasterly flow on the front side of the trough keeps weather very active on 1 and 2 April 1985 in many parts of India. The low level flow is cut off on 3 April and weather activity also ceases. The total precipitation received during the week ending 3 April 1985 is shown in Fig. 8. Most parts of India west of 80°E received excess or normal rainfall whereas the rainfall during the previous week was much less. This shows how ITML can lead to an increase of precipitation over a very large area during pre-monsoon season. Most of the precipitation received was associated, with the thunderstorms reported from many stations. This signifies the importance of ITML in conditioning the atmosphere to trigger convective developments.

3.3. *ITML during monsoon*

From a study of Russian and Japanese charts for the period 1965-1968, Kalsi (1980) linked ITML during monsoon to the large amplitude troughs in mid-latitude westerlies at 500 hPa. Rao (1976) described the effect of mid-latitude systems on monsoon as of four kinds :

(*i*) Intensifying or developing lower tropospheric lows or troughs,

(*ii*) Enhancing rainfall in pre-existing systems,

(*iii*) Causing recurvature of depressions and lows,

(*iv*) Leading to onset of break conditions.

Monsoon trough has gigantic circulation when depressions develop in it but the stability of the position of western part of monsoon trough is less than that of central and eastern part and this is explained by the influence of mid-latitude systems (Rao 1976). Seen in a different perspective from the point of view of satellite analysis of cloud imagery, all the above aspects seem to be well explained in some respects by Weldon, (1979) observations on development, of new deformation zones and shearing off of the low level disturbances by the developing mid level trough in westerlies. As a result of ITML, a new zone of convergence is created over western Himalayas in the deformed western end of monsoon trough which pulls up low level flow towards the hills that substantially increases the rainfall potential over the same area. In the next paragraph, discussion is concentrated on ITML that took place during the period 9-13 August 1986.

A monsoon depression formed in the central Bay of Bengal on the morning of 11 August 1986 when it lay centred near 18°0′ N, 86°5′ E. It intensified into a deep depression in the evening, moved westward and crossed north Andhra coast close to Kalingapatnam on 12th night. It continued to move as deep depression over east Madhya Pradesh on 13th and then weakened into a depression near Raipur on 14th morning. In addition to this depression, a circulation moved westward over north Arabian Sea and entered Arabian peninsula on 12th. An upper tropospheric westerly trough moved eastward from 9 to 12 August and became unimportant on 13 August over western Himalayas. The western end of the monsoon trough shifted to foothills on 11th evening and lay there upto 0000 UTC of 13th August. The upper air chart for 12 August is shown in Fig. 9. Satellite pictures for this period are shown in Fig. 4. ITML during this epoch is first noticed on 9 August in the satellite imagery in the form of an almost north-south band of cloud running across west Pakistan (not shown). As the circulation

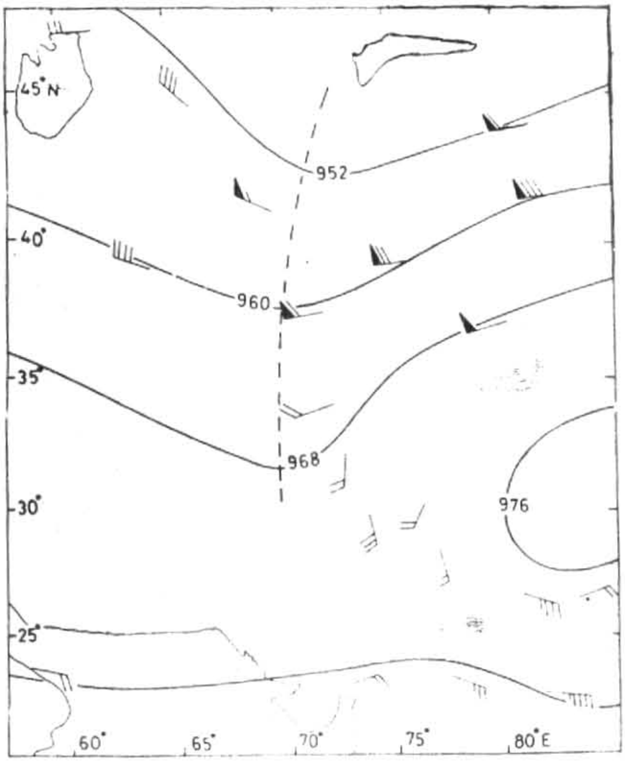


Fig. 9. Trough in westerlies at 0000 UTC of 12 August 1986

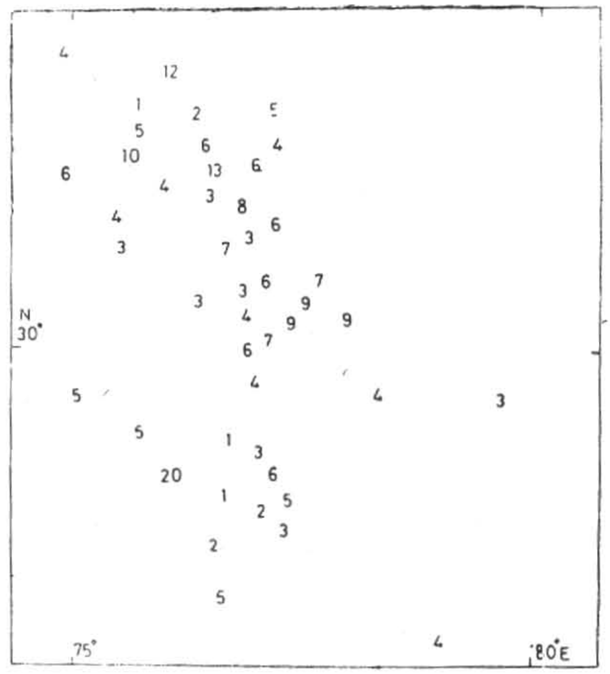


Fig. 10. Rainfall of 13 and 14 August 1986 realised over Northwest India

over north Arabian Sea moves westward the southern part of the cloud band also moves westward. The westerly trough remains stationary on 10 and 11 August along about 65°E north of 30°N and comes to 70°E on 12th morning. Accordingly the cloud band due to ITML runs almost northeast-southwest on 10th (Fig 4a) and 11 August (figure not shown). The central and southern parts of this band disappear on 12 August (Fig. 4b) and northern part is becoming increasingly zonal indicating that perturbation ir westerlies leading to ITML is weakening now. Meanwhile the increased convective activity over Punjab, Haryana, Himachal Pradesh and neighbourhood on 12 and 13 August indicates increased convergence over the area due to the shift of the monsoon trough, as a result of ITML. The frequent oscillations of western end of monsoon trough and spells of precipitation in Kashmir have been attributed to ITML (Rao 1976). This gives rise to increase in the rainfall activity. Monsoon activity was described as vigorous in Himachal Pradesh and hills of west Utter Pradesh on 13 August. It was active in Haryana and east Rajasthan on the same day and in Himachal Pradesh and Punjab on the next day. The precipitation received on these two days over these areas is shown in Fig. 10. The weakening of the westerly trough is discerned through change of shape of cloud band associated with it which becomes more zonal after 12 August and its effect disappears on the afternoon of 13 August. Rainfall activity also decreases over these areas after 14 August. The low level monsoon trough again shifts to its normal position. So in this case the westerly trough increases the monsoon activity over northwest India and at the same time it does not lead to break conditions. The eastward movement of the trough and its subsequent weakening is well observed through satellite imagery. This information is crucial as very scanty data is received from the area where the upper air trough moved and finally weakened.

Another case of ITML is seen during the period 2-6 October 1987. Satellite pictures for 3 and 5 October 1987 are shown in Fig. 5, in this connection. Here a monsoon depression in the east central Arabian Sea was deformed northeastward after 3 October when the trough in westerlies becomes sharply defined along 70°E in the middle troposphere and extends up to 15°N (Chart not shown).

The clouds associated with the depression and the monsoon trough along about 15°N in the lower troposphere on 2nd October 1987 now extend northeastward. After 5 October, the trough in westerlies becomes flat and the cloud band also becomes zonal. In this case the ITML is increasing development of clouds over a very large area and is also influencing the monsoon trough orientation.

Satellite imagery provides a very important tool to monitor ITML during monsoon and this diagnosis could be most crucial in meeting certain emergency situation, the kind of which developed in the fourth week of September 1988. Satellite imagery was used very judiciously to provide hydrometeorological support to Bhakra Beas Management Board. A separate case study on this spell is being persued.

3.4. *ITML during tropical cyclone epochs*

Tropical cyclones interact with adjacent weather systems to produce intensity and other structural changes in a number of ways. The first type of interaction involves development of a strong outflow channel to the westerlies as an upper tropospheric trough approaches or develops to the west of the tropical cyclone. Another possible mechanism is the coming of a cold upper tropospheric low into close proximity of a tropical cyclone. A sudden sinking of the upper low has been associated with intensification of a tropical cyclone (Riehl 1979). Kalsi and Jain (1989) have also presented a case study of intensification of tropical cyclone through this mechanism. Though there are numerous cases of shearing off of tropical cyclones by mid-latitude westerlies, the following paragraphs shows the impact of a westerly trough on a marginal cyclone which got deformed northeastwards as a result of ITML.

A vortex moving northwestward over the Andaman Sea and east Bay of Bengal rapidly intensified to a marginal cyclone (T. 2.5) just before landfall on 19 October 1988. It displayed a comma-cloud pattern with tail pointing southward. There was simultaneous development of convective clouds over northeastern States (Assam, Meghalaya, Arunachal Pradesh, Tripura & Mizoram) mainly in the deformation band ahead of the westerly trough (Fig. 6a). The chart for this sequence is not shown. The cyclone was seen at the base of a 500hPa trough in the westerlies and the intensification of this cyclone might be a case of sub-tropical genesis in which cold air pool cut off from westerlies eventually evolves rapidly into a cyclone (Herbert and Potent 1975). But in this case sudden development of an extensive belt of precipitation is a much more important attribute of ITML. Another case of ITML involving a tropical cyclone was observed on 2 February 1987 when a vortex with T 4.0 intensity in the Bay of Bengal was sheared off by the mid-latitude westerlies. Satellite picture showing weakening on account of ITML is given in Fig. 6b. A case study on the development of this cyclone (Mandal *et al.* 1990) has been published in *Mausam*. Still another tropical vortex showed a highly abnormal fast movement of about 5 in 9 hours on 16 November 1988 on account of ITML. It is speculated that an existing innocuous vortex (positioned at X in Fig. 6c) on the northern side of the tropical depression developed suddenly on account of movement of the tropical depression and its merger with the northern vortex. A long extensive outflow band was seen emanating from the storm area being channelised by the strong mid-latitude westerly seen further to the east and northeast of the vortex. In this case ITML leads not only to fast movement (apparently due to merger and fast development of northern vortex) but also to overall intensification of the tropical system which became a severe cyclone by 1200 UTC of 16 November 1988.

4. Conclusions

From the foregoing discussions it is abundantly clear that interaction between tropics and mid-latitude is frequent during anomalous and disturbed weather epochs in all seasons of the year in India and neighbourhood. It leads to intensification of western disturbances, outbreak of convection, oscillations of monsoon trough and deformation of circulations including cyclonic storms. Satellite imagery provides a means of monitoring ITML in relation to all these development. ITML manifesting itself in a "deformation type" band of cloud seen generally oriented orthogonally to the wind maxima over oceanic areas can easily be discerned in the satellite imagery. Short waves which are not resolved in the conventional net work can also be tracked in the satellite imagery. Their influence on overall modification of the circulation can be diagnosed. In the report of the CAS working group on tropical meteorology (WMO 1988), five zones have been identified where ITML is seen to occur. These are the SW Pacific, SE Asia, N. Africa, Brazil & S. Africa. According to this study, it is apparent that ITML plays an important role in many of the weather producing processes in and around India.

Acknowledgements

The senior author is thankful to Dr. S.K. Ghosh, the then Regional Director, Regional Meteorological Centre, New Delhi and S/Shri M.S. Singh & K. Veeraraghavan, the then Directors in the office of the Director General of Meteorology for going through the manuscript and for providing very useful comments.

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