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A satellite study of the tropical easterly jet stream during 'Monsoon--77'*

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सार – मेघ क्षेत्र में उष्णकटिबंधीय पुरवा जेट का यह एक प्रेक्षणात्मक अध्ययन है। मानसून-77 (20-26 जून) के दौरान भारत और उसके आस पड़ौस में संयुक्तराष्ट्र अमेरिका के मौसम उपग्रह के दृश्य और अवरक्त बिम्बावली का उपलब्ध उपरितन वायु के रेडियो पवन प्रेक्षणों के साथ संयोग करके जेट धारा में पड़ने वाले मेघों के अध्ययन के लिए उपयोग में लाया गया है। जेट धारा मेघों को ऊपरी क्षोभमंडलीय पुरवा धाराओं में विकृतियों के सहचर्य में प्रेक्षित किया गया है। प्रेक्षित मेघ प्रतिमान तत्सम्बंधित अधिकतम पवन क्षेत्र से तथा कभी-कभी 150 और 100 मि० बार के गति क्षेत्र सहित अच्छी तरह से मिलते जुलते पाए गए। ऊर्ध्वाधर पवन अपरूपण पर आधारित अनुदैर्ध्य और अनुप्रस्थ विधाओं में मेघों के संगठन को भी प्रेक्षित किया गया। उपग्रह से देखे गए जेट स्ट्रीम मेघों के मामलों में गणना किए गए ऊर्ध्वाधर पवन अपरूपण के मान जेट क्रोड से लगभग 5 कि0 मी0 नीचे 25 से 32 तक प्रति घंटा विचरित होते हुए पाए गए। जोकि पवन क्षेत्र में जेट के पूर्व के अध्ययन कर्त्ताओं द्वारा रिपोर्ट किए मानों से अधिक थे। जेट मेघों के दांए निर्गम त्रिज्यखंड में मानसन सक्रिय देखे गए और समुद्र पर एक सतही अवदाब तंत्र स्थित होने पर संवहन सक्रियता काफी सुस्पष्ट दिखाई पड़ी।

ABSTRACT. This is an observational study of the tropical easterly jet in the cloud field. The visible and infrared imagery of NOAA-5, US weather satellite, have been used to study jet stream clouds in conjunction with the available upper air radiowind observations over India and neighbourhood during Monsoon-77 (20-26 June). The jet-stream clouds have been observed in association with perturbations in upper tropospheric easterly currents. The observed cloud patterns are found to agree fairly well with the corresponding maximum wind field and sometimes with the motion fields of 150 and 100 mb. The organisation of clouds in longitudinal and transverse modes having dependence on verticle wind shear have also been observed. The values of vertical wind shear computed in cases of the satellite-viewed jet-stream clouds are found to vary from 25 to 32 hr^{-1} about 5 km below the jet core, which are more than the values reported by earlier workers based on the study of the jet in the wind field. Monsoon is observed to be active in the right entrance sector of the jet clouds and the convective activity appears to be more pronounced when a surface low pressure system is present over the area.

1. Introduction

The tropical easterly jet stream which is one of the most fascinating features of the monsoon system has been the subject of investigation during the past three decades. Krishna Rao (1952) for the first time inferred the existence of this jet stream over south India in summer with the aid of the observed strong winds from the east during the periods of weak monsoon when pilot balloons could be followed to great heights. Koteswaram (1958 a & b) examined the structure of the summer easterly jet south of the Tibetan anticyclone. The principal results of his investigations are (*i*) The core of the jet stream is located approximately over 15 deg. N at a

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pressure level of 150 to 100 mb over south Asia and about 10 deg. N over Africa, (*ii*) Below the level of strongest winds temperatures decrease from right to left across the current looking down stream and above the level of strongest winds, the reverse is true, (*iii*) The burst of the south-west monsoon along Kerala coast is found to occur in association with the advance of the easterly jet-stream over south India, (*iv*) Temporary activation of the monsoon occurs sometimes in association with wavelike perturbations in upper easterlies, (*v*) Since the easterly jet stream is observed over south Asia and Africa but not over the Pacific and Atlantic Oceans, he feels that the current originates as a result of the large scale distribution of land masses and Ocean and with the elevated heat source of the Tibetan plateau. Koteswaram (1969) studied the mean cross-section of the tropical easterly jet (TEJ) along 80 deg. E in July using 15 years of radiosonde rawin data and indicated two mean maxima of 80 kt over 15 deg. N at 125 mb, 60 kt over equator at 175 mb. Mokashi (1970) studied the vertical wind profile of the tropical easterly jet stream over Madras, Visakhapatnam and Trivandrum using rawin observations for the months June to September during five consecutive years (1961-1965). He found that the stronger the tropical easterly jet stream, the higher was the altitude of the maximum wind. The jet strengthens as one moves towards south from Visakhapatnam to Trivandrum while the level of its occurrence lowers. Mokashi (1974), with the same rawin observations, further studied the vertical structure of the tropical easterly jet-stream over the Peninsular India and over the regions to the south of it upto the equator. The main finding of his study is that the axis (core) of the easterly jet stream is near Trivandrum in June and August and near Colombo in September. In July, there is a broad band of high winds. Mokashi in this study also noted the simultaneous existence of another speed maximum in the neighbourhood of Goa (Lat. 15 deg. N) at about 16 km.

So far the behaviour of the easterly jet stream has been studied in the wind field with limited number of radiowind observations over south Asia and Africa. With the availability of visible and infrared imagery from weather satellites, the study of westerly jet stream clouds have been made by Oliver *et al.* (1964), Whitney *et al.* (1966) and Viezee *et al.* (1967) over North American areas and by Srinivasan (1971) over Indian sub-continent. The easterly jet stream has not yet been studied in the cloud field using satellite imagery. In the present paper, an attempt has been made to study this jet stream using scanning radiometer pictures of NOAA-5 environmental satellite in visible and thermal infrared channels during 'Monsoon-77'. Since conventional data are not routinely available over oceanic areas which cover large part of the tropical monsoon field, satellite derived upper tropospheric information will prove to be very valuable observational input to the atmospheric modelling and also will be of great help in aeronautical operations. The study presented here is preliminary in nature concentrated mainly on the interpretation of the cloud characteristics associated with tropical easterly jet streams in relation to upper tropospheric wind patterns. Detailed study incorporating a number of cases in recent years is underway.

2. Source of data

The visible and infrared imagery of NOAA-5 weather satellite in Mercator projection received from the National Environmental Satellite Service, NOAA, Washington D.C. during 'Monsoon-77' have been utilized in this study. Meteorological charts such as constant pressure charts, rainfall charts, surface charts and tephigrams for the month June 1977 available at Northern Hemisphere Analysis Centre have been used. Pilot charts of Meteorological Office, Safdarjung Airport for the same month have also been examined.

3. Observational features

As the easterly jet stream occurs between 150 and 100 mb, it has more dominant appearance in infrared imagery than visible one due to associated cold cirriform clouds. Extended mass of cirrus clouds mostly in long cirrus bands along the jet axis have been observed. On some occasions the equatorward edge of the cirrus shield is seen to be sharp which is just opposite of the earlier findings by Singh *et al.* (1978) and Anderson *et al.* (1974) in the case of sub-tropical westerly jet stream where sharp poleward edge of the cirrus shield was observed. The sharp edge in the westerly and easterly jets give limit of cloudiness and vertical ascent and indicates that ascent takes place in the warm air in both cases. The clear skies observed to the south of TEJ are in accordance with the descent over the equatorial areas indicated by Koteswaram (1958b) in the meridional monsoon cell. In the present study seven cases of jet stream clouds during 20 to 26 June 1977 have been studied and their details are given below.

3.1. *20 June 1977*

Extended mass of cirrus clouds about 2000 km long between **A** & **B** seen in the infrared

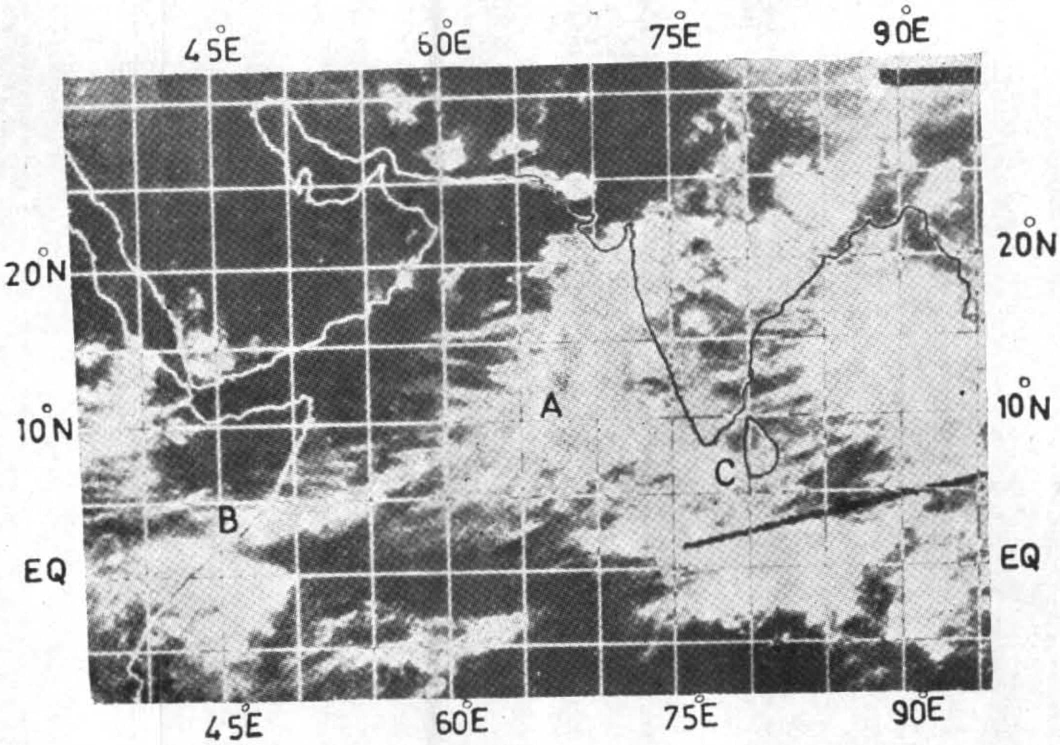

Fig. 1. Jet associated cirriform clouds seen along CAD in the infrared imagery of NOAA-5 satellite on the night of 20 June 1977

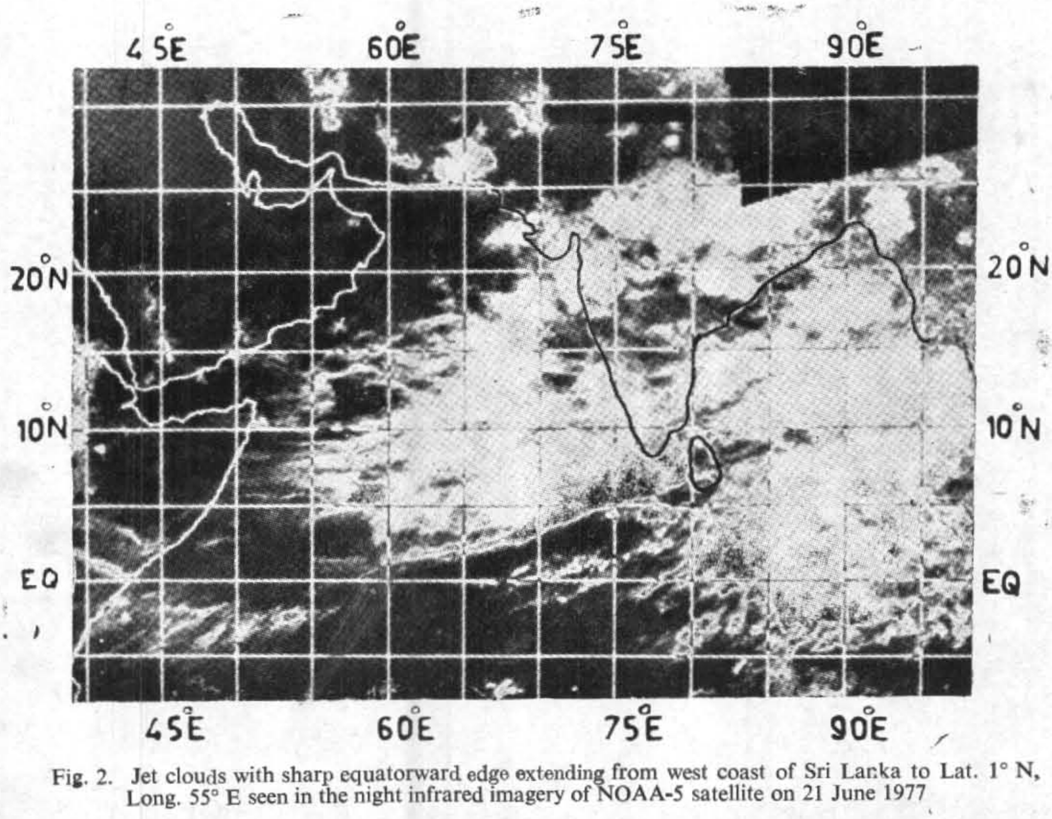

Fig. 2. Jet clouds with sharp equatorward edge extending from west coast of Sri Lanka to Lat. 1° N, Long. 55° E seen in the night infrared imagery of NOAA-5 satellite on 21 June 1977

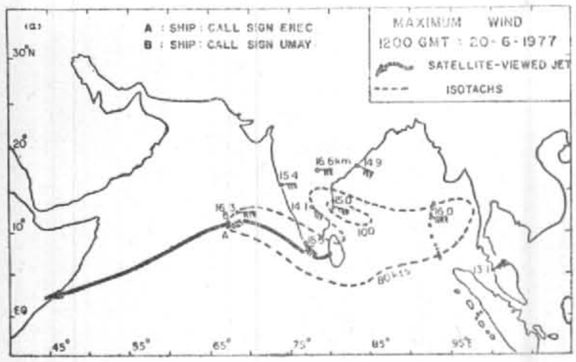

Fig. 3. Satellite-viewed jet clouds in relation to the maximum wind pattern at 1200 GMT on 20 June 1977 are shown by thick arrow

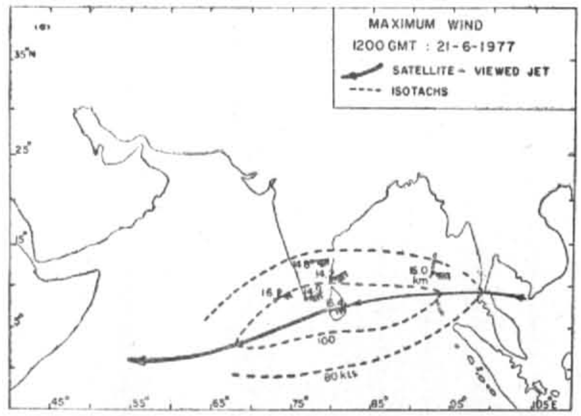

Fig. 4. Satellite-viewed jet clouds in relation to the maximum wind pattern at 1200 GMT on 21 June1977 are shown by thick arrow

imagery on the night of 20 June (Fig. 1) is associated with the tropical easterly jet stream. This is also supported by the concurrent maximum wind field (Fig. 3). The southeasterly winds at Trivandrum and Bangalore and E/ ENE'ly winds reported by two Russian ships, call signs *EREC and UMAY* at 1200 and 1800 GMT respectively show that the jet clouds appear in association with a trough in easterlies. The exact location of the jet stream cloudiness over eastern Arabian Sea cannot be determined accurately due to the multilayered monsoonal cloud decks below. However, the jet axis may be located over this area by extrapolating jet clouds lying over western Arabian Sea towards east, on the basis of the prevailing maximum wind field over the southern Peninsula. The wave type appearance of the jet clouds along BAC (Figs. 1 and 3) follows the perturbation in the easterly current, which exists in fairly deep layer of the troposphere between 300 mb and the jet core.

The vertical wind shears computed using the vertical sounding data (12 GMT) of the Russian ship (call sign *EREC*) located at Lat. 10.7 deg. N, Long. 67.3 deg. E which lies in the vicinity of the jet clouds come out to be 32 hr^{-1}= 32 kmph/km between 12.4 and 14.2 km and 25 hr^{-1} between 9.6 and 14.2 km. These values are comparatively larger than the values reported by Rao (1976) and Rao and Ramamurti (1968). According to them, the values of the vertical wind shears vary from 15 to 20 hr^{-1} between 9 and 16 km. The values of the vertical wind shear computed at Trivandrum which lies within 100 km of the jet clouds is 25 hr^{-1} between 10.9 and 16.5 km.

3.2. *21 June 1977*

Well marked jet stream clouds extend between Colombo and Lat. 1 deg. N, Long. 60 deg. E as seen in the infrared imagery on the night of 21 June (Fig. 2). The cloud shield has a sharp and distinct edge on the equatorward side. It can well be distinguished from the other cloud boundaries by its straight smooth appearance and its extensive length. The identification of the jet clouds finds good support in the corresponding maximum wind field shown in Fig. 4. Colombo from where the jet clouds are seen to emanate reported ENE'ly wind of 110 kt speed at 16.4 km. The examination of the upper tropospheric charts reveals that a trough persists over southwest and west central Bay of Bengal from 300 mb aloft upto 100 mb and the jet clouds are seen to appear ahead of the trough.

The vertical wind shears computed over Colombo (Just below the jet clouds), Trivandrum (about 200 km north of the jet clouds) and Minicoy (about 300 km north of the jet clouds) come out to be 30 hr^{-1} between 10.8 and 16.4 km, 26 hr^{-1} between 10.8 and 14.9 km and 22 hr^{-1} between 9.7 and 16.2 km respectively. The gradual decrease in the values of the vertical wind shears as one moves northwards from the jet clouds lends credence to the reliability of the identification of this cloudiness as jet clouds.

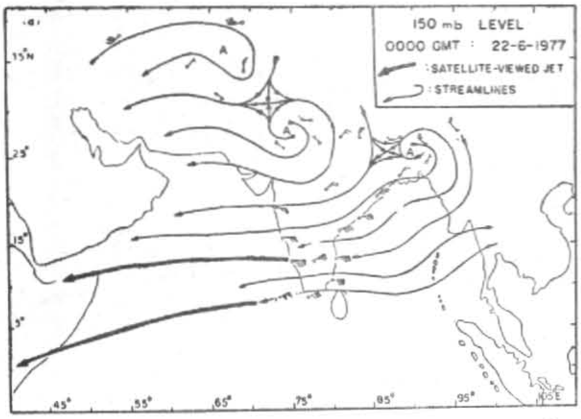

Fig. 5. Satellite-viewed jet clouds in relation to the motion field at 150 mb at 00 GMT on 22 June 1977 are shown by thick arrow

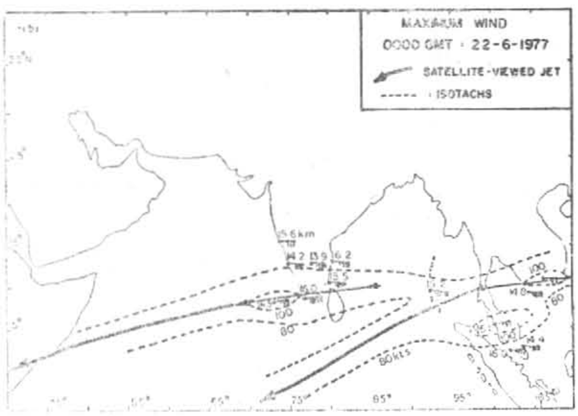

Fig. 6. Satellite-viewed jet clouds in relation to the maximum wind pattern at 00 GMT on 22 June 1977 are shown by thick arrow

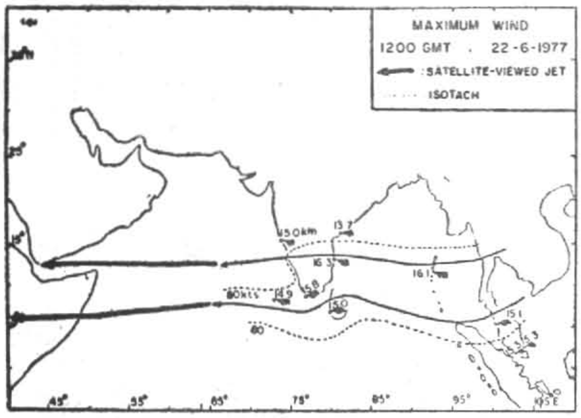

Fig. 7. Satellite-viewed jet clouds in relation to the maximum wind pattern at 1200 GMT on 22 June 1977 are shown by thick arrow

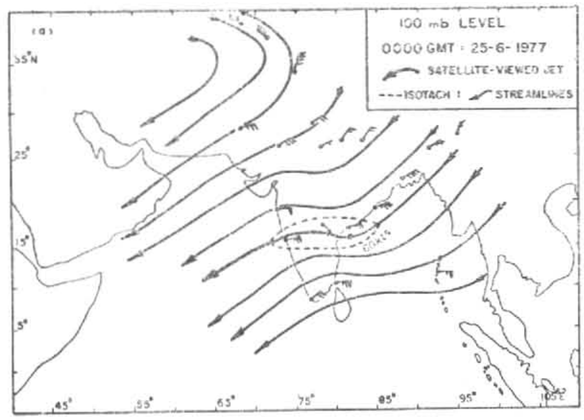

Fig. 8. Satellite-viewed jet stream clouds in relation to the motion field at 100 mb at 00 GMT on 25 June 1977 are shown by thick arrow

3.3. *22 June 1977*

Three distinct cirriform cloudiness associated with the easterly jet are seen along AB, CD and EF in the infrared imagery received on the morning of 22 June (Fig. 9). The cloudiness along EF has an extensive cirrus shield with fairly sharp equatorward edge. The alignment of the jet clouds along AB fits fairly well with the wind pattern of 150 mb level (Fig. 5) and that along EF appears to correspond to the maximum wind pattern (Fig. 6) whereas jet clouds along CD confirm to the wind patterns of both 150 mb level and level of maximum wind (L M W).

Jet clouds AB and CD can easily be identified over western Arabian Sea and off Somali coast due to the absence of low clouds. These clouds when extrapolated eastwards over the eastern Arabian Sea and Indian Peninsula are seen to pass through Mangalore and Minicoy respectively. The vertical wind shears computed over these stations are 31 hr^{-1} between 9.6 and 14.2 km and 38 hr^{-1} between 9.6 and 14.3 km respectively. Carnicobar which lies under the cirrus shield along EF has vertical wind shear 25 hr^{-1} between 9.6 and 15.2 km.

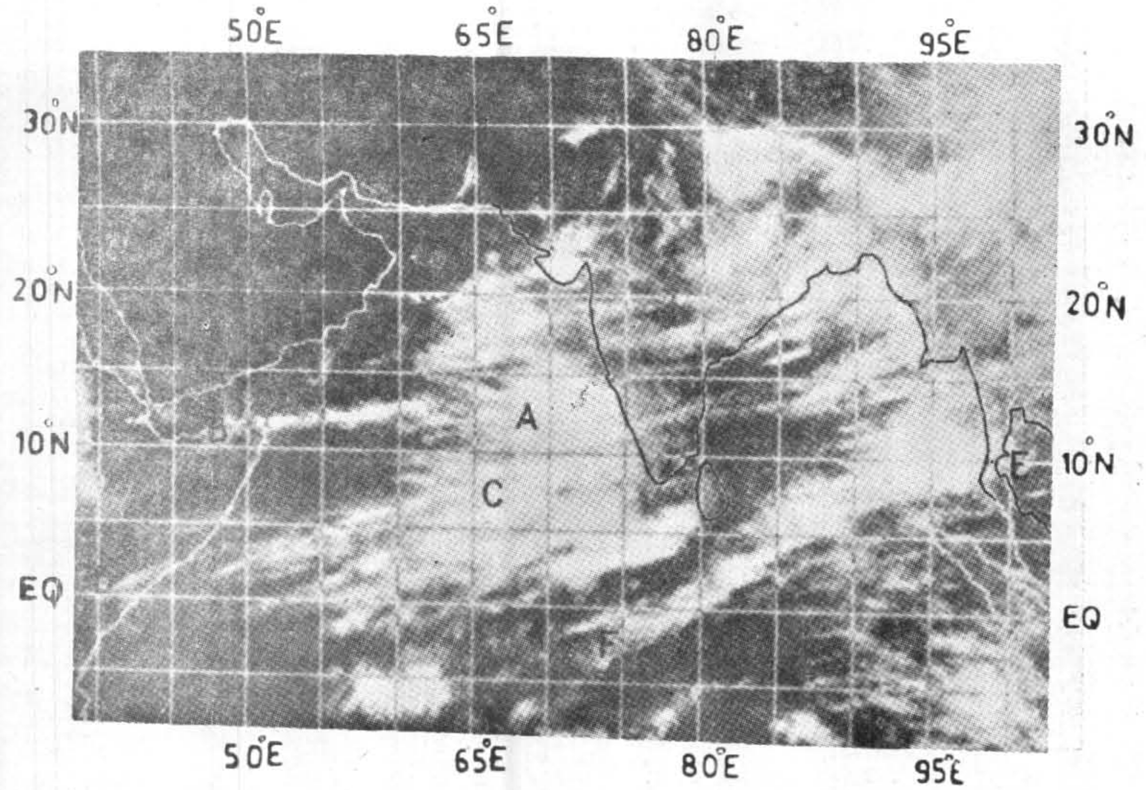

Fig. 9. Three distinct jet stream cloudiness seen along AB, CD and EF in the day infrared imagery of NOAA-5 satellite on 22 June 1977

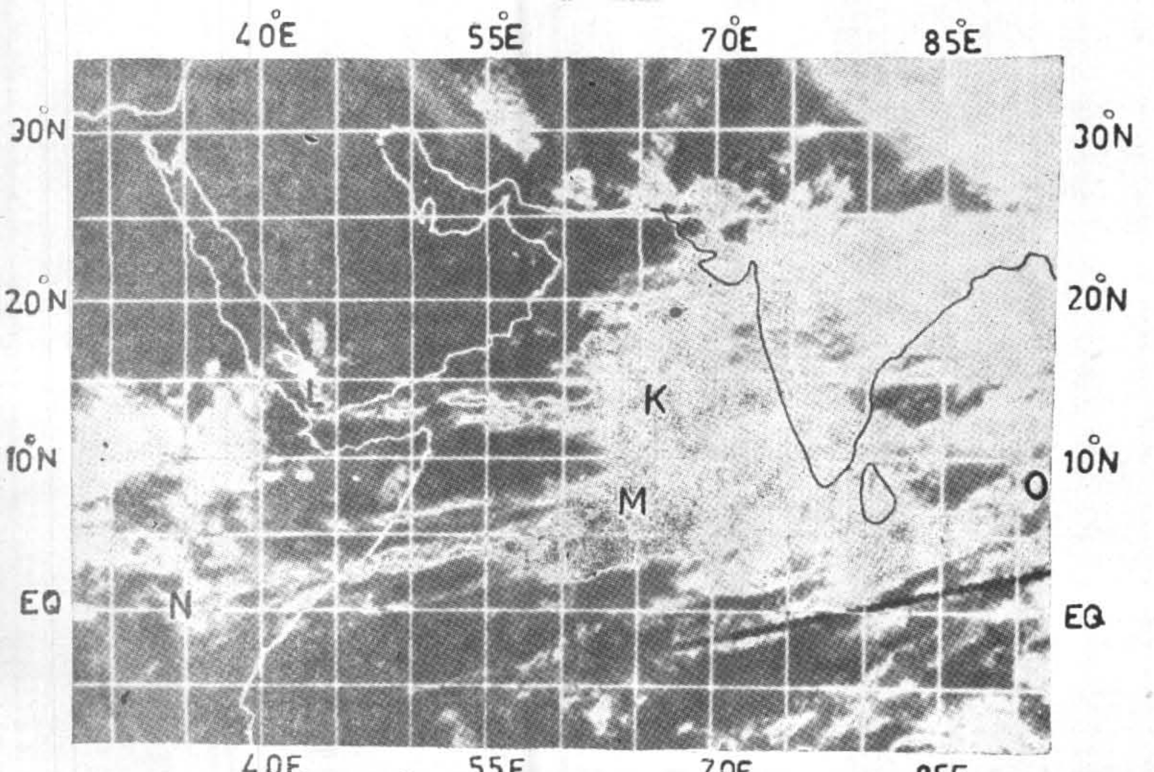

Fig. 10. Three distinct jet stream cloudiness along KL, MN and OP in the night infrared imagery of NOAA-5 satellite on 22 June 1977

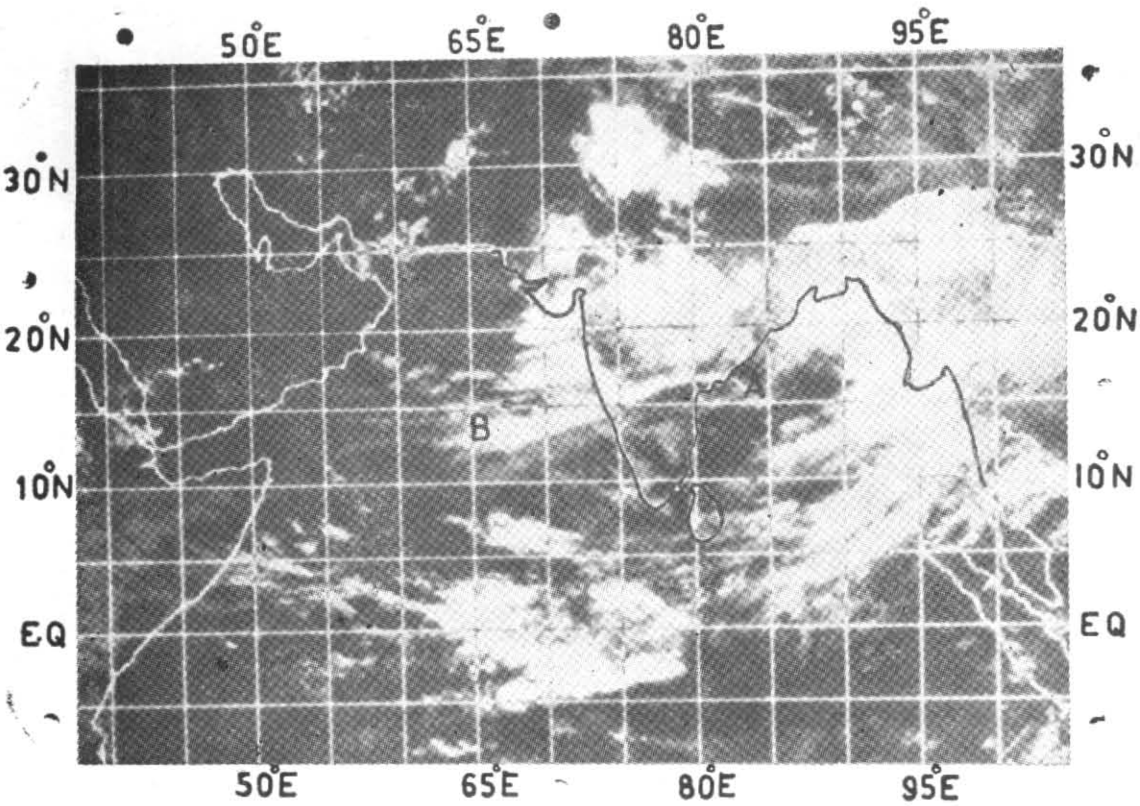

Fig. 11. Cyclonically curved jet clouds along AB seen in the day infrared imagery of NOAA-5 satellite on 25 June 1977

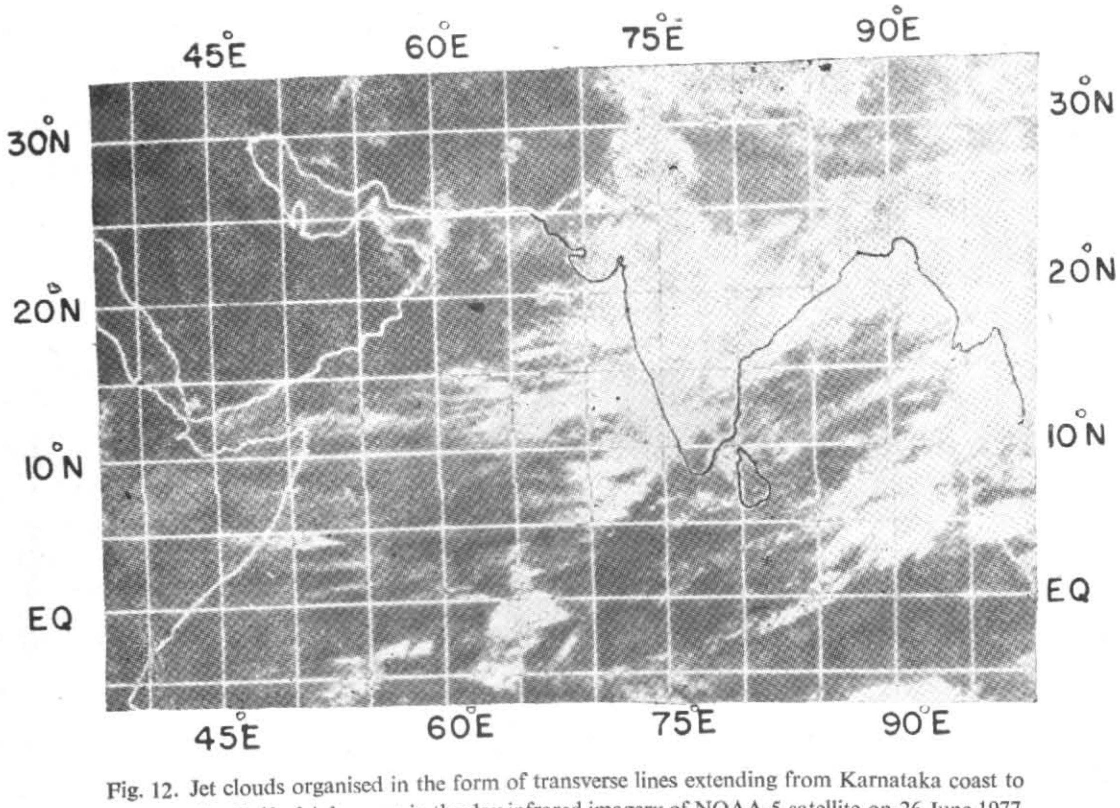

Fig. 12. Jet clouds organised in the form of transverse lines extending from Karnataka coast to the Gulf of Aden seen in the day infrared imagery of NOAA-5 satellite on 26 June 1977

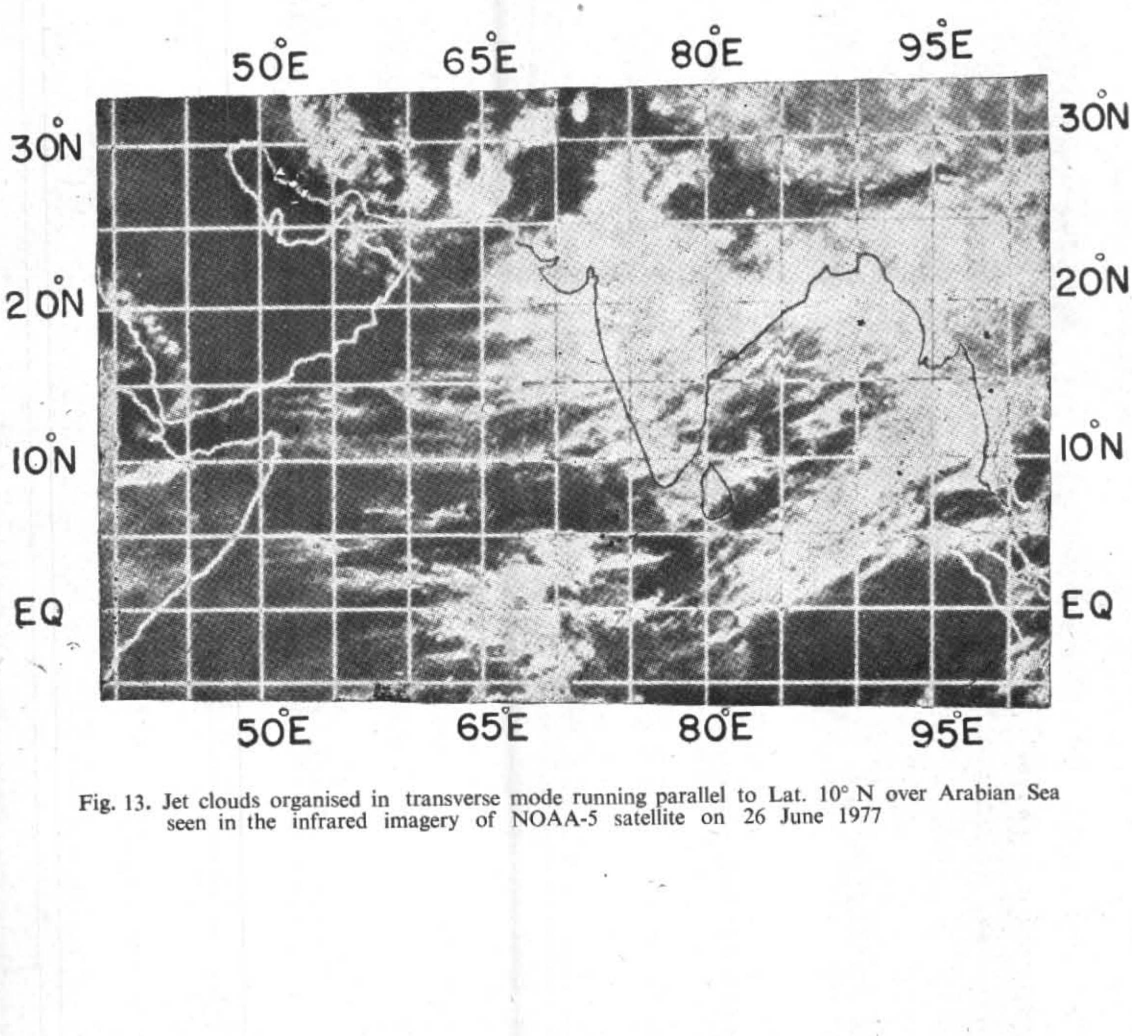

Fig. 13. Jet clouds organised in transverse mode running parallel to Lat. 10° N over Arabian Sea seen in the infrared imagery of NOAA-5 satellite on 26 June 1977

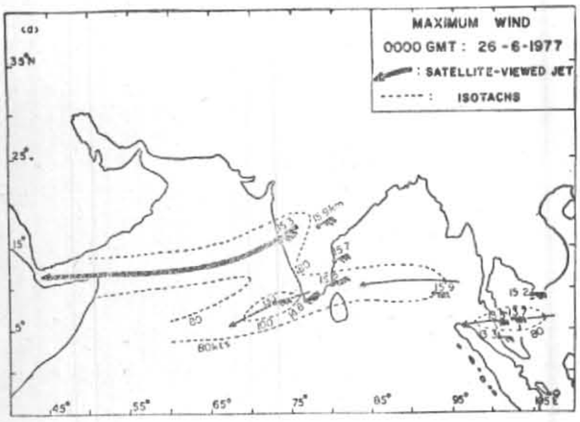

Fig. 14. Satellite-viewed jet stream clouds in relation to the maximum wind pattern at 00 GMT on 26 June 1977 are shown by thick arrow

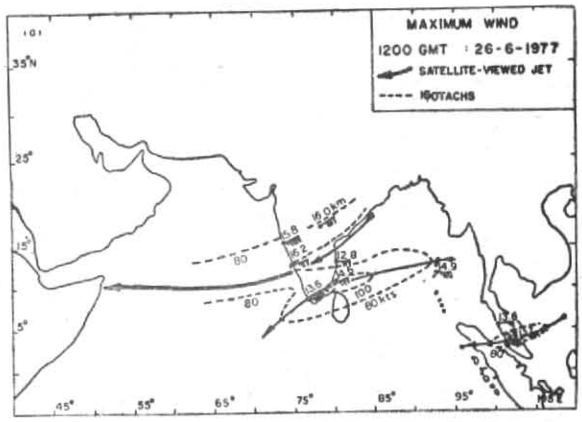

Fig. 15. Satellite-viewed jet clouds in relation to the max mum wind pattern on 1200 GMT on 26 Jun 1977 are shown by thick arrow

In the infrared imagery received on the night of 22 June (Fig. 10), three distinct jet cloud-streaks can be located along KL, MN and OP having more or less same orientation and position as observed in the morning infrared picture. The cloudiness along KL and MN conform to the maximum wind pattern (Fig. 7). However, the third jet cloudstreak along OP is not well reflected in the maximum wind field due to inadequate wind observations over the area. The vertical wind shear at Minicoy is found to be 27 hr between 9.6 and 14.9 km.

3.4. *25 June 1977*

The infrared imagery recorded on the morning of 25 June shows jet-associated cirriform clouds along AB (Fig. 11). The jet clouds seem to assume cyclonic orientation in association with a trough in the upper easterlies. This is well reflected in the 100 mb pattern shown in Fig. 8. The vertical wind shear at Goa which lies under the jet cloudiness is found to be 25 hr^{-1} between 10.9 and 15.5 km.

3.5. *26 June 1977*

In the cases discussed above, the cirriform clouds are seen to be organised in the longitudinal mode, *i.e.*, cirrus flow takes place in the direction of the jet stream. But the infrared imagery recorded on the morning and night of 26 June shows also transverse lines in the clouds associated with the jet (Fig. 12) and Fig. 13), *i.e.*, a small-scale cloud lines at an angle almost perpendicular to maximum wind flow. Jet clouds in the morning picture run parallel to Lat. 12 deg. N over central and west Arabian Sea extending upto the gulf of Aden. Over eastern Arabian Sea and Indian Peninsula, it has NE-SW orientation. The same cloud characteristics are also observed in the infrared imagery received at night. The only difference is that jet clouds run parallel to Lat. 10 deg. N between northern tip of Somali coast and Long. 70 deg. E. The alignment of jet clouds in both the cases conforms to the maximum wind patterns (Figs. 14 and 15).

The vertical wind shear at Goa which lies under jet clouds in the morning infrared imagery is found to be 27 hr^{-1} between 9.6 and 15.3 km at 00 GMT and the same at Mangalore which lies under jet clouds in the night infrared imagery is found to be 22 hr^{-1} between 9.6 and 14.0 km at 1200 GMT.

4. The jet stream — precipitation relationship

Jet stream environs are recognised as areas of vertical exchange processes. The right entrance and the left exit sectors of the jet stream are prone to heavy precipitation activity (Koteswaram 1958 a). Under the influence of the strong easterly jet on the evening of 20 June (Fig. 3), monsoon was active in Kerala and coastal Karnataka and widespread rain also occurred over Lakshadweep. Heavy rainfall recorded over this area at 0300 GMT of 21 June were Agumbe 12 cm, Kasargode (Cannanore district) 11 cm, Mangalore A.P. 10 cm, Calicut, Belthangady and Coondapur 8 cm each and Thodupuzha (Idikki district) 7 cm. On the night of 21 June, jet clouds were located about 100 km south of the southern tip of the Indian Peninsula. The heavy rainfall recorded at 0300 GMT of 22 June were: Androth 10 cm, Agumbe and Mangalore 9 cm each and Calicut 7 cm. On 22 June two jet streams were seen over the Arabian Sea diverging from the west coast of India through Mangalore and Minicoy latitudes both in morning and evening pictures. In association with this synoptic feature, monsoon was active in coastal and south interior Karnataka. Rainfall was also widespread in Kerala and Lakshadweep. The heavy rainfall recorded at 0300 GMT of 23 June were: Agumbe 21 cm, Mangalore 9 cm, Kasargode, Shirali, Belthangadi, Coondapur, Mercara and Talaguppa 7 cm each. On 25th morning jet clouds assumed more northerly positions (Fig. 11). A well marked low pressure area lay over north Madhya Pradesh and a cyclonic circulation was located over northeast Arabian Sea, both extending upto mid-tropospheric levels. The effect of the low level convergence due to the two low pressure systems situated to the right of the jet was accentuated due to the upper level divergence caused by the advection of positive vorticity over this area resulting in vigorous monsoon activity over east Madhya Pradesh and Gujarat region. The heavy rainfall recorded at 0300 GMT of 26 June were: Mandla 18 cm, Jabalpur 14 cm, Surat and Dahanu 13 cm each, Bhopal and Mahabaleswar 11 cm each, Gondia 8 cm and Panchmarhi 7 cm. Almost the same synoptic situation also prevailed on 26 June as a result of which monsoon was vigorous over west Madhya Pradesh and Gujarat region. The heavy rainfall recorded at 0300 GMT of 26 June were Jabalpur 16 cm, Agumbe 15 cm, Nandurbar 13 cm, Narsinghpur and Baroda 12 cm each, Surat 10 cm and Umaria 7 cm.

5. Discussion

In all the infrared imgery chosen for the study, it is seen that the western Arabian Sea, Somali coast, Gulf of Aden and Arabian coast are free from low clouds. This observation is in conformity with the finding of Pant (1978) who using ISMEX (Indo-Soviet Monsoon Experiment) 1973 data showed that temperature inversions exist in the planetary boundary layer over western Arabian Sea thereby inhibiting cloud formation. Due to the absence of the low and medium clouds over this region, it is easy to locate jet stream cloudiness. In the cases studied here, jet-associated clouds were first identified over this region and then extrapolated eastwards to eastern Arabian Sea and Indian Peninsula with the help of upper tropospheric and wind data.

In the case of westerly jet stream which has been thoroughly studied in north American areas with sufficiently dense network of upper air observations, it has been established that the jet core lies parallel to and within 100 km of the poleward edge of the Cirrus Shield (Johnson *et al.* 1976). On the basis of their finding, it may be expected that more or less similar relationship between the easterly jet clouds and jet core also holds as the physical processes responsible for the formation of the jet clouds in both cases should be the same. However, this may be verified when larger number of radiowind observations may be available over the Arabian Sea and the Bay of Bengal during MONEX-79.

6. Forecasting implications

As shown in section 4, the right entrance sector of the jet is seen to be a favourable area for heavy convective precipitation. The location of the jet stream in satellite imagery would, therefore, render valuable help to the forecaster in issuing heavy rainfall warnings during monsoon season. The monsoon rainfall is also seen to be greatly accentuated on 25 and 26 June 1977 when the low pressure systems in lower atmosphere lie in the right entrance sector of the jet. This synoptic feature should be kept in view while forecasting monsoonal rainfall over Indian sub-continent.

The behaviour of the jet over remote areas such as Arabian Sea and Bay of Bengal could not be studied in detail due to the limited number of observations available during the period under study. The Monsoon Experiment in 1979 may provide better data base to study various characteristics of the jet in relation to jet associated cloudiness. On the morning and night of 26 June, transverse cloud lines have been observed over the Arabian Sea. Available literature on the study of the westerly jet cloudiness Anderson *et al.* (1974) shows that the transverse lines are usually associated with wind speeds of 80 kt or higher and strong vertical wind shears. Severe and extreme turbulence has been reported frequently in cases associated with transverse lines. From the analogy it can be inferred that the similar physical processes may also be responsible for the formation of transverse lines in the case of easterly jet streams. Such information will provide the aviation forecaster with the tangible benefits in briefing about severe turbulence in the areas having transverse lines.

At present, wind informations upto 12 km are routinely required for commercial aviation in India for supersonic transport winds upto 18 km will be needed for aeronautical operations. The detection of the easterly jet stream over remote oceanic areas will provide useful information in the preparation of the flight plans for supersonic jet operations. This may also serve the purpose of meteorological briefing for long distance flights especially for the long oceanic routes, Bombay-Nairobi, Bombay-Mauritius, Madras-Singapore etc.

7. Conclusion

(*i*) The tropical easterly jet stream in the cloud field appears in association with the perturbations in upper tropospheric easterly currents.

(*ii*) The jet is found to be associated with strong vertical wind shears which vary from 25 to 32 hr^{-1} about 5 km below the jet core. These values are higher than those reported by earlier workers.

(*iii*) The jet clouds have been observed both over the Arabian Sea and the Bay of Bengal. But they have more identifiable appearance over the western Arabian Sea, off somali coast, Gulf of Aden and off Arabian coast where low and medium clouds are absent.

(*iv*) On 21 and 22 June, the cirrus cloud shield has sharp and distinct edge on the equatorward side which is well distinguished from the other cloud boundaries by its straight and smooth appearance and its extensive length.

(*v*) The monsoon is observed to be active in the right entrance sector of the jet clouds. The convective activity is seen to be enhanced when a low pressure system in lower levels is present over the area.

(*vi*) The transverse lines in the jet stream cloudiness have been observed over Arabian Sea. These are indicative of the area of potentially severe turbulence.

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