Mausam, (1982), **33**, 2, 221-230

551.515.1 : 551.553.21(267)

Some features of a tropical depression over the Arabian Sea during the onset of the southwest monsoon during Monex 1979

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(*Received 4 March 1980*)

सार – दक्षिण-पश्चिम मानसून के प्रारंभ काल में अरबसागर पर कभी-कभी भारी विक्षोभ/चक्रवाती झंझा बनते हैं। इस शोध पत्र में विस्तीर्ण आंकड़ों से अरबसागर पर बनने वाले उष्ण कटिबंधीय विक्षोभों की संरचनाओं एवं संघटनों के कुछ पहलुओं का अध्ययन किया गया है। आपेक्षिक भ्रमिलता, अपसरण, ताप और नमी के क्षेत्रों की प्रणालियों का विश्लेषण किया गया है। यह अध्ययन उष्णकटिबंधीय विक्षोभ के निम्नलिखित मुख्य अभिलक्षणों के अस्तित्व को दर्शाता है। वे इस प्रकार हैं :

(क) मध्य तलीय भ्रमिल से विकसित विक्षोभ, (ख) निम्नतलीय पछुआ जेट की अपरूपण भ्रमिलता, कपासी संबहन एवं निम्न ऊर्ध्वाधर पवन अपरूपण इसके विकास में महत्वपूर्ण भूमिका अदा करना, (ग) मध्य तल में अधिकतम चक्रवाती भ्रमिलता, (घ) झंझा के केन्द्र के अग्रवर्ती त्रिज्यखंड से पश्चिम तक अधिकतम अभिसरण, (ङ) 700 मि० बार के आसपास अपसरणहीन तल, (च) निम्नतर क्षोभमंडल का दक्षिण-पश्चिम त्रिज्यखंड का निम्नतम तापमान एवं उत्तरी त्रिज्यखंड का अधिकतम तापमान और (छ) मध्य क्षोभमंडल तक झंझा केन्द्र के आस-पास अधिकतम नमी।

ABSTRACT. During the onset phase of the southwest monsoon, occasionally, deep depressions/cyclonic storms form over the Arabian Sea. Some aspects of formation and structure of a tropical depression which formed over the Arabian Sea have been studied based on extensive data. The relative vorticity, divergence, thermal and moisture fields for the system have been analysed. This study revealed the existence of the following main characteristics of the tropical depression/storm: (*a*) the depression developed from the middle level vortex; (*b*) the shear vorticity of the low level westerly jet, cumulus convection and low vertical wind shear played significant role in its development, (*c*) cyclonic vorticity maximum in the middle level, (*d*) convergence maximum in the forward sector to the west of the storm centre, (*e*) level of non-divergence around 700 mb, (*f*) lowest temperature in the southwest sector and highest temperature in the northern sector in the lowest troposphere and (*g*) moisture maximum around the storm centre upto middle troposphere.

1. Introduction

Tropical depressions generally form over the oceans on the intertropical convergence zone. Under favourable conditions, these intensify into cyclonic storms/severe cyclonic storms. Tropical depressions over the Arabian Sea play an important role in the advance of the southwest monsoon over India. During the Arabian Sea phase of Monex-79, a depression formed over the Arabian Sea on 16 June. Moving northwestwards, it intensified into a cyclonic storm on 18 June. Under the influence of this system the monsoon rapidly advanced on the west coast of India.

The structures of tropical monsoon depressions have been studied by many meteorologists. During recent years Rao *et al.* (1978) made a diagnostic study of the life cycle of a monsoon depression and noticed large geostrophic cyclonic vorticity values in a narrow vertical column between 700 and 300 mb with a maximum at 700 mb (80×10^{-5} sec^{-1}). Keshavamurthy

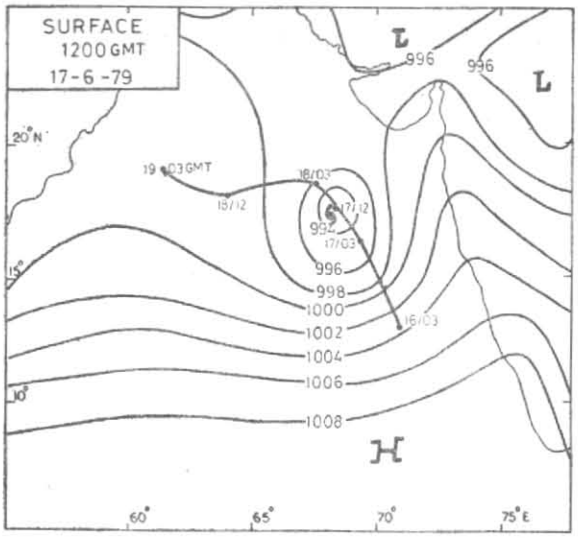

Fig. 1. Surface chart for 1200 GMT on 17 June 1979 along with the track of the depression/storm from 16 to 19 June 1979

et al. (1978) studied the mean structure of the monsoon depression by compositing 15 depressions. They observed greatest intensity at 700 mb with a tilt NNE to SSW in the lower levels. The depression had lower temperatures to its west and tilted westward with height.

Daggupathy and Sikka (1978) studied the vorticity budget and vertical velocity distribution associated with the life cycle of a monsoon depression. They noticed the presence of a low level of non-divergence around 850 mb. It was found to have a significant role in the dynamics of monsoon depression. They observed cyclonic vorticity depletion with time in the middle and upper troposphere and showed that a deep convective activity in the western sector provides the necessary process to compensate the negative vorticity tendency in the middle and upper troposhere. Rao and Rajamani (1972) found that the maximum convergence and vertical velocity were 2 degree west of the centre of tropical depressions.

During Monex-79 exensive data were available over the Arabian Sea. It was considered worthwhile to study the structure of the deep depression/cyclonic storm in the Arabian Sea during the onset phase of monsoon.

2. Data used

The dropsonde data of USA aircrafts CV990 and Electra on 15 June 1979, of CV-990, Electra and P-3 on 17th and of CV-990 and P-3 on 18th with NRSA aircraft data for 5000 ft and 10,000 ft were utilised for this study. The aircraft flight took place between 0500 and 1200 GMT on these days. These data were also supplemented with the 12 GMT radiosonde data of the west coast of India and commercial aircraft reports for the relevant period.

3. Synoptic situation

A depression formed over the Arabian Sea on 16 June 1979 at 0300 GMT with centre near 13 deg. N, 71 deg. E. Moving northwestwards, it became a deep depression on 17th at 0300 GMT and was centred at 16.5 deg. N, 69.5 deg. E. It continued to move northwestwards and was centred near 18.5 deg. N, 67.5 deg. E at 0300 GMT on 18 June. It intensified into a cyclonic storm by 1200 GMT of 18th and was centred at 18 deg. N, 64 deg. E. Thereafter, it rapidly moved westwards and was centred at 0300 GMT on 19th near 19 deg. N, 61.5 deg. E. The synoptic surface chart at 12 GMT of 17 June 1979 along with the track of the storm is shown in Fig. 1. The upper air charts for 860 mb and 700 mb for 17 June at 12 GMT are shown in Figs. 2(a) and 2(b) respectively. The surface centre was located at 12 deg. N, 72 deg. E (approx.)); 17.5 deg N, 68.5 deg. E and 18 deg. N, 64 deg. E at 1200 GMT on 15, 17 and 18 June respectively.

4. Method of analysis

The upper air stream line charts for 850, 700, 550 and 250 mb at 12 GMT over the Arabian Sea and adjoining west coast of India were

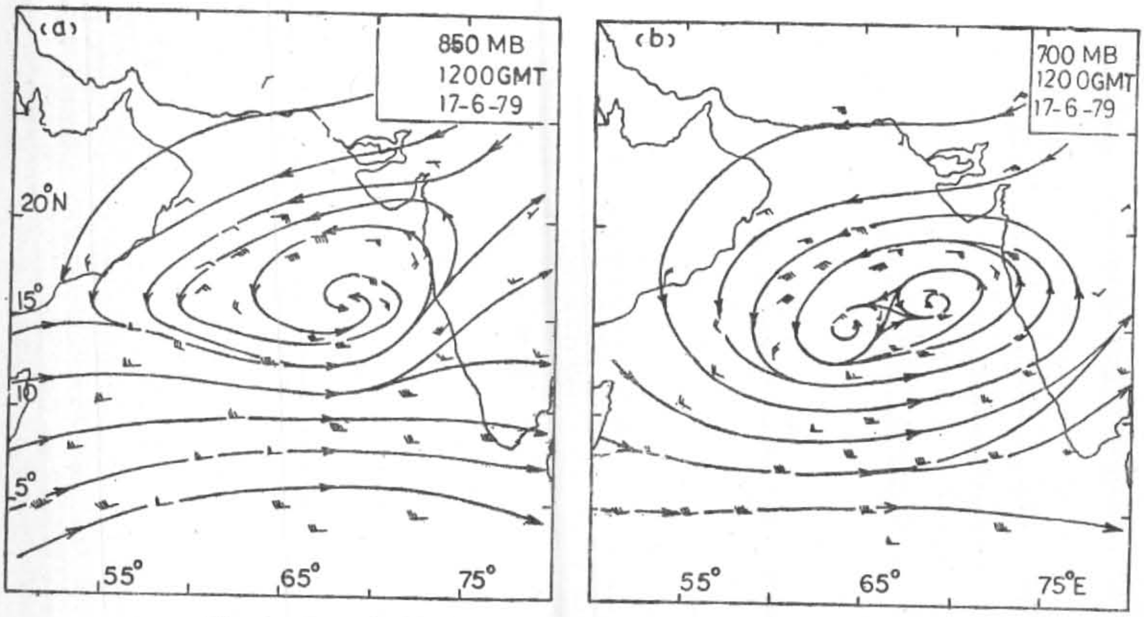

Fig. 2. Upper air chart for 850 mb and 700 mb at 1200 GMT on 17 June 1979

analysed for 15, 17 and 18 June 1979. U and V conponents were computed and fields analysed.

The relative vorticity, divergence, thermal and moisture fields for the tropical depression were then prepared. The divergence and relatve vorticity were computed from U and V components using the finite difference grid.

5. Formation and development of depression

Weak cyclonic circulations were first noticed within the shear zone at 850 and 700 mb over southeast Arabian Sea off Kerala coast on 12 June 1979. The equatorial westerlies to the south of the shear zone were of the order of 25-30 kt. There was an abrupt strengthening of the equatorial westerlies (40-50 kt) and intensification of shear zone between 12&14 June 1979. By 14 June a strong horizontal shear developed at 700 mb and below, leading to increase in cyclonic vorticity. The cyclonic circulation at middle level intensified and appeared to have descended downwards. Two cyclonic vortices were observed at 700 mb. A well marked low pressure area formed over east central Arabian Sea at 12 GMT on 14 June. It concentrated into a depression on the morning of 16 June. The associated cyclonic circulation was extending upto 400 mb from 14 to 16 June and upto 300 mb on 17 June 1979. Thus a cyclonic vortex first formed in the middle levels and then it extended downward and upward. There was no westward moving upper air trough in the easterlies over Indian Peninsula or Arabian Sea.

Gray (1968) considered that small vertical wind shear is a primary factor for the development of a cyclonic storm. Raman *et al.* (1978) found that decrease of vertical wind shear below 10 m per second from the normally prevalent large value appeared to be a precursor to formation of monsoon depression over the Bay of Bengal.

In the case of formation of depression over Arabian Sea under study, the daily zonal vertical wind shears between 200 mb and 850 mb for the stations, Bombay, Goa and Mangalore and Russian ship *EREB* from 10 June to 16 June are shown in Figs. 3(a) and 3(b).

The shear ($U = U_{200} - U_{850}$) at Bombay continuously decreased from 12 to 15 June. The shear fell sharply at Goa and Mangalore between 11 and 13 June.

However, the shear at the position (9.2 deg. N, 66.7 deg. E) of Russian ship *EREB* had continuously increased from 11 to 13 June. This ship was located about 600 km to the southeast of the position where the depression formed on 16 June.

It is seen that two to three days prior to the formation of the depression the shear became as low as 5 kt at the stations on the west coast.

6. Thermal structure

Kumar and Sethumadhavan (1980) have given the composite structure of the ITCZ over Arabian Sea during the onset phase of the monsoon in Monex-79. They have noticed the presence of temperature minimum in the lower troposphere from the surface position of the ITCZ to 100 km south of it and considered the ITCZ to be coldcored in the lower troposphere slight warming at 300 mb was also observed.

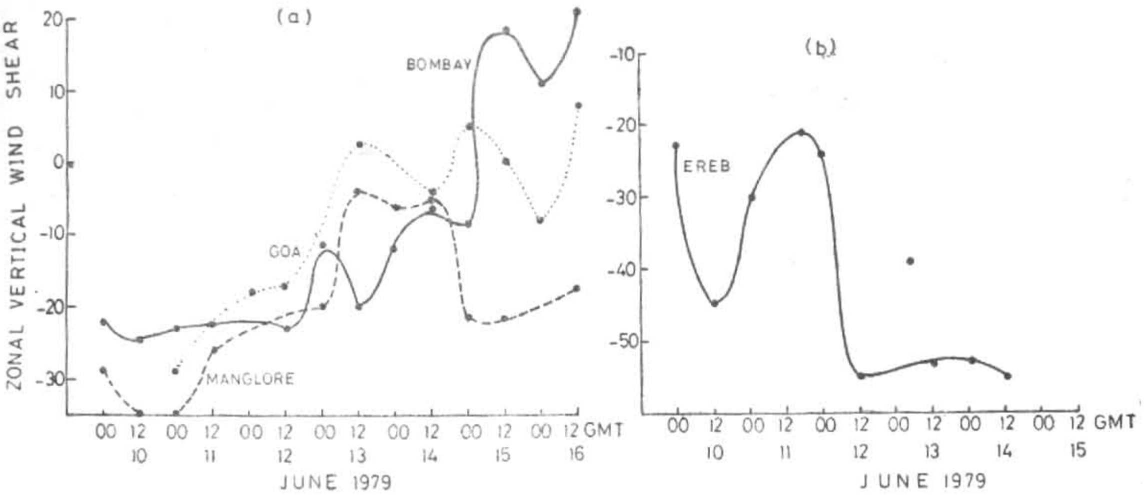

Fig. 3. Variation of vertical wind shear U_{200}—U_{850} in knots from 10 to 16 June 1979. Easterly zonal wind taken as negative

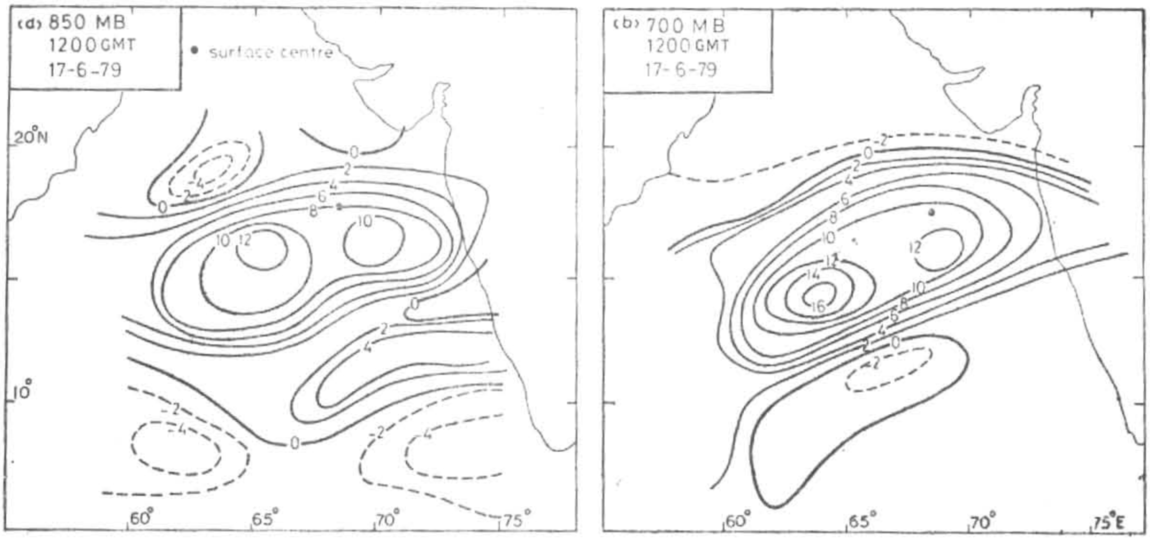

Fig. 4. Relative vorticity fields for 850 mb and 700 mb at 1200 GMT on 17 June 1979 ($\times$ 10^{-5} sec $^{-1}$)

During the preformative stage of depression on 12-13 June, a cold region was first noticed below 500 mb. On 14 June the cold region started reducing in vertical extent and was seen only upto 700 mb. By 15 June vertical extension of cold region further reduced to a level just below 850 mb. Gradually the slight warm region in the upper levels descended downward and by 17 June, the cold region has entirely disappeared and whole region became very warm. However, the surrounding of the depression was colder, especially to the south. The downward penetration of warming from a upper level during the formative stage of depression suggests, the role of cumulus convection in the development of the depression.

7. Vorticity

In the formative stage of depression the relative vorticity field for 850 mb on 15 June shows that the area of cyclonic vorticity extends from northeast to southwest with primary vorticity maximum of 8×10^{-5} sec^{-1} close to surface position of the vortex and secondary maximum of 6×10^{-5} sec^{-1} at a distance of 400 km to the south/southwest. In the middle level at 700 mb also there are two centres of maximum vorticity, one to the north/northeast at a distance of about 200 km and the other to the southwest about 600 km away from the surface centre.

At 550 mb, the area of cyclonic vorticity generally surrounds the surface centre ($4\text{-}6 \times 10^{-5}$ sec^{-1}) with most of the area of cyclonic vorticity

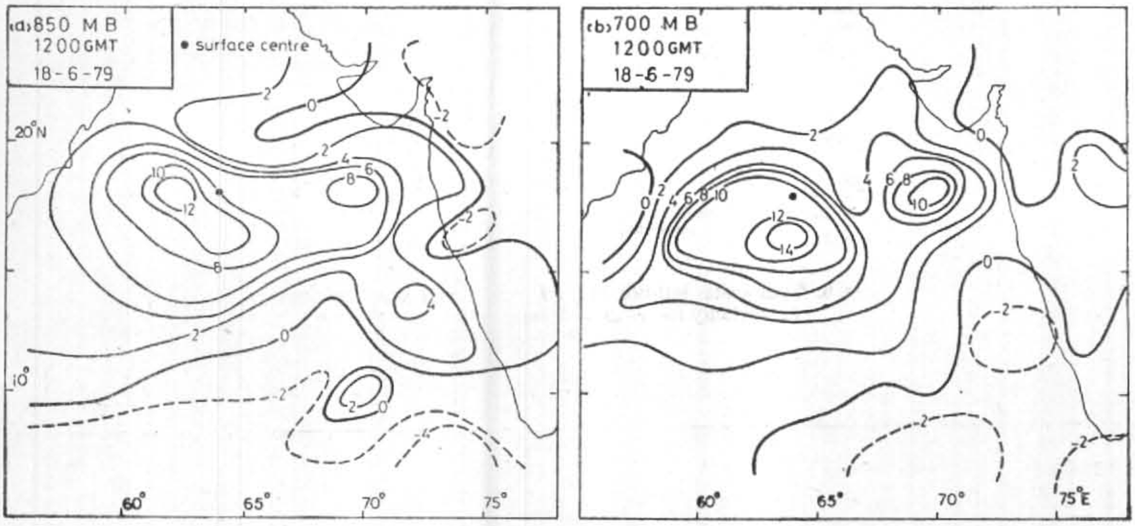

Fig. 5. Relative vorticity fields for 850 mb and 700 mb at 12 GMT on 18 June 1979 ($\times 10^{-5}$ sec^{-1})

lying elongated in the east-west direction across the centre.

With the development of the system, the relative vorticity field for 850 mb on 17 June (Fig. 4 a) shows that the cyclonic vorticity exists all around the surface centre of the deep depression and increases to the south of the centre. The cyclonic vorticity maximum of 12×10^{-5} sec^{-1} is located at a distance of 400 km to the SW and a secondary maximum at 200 km to the southeast of the centre.

There is an area of anticyclonic vorticity to the north. It exceeds -4.0×10^{-5} sec^{-1} at a distance of about 400 km to the northwest.

At 700 mb in general the cyclonic vorticity is greater around the surface centre, as compared to 850 mb level. The vorticity maximum exceeding 16×10^{-5} sec^{-1} is located about 600 km to the southwest of the surface centre with secondary maximum at a distance of 100 km to the southsoutheast of the centre (Fig. 4b).

The cyclonic vorticity around the surface centre is also noticed at 550 mb except in the northwest quadrant where anti-cyclonic vorticity predominates. At this level also cyclonic vorticity maxima (12×10^{-5} sec^{-1}) are located in the southwest quadrant at a distance of 200 and 600 km from the depression centre.

At 250 mb level the vorticity patterns show slight anti-cyclonic vorticity around the surface centre. However, a cyclonic vorticity maximum is seen at a distance of 450 km to the SSW of the storm centre.

The deep depression concentrated into a tropical storm by 1200 GMT of 18th. The vorticity field for the storm at 850 mb shows that the cyclonic vorticity is all around the surface centre with vorticity maximum exceeding 12×10^{-5} sec^{-1} in the sector SSW to WNW at a distance of about 200 km (Fig. 5a). A secondary maximum is seen at a distance of about 600 km to the east of the storm centre.

As compared to 850 mb the cyclonic vorticity is greater at 700 mb around the storm centre with vorticity maximum (14×10^{-5} sec^{-1}) at a distance of 200 km to the SSW of the storm centre. A secondary maximum (10×10^{-5} sec^{-1}) is also noticed at a distance of 600 km to the east of the centre (Fig. 5b).

At 550 mb generally cyclonic vorticity is seen all around the centre with maximum (10×10^{-5} sec^{-1}) vorticity in the southwest quadrant at a distance of 600 km to the WSW. The vorticity field at 250 mb shows that the centre is surrounded by an area of weak anti-cyclonic vorticity with a maximum (-6.0×10^{-5} sec^{-1}) in the southeast quadrant at a distance of about 600 km. The cyclonic vorticity maximum (7×10^{-5} sec^{-1}) lies about 450 km to the north of the storm centre and secondary maximum exceeding 4×10^{-5} sec^{-1}) in the southwest quadrant at a distance of 400 km to the southwest.

The composite latitudinal and meridional cross-section for the vorticity fields on 17 and 18 June 1979, through the surface storm centres are presented in Figs. 6(a) and 6(b) respectively.

It may be seen that the cyclonic vorticity surrounds the centre of the storm from surface to about 300 mb. The maximum cyclonic vorticity exceeding 12×10^{-5} sec^{-1} exists in the middle troposphere. The axis of maximum vorticity tilts southwards and westwards with height.

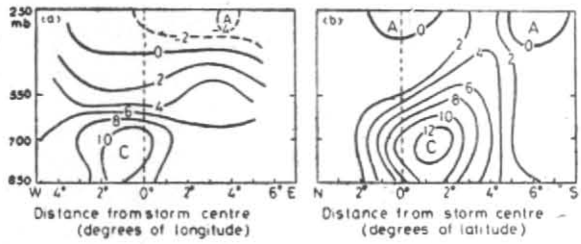

Fig. 6. Composite latitudinal and meridional corss-sections of vorticity for 17 and 18 June 1979

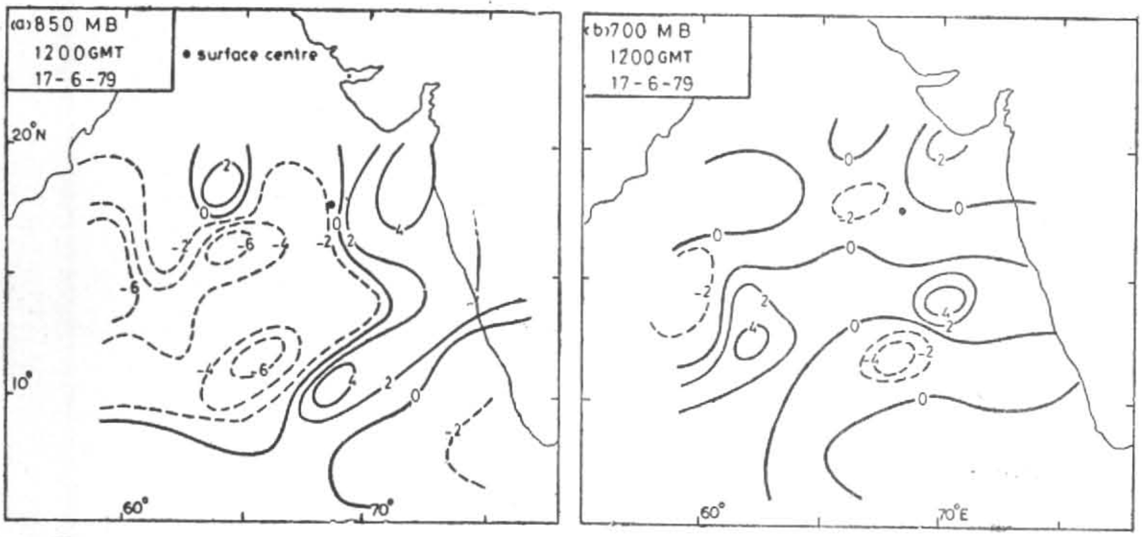

Fig. 7. Divergence fields for 850 mb and 700 mb at 1200 GMT on 17 June 1979 ($\times 10^{-5}$ sec^{-1})

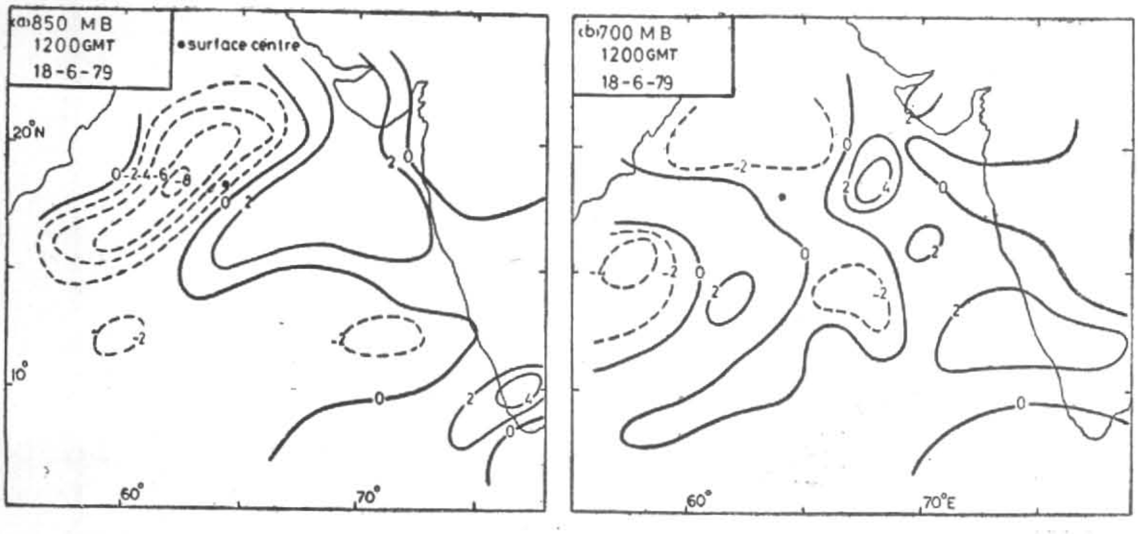

Fig. 8. Divergence fields for 850 mb and 700 mb at 1200 GMT on 18 June 1979 ($\times 10^{-5}$ sec^{-1})

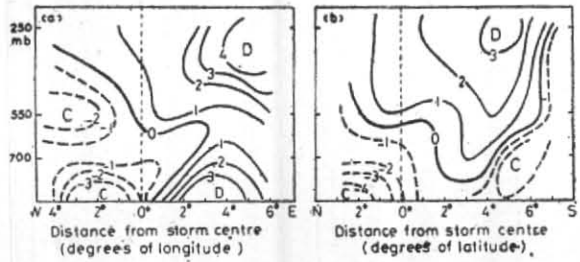

Fig. 9. Composite latitudinal and meridional cross-section of divergence for 17 and 18 June 1979

8. Divergence

The divergence pattern in the formative stage of depression at 1200 GMT on 15 June at 850 mb shows that the centre is divergent with maximum divergent area of 2×10^{-5} sec^{-1} located to the south of the surface centre. The convergent areas lies in the northwest and southwest quadrants.

In the middle level at 700 mb the divergence predominates in the southeast and northeast quadrants. The convergence areas are located in the direction northnorthwest (3.5×10^{-5} sec^{-1}) and southsouthwest (4×10^{-5} sec^{-1}).

At 550 mb the surface centre lies in a weak divergent area. The maximum divergence (4×10^{-5} sec^{-1}) is located at a distance of about 500 km to the northwest and a secondary maximum of (2×10^{-5} sec^{-1}) on north Kerala coast. The sector from southwest to west is convergent with a maximum of (3×10^{-5} sec^{-1}) at a distance of about 400 km.

With the development of the depression, the divergence pattern for 850 mb at 1200 GMT of 17 June shows that the convergence has spread in the forward sector except for a small divergent area (2×10^{-5} sec^{-1}) located at a distance of 500 km to the northwest. The convergence maximum lies in the left forward quadrant towards WSW at a distance of 500 km. However, near the surface centre it is divergent in the rear exceeding 4×10^{-5} sec^{-1} (Fig. 7a).

At 700 mb near the centre, weak convergence is seen, but it is prominent in the northwest quadrant (2.5×10^{-5} sec^{-1}) as compared to the other sectors (Fig. 7b). This is surrounded by divergent areas with maxima exceeding (4×10^{-5} sec^{-1}) in southwest and southeast sectors.

In the middle troposphere at 550 mb the convergence is prominent in the westnorthwest sector (6.5×10^{-5} sec^{-1}) and southeast sector (2.5×10^{-5} sec^{-1}). The divergent area is noticed in the southwest quadrant with maxima exceeding (4×10^{-5} sec^{-1}). Another small divergent area (3×10^{-5} sec^{-1}) lies to the north of the centre.

In the upper troposphere at 250 mb weak convergence is seen near the centre with a maximum in the southwest sector (2×10^{-5} sec^{-1}). The divergence maximum lies to the south (5×10^{-5} sec^{-1}) at a distance of 600 km and to the east (3×10^{-5} sec^{-1}) at a distance of 500 km.

The divergence pattern at 850 mb on 18 June 1979 (Fig. 8a) shows that the forward sector extending from southwest to northeast is convergent with maximum (8×10^{-5} sec^{-1}) located at a distance of 200 km to the westnorthwest. In the rear of the storm centre there is divergent area exceeding 2×10^{-5} sec^{-1}.

At 700 mb the centre is surrounded by weak convergence which increases in the northwest and southsoutheast. There is a divergence maximum(4×10^{-5} sec^{-1}) at a distance of 350 km to the northeast and secondary maximum (2×10^{-5} sec^{-1}) in the southwest sector at a distance of 500 km (Fig. 8 b). In the middle troposphere at 550 mb close to the centre there is an area of weak convergence, especially, in the northwest quadrant. The other sectors are generally divergent with maxima (3×10^{-5} sec^{-1}) to the SSW and ESE (2×10^{-5} sec^{-1}).

In the upper troposphere at 250 mb the centre is surrounded by a divergent area with a maximum exceeding (4×10^{-5} sec^{-1}) in the southeast sector. There is also a small area of convergence (2×10^{-5} sec^{-1}) at a distance of 550 km towards NE.

The composite latitudinal and meridional cross-section for the divergence fields on 17 and 18 June 1979 through the surface storm centres are presented in Fig. 9(a) and Fig. 9(b) respectively.

The latitudinal cross-section shows that the convergence is maximum in the lower and middle troposphere west of the storm centre. There is a divergence maximum (4×10^{-5} sec^{-1}) to the east of the centre at 850 and 250 mb at a distance of 3 deg. to 5 deg. where the divergence generally covers all levels but is minimum in the middle troposphere. Over the storm centre and to the west of it only weak divergence field exists at 250 mb.

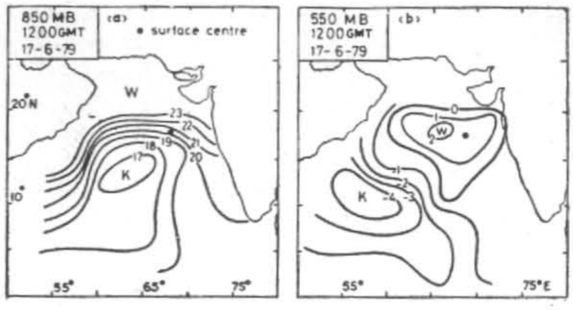

Fig. 10. Temperature fields (°C) for 850 mb and 550 mb at 1200 GMT on 17 June 1979

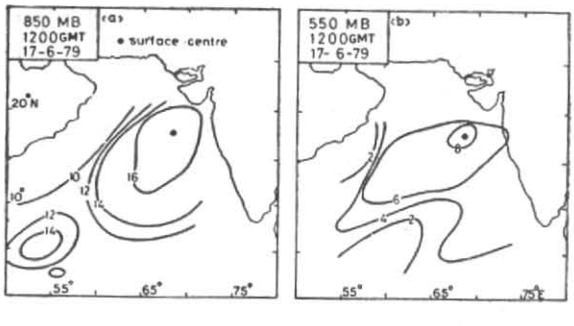

Fig. 11. Moisture fields (g/kg) for 850 mb and 550 mb at 1200 GMT on 17 June 1979

The meridional cross-section shows that the maximum convergence in the lower level lies 2 deg. to 3 deg. north the storm centre and is overlaid by weak divergence at 250 mb. The secondary convergence maximum lies 5 deg. to 6 deg. south of the storm centre. The maximum divergence in the upper troposphere lies 4 deg. to 5 deg. south of the centre.

9. Thermal field

The temperature fields on 17 June 1979 for 850 mb and 550 mb are depicted in Figs. 10(a) and 10(b) respectively.

On 17 June, the thermal fields of the deep depression in the lower and middle troposphere show that the southwest sector of the depression is colder than its environment and north or northwest sector is warmest.

On 18 June when the deep depression has already intensified into a storm, it may be seen that the colder sector has shifted towards the east and lies to the south of the storm centre. However, the warm sector is still to the north or northeast. In the middle troposphere the area around storm centre is warmer than its surroundings.

10. Moisture field

The moisture fields (mixing ratio in g/kg) on 17 June 1979 for 850 mb and 550 mb are shown in Figs. 11(a) and 11(b) respectively.

The moisture maximum is seen around the surface centre of the depression/storm in the lower and as well as middle troposphere. The moisture decreases rapidly to the north of the centre especially in the northwest quadrant; whereas little variations in the moisture are noticed to the south of the centre. The moisture fields on 18 June 1979 for 850 mb and 550 mb are almost identical except for slight increase of moisture in the lower levels.

11. Concluding remarks

The salient features of the tropical depression in the Arabian Sea are given below :

(*i*) The depression formed within the ITCZ and developed from a middle level vortex.

(*ii*) The shear vorticity associated with low level westerly jet played a significant role in the development of the depression.

(*iii*) In the formative stage this depression was similar to a mid-tropospheric cyclone.

(*iv*) In the pre-formative stage, the system has a cold core below 500 mb and slight warm region at 300 mb in the upper troposphere. Along with the development of the depression the warm region penetrated downward and the cold region gradually disappeared. Thus the deep depression became a warm cored system. This process suggests the role of the cumulus convection in the development of the depression.

(*v*) The decrease of vertical wind shear at the stations on the west coast two to three days prior to formation of depression also contributed to the development of depression.

(*vi*) The relative cyclonic vorticity in the lower troposphere increases with height and attains maximum value in the middle troposphere at 700-600 mb.

(*vii*) The axis of maximum vorticity tilts southwestwards with height and is generally maximum in the southwest quadrant.

(*viii*) In the lower troposphere the convergence is maximum in the forward sector extending from southwest to northeast. The divergence is maximum in the rear to the east of the storm centre.

(*ix*) The convergence decreases rapidly with height and a level of non-divergence appears around 700 mb.

(*x*) It is interesting to find the appearance of significant convergence in the right forward sector in the middle troposphere, whereas divergence is maximum in the left forward sector.

(*xi*) In the lower troposphere the area of convergence generally coincides with the area of cyclonic vorticity.

(*xii*) In the lower troposphere, the southwest sector is generally coldest and north or northwest sector is warmest.

(*xiii*) The area around the storm centre is warmer than surroundings in the middle troposphere.

(*xiv*) The moisture maximum is noticed around the storm centre upto middle troposphere.

(*xv*) The gradient of moisture is more to the north than to the south of the storm centre.

(*xvi*) The satellite pictures indicate that the maximum convective clouds are in the sector extending from west to northwest from the storm centre. These are found close to the location of shear line between westerlies and easterlies at 850 mb.

The occurrence of lowest temperature in the southwest quadrant upto 700 mb may be attributed to the influx of relatively humid and cool monsoon airmass and to cooling produced by general precipitation and reduced insolation under overcast skies. The highest temperature in the northwest and north may be due to the fact that warmer continental air may be drawn into the field.

In the middle troposphere the release of latent heat overcomes the effect of the low level cooling. The fact that cyclonic vorticity is maximum in the middle troposphere and is located in the southwest quadrant is in agreement with the thermal structure of the storm indicating lowest temperatures in the southwest quadrant in the lower troposphere.

Acknowledgement

The authors are grateful to Dr. P. K. Das, Director General of Meteorology for providing Monex-79 data for this study. We are thankful to Mr. V. Lakshmanan and Mr. K. Rajgopalan of the Meteorological Office, Bombay for their help in the preparation of the diagrams.

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