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Development and movement of a mid-tropospheric cyclone in the westerlies over India

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ABSTRACT. The effect of a developing upper tropospheric ridge in the westerlies on the trough ahead has been studied. It has been shown that growth of an upstream ridge is one of the important factors for the development of the downstream trough, and if the ridge continues to build up, the trough, inspite of the formation of a cut off low in it, continues to deepen and so does the cut off low which can become a deep cyclone showing SE'ly movement as envisaged by Bjerknes (1951).

1. Introduction

Investigations into the formation and structure of "western disturbances" over the Indian sub-continent have led to the conclusion that these low level systems intensify mostly under the influence of upper tropospheric westerly troughs (Pisharoty and Desai 1956, Singh 1977, 1979). Singh (1977, 1979) following Newton (1958) further showed that the intensification takes place only if the low level trough or low is influenced by a developing upper air trough with a well developed baroclinic zone in its western sector. Hence for the prediction of intensification of western disturbances, the evolution of westerly upper air troughs over West Asia and the northern latitudes of the Indian sub-continent has to be properly understood. The present paper discusses the development and movement of an upper westerly trough which affected Afghanistan and northern part of Indo-Pakistan between 15 and 18 February 1978.

2. Synoptic situation

2.1. A western depression developed out of a feeble low level trough over central Pakistan and adjoining Punjab (India) at 0300 GMT of 17 February 1978 and weakened completely by 0300 GMT of 18th in the same area. The sudden intensification and weakening of this western disturbance was studied with the help of synoptic charts prepared by the Northern Hemisphere Analysis Centre, New Delhi. They showed that at 0000 GMT of 16th (Fig. 1b) a deep upper tropospheric cyclone lay over northeast Afghanistan and adjoining north Pakistan and a feeble low level trough over the central parts of Pakistan and neighbourhood. In the next twenty-four hours the upper cyclone moved southeast and approaching the low level trough from the northwest intensified it into a western depression (by 0300 GMT of 17th). The pressure at the centre of the depression fell by 7 mb in twenty-four hours and weather activity was widespread over the Punjab and Himachal Pradesh. In fact, at this time, the lower and the upper cyclones merged into one extending the combined cyclonic circulation from the surface upto 10.3 km (*Indian Daily Weather Report*). The upper level system, however, was fast moving and by 0000 GMT of 18th it had moved away NE'wards, far ahead of the lower system. The result was that the western depression weakened rapidly and became a feeble low pressure area again. The pressure at the centre rose by 8 to 9 mb by 0300 GMT of 18th. Thus the rapid intensification and equally rapid weakening of the western disturbance between 0300 GMT of 17th and 0300 GMT of 18th was the result of the superposition of the upper level cyclone over the surface trough and its subsequent movement away from the low level system, as has been shown by Singh (1979).

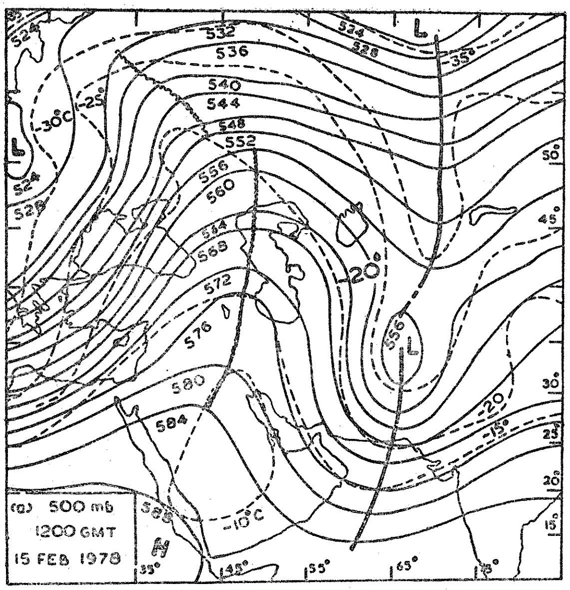

Fig. 1(a). 500 mb chart of 1200 GMT on 15 February 1978

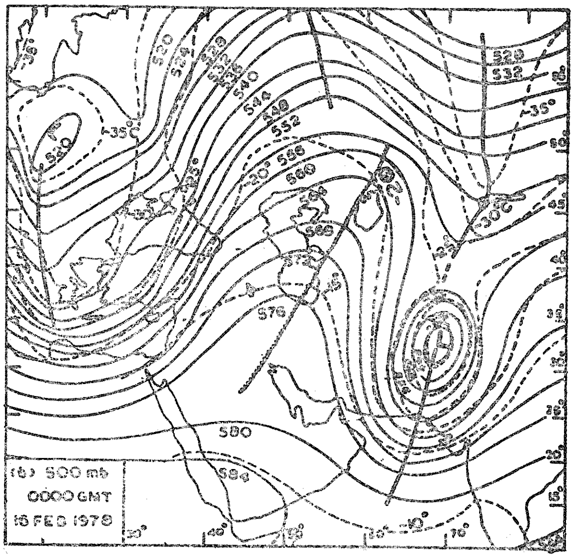

Fig. 1(b). 500 mb chart of 0000 GMT on 16 February 1978

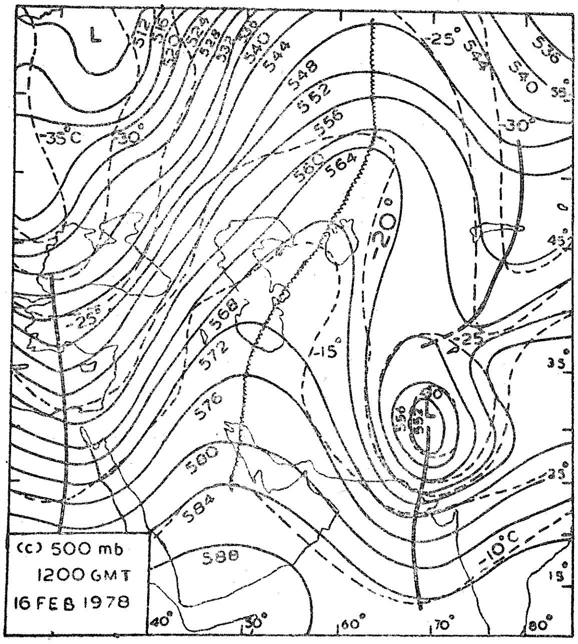

Fig. 1(c). 500 mb chart of 1200 GMT on 16 February 1978

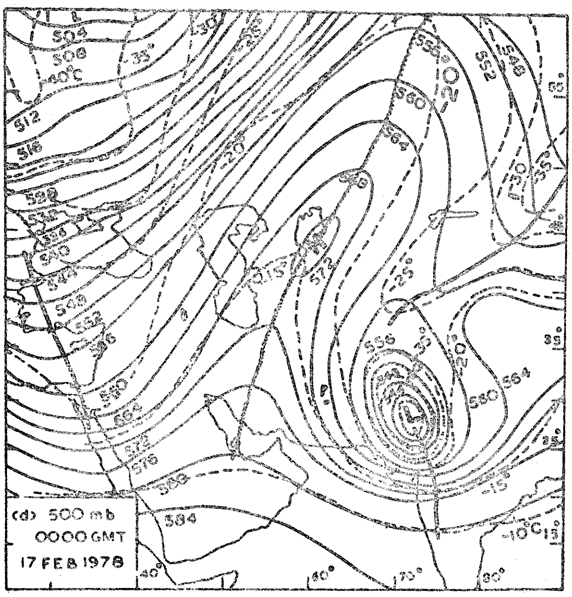

Fig. 1 (d). 500 mb chart of 0000 GMT on 17 February 1978

2.2. Now we shall see how this upper tropospheric cyclone evolved during this period.

3. Upper air features

3.1. Figs. 1(a) to 1(f) give charts of 500 mb level for the period 1200 GMT of 15th to 0000 GMT of 18 February 1978 at 12 hourly intervals.

3.2. Fig. 1(a) (1200 GMT of 15th) shows a deepening trough in the midtropospheric westerlies with a closed circulation at the centre. In the next 12 hours (Fig. 1b) this trough intensified considerably and formed a cut-off cyclone centred at about 33 deg. N, 69 deg. E with central temperature of about —35 deg. C and lowest contour height of 5440 gpm. The intensification of this trough could be attributed to the

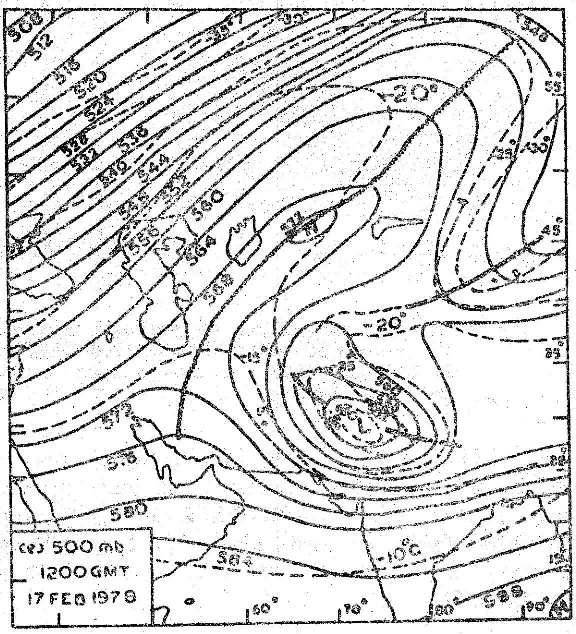

Fig. 1 (e). 500 mb chart of 1200 GMT on 17 February 1978

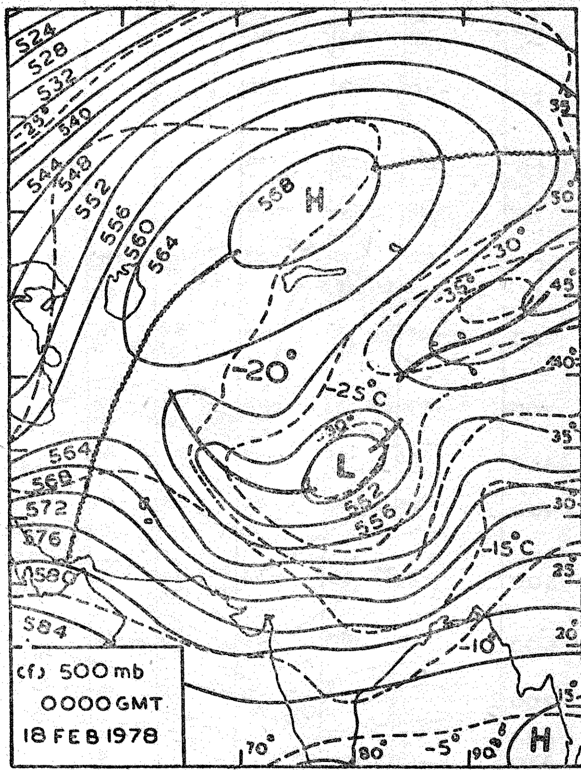

Fig. 1 (f). 500 mb chart of 0000 GMT on 18 Feb 1978

growth of the ridge up-stream. The comparison of ridges in Figs. 1(a) and 1(b) would show that the ridge in Fig. 1(b) was much sharper than in Fig. 1(a) as the advection of warm air from the south extended further northward. It can be noted that —20 deg. C isotherm extended from Caspian Sea at 1200 GMT of 15th to north of Aral Sea by 0000 GMT of 16th.

3.3. Fig. 1(c) depicts the condition twelve hours later. The cut-off cyclone shifted SSE'-wards and was located at about 30 deg. N, 70 deg. E. It weakened considerably, as expected, and the temperature at the centre rose by about 5 deg. C and central contour height by about 80 gpm. The ridge upstream, however, continued to build up. It sharpened further with warm air advection pushing far north. The —20 deg. C isotherm which was passing across Aral Sea in Fig. 1(b) moved to 52 deg. N in Fig. 1(c), a shift of more than 5 deg. Lat. to the north.

3.4. This continuous build up of the upstream ridge which became extremely sharp with the —20 deg. C isotherm reaching to almost 60 deg. N at 0000 GMT of 17th (Fig. 1d), halted the weakening of the cut-off cyclone and actually intensified it again. By 0000 GMT of 17th (Fig. 1d) the upper cyclone had become much stronger with central contour again falling to 5440 gpm and temperature to —35 deg. C. It was centred at about 28 deg. N, 72 deg. E, showing a SE'ly movement. Its orientation too became NW-SE instead of the normal NE-SW. It extended down to 850 mb indicating that vigorous convection was taking place in the system. It was on this day that it intensified the low level trough over central Pakistan , as mentioned earlier. Finally, it extended down to the ground as it intensified and the low level trough simply became a part of it.

3.5. By 1200 GMT of 17th (Fig. 1e), however, the ridge weakened as could be guessed from the position of —20 deg. C isotherm which shifted to 55 deg. N from 60 deg. N (Fig. 1d). As the ridge weakened, the cyclone too weakened and resumed its normal NE'ly movement (centre 29 deg. N, 73 deg. E). Its orientation too changed from NW to ESE, almost appearing as if it was caving in the ridge up-stream. In fact, at this time (Fig. 1e) the ridge covered the upper cyclone from west and north.

3.6. At 0000 GMT of 18th (Fig. 1f) the ridge formed a cut-off high centred at about 50 deg. N, 75 deg. E and the weakened cyclone was located to the south of it at 34 deg. N,

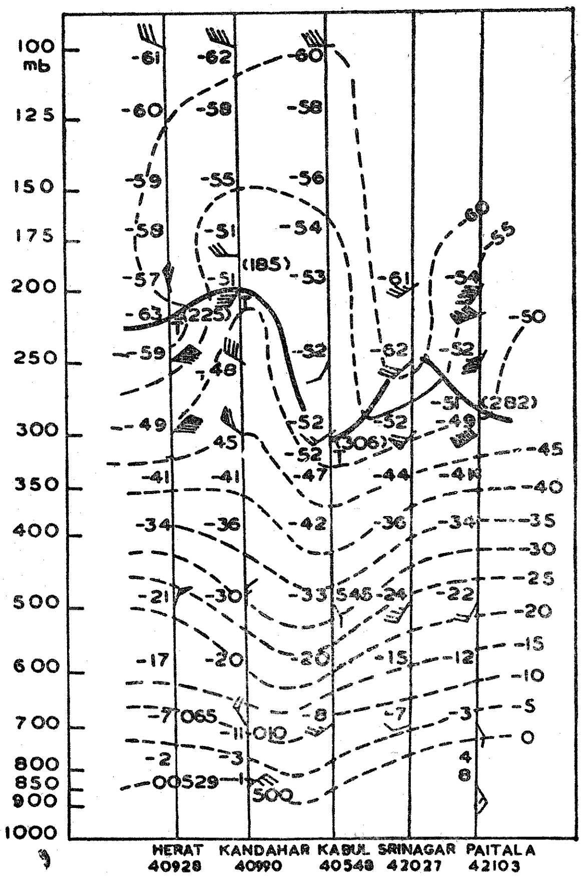

Fig. 2. Vertical cross-section along 33°N Lat. in E-W direction at 0000 GMT of 16 February 1978

79 deg. E. Its orientation was now almost NE-SW.

3.7. From the foregoing it can be stated that the continuously growing upstream ridge from 1200 GMT of 15th to 0000 GMT of 17th deepened the downstream trough, caused the formation of a cut-off cyclone in it at 0000 GMT of 16th, and also prevented the latter from weakening and dissipating. Rather, it intensified it further at 0000 GMT of 17th and gave it a SE'ly movement. It is during this intensifying stage that the upper cyclone intensified the low level system over NW India at 0300 GMT of 17th. As the ridge started weakening after 0000 GMT of 17th the upper cyclone too weakened and resumed NE'ly movements is normal for such systems.

3.8. Some of the special features of this mid-tropospheric ridge may be noted here. The ridge, as it grew, developed an anticyclonic bulge downstream of the crest by 1200 GMT of 16th (Fig. 1c), which accentuated further by 0000 GMT of 17th (Fig. 1d). In fact, in this figure

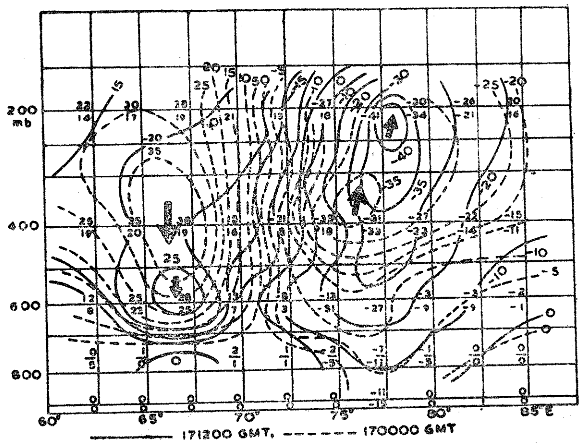

Fig. 3. Vertical cross-section of vertical velocities W (mm/sec) at 0000 GMT and 1200 GMT of 17 February 1978 (based on 5-layer quasi-geostrophic model)

(Fig. 1d), it appears to be bulging westwards on its eastern side. This process is still more prominent in Fig. 1(e) (1200 GMT of 17th), and by 0000 GMT of 18th (Fig. 1f) this bulging process caused the rupture of the ridge into a cut-off high.

4. Discussion

4.1. The variation of relative vorticity with time is given by the following expression (Bjerknes 1951)

$$\frac{d\zeta}{dt} = \frac{\partial p}{\partial x}\frac{\partial \alpha}{\partial y} - \frac{\partial p}{\partial y}\frac{\partial \alpha}{\partial x} - \left(\zeta + f\right) \text{div}_H \mathbf{V} - \frac{2\Omega \cos\phi}{a} v_y + \frac{\partial v_z}{\partial y}\left(2\Omega\cos\phi + \frac{\partial v_x}{\partial z}\right) - \frac{\partial v_z}{\partial x}\frac{\partial v_y}{\partial z}$$

where p is the pressure, α the specific volume' Ω the angular momentum of earth's rotation and ϕ, the latitude. v_x, v_y, v_z are components of wind vector $\mathbf{V}$ in x, y, z directions and a, the radius of the earth. In this equation the first term, *i.e,* $\left(\frac{\partial p}{\partial x}\frac{\partial \alpha}{\partial y} - \frac{\partial p}{\partial y}\frac{\partial \alpha}{\partial x}\right)$ is the effect of isobaric-isosteric solenoids on the change of vertical vorticity and is insignificant in comparison to the following two terms. The second term, *i.e.,* $-(\zeta+f)\,\text{div}_H\mathbf{V}$ or $-QD$ (where $Q=\zeta+f$, $D=\text{div}_H\mathbf{V}$), is the ffect of divergence term.

4 .2. The third term, *i.e.,* $(-2\,\Omega\,\cos\phi/a)\,v_y$, is the advection term which decreases positive relative vorticity in poleward movement of air parcel and *vice versa*. The last two terms are the tilting terms which are less significant than the two terms given above.

4.3. Considering the effect of the divergence terms *i.e.*, $-QD$, on the production of vorticity, *i.e.*, $d\zeta/dt$, Bjerknes (1951) argues that when Q is large, *i.e.*, ζ is positive, the individual vorticity change with time *i.e.*, $d\zeta/dt$ becomes quite sensitive to horizontal convergence / divergence. On the, other hand, when ζ acquires large negative values, Q may go to zero or even beome negative. This happens exclusively in the upper troposphere and lower stratosphere where the wind velocities are very strong.

4.4. On wave crests (ridges) where Q reaches values close to zero, the vorticity change, *i.e.*, $d\zeta/dt$ is only feebly influenced by horizontal divergence and obeys the terms of meridional advection, *i.e.*, $(-2\,\Omega\,\cos\,\phi/a)\;v_y$. This would be equivalent to motion under approximately constant absolute vorticity, *i.e.*, $Q\approx 0$ or $-\zeta = f$. In such a case, a particle moving downstream from the crest will maintain its anticyclonic vorticity for a long time and will, inspite of its southerly movement, cause a ridge like bulge downstream of the crest and move fairly deep south before turning cyclonically. Thus, the ridge will show a bulge on its eastern side and the trough downstream will deepen. Any cut-off cyclone embedded in it, therefore, will not only deepen but move south or SE' ward instead of the normal NE' ward. Its orientation will also turn to NW-SE instead of the normal NE-SW. These developments usually lead to very deep slow moving wave formations in the westerlies and extend through the whole troposphere. And as Bjerknes noted, this type of development is not dependent on absolute vorticity acutally having reached zero. The action starts even when Q is positive but numerically small.

4.5. In the case discussed here, a growing ridge intensified the trough downstream and caused a cut off cyclone in it by 0000 GMT of 16th. The ridge, however, continued to grow and reached its maximum intensity by 0000 GMT of 17th. At this time the vorticity at the crest must be reaching almost zero. It is because of this that the bulging of the ridge downstream occurred, the trough and the embedded cyclone deepend and they moved SSE' ward. Thus, this case establishes tne correctness of Bjerkness' (1951) hypothesis.

4.6. In Fig. 2 is presented a vertical cross-section at 0000 GMT of 16th along 33 deg. N (across cut-off cyclone). It can be seen that the cyclone is thermally symmetrical with warm air on both sides and cold air with low tropopause in between, as shown by Palmen (1951). The centre of the cut-off cyclone on this day was located between Kandahar and Kabul at 33 dge. N, 69 deg. E.

4.7. In Fig. 3 are presented the vertical cross-sections of vertical velocities across the cut off cylone at 0000 and 1200 GMT of 17th. The calculation is based on the 5 layer quasi-geostrophic model used by the Northern Hemisphere Analysis Centre, New Delhi. Calculations have been done along 30 deg. N in an east-west direction. The dotted lines present the distribution of vertical velocities at 0000 GMT of 17th when the cyclone was at its peak intensity and solid lines at 1200 GMT of 17th, when it was weakening. It can be seen that at its peak, the cyclone had maximum upward as well as downward velocities in the middle layers, *i.e.*, at 400 mb, with values of the order of 3.5 cm/sec. The up and down drafts were nearly equal, the western portion showing sinking and the eastern portion rising air mass, as expected. At 1200 GMT of 17th, the downdraft on the west side had weakened (2.8 cm/sec) and its maximum occurred at a lower level (600 mb). The updraft on the east side, on the other hand, was still intensifying almost at all levels with maximum reaching to 4.1cm/sec at about 200 mb. From this diagram it is seen that during the stage of maximum development the cut off cyclone is symmetrical as far as its up and down drafts are concerned. Both are of nearly the same magnitude and maxima are located in middle levels of the troposphere. In the weakening stage, however, the downdraft lowers and weakens followed by the updraft which increases and rises higher for sometime more before weakening.

5. Conclusions

The study of this mid-tropospheric cyclone in the westerlies near India has brought out that :

(*i*) The growing upstream ridge is one of the important mechanisms to create a deep trough down-stream.

(*ii*) The trough grows as long as the ridge intensifies inspite of the former being cut-off from the cold air supply by the formation of a cut-off cyclone in it.

(*iii*) Even after the formation of cut-off cyclone, the trough and the cyclone both intensify if the ridge upstream continues to grow. The mechanism of this process is as enunciated by Bjerknes (1951).

(*iv*) In the extreme case of ridge development, a bulge appears downstream from the crest and the ridge tilts SE-NE. Finally the process leads to a cut-off anticyclone in the higher latitudes.

(*v*) In this situation, the cut-off cyclone not only intensifies but also moves S/SE' ward and gets oriented NW-SE instead of the normal NE-SW.

(*vi*) The study of the structure of the cut-off cyclone shows that it is a thermally symmetrial system. In its maximum intensity stage the vertical velocities are nearly equal and maximum in the middle levels (400 mb) of the troposphere and in weakening stage vertical velocities reach opposite extremes, *i.e.,* weakened downdraft at lower levels (600 mb) and strengthened updraft at higher levels (200 mb). The downdraft weakens earlier than the updraft which reaches a maximum at higher levels before weakening.

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