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A quantitative approach for determining the movement of depression/cyclone

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सार–यह तर्क प्रस्तुत किया गया है कि एक स्पष्ट निम्न दाब प्रणाली (अवदाब/चक्रवात) के केन्द्र को सिद्धान्त रूप में सदिश $\nabla(\partial\eta/\partial t)$ की दिशा में आगे बढना चाहिए। सदिश का आरम्भिक बिन्दु निम्न दाब प्रणाली के केन्द्र में होता है जहां से यह प्रणाली आगे की स्थिति में बढ़ती है। 3 से 8 जुलाई 1979 के अवदाव के मामले का अध्ययन इस तर्क की वैधता को सिद्ध करता है। जहां गति की दिशा को सदिश $\nabla(\partial\eta/\partial t)$ द्वारा निर्धारित किया जाता है वहां अनुवर्ती चाल अदिश, C, को यद्यपि क्रमागत स्थितियों में भ्रमिलता प्रवृतियों के मध्य अन्तर बताने के लिए आनुपातिक होना तर्क संगत बताया जा सकता है किन्तु यहां पर प्रयुक्त आंकड़े इस तर्क का समर्थन नही करते हैं।

ABSTRACT. It has been argued that centre of a well marked low pressure system (depression/cyclone) should theoretically move in the direction of vector $\nabla(\partial\eta/\partial t)$. The initial point of the vector is at the centre of low pressure system from where the system moves to next position. A case study on the depression of 3-8 July 1979 have stood the test of validity of this logic. While the direction of movement is dictated by the vector $\nabla(\partial\eta/\partial t)$, the corresponding speed scalar, C, could although be reasoned out to be proportional to difference between vorticity tendencies at the consecutive positions, but the data used here do not support the reasoning.

1. Introduction

A weather forecaster often bases his forecasts for the movement of depression/cyclone on the simple criterion, namely, looking for asymmetries in the distribution of available meteorological parameters near to and in the region of depression/cyclone. Perhaps better results are arrived at when one looks at the distribution patterns of the temporal tendencies of such parameters. While doing so, a forecaster apparently believes that the direction of movement of a cyclone/depression is dictated by the fresh tendencies of the various meteorological parameters. In other words, distribution patterns of tendencies of one or the other meteorological parameter, such as vorticity changes, changes in sea surface temperature etc associated with depression/cyclone movement may be indicative of direction of movement of such a system.

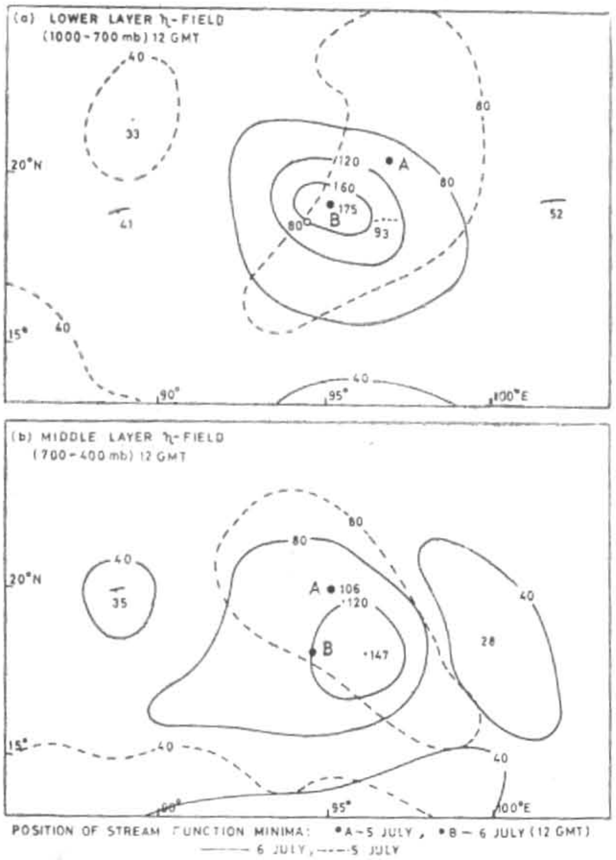
Sutcliffe (1947) in his well-known theory of cyclone development used time development of absolute vorticity, η, in a region as an indicative of development of a cyclone over the region. A similar approach has been made here for finding the direction of movement of a well-marked low pressure system (LPS). The movement of a low pressure system to neighbouring position is essentially a development of a absolute vorticity field at its new location while such a field is fading at its previous location. The methodology in this note uses finding gradient vector on absolute vorticity tendency field over the region covered in succession by LPS.

It has been assumed here implicitly that when a LPS moves, it affects certain distribution of meteorological parameters and such patterns in turn guides the movement of LPS, thus again affecting a new distribution of meteorological parameters to guide its further movement. This process continues during the motion of LPS. We had not to consider here any external force, such as steering embedded air-flow as we have based our approach directly on η-field tendencies.

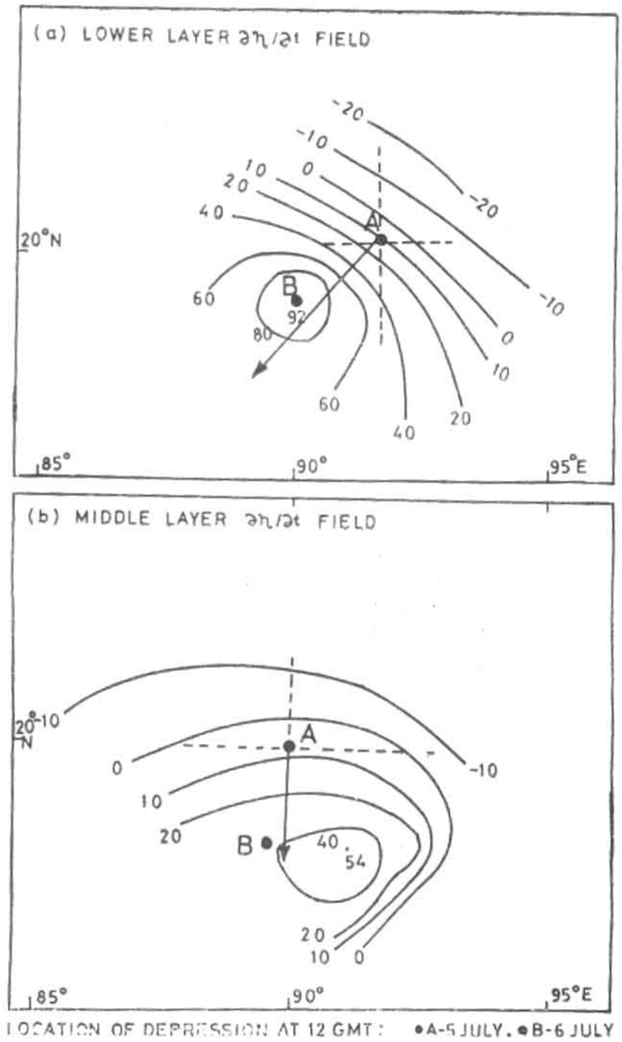
2. Theory

A low pressure system (depression or cyclone) is an organised concentration of positive absolute vorticity in the lower and middle troposphere. It can shift to new location in its neighbourhood when area around new location show tendency of generation of absolute positive vorticity (η). That means, a low pressure system shall move to an area in its vicinity where positive vorticity field is developing at a faster rate and the centre of LPS shall occupy a new position at which vorticity generation rate is maximum. It is apparent here that a low pressure system shall not move to new location in its vicinity if the rate of development of positive vorticity field is uniform around its old position.

The direction of movement of a LPS will be from lower tendency of η generation to higher tendency of η generation. Also, a LPS may move in different directions at different levels. Quantitatively we can represent this direction of movement of LPS by the direction of



Figs. 1(a) & (b). Absolute vorticity patterns (*After* Sanders) for lower layer (1000-700 mb) and for middle layer (700-400 mb) respectively at an interval of 40×10^{-6} sec^{-1}. η-field in full lines are for 6 July (12 GMT) and that of 5 July (12 GMT) in dashed lines. Locations marked as A and B are the positions of stream function minima (taken from paper by Sanders) for 5 July (12 GMT) and 6 July (12 GMT) respectively for corresponding layers. These locations have been taken here as the locations of the depression centres for respective layers at 12 GMT.



Figs. 2 (a & b). Absolute vorticity tendency pattern of lower and middle layers ($\partial\eta/\partial t$)-field over the period 5 July (12GMT) to 6 July (12 GMT) obtained by subtracting graphically the absolute vorticity pattern of 5 July (12 GMT) from 6 July (12 GMT) pattern (Fig. 1). Vector $\nabla(\partial\eta/\partial t)$ has been shown as an arrow whose length is in proportion with magnitute of the vector and whose initial point is at the centre. It is clearly seen that vector $\nabla(\partial\eta/\partial t)$ is pointing to the location B of depression on 6 July (12 GMT)

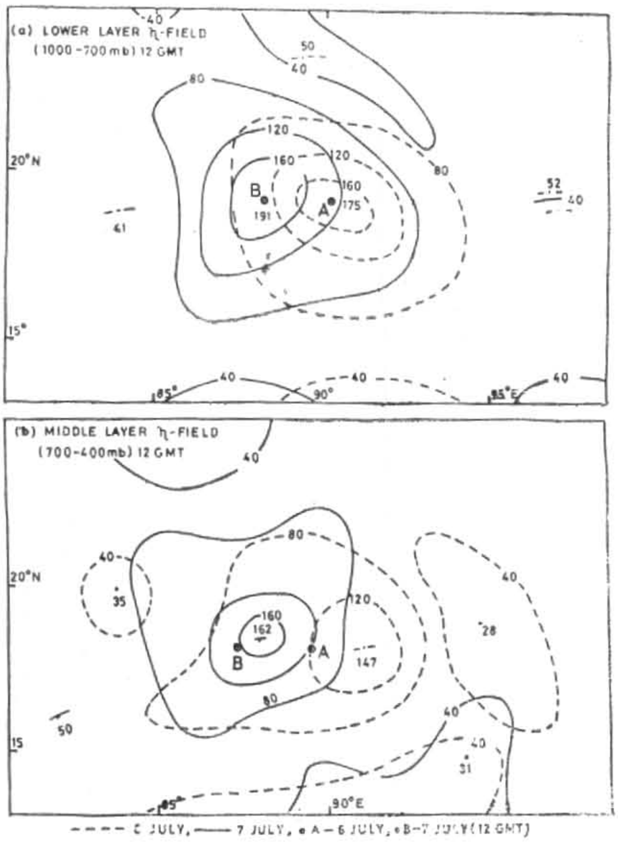
ascendent gradient of $\partial\eta/\partial t$, *i.e.*, $\vec{\nabla}$ $(\partial\eta/\partial t)$. The vector, ∇ $(\partial\eta/\partial t)$ calculated at old centre of LPS will point towards the new position of LPS. Since a LPS in general moves in different directions at different levels in the vertical, vector ∇ $(\partial\eta/\partial t)$ will be calculated using particular level's $\partial\eta/\partial t$-field to know the direction of movement at that level.

The reliability of wind observation over pressure observation and also the availability of wind data rather than pressure data (which are invariably absent) over regions of LPS that the vorticity values evaluated from wind observation were looked into for their possible use in determining the movement of LPS quantitatively, rather than pressure observations.

If one tries to build up a logic to say, that direction of movement of LPS is given by direction of vector, ∇ $(\partial\eta/\partial t)$, then obviously by the similar reasoning, it is easier to speculate that direction of movement of LPS is given by $-\nabla$ $(\partial p/\partial t)$ also. Nevertheless, the two vector, *i.e.*, ∇ $(\partial\eta/\partial t)$ and $-\nabla$ $(\partial p/\partial t)$ shall point to exactly same direction if lines of equal values of η are coinciding with the isobars in a LPS. Observations show that in a well organised system the situation is simliar enough so that the direction of ∇ $(\partial\eta/\partial t)$ agrees with the direction of movement of LPS.

As mentioned above and also seen in Figs. 2 and 4 given here, the new position of LPS is located in the region of maxima of $\partial\eta/\partial t$-field.

Further, it directly follows from above logic for direction of movement of LPS, that the faster is the generation of η at new position in comparison to η-tendency at old position, the faster will be the movement of LPS between these two positions. Mathematically one can say that speed of LPS will be proportional to a quantity $(\partial\eta_1/\partial t) - (\partial\eta_0/\partial t)$, where subscript 1 and 0 refers to new and old positions. The term $(\partial\eta_1/\partial t) - (\partial\eta_0/\partial t)$ is a measure of comparative development of LPS at two



Figs. 3(a & b). Same as Fig. 1 except that patterns in dashed lines are for 6 July (12 GMT) and in full lines for 7 July (12 GMT). Locations marked A and B are the centres for 6 July (12 GMT) and 7 July (12 GMT) respectively

nearby locations and this is precisely why a LPS should shift between two locations and hence it is reasonable to believe broadly that larger is comparative development the faster will be the movement of LPS between two locations. Although this logic also seems to be correct but the observation reproduced here do not support it. One of the several reasons could be that speed of movement of a LPS is, perhaps, made up of several factors which influence each other among themselves and thereby impairing the possibility of seeing that speed is proportional to a single factor such as $(\partial\eta_1/\partial t) - (\partial\eta_0/\partial t)$.

3. Data and analysis

To test the validity of our heuristic approach for determining the direction of movement of LPS and for determining at least one possible factor of speed of movement of LPS, a case study has been made using data for depression which formed over Bay of Bengal during MONEX-79. This is a rare example of depression for which dense aerological data were available to permit calculations of reliable vorticity field and stream functions over the region the depression formed and moved. This depression appeared on 3 July as a weak trough and it was only on 5 July that it changed to a weak circulation when its centre could be identified. On 6 July it appeared as a well developed circulation and by 7 July it attained its peak intensity before it reached inland on 8 July. The data used here are the absolute vorcitity patterns of 5, 6 and 7 July 1979 (12 GMT), published by Sanders (1981) for this depression. For that reason, movement of the depression from 5 July (12 GMT) to 6 July (12 GMT) and from 6 July (12 GMT) to 7 July (12 GMT) only have been quantified to test our logic. Sanders used vectorially vertically averaged areal winds over pressure depths 1000-700 hPa (power layer) and 700-400 hPa (middle layer), to avoid any contamination by small-scale variability, for determining absolute vorticity patterns at lower and middle layers. The same are shown here in Figs. 1(a), 1(b), 3(a) and 3(b). These η-fields on 5, 6, 7 July for lower and middle layers have been used in this note to determine graphically the absolute vorticity tendency fields ($\partial\eta/\partial t$-field) for respective layers for time intervals.

5 July (12 GMT) to 6 July (12 GMT) and
6 July (12 GMT) to 7 July (12 GMT).

These ($\partial\eta/\partial t$)-fields are shown in Figs. 2(a), 2(b), 4(a) and 4(b). Vector $\nabla(\partial\eta/\partial t)$ has been calculated and depicted as an arrow whose length is drawn in proportion to its magnitude at either layers for locations occupied by LPS on 5 July in Figs. 2(a) and 2(b) and for locations occupied by LPS on 6 July in Figs. 4(a) and 4(b). All locations of centres of LPS refer to stream function minima (given by Sanders) of respective layers.

It may be seen in Figs. 2(a) and 2(b) that vectors $\vec{\nabla}(\partial\eta/\partial t)$ for either layers at 5 July (12 GMT) location is pointing very nearly towards the location of LPS on 6 July (12 GMT) at corresponding layer. Similarly, in Figs. 4(a) and 4(b) the vector $\nabla(\partial\eta/\partial t)$, calculated for location of LPS, on 6 July (12 GMT) is pointing very nearly towards its location on 7 July (12 GMT) at corresponding layer. It is expected that the vector $\nabla(\partial\eta/\partial t)$ calculated using ($\partial\eta/\partial t$)-fields over time intervals shorter than 24 hours used here would point more accurately to subsequent position of LPS. ($\partial\eta/\partial t$)-fields over time intervals shorter than 24-hr will be most required when a LPS changes its direction of movement quite frequently in its course of movement.

A single case study is far from sufficient to establish a theory yet it can stimulate investigations to prove further the validity of an idea reasoned out theoretically such as the one here. Due to paucity of aerological data the logic could not be tested on any other LPS.

Table 1 shows values of :

$$\frac{\partial}{\partial x}\left(\frac{\partial\eta}{\partial t}\right),\ \frac{\partial}{\partial y}\left(\frac{\partial\eta}{\partial t}\right),\ \vec{\nabla}\left(\frac{\partial\eta}{\partial t}\right),\ \left(\frac{\partial\eta_1}{\partial t}-\frac{\partial\eta_0}{\partial t}\right)\text{ and}$$

speed, C, for either layers. It may be cautioned again that magnitudes of various terms are in arbitrary units as the relative magnitudes sufficed here to determine direction vector. On comparison of values under Col. 5 and

TABLE 1

Diagram	$\frac{\partial}{\partial x}\left(\frac{\partial \eta}{\partial t}\right)$ in units of $\frac{10^{-6}\ \text{sec}^{-1}}{20\ \text{mm} \times \text{scale factor} \times 24\ \text{hr}}$	$\frac{\partial}{\partial y}\left(\frac{\partial \eta}{\partial t}\right)$ in units of Col. 2	$\left\lvert \vec{\nabla}\left(\frac{\partial \eta}{\partial t}\right)\right\rvert$	$\frac{\partial \eta_1}{\partial t} - \frac{\partial \eta_0}{\partial t}$ in units of $\frac{10^{-6}\ \text{sec}^{-1}}{24\ \text{hr}}$	Speed C in units of $\frac{\text{mm} \times \text{scale factor}}{24\ \text{hr}}$
(1)	(2)	(3)	(4)	(5)	(6)
Fig. 2(b)	4—5 = —1	—10—30 = —40	$\sqrt{(-40)^2+(-1)^2}$ =40.01	40—7 =33	16
Fig. 2(a)	—6—40 = —46	—10—40 = —50	$\sqrt{(-46)^2+(-50)^2}$ =67.9	92—10 =82	16
Fig. 4(b)	—65—50 = —115	5—(—30) = 35	$\sqrt{(-35)^2+(-115)^2}$ =120.6	72—0 =72	16
Fig. 4(a)	—50—40 = —90	—10—(—25) = 15	$\sqrt{(15)^2+(90)^2}$ =91.2	71—(—45) =116	15

Col. 6 of the table we find that values of $(\partial\eta_1/\partial t)-(\partial\eta_0/\partial t)$ are not in proportion with corresponding values of C and thus does not support, as mentioned above, our reasoning that speed in proportional to $(\partial\eta_1/\partial t)-(\partial\eta_0/\partial t)$. Apart from the reason given above for this failure, another reason could be that the distances between old and new position of LPS used here are the shortest distances although LPS might have traced a zig-zag path as it does generally. A nearer more exact proportionality of speed to $(\partial\eta_1/\partial t)-(\partial\eta_0/\partial t)$ could, perhaps, be shown when vorticity tendencies were available over time intervals shorter than 24 hours used here and also the distances measured along the actual track to know the correct speed.

Having found that direction of movement of centre of a LPS is given by the direction of the vector, $\nabla(\partial\eta/\partial t)$, we may try to get more physical insight of the movement phenomenon through vorticity equation as follows :

Vorticity equation in (x, y, z, t) coordinates is :

$$\frac{\partial \eta}{\partial t}+\mathbf{V}.\vec{\nabla}\eta=-\eta\,\vec{\nabla}_H.\mathbf{V}+\mathbf{k}.\left(\frac{\partial \mathbf{V}_H}{\partial z}\times\vec{\nabla}_H w\right)-\mathbf{k}.\left(\vec{\nabla}_H \alpha\times\vec{\nabla}_H p\right) \quad (1)$$

Taking horizontal gradient of various terms of Eqn. (1) we get :

$$\vec{\nabla}_H\left(\frac{\partial \eta}{\partial t}\right)=\vec{\nabla}_H\left(-\mathbf{V}.\vec{\nabla}\eta\right)-\vec{\nabla}_H\eta\,\vec{\nabla}_H.\mathbf{V}-\eta\,\vec{\nabla}_H\left(\vec{\nabla}_H.\mathbf{V}\right)+\vec{\nabla}_H\left[\mathbf{k}.\left(\frac{\partial \mathbf{V}_H}{\partial z}\times\vec{\nabla}_H w\right)\right]-\vec{\nabla}_H\left[\mathbf{k}.\left(\vec{\nabla}_H \alpha\times\vec{\nabla}_H p\right)\right] \quad (2)$$

Calling, $\vec{\nabla}_H(\partial\eta/\partial t)=K\mathbf{n}$, where $\mathbf{n}$ is a unit vector in the direction of movement of LPS and

$$K=\left\lvert\vec{\nabla}_H\left(\frac{\partial \eta}{\partial t}\right)\right\rvert$$

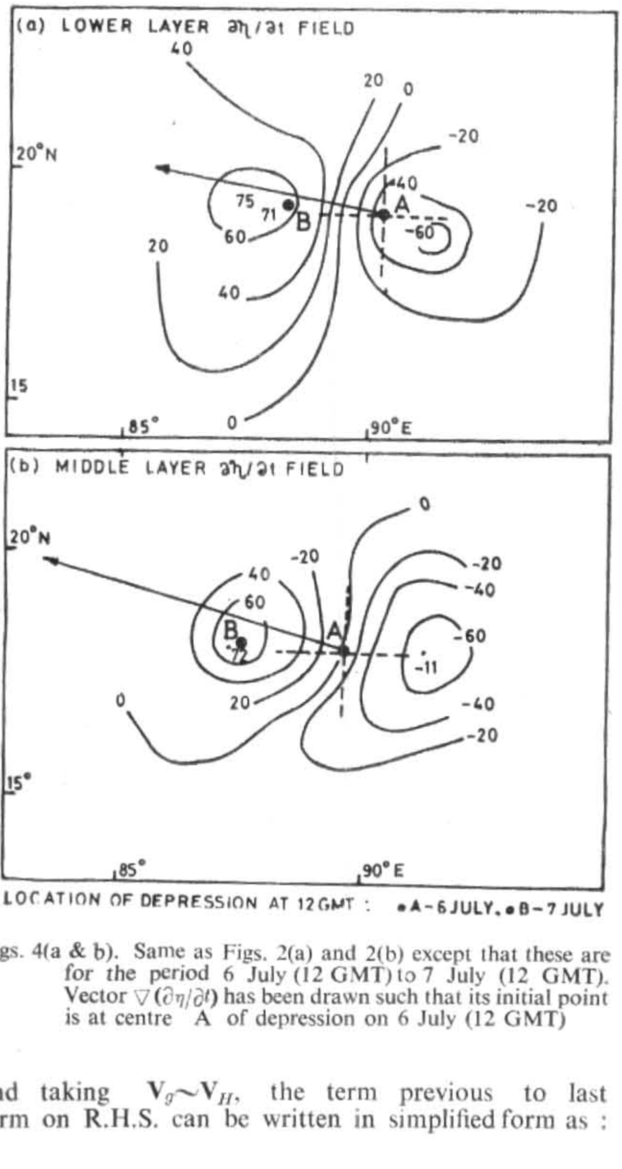
Last term on R.H.S. of Eqn. (2) can be written in simpler form as :

$$-\vec{\nabla}_H\left[\mathbf{k}.\left(\vec{\nabla}_H\alpha\times\vec{\nabla}_H p\right)\right]=\vec{\nabla}_H\left(f\,\mathbf{V}_g.\,\frac{\vec{\nabla}_H T}{T}\right)$$

Also,

$$\frac{\partial \mathbf{V}_H}{\partial z}\simeq\frac{\partial \mathbf{V}_g}{\partial z}=-\frac{g}{fT^*}\vec{\nabla}_p T^*\times\mathbf{k}$$

$$\sim-\frac{g}{fT}\vec{\nabla}_H T\times\mathbf{k}$$



Figs. 4(a & b). Same as Figs. 2(a) and 2(b) except that these are for the period 6 July (12 GMT) to 7 July (12 GMT). Vector $\nabla(\partial\eta/\partial t)$ has been drawn such that its initial point is at centre A of depression on 6 July (12 GMT)

and taking $\mathbf{V}_g \sim \mathbf{V}_H$, the term previous to last term on R.H.S. can be written in simplified form as :

$$\vec{\nabla}_H\left(\mathbf{k}\cdot\frac{\partial \mathbf{V}_H}{\partial z}\times\vec{\nabla}_H w\right)$$

$$\sim \vec{\nabla}_H\left[\mathbf{k}\cdot\left(-\frac{g}{fT}\,\vec{\nabla}_H T\times\mathbf{k}\right)\times\vec{\nabla}_H w\right]$$

$$= \vec{\nabla}_H\left[\mathbf{k}\times\left(-\frac{g}{fT}\vec{\nabla}_H T\times\mathbf{k}\right)\cdot\vec{\nabla}_H w\right]$$

$$= \vec{\nabla}_H\left[\left\{-\frac{g}{fT}\vec{\nabla}_H T\left(\mathbf{k}.\mathbf{k}\right) - \right.\right.$$

$$\left.\left. -\left(-\frac{g}{fT}\vec{\nabla}_H T\cdot\mathbf{k}\right)\mathbf{k}\right\}\cdot\vec{\nabla}_H w\right]$$

$$= \vec{\nabla}_H\left[\left(-\frac{g}{fT}\vec{\nabla}_H T\cdot\vec{\nabla}_H w\right)\right]$$

$$\because \left(\vec{\nabla}_H T\cdot\mathbf{k}\right) = 0$$

Now Eqn. (2) becomes :

$$K\mathbf{n} = \vec{\nabla}_H\left(-\mathbf{V}_H\cdot\vec{\nabla}\eta\right) + \vec{\nabla}_H\left(-w\cdot\frac{\partial\xi}{\partial z}\right)$$

(I) (II)

$$-\vec{\nabla}_H\eta\,\vec{\nabla}_H\cdot\mathbf{V} - \eta\,\vec{\nabla}_H\left(\vec{\nabla}_H\cdot\mathbf{V}\right) +$$

(III) (IV)

$$+\nabla_H\left(-\frac{g}{fT}\vec{\nabla}_H T\cdot\vec{\nabla}_H w\right) + +$$

(V)

$$+\vec{\nabla}_H\left(\frac{f}{T}\mathbf{V}_H\cdot\vec{\nabla}_H T\right) \qquad (3)$$

(VI)

We shall see the influence of each of the six terms of RHS of Eqn. (3) individually on the direction of movement of LPS, given by vector, $K\mathbf{n}$, as if other terms are absent.

Term (I) – According to the direction of $\vec{\nabla}_H(-\mathbf{V}_H\cdot\vec{\nabla}\eta)$, a LPS shall move from an area of less horizontal positive vorticity-advection to an area of more horizontal-positive vorticity advection. The effect of this term is easily understandable.

Term (II) – Similar to the term (I), direction of movement of LPS according to vector, $\nabla_H\ (-w.\partial\xi/\partial z)$, will be from an area of less upward-positive-vorticity advection to an area of more upward-positive-vorticity advection. The implication of terms (I) and (II) can be understood as these two terms are directly related with prapogation of areas of positive vorticity and thus with the direction of movement of LPS.

Term (III) — The term, $-\vec{\nabla}_H\eta\,\vec{\nabla}_H\cdot\mathbf{V}$, when present alone will propagate the LPS from an area of less positive vorticity to an area of more positive vorticity when both these areas are in the region of convergence. Reverse shall be the direction of movement when these areas are in the region of divergence.

Term (IV) – Influence of the term, $-\eta\,\vec{\nabla}_H(\vec{\nabla}_H\cdot\mathbf{V})$, will be such as to take away the LPS from an area of less convergence to an area of more convergence when both the areas lie in the positive vorticity field. In the negative vorticity field reverse shall be the direction of movement of LPS.

Term (V) — Effect of this term can be understood as follows : If we construct a scalar field of a quantity obtained at each point of the region around centre of LPS by scalar product of the descendent vector of temperature, $-\nabla_H T$ and the ascendent vector of vertical velocity field, $\nabla_H w$, at respective point, then the direction of movement of LPS is given by the ascendent vector of the so constructed scalar field.

At the surface, the influence of the term :

$$\vec{\nabla}_H \left(-\frac{g}{fT} \vec{\nabla}_H T . \vec{\nabla}_H w \right)$$

can be easily verified. Around the centre of a cyclone, the surface temperatures are such that there is a fall of temperature from the centre of the cyclone to wall-cloud region. At the same time, there is an increase of vertical velocity as one moves out of the centre to the wall cloud region, which means that vectors — $\nabla_H T$ and $\nabla_H w$ have the same direction and their scalar product value also increases as one moves out of centre of a cyclone to wall cloud region. So it is easy to understand that a LPS will move along the ascendent gradient of :

$$\vec{\nabla}_H \left(-\frac{g}{fT} \vec{\nabla}_H T . \vec{\nabla}_H w \right) .$$

Term (VI) – Effect of the term $\vec{\nabla}_H \left(\frac{f}{T} \mathbf{V}_H . \vec{\nabla}_H T \right)$, is such that LPS moves from an area of less cold-temperature advection to an area of more cold-temperature advection.

It may be remembered that each of the above six terms is to be calculated at previous centre of LPS.

Although the centre of LPS shall be moving along the resultant vector $\nabla(\partial\eta/\partial t)$, of all the six vector terms explained above, yet in a real situation, the effect of some term(s) can be far more than the rest of the term(s). In addition to it, the effect of some term(s) may cancel the effect of other term(s). In this study, the magnitude of influence of each term has not been attempted as the resultant vector $\vec{\nabla} (\partial\eta/\partial t)$ was directly calculated from η-fields.

4. Conclusions

This note merely shows validity of a logic built for determining movement of a LPS. Forecasting utility of the formulation given here rests on the availability of forecast vorticity tendency field around the centre of LPS. Besides this, the study may have academic utility.

From the above analysis we conclude that :

(*i*) Direction of movement of a well marked LPS (depression/cyclone) is given by the direction of the vector, $\nabla(\partial\eta/\partial t)$, calculated at previous location of LPS.

(*ii*) The direction vector, $\vec{\nabla}(\partial\eta/\partial t)$, is the resultant of vector quantities obtained by taking horizontal gradient of vorticity equation. Physical insight of the movement process is gained through the interpretation of the constituent vectors.

(*iii*) The subsequent centre of LPS appears to be located at the maxima of vorticity tendency field.

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