

# A METHOD OF ESTIMATING THE VELOCITY OF SEVERE THUNDERSTORMS

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J. R. Colquhoun

Regional Office, Bureau of Meteorology, Sydney

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## ABSTRACT

Ludlam's (1961) severe local storm model is extended to three dimensions. Using this modified model, the vertical wind profile in the environment of the storm between the surface and 450 mb and a new hypothesis, the velocity of thunderstorms in their severe stage may be estimated. In a test using nine SH storms the method of this paper compared favourably with other methods of estimating severe storm velocity.

It is suggested that the vertical wind profile in the environment of the storm determines whether it, in becoming severe, evolves to an SH, SL or SN type. Storm pairs resulting from the splitting of a single storm may be an exception. A severe storm's intensity may also be estimated.

A storm which develops in a wind profile where  $|v_M| < |v_L|$  has an updraft which originates from behind the storm and a downdraft which is fed from the front of the storm.

## INTRODUCTION

Winston (1956) defines severe local storms (in this paper called severe thunderstorms) as thunderstorms accompanied by very strong surface winds or large hailstones. Another characteristic of these storms (Browning 1968) is that in the mature stage the storm 'takes on a new lease of life in which the continually evolving individual cloud cells are superseded by a much larger supercell with an intense updraft and downdraft coexisting in a more nearly steady state, sometimes for periods in excess of an hour. The updraft in the new organisation may extend several kilometres above the level of the tropopause, being characterised by ascent of the order of several tens of metres per second'. Tornadoes are often produced by these storms.

The velocity of a severe thunderstorm in the mature stage is different from the storm's initial velocity. Newton and Fankhauser (1964) described storms which 'moved more nearly with the mean wind early and late in their lives when they were relatively small, but up to  $60^\circ$  to the right of the mean winds when they were most strongly developed'. Their 'mean wind' is the vector mean of the 850, 700, 500 and 300 mb winds. Browning (1968) says 'although the anomalous travel of severe storms is apparently an important feature of their organisation, it is by no means clear what causes them to travel anomalously in the first place. It is even less clear what determines whether a storm travels to the right or left.' An attempt is made here to explain this anomalous movement.

## THEORETICAL CONSIDERATIONS

Ludlam (1961 and 1963) and Browning and Ludlam (1962) present a two dimensional model of airflow within a vertical section through a typical severe hailstorm which is assumed to travel at the speed of the wind at some mid-tropospheric level. Browning (1968) points out that this model is artificial in that 'it requires the downdraft to be initiated within evaporatively chilled air at high levels' and he also states that Ludlam's (1961) model applies strictly to a storm which travels at the velocity of the middle level winds. Browning presents a three dimensional model of a severe storm in which cold middle level air enters the storm ahead of the updraft and, after being evaporatively cooled, descends and produces a downdraft. This model, however, is unrealistic in that the speed of the middle level winds are represented as being equal to the low level wind speeds. Usually in severe storm environments the middle level wind speeds are considerably stronger.

Ludlam's (1961) model becomes more realistic if the middle level wind speeds are assumed stronger than the low level speeds, if the severe storm speed is less than the middle level wind speed and if the direction of movement is to the right of these winds. Browning labels this storm SR. Spillane and Dixon (1969) suggest that Browning's SR storm would be better named SH, indicating movement in the severe stage to the high pressure side of the mid-tropospheric flow and that his SL storm does not necessarily indicate movement to the left but to the low pressure side of the mid-tropospheric flow. Spillane and Dixon's nomenclature is used in this paper.

The Ludlam model can be made three dimensional by assuming that the sloping interface between the updraft and downdraft can be represented by a surface, the horizontal cross-section of which is perpendicular to the direction of motion of the storm and also by assuming that the width of the winds feeding the updraft and downdraft does not vary with height.

Spillane and McCarthy (1969) give a theoretical basis for estimating trajectories in the downdraft and temperatures along these trajectories. They state that 'A criterion for the stability of the mature stage is that equal quantities of air are brought into the open system by the downdraft and updraft. Hence the movement of the storm must provide a balance between the relative flow to the updraft at cloud base and the relative flow to the downdraft. From scale considerations, the upper limit of origin of downdraft air in the environment, from cooling and from weight of rain upstream of an updraft core, is about 450 mb.' On the basis of this work the modified Ludlam model described above can be further refined by imposing an upper limit to the downdraft air of 450 mb and by imposing the balanced flow constraint. However, even with these modifications the velocity of a severe thunderstorm is not specified as balanced flow can be attained with many storm velocities. In this paper it is additionally hypothesized that the maximum storm intensity is reached when it moves with the velocity giving the maximum rate of inflow of air to the updraft/downdraft system.

Kropfli and Miller (1975) used a dual-Doppler radar system to obtain the three dimensional velocity structure within a severe thunderstorm. Their schematic representation (their Fig 3 bottom) of the flow pattern in the vertical plane supports Spillane and McCarthy's view that 450 mb is the upper limit of origin of the downdraft air.

If the modified Ludlam model is representative of the structure of severe storms and the new hypothesis is valid, the following argument shows that one is able to estimate the severe steady state storm velocity.

Assuming the downdraft to be fed by winds between  $p_T = 450$  mb and  $p_m$ , and the updraft fed by winds between  $p_m$  and  $p_0 =$  surface pressure, then if  $V(p)$  represents the wind velocity at pressure  $p$  and  $D(p)$  is the horizontal width of the winds feeding the storm at that pressure (measured normal to the direction of motion of the storm), then the mass flux into the storm, moving with a velocity  $V_S$ , at level  $p$ , can be denoted by:

$$|\underline{V}(p) - \underline{V}_S| \rho \quad (\text{kg} \cdot \text{s}^{-1} \cdot \text{m}^{-2})$$

where  $\rho$  = density.

The rate of transport through a small height increment  $\delta z$  would then be

$$|\underline{V}(p) - \underline{V}_S| D(p) \rho \delta z \quad (\text{kg} \cdot \text{s}^{-1})$$

which on account of the hydrostatic equation

$$= - \frac{D(p)}{g} |\underline{V}(p) - \underline{V}_S| \delta p$$

The total rate of mass transport into the top of the storm is then

$$\frac{-1}{g} \int_{P_m}^{P_T} D(p) |\underline{V}(p) - \underline{V}_S| dp$$

and into the bottom

$$\frac{-1}{g} \int_{P_0}^{P_m} D(p) |\underline{V}(p) - \underline{V}_S| dp$$

The Spillane and MCarthy (1969) criterion equates these rates of transport, thus:

$$\int_{P_m}^{P_T} D(p) |\underline{V}(p) - \underline{V}_S| dp = \int_{P_0}^{P_m} D(p) |\underline{V}(p) - \underline{V}_S| dp \quad \dots 1$$

It is convenient to introduce at this point velocities  $\underline{V}_L$  and  $\underline{V}_M$  which are representative environmental velocities from  $p_0$  to  $p_m$  and  $p_m$  to  $p_T$  respectively, such that

$$\int_{P_m}^{P_T} |\underline{V}_M - \underline{V}_S| dp = \int_{P_m}^{P_T} D(p) |\underline{V}(p) - \underline{V}_S| dp \quad \text{and similarly}$$

for  $\underline{V}_L$ , assuming  $D(p)$  constant and setting it equal to unity at all levels. Then equation 1 reduces to

$$|\underline{V}_M - \underline{V}_S| = |\underline{V}_L - \underline{V}_S| \quad \dots 2$$

if  $p_T - p_m = p_m - p_0$ .

The change in the velocity of a thunderstorm as it evolves from the non severe to the severe stage may be related to:

- (a) The increase in the height of the top of the storm as it changes from the non severe to the severe stage and its deep penetration of the tropopause in the severe stage.

As a thunderstorm changes from the non severe to the severe stage the height of its top increases and penetrates well into the tropopause. The increase in buoyancy of the updraft, which causes the growth, occurs because of the increased release of latent heat of condensation due to the increased inflow of moisture to the updraft.

(b) The subsequent long life of many supercell storms.

Thunderstorms usually have a short life. It is generally accepted that this is because the updrafts are often 'killed' by water loading as precipitation grows within them. But when a storm's direction of travel deviates from the mean tropospheric wind there is a tendency for much of the precipitation to fall to one side of the updraft and hence to avoid overloading it. Another reason for the short life of thunderstorms is that the cold air outflow from the downdraft spreads beneath and ahead of the storm and reduces the supply of warm moist air to the updraft. In deviating toward the direction  $\underline{V}_M - \underline{V}_L$  (the significance of this direction is explained later) as it changes from the non severe to the severe stage, a storm not only increases the supply of warm moist air but also moves away from the outflow of cold air from the downdraft.

The second criterion can be expressed as

$$\frac{1}{g} \int_{P_0}^{P_T} D(p) |(\underline{V}(p) - \underline{V}_S) \cdot \hat{\underline{V}}_S| dp \quad \dots 3$$

to be a maximum, where  $\hat{\underline{V}}_S$  is the unit vector in the  $\underline{V}_S$  direction.

This may be thought of as

$$(\underline{V}_M - \underline{V}_S) \cdot \hat{\underline{V}}_S - (\underline{V}_L - \underline{V}_S) \cdot \hat{\underline{V}}_S \quad \dots 4$$

is a maximum.

Figure 1(a) shows a vertical wind structure often associated with SH storms in the southern hemisphere,  $|\underline{V}_M| > |\underline{V}_L|$  and winds back (according to international usage\*) with height. The storm direction giving the maximum rate of mass transport is the direction  $\underline{V}_M - \underline{V}_L$  and the speed giving stability attained when

$$|\underline{V}_M - \underline{V}_{SH}| = |\underline{V}_L - \underline{V}_{SH}|.$$

For this wind structure  $\underline{V}_{SH}$  is the only solution to the problem of what the storm velocity will be in the severe stage if the rate of mass transport is maximised.

Severe storms may occur in other wind profiles. If the winds veer with height and increase in speed an SL storm will result (Fig 1(b)). This wind profile is rare, so storms of this type should also be a rare occurrence.

If  $|\underline{V}_M| < |\underline{V}_L|$  and winds back with height (Fig 1(c)) an SL storm is produced. In this situation the velocity giving maximum rate of mass transport is in the direction  $\underline{V}_L - \underline{V}_M$ .

If  $|\underline{V}_M| < |\underline{V}_L|$  and the winds veer with height an SH storm results (Fig 1(d)).

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\* The terms backing and veering have the internationally accepted meaning, *ie*, for backing a change in wind direction in an anticlockwise sense.

If there is no change in wind direction with height the storm, which may be labelled SN, will not deviate from track as it becomes severe. With no vertical direction or speed wind shear a severe storm cannot develop.

It is readily seen that a severe storm resulting from a wind profile where  $|\tilde{V}_M| < |\tilde{V}_L|$  cannot have the same structure as one developing in a profile where  $|\tilde{V}_M| > |\tilde{V}_L|$ . When the low level winds are stronger the updraft must originate from behind the storm and the downdraft from the front.

The type of severe storm produced in the southern hemisphere by different wind profiles is shown in Table 1.

Table 2 shows the type of severe storm produced by different wind profiles in the northern hemisphere where backing and veering have the same sense in both international and United States meanings of the terms, *ie*, backing is a change in wind direction in an anticlockwise sense.

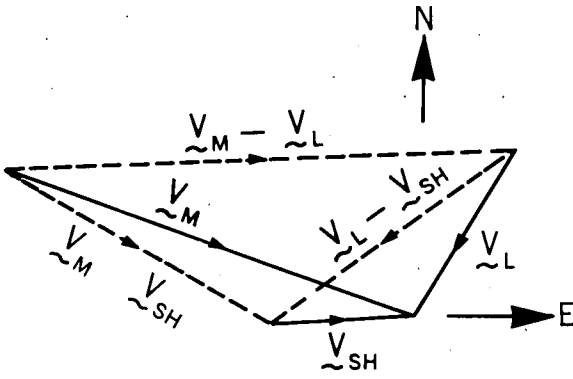
Table 1 Severe storm type resulting from various wind profiles according to model presented here (southern hemisphere)

	Change in wind direction with increasing height		
	Backs	Veers	No change
$ \tilde{V}_M  >  \tilde{V}_L $	SH	SL	SN
$ \tilde{V}_M  =  \tilde{V}_L $	Stationary	Stationary	-
$ \tilde{V}_M  <  \tilde{V}_L $	SL	SH	SN

Table 2 Severe storm type resulting from various wind profiles according to model presented here (northern hemisphere)

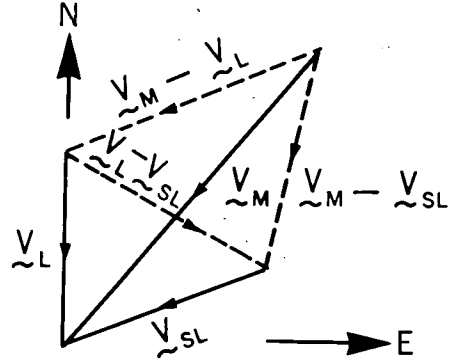
	Change in wind direction with increasing height		
	Backs	Veers	No change
$ \tilde{V}_M  >  \tilde{V}_L $	SL	SH	SN
$ \tilde{V}_M  =  \tilde{V}_L $	Stationary	Stationary	-
$ \tilde{V}_M  <  \tilde{V}_L $	SH	SL	SN

The northern hemisphere situations have not been shown on diagrams as they are the mirror image of the equivalent southern hemisphere situation, *eg*, in the northern hemisphere if  $|\tilde{V}_M| > |\tilde{V}_L|$  and the wind veers with height an SH storm is produced. This situation is shown diagrammatically as the mirror image of Fig 1(a).



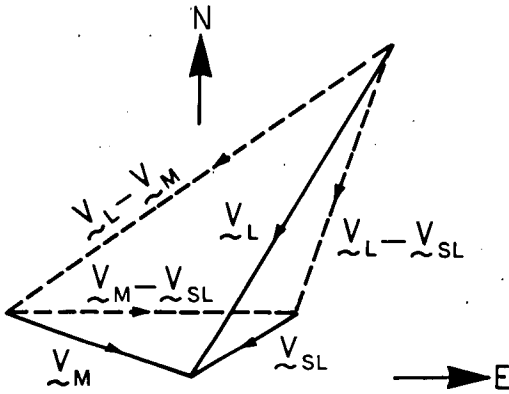
(a) SH storm in winds backing with height

$$|\tilde{V}_M| > |\tilde{V}_L|$$



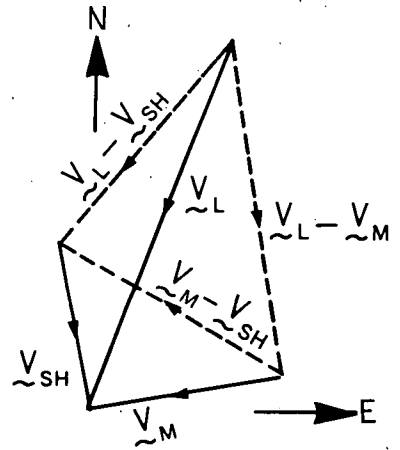
(b) SL storm in winds veering with height

$$|\tilde{V}_M| > |\tilde{V}_L|$$



(c) SL storm in winds backing with height

$$|\tilde{V}_M| < |\tilde{V}_L|$$



(d) SH storm in winds veering with height

$$|\tilde{V}_M| < |\tilde{V}_L|$$

Fig 1 Type of severe storm in various vertical wind structures (southern hemisphere)

## CASE STUDIES

In practice the storm's velocity giving the maximum rate of mass transport, with the balance flow constraint, can be calculated from the vertical wind profile in the environment of the storm without calculating  $V_L$  and  $V_M$ . Colquhoun (1975) describes the procedure used and also gives details of several severe storms which were studied to test the new hypothesis. If the assumptions inherent in the model are valid, the rate of mass transport calculated for each storm is proportional to the storm's total rate of mass transport. In most cases storms were SH types and the observed and calculated velocities were similar. The intensity of ten storms was subjectively estimated. More intense storms were generally associated with large rates of mass transport.

The method of this paper was tested against three other methods of determining severe storm velocity. These were:

1. the method of Newton and Katz (1958);
2. the mean vector wind from the surface to 450 mb;
3.  $\frac{V}{2}(500)$ , where  $V_{(500)}$  is the 500 mb wind velocity.

The method of Newton and Katz, although not directly applicable to individual cells, was used because of the lack of more relevant methods. Nine severe storms were used in this comparison. Three occurred in the southern hemisphere and six in the northern. Details of these six storms were obtained from Barnes (1972), Marwitz (1973), Donaldson *et al.* (1969), Brown *et al.* (1973) and Fujita and Grandoso (1968). The method of this paper gave good results. For most storms the deviation of the severe storm from the initial direction was slightly overestimated but there was little bias in estimates of speed. The average absolute direction error was 5.6 degrees and the average absolute speed error 1.5 knots. These compare with values of 17.4 degrees and 9.7 knots using the Newton and Katz method, 30.3 degrees and 6.2 knots using the mean vector wind and 14.9 degrees and 2.7 knots using  $\frac{V}{2}(500)$ .

Foote and Fankhauser (1973) describe a Colorado hailstorm, the low level radar echo of which moved with a velocity of  $275^{\circ} 13 \text{ m s}^{-1}$ . The method of this paper predicts a velocity of  $260^{\circ} 5.5 \text{ m s}^{-1}$ . However, the authors note that 'it was possible that only air passing under the cloud perimeter at levels near 3 km and higher was actually entering the base of the cloud'. If winds between 3 km (710 mb) and 450 mb are used a storm velocity of  $275^{\circ} 10 \text{ m s}^{-1}$  is deduced. If the base of the updraft air is assumed to be 3.3 km (680 mb) a velocity of  $270^{\circ} 12.5 \text{ m s}^{-1}$  is predicted. Thus this theory supports the view that only air above about 3 km was entering the updraft of the storm. If this was so then the mass inflow and precipitation efficiency values given by Foote and Fankhauser are in error by a factor of about two.

Two occurrences of pairs of severe storms produced by the splitting of a single storm were studied. This method gave a good estimate of the velocity of the most severe of each pair, but cannot be used to estimate the velocity of the less severe storm. However, if the velocity of this storm is known its severity may be estimated by calculating the rate of mass transport.

## CONCLUSIONS

Ludlam's (1961) severe local storm model was extended to three dimensions by assuming that:

- (a) the sloping interface between the updraft and downdraft can be represented by a surface, the horizontal cross-section of which is perpendicular to the direction of motion of the storm, and
- (b) the width of the winds feeding the updraft and downdraft does not vary with height.

The velocity of severe thunderstorms in the steady state stage can be estimated using this modified model, the vertical wind profile in the environment of the storm between the surface and 450 mb and the hypothesis that the maximum storm intensity is reached when it moves with the velocity giving the maximum rate of inflow of air to the updraft/downdraft system. A constraint is that equal quantities of air are brought into the open system by the updraft and downdraft.

The method of this paper gave good results when compared with other methods of calculating severe storm velocity. However, the number of severe storms used in this comparison (nine) is small, and all were type SH, so these methods should be tested on a larger sample of severe storms and on other severe storm types. It is important that a wind profile is obtained which is representative of the environment of the storm. If a profile from a single station is to be used its representativeness should be checked by comparison with an estimate obtained from streamline/isotach analyses at various pressure levels or heights. Usually it is not sufficient to use only winds at standard pressure levels (*ie*, surface, 850, 700, 500 and 300 mb). A severe storm's intensity may be associated with the magnitude of the rate of mass transport.

It is also suggested that whether a storm (excepting storms resulting from the splitting of a storm) in changing from the non severe to the severe stage evolves to an SH, SL or SN type is determined by the vertical wind structure. A storm which develops in a wind profile where  $|v_M| < |v_L|$  has an updraft which originates from behind the storm and a downdraft which is fed from the front of the storm.

The method of this paper accurately estimated in two cases the velocity of the more severe of a pair of storms produced by the splitting of a single storm, however the method should be applied to more storms of this type before definite conclusions are drawn.

There are forecasting applications for this method in the field of radar meteorology. A forecast could be made of the velocity of severe storms from the expected vertical wind profile in the storm area. Any storm which subsequently moved with this velocity would be severe, provided that no major change from the forecast wind profile occurred. This method will give poor results if all the air from the surface to the cloud base does not enter the updraft of a severe storm.

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