Mesoscale Wind Structure Revealed by Doppler Radar[1]

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ABSTRACT

Doppler wind soundings were taken in the lower 4.5 km of the atmosphere at 12 minute intervals during a seven hour period in a snowstorm over eastern Massachusetts. A time-height cross section of the wind revealed numerous small scale, short period changes in the wind structure.

Initially there was a region of strong wind shear near 4 km, above the warm front zone. Periodic breakdowns in the wind shear appeared to result in a downward transfer of momentum. In this way, winds at lower levels increased by as much as 10 m sec^{-1} within a half hour period. The series of three breakdowns occurred at about hourly intervals at successively lower levels, until by the end of the period the wind speed at all levels had increased by about a factor of two, and the wind shear zone was confined to the lowest few hundred meters.

A time-height cross section of vertical motions indicated that each breakdown was preceded by a downdraft, followed by a turbulent region of successive updrafts and downdrafts of 2 to 4 m sec^{-1}. These turbulent regions may be responsible for much of the short period change in structure of "uniform" precipitation.

A comparative analysis, using hourly rawinsondes during a rainstorm with an analogous wind structure also revealed similar breakdowns, although the absence of resolution precluded delineation of the smaller scale turbulence which the Doppler observations so clearly reveal.

1. Introduction

Strong horizontal wind shear in the lower troposphere frequently characterizes conditions in advance of a cyclonic system. At a location a few hundred kilometers ahead of the advancing system, winds may be relatively light below the warm front which is characterized by a zone of strong vertical wind shear. Typically as the system advances, the warm front lowers and the wind speed increases at lower elevations. Atmospheric cross sections generally depict the warm front as a continuous zone increasing in height with distance from the cyclonic center. Such an analysis is generally based on observations taken at 12 hour intervals at stations a few hundred kilometers apart. Undoubtedly a closer network of stations or more frequent observations might reveal a mesoscale structure hitherto unsuspected.

In this paper an analysis of the wind structure in advance of a cyclonic storm on 12 March 1962 is made from observations taken at 12 minute intervals over a seven hour period with the aid of a Doppler radar located at Sudbury, Mass. Winds and vertical velocities were calculated by the VAD (velocity azimuth display) technique in which the range gate moves out slowly while the beam rotates in azimuth at a constant elevation angle of 30° (Lhermitte and Atlas, 1961).

2. Theory

The theory of the VAD technique has been discussed by Lhermitte and Atlas; it is repeated here with modification. The Doppler speed in the upstream (u) and downstream (d) directions may be written as:

$$v_u = u_u \cos\alpha + (v_f + w)\sin\alpha \qquad (1)$$

$$v_d = u_d \cos\alpha - (v_f + w)\sin\alpha, \qquad (2)$$

where α is the angle of elevation, v_f is the mean fall speed of the particles, u is the horizontal wind and w the downdraft velocity (negative for updrafts) assumed uniform in upwind and downwind directions. Assume a horizontal wind distribution which is increasing uniformly from the downwind to the upwind direction:

$$\begin{aligned} u_u &= u_0 + \Delta u \\ u_d &= u_0 - \Delta u. \end{aligned} \qquad (3)$$

Substituting in (1) and (2) and adding we may solve for u_0:

$$u_0 \cos\alpha = \frac{v_u + v_d}{2}. \qquad (4)$$

Eq. (4) allows the wind above the radar to be determined for conditions where the wind is uniformly

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changing from the downwind to the upwind direction. Changes in the vertical motions or fall speed of the precipitation particles in the two directions would have relatively little effect except possibly for extremely light winds.

Subtracting (1) from (2) we find for the mean downdraft:

$$2w \sin\alpha = v_u - v_d - 2\Delta u \cos\alpha - 2v_f \sin\alpha. \qquad (5)$$

If v_f were subject to an error of 0.5 m sec^{-1}, then w would be subject to the same error. The error involving Δu is more difficult to determine. At an elevation angle of 30° and a height of 3 km, the horizontal distance of the detected precipitation from the radar is about 5 km. If we assume that the horizontal wind shear is as much as 10 m sec^{-1} in 50 km, then Δu is 1 m sec^{-1} over the 5 km interval. The vertical velocity w at 3 km elevation would then be subject to an error of about 1.7 m sec^{-1}. The error would be less at lower elevations, and greater at higher elevations; at 4.5 km the error could be as much as 2.8 m sec^{-1}. Hence in regions of rapidly changing wind, the determination of w may be subject to an error of about 2 m sec^{-1}. A first order correction may be possible by estimating the value of Δu during these periods.

3. Synoptic situation, 12 March 1962

At 0700E a deep cyclonic storm was centered over Lake Michigan while a developing weak secondary was located over Chesapeake Bay. By 1300E (Fig. 1) the secondary had deepened slightly and was over New Jersey. Under the influence of the secondary, snow fell over eastern Massachusetts during the morning, changing to rain in the early afternoon. At the surface there was a strong pressure gradient, with a flow from the southeast between eastern Massachusetts and the secondary center.

Aloft at 0700E, there was strong horizontal wind shear between eastern Massachusetts and New York State: at Nantucket 700-mb winds were southwest at 7 kn, while at Albany they were south–southwest at 50 kn. During the succeeding 12 hours, winds at Nantucket also increased to about 50 kn. Hence, the significant feature of the winds was an increase in speed at all levels during the period covered by the Doppler radar observations.

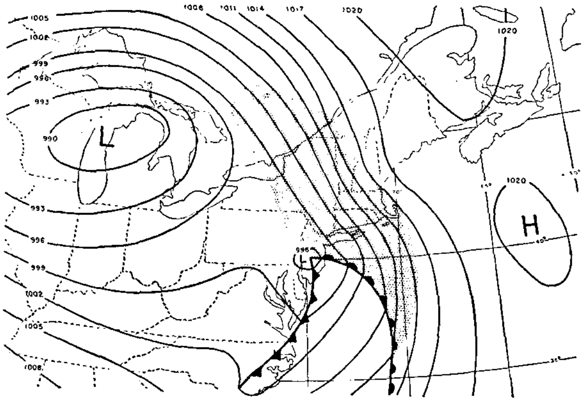

Fig. 1. Synoptic situation at sea level over northeastern U. S. at 1300E, 12 March 1962.

4. Time height cross section

Fig. 2 shows a somewhat simplified time height cross section of Doppler wind speeds and directions taken at height intervals of 150 m, and time intervals of 12 minutes between 0900 and 1600E, 12 March 1962. Above the wind data is shown the concurrent rate of precipitation as determined from a 25.5 inch recording raingage at W. Concord, Mass., about 2.5 miles northeast of the Doppler radar site. The absolute values of wind speed were subject to some uncertainty but the relative wind speeds are considered to be quite accurate. The plotted values were obtained from a calibration of the Doppler radar with a frequency meter. Fig. 3 compares the Hanscom rawin data at 1134E with the Doppler wind observed about 20 minutes before and 20 minutes after 1134E. The agreement is remarkably good. Any differences between the data can be attributed to the 9 nm distance between the radar locations at Sudbury, Mass., and Hanscom Field.

The increasing winds during the period are clearly shown in Fig. 2; wind speeds at the end of the period are about double those at the beginning at all levels. It is to be noted also that there is considerable vertical wind shear aloft at the beginning of the period, but very little towards the end; near the ground the reverse is true.

A persistent feature of Fig. 2 is a wind speed maximum of 31 to 38 m sec^{-1} and a wind speed minimum, 8 to 10 m sec^{-1} lower, located 600 to 1000 m below the maximum. At 0900–1000E the maximum is located at 4.2 km, gradually sinking to 3.8 km at 1100E and then lowering to 3.3 km where it appears to lose its identity after 1400E.

The most intriguing phenomena revealed by the analysis are the repeated breakdowns in the zone of vertical wind shear between the maximum and the minimum. The first breakdown occurs at about 1130E and is marked by a sudden increase in wind speed from the top of the sounding down to the 2-km level—an interval of some 2.5 km. The maximum wind speed increment is greater than 6 m sec^{-1} at the 3-km level which was the level of minimum wind 12 minutes earlier. Another particularly striking feature evident in the next sounding, 12 minutes later, is a sharp decrease in wind speed at all levels, the greatest change again being observed at the 3-km level where the speed decreases as much as 11 m sec^{-1} from the maximum. This decrease at all levels is difficult to understand and does not appear in later breakdowns. However this condition is short lived and during the next three

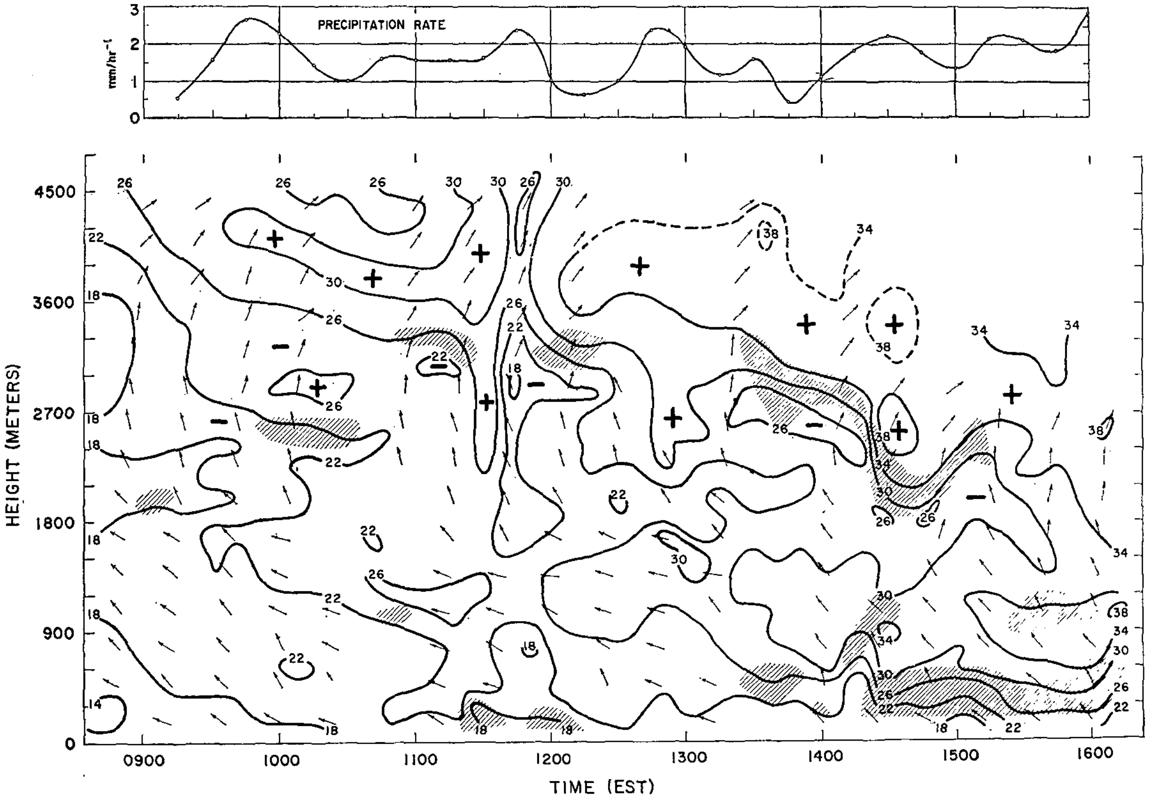

FIG. 2. Time-height cross section of Doppler wind, 12 March 1962. Isotachs at 4 m sec^{-1} intervals, arrows represent wind direction. "+" indicates wind speed maximum, "−" wind minimum. Hatched areas correspond to region of $R_i < 1$.

soundings, a period of 36 minutes, conditions existing prior to the breakdown are quickly restored, with a strong shear zone again appearing but at a somewhat lower level. About one hour after the first breakdown a second one occurs, quite similar in most respects to the first, except for a duration of about forty minutes (representing a horizontal distance of perhaps 40 km). This second episode consists of an apparent downward intrusion of high speed wind for a depth of 1.2 km, to about the 2.2 km level, the maximum wind incre-

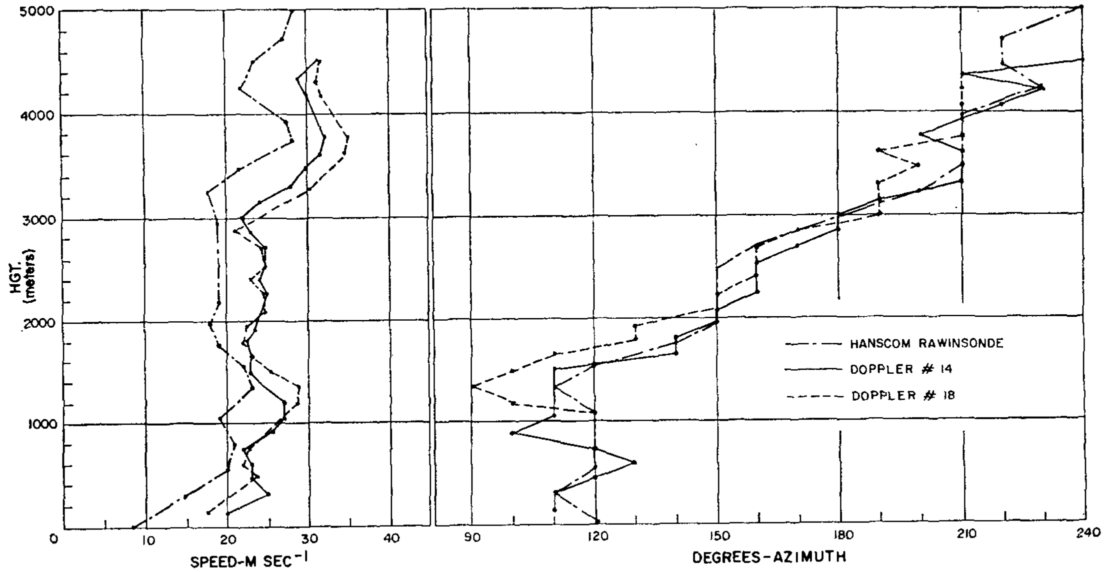

FIG. 3. A comparison of the Hanscom rawin observation released at 1134E 12 March, with individual Doppler wind soundings 14 and 18 observed 20 minutes earlier and 20 minutes later.

ment being about 9 m sec^{-1} near the 2.9 km level. Forty-five minutes after the beginning of the breakdown, the previous conditions of shear are again restored for the next 72 minutes. The first two breakdowns are accompanied by a gradual lowering of the shear zone by about 900 m.

The third and final breakdown evident in the record occurs at about 1415E, or one and a quarter hours after the second. Like the other two, it is also manifested by a sudden increase in wind speed. This breakdown penetrates some 900 m and shows the greatest increment of wind speed of all three, as much as 15 m sec^{-1} at 2.4 km, and is followed by the highest wind speed of the cross section, 41.5 m sec^{-1} at 2.5 km. Subsequently, the strong shear which characterized the cross section earlier largely disappears.

During the period of record, the precipitation was continuous but with numerous short period fluctuations, as shown in Fig. 2 in the curve above the Doppler wind section. Although it is not feasible to relate these fluctuations to changes in the wind field, it appears possible that they may be associated with variations in the field of vertical motion as will be discussed in Section 6.

PPI photographs of the Massachusetts Institute of Technology (MIT) CPS-9 radar in Cambridge, Mass., about 18 nm east of the Doppler radar site, are in the form of range corrected isoecho contours. At 0930E, near the beginning of the period (Fig. 4a), a relatively uniform precipitation field is indicated but, near the middle, at 1230E (Fig. 4b) and, at 1530E (Fig. 4c) close to the end of the Doppler record considerable structure is evident, indicating the presence of cells embedded within the overall stratiform precipitation field. The breakdowns depicted in the Doppler wind analysis may be related to this cellular structure.

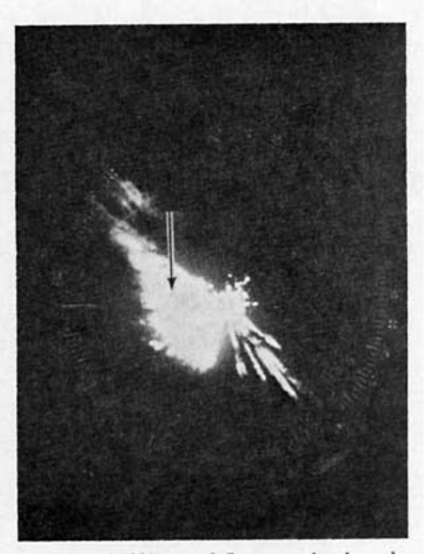

Fig. 4a. 0930E, at 0.5 μsec pulse length.

Fig. 4b. 1230E, at 5.0 μsec pulse length.

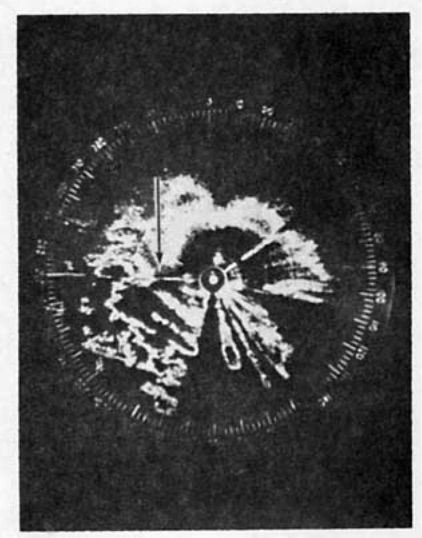

Fig. 4c. 1530E, at 5.0 μsec pulse length.

Fig. 4. PPI displays of range-corrected isoecho contours at 3 hour intervals from MIT CPS-9 60 m range, 10 m range marks 1° antenna elevation. Arrow shows approximate positions of Doppler site.

TABLE 1. Comparison of Doppler derived winds and smoothed radar echo element velocities on 12 March 1962.

Time (EST)		0900	1000	1100	1200	1300	1400	1500	1600
Doppler wind	dir (deg)	145	165	175	185	195	200	205	210
	Speed (m sec^{-1})	15	24	24	22	32	34	36	36
Radar echo	Level of direction agreement (km)	2.1	2.7	2.9	3.0	3.3	3.0	3.0	3.0
	Speed (m sec^{-1})	11	13	15	17	19	20	21	22
Ratio:	$\frac{\text{Echo speed}}{\text{Doppler speed}}$	0.7	0.5	0.6	0.8	0.6	0.6	0.6	0.6

Echo element velocities derived from the MIT PPI data show a gradual veering in the wind direction and an increase in the speed with time during the Doppler sampling. Table 1 compares the Doppler-derived wind with the MIT echo element motion at the level where the directions are the same. The table also shows that the echo element direction corresponds closely with the Doppler wind direction near an elevation of 3 km (or approximately at the 700-mb level), while the ratio of the echo element speeds to the Doppler derived speeds range from 0.5 to 0.8. While these values are subject to some uncertainty, as previously referred to in Section 4, the ratios of echo speed to Doppler speed are less than unity. This signifies that the precipitation cells as observed by the radar are undergoing dissipation on the downwind sides and development on the upwind sides.

5. Richardson number analysis

The hatched areas in the wind speed analysis of Fig. 2 represent regions where the Richardson number is less than one. The Richardson number was computed from the formula

$$R_i = g\left(\frac{\Delta \ln\theta}{\Delta z}\right) \Big/ \left(\frac{\Delta w}{\Delta z}\right)^2, \qquad (6)$$

where θ is the potential temperature and Δw is the change in wind speed occurring over the height interval Δz. Altitude intervals of 300 m were used except for a few critical regions of 150 m intervals. The potential temperature was obtained from the rawinsonde (Fig. 5) released at 1134E from Bedford, Mass., while Δw was taken from the Doppler wind records. The Hanscom sounding is unusually stable for precipitation, especially in the layer between 3.2 and 5.2 km, and may be in error since soundings taken at 0700E and 1900E of the same day at New York, Albany and Nantucket show much steeper lapse rates in this layer. A less stable lapse rate would result in lower R_i values above 3.2 km, and would thereby increase the size of areas of $R_i < 1$, but otherwise would not greatly alter the results.

Examination of rawinsondes for surrounding stations indicates that no significant large scale change in stability below 3.2 km occurred during the period of Doppler wind observations. This does not rule out the possibility of important local short period changes due to breakdowns through the shear zone, as revealed in the Doppler wind cross section. In spite of some doubts regarding the actual lapse rate during the period of Doppler wind soundings, the principal factor in determining R_i is the wind shear, since in computing R_i from Eq. (6) the wind shear term varied by a factor of about 60 while the stability term varied only by a factor of 2.

It is apparent from the cross section (Fig. 2) that each of the three breakdowns is preceded by a region of $R_i < 1$; minimum values were about $R_i = 0.5$. After the last breakdown, a region of $R_i < 1$ persists in a shallow shear zone 1430–1500E. Other regions of $R_i < 1$

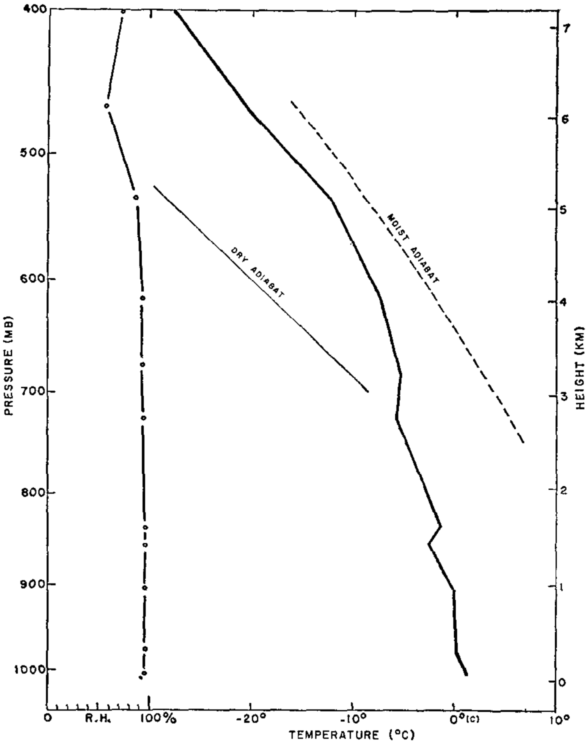

FIG. 5. Temperature and humidity data from Hanscom Field rawinsonde released at 1134E at Bedford, Mass.

are mostly in the 1-km layer above the ground during the last half of the period; these regions may be associated with periodic breakdowns of the lower shear zone, which are indicated by the onset of somewhat stronger and gusty surface winds at Hanscom Field during the period beginning at 1400E. However, these breakdowns are not apparent on the cross section. Another region of $R_i < 1$ is a small shear zone at 2.5 km between 1000 and 1036E, which appears to be unrelated to any observed wind phenomena.

6. Field of vertical velocity

Fig. 6 shows the field of mean vertical velocity (downdrafts positive) from 0900 to 1500E as computed from Eq (5) by assuming $\Delta u = 0$ and $v_f = 1.5$ m sec^{-1}. As seen from Fig. 2, there are several periods of rapidly changing wind: near 0900, 1130 and 1415E, all in the vicinity of 3 km. Hence the values of w near these periods may be subject to error. It is possible, however, to make a first order correction by estimating the value of Δu from Fig. 2. These corrections resulted in lowering the extreme values of the vertical velocities; thus at about 1130, a 4 m sec^{-1} downdraft at 3 km was reduced to 2 m sec^{-1}. However, the overall pattern remained very similar. Hence, although the pattern may be subject to a maximum error of $w = 2$ m sec^{-1}, it is apparent that there are several regions of up and downdrafts in excess of 2 m sec^{-1}. These results may be somewhat surprising, especially when considering the fact that the surface precipitation rates can be accounted for by updrafts of less than 40 cm sec^{-1} above 3 km.

During the period 0900–0925, Fig. 6 shows a region of strong downdrafts between about 2.7 and 4.2 km, with maximum values of 6 m sec^{-1}. These downdrafts coincide with the region of rapidly increasing wind speed, from about 16 to 23 m sec^{-1} within a half hour period (see Fig. 2). Following this period, until about 1130, the winds are fairly steady and are associated with weak up and downdrafts.

The first major breakdown at 1130E is preceded by a downdraft indicated at about 4 m sec^{-1} (corrected, 2 m sec^{-1}). This is followed by a series of vertically oriented up and downdrafts of about 2 m sec^{-1}. The second breakdown at 1300 is also preceded by a downdraft of 2 m sec^{-1} and is followed by an updraft and then a downdraft of about equal magnitude. The final breakdown at 1430 is again preceded by a 2 m sec^{-1} downdraft and is followed by a very turbulent region of up and downdrafts of ±4 m sec^{-1} magnitude. It seems significant that the regions of most prominent cellular structure with alternating up and downdrafts, tend to occur in the ozones of maximum wind shear and $R_i < 1$ in Fig. 2. Since this is the zone in which vertical exchange would ordinarily be expected, it gives us some confidence in the reality of the vertical motion field. However, we must await further observations before attributing great significance to these measurements.

The regions of +4 values indicated near the ground after 1200E are associated with the change of snow to rain so that the assumed 1.5 m sec^{-1} fall speed does not apply in this region.

7. Comparative analysis of hourly rawinsondes

It is of interest to compare the detailed Doppler observations with hourly rawinsondes such as those

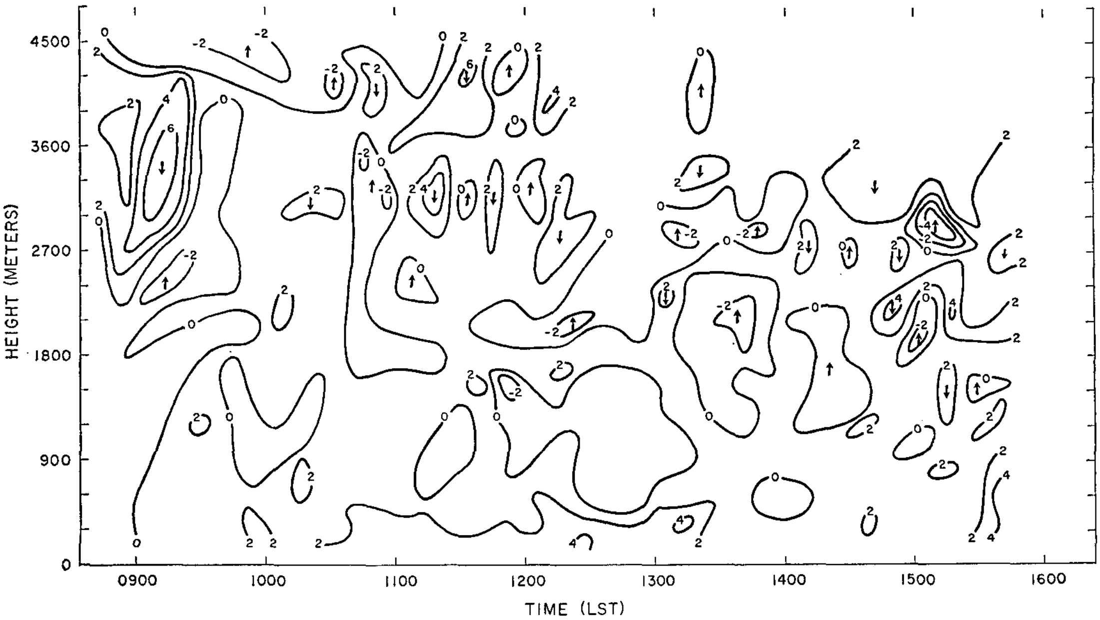

FIG. 6. Field of computed mean vertical velocity (downdrafts positive) assuming $\Delta\mu = 0$ and $v_f = 1.5$ m sec^{-1}.

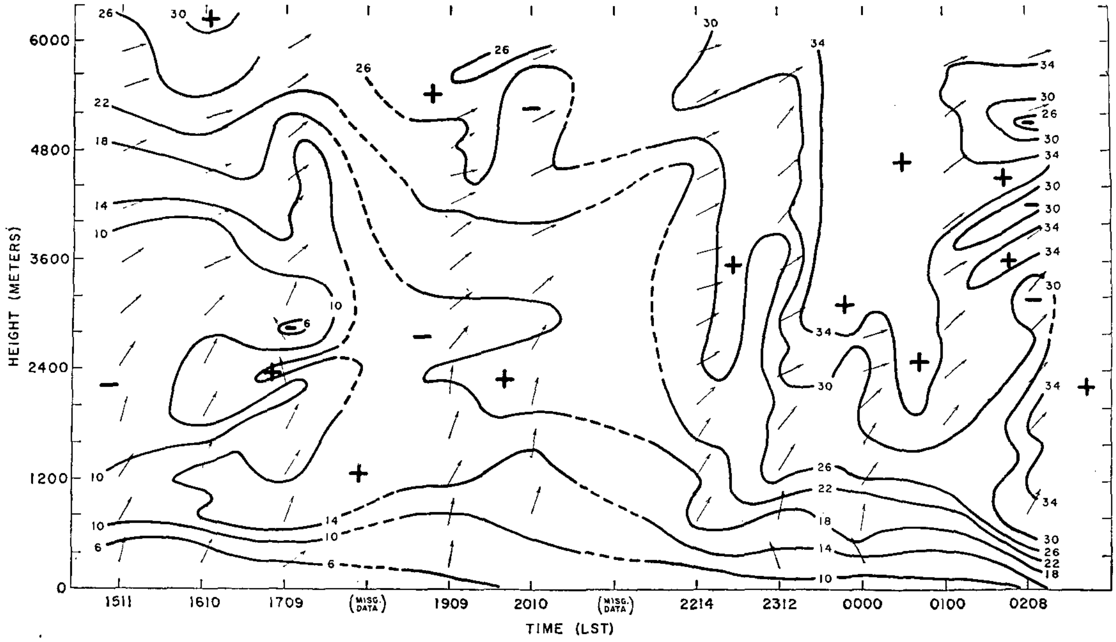

FIG. 7. Time height cross section of winds based on rawin observations at Hanscom Field, Bedford, Mass., taken at approximately hourly intervals, during a rainstorm on 3–4 April 1960. Isotachs at 4 m sec^{-1} intervals. Arrows indicate wind direction. Positive and negative signs indicate wind speed maxima and minima, respectively.

reported by Court and Salmela (1961) for the first week of April 1960. A rainstorm with winds aloft increasing with time occurred on 3–4 April 1960 and is therefore somewhat analogous to the 12 March 1962 case. Fig. 7 is a time cross section of these hourly observations (with some breaks in the data) from 1511E, 3 April to 0208E, 4 April. During the period the southwesterly wind aloft increased in speed by a factor of 2 to 3. For the first 3 hours a region of strong wind shear is evident from an altitude of about 4 to 7 km. By the fifth hour[3] this shear zone has descended to lower levels and wind speeds at 3 to 4 km have more than doubled. At the eighth hour, the entire wind shear zone at upper levels has broken down and wind speeds near 2 km have increased from 15 to 26 m sec^{-1} in a three hour period. In the last portion of the period a zone of very strong wind shear has been created in the lowest kilometer above the surface.

Although Fig. 7 shows the penetration of the upper level strong winds to lower levels, the data lacks the resolution to delineate the smaller scale turbulent areas which, from the Doppler data, were about 20 km in horizontal dimension, or less than a half hour duration on the time-height cross section. Loss of resolution of the rawindsonde data also occurs due to the one minute averaging process, which smooths the fluctuations along the vertical, and to the variable range intervals, which introduce uncertainty as to the relative location. Nevertheless, the wind structure bears remarkable similarity to the general features of the Doppler wind data on 12 March 1962 (Fig. 2).

8. Conclusion

This seven hour record of winds measured by Doppler radar at 12 minute intervals reveals a mesoscale structure never before observed by other techniques. The analysis indicates that the warm front zone, characterized by strong vertical wind shear in advance of an approaching cyclonic storm, descends discontinuously. It is suggested that the descent occurs by a transfer of momentum from upper to lower levels by means of a breakdown of laminar into turbulent flow in this fashion: initially, the upper portion of the precipitation, at 3.5 km to 4.5 km, is characterized by an increase of wind with height. The wind shear evidently builds up to a critical Richardson number (R_i), after which a breakdown occurs and the wind speed at lower levels increases by as much as 10 m sec^{-1} within a half hour period. There are indications that the breakdown is preceded by a downdraft, followed by a succession of updrafts and downdrafts of 2 to 4 m sec^{-1}.

The onset of turbulence in regions of wind shear may have considerable bearing on the change in structure of "uniform" precipitation during an advancing cyclonic condition. The mesoscale motions are evidently responsible for the frequently unsteady or shower-like characteristics of such precipitation.

While the time dimension of the Doppler data sug-

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[3] There are no data for the fourth and seventh hours.

gests a breakdown mechanism, an analysis in three-dimensional space (feasible with CAPPI radar) might well reveal that the "breakdowns" described above were pre-existent convective cells which were simply advected over the Doppler sampling area.

In any case, it is rather surprising to find such mesoscale structure in both the horizontal and vertical winds accompanying supposedly stratiform precipitation. While it has long been known that cellular structures are frequently imbedded in a uniform background of precipitation, the present observations indicate that the wind may also vary strikingly in distances of the order of 5 km. Clearly, the representativeness of a single wind sounding is subject to great doubt in situations of this kind.

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