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MESOSCALE STRUCTURE OF LINE CONVECTION AT SURFACE COLD FRONTS

P K James and K A Browning
Meteorological Office Radar Research Laboratory
Royal Signals and Radar Establishment
Malvern, Worcs

SUMMARY

In this paper we consider 15 cases of line convection at ana-cold fronts which have been observed by radar. Although line convection can be a simple two dimensional feature, it is usually broken up into line elements having lengths from a few to many tens of kilometres separated by somewhat smaller gaps. The passage of a line element is accompanied by a short burst of precipitation, a temperature drop of about $2^{o}C$, a sudden veer and decrease in wind speed, and a pressure jump of 1 to 2 mb. If a gap between line elements passes over a station, however, the changes can occur gradually over a period of up to an hour. Despite the variable size of the line elements, they are found to share common characteristics. They are always oriented slightly clockwise with respect to the synoptic cold front. They all move with the same velocity as their neighbours on a given front, with a component parallel to the front in the direction of the strong low level flow which occurs ahead of the front. Moreover, the line elements tend to travel in a fairly predictable manner, largely unaffected by topography and with the major features having lifetimes of several hours.

1 INTRODUCTION

In recent radar studies of cold fronts over the British Isles (Browning and Pardoe (1973); Browning, Pardoe and Hill (1975)) the frontal structure has been described by means of vertical sections normal to the surface front. It was considered that at the resolutions involved, approximately 50 km or 1 hour, variations in the flow along the length of the front and with time were less significant than those normal to the front. Indeed, an earlier detailed study using Doppler radar (Browning and Harrold (1970)) had revealed no great departures from two-dimensionality over a 24 km length of a particular cold front. Nevertheless significant variations in structure usually do exist in the direction parallel to the front and the purpose of this short paper is to examine these variations on scales from several kilometres to more than 100 km. The fronts considered here all displayed line convection as defined by Browning and Harrold (1970). Such line convection in association with surface cold fronts has been observed by radar on numerous occasions over the British Isles and also over the Western seaboard of the United States (Houze et al (1976)).

2 NATURE OF THE DATA

The primary source of data for this study are the films of the PPI radar displays obtained by the Meteorological Office Radar Research Laboratory during project periods in each of the winters from 1969 to 1976. Also included are cases of line convection observed by the London Weather Centre on 1 December 1966 (Handbook of Weather Forecasting (1975)) and by the University of Birmingham weather radar on 1 December 1975 (James et al (1978)). An example of the kind of data used is given in Fig 1. This shows the PPI display of a radar sited at Castlemartin, Dyfed, on 26 January 1974. The line convection is represented by the broken white line running NE-SW to the NW of the radar site. The line convection is observed by virtue of the radar return from the precipitation grown within the vigorous updraught at the surface cold front.

Out of a sample of 35 cold fronts for which we have detailed radar data, 13 cases (37%) were found to display line convection. The synoptic situation for each of these cases and the two additional cases mentioned above is shown in Fig 2. All 15 cases were found to be associated with ana-cold fronts as defined by Sansom (1951). Six of the cases (labelled a to f) were analysed in more detail because of the availability of hourly radiosonde ascents during the passage of the front. The characteristics of these fronts broadly fit the model of Browning and Pardoe (1973) (see also James et al (1978) for a 3-dimensional representation). The detailed characteristics of the six fronts, as summarised in Table 1, will be referred to later in the paper.

3 HORIZONTAL STRUCTURE OF LINE CONVECTION AS SEEN BY RADAR

Fig 3 shows tracings of echoes from the line convection at a single time for each of the 15 days. The line convection gave rise to the most intense precipitation observed in each case and, in order to simplify the diagrams, weaker echoes from other precipitation have been omitted. The line convection was always found to be arranged along the line that an analyst would call the surface cold front. However, it is apparent from Fig 3 that line convection was rarely a simple linear feature and that it was usually broken up into line elements.

Front (a) as depicted in Fig 3 is the case analysed by Browning and Pardoe (1973) and Browning et al (1975). It evidently represents an extreme type of line convection in that it is very uniform along a portion more than 200 km long. It shows very little evidence of elemental structure although the line convection did contain pockets of slightly higher echo intensity which could be followed for some time. The other fronts were all observed to have marked elemental structure. The elements vary in length from a few kilometres to more than 100 km. The gaps between the elements also vary widely in length, usually in the range from a few kilometres to a few tens of kilometres, but on one occasion (12 February 1973) being as great as 95 km. Fig 4 shows the cumulative frequency distributions of the observed lengths of elements and gaps. Data from all 15 days were used but for each day only a single time was considered, generally the time with the best radar cover. The mean length of elements ($\bar{\ell}_e$) was 22 km and the mean length of the gaps ($\bar{\ell}_g$) 9 km.

The lifetimes of the elements were found to be as variable as their size. Elements were found to break up, coalesce, dissolve or reform on time scales from 10 mins to over 4 hours. The most persistent features were found to be the larger ones (> 10 km) - especially the gaps, since the large elements often subdivided. Fig 5 shows the behaviour of the elements in case (c). A solid line is drawn through the elements at each time, the larger gaps appearing as steps in the line. The figure shows that the gaps ij, kℓ and mn persist for at least 3½ hours (the period of data available). It was not possible, however, to compile statistics of the lifetimes of elements because on most of the days data were collected for only short periods and at differing time intervals, and the data were of variable quality owing to differing beam widths and ground return patterns. A larger beam width means that the smaller gaps appear to 'fill in' at longer ranges.

Despite the existence of elements varying in both length and lifetime by an order of magnitude they all displayed some common features. The elements were always oriented slightly clockwise with respect to the synoptic cold front and elements of different sizes on a particular cold front all moved in the same direction, with a component parallel to the front in the direction of the strong flow ahead of the front.

The available observations revealed no thermodynamic or dynamical characteristics other than perhaps its rather slow movement and a greater change of vector wind and temperature across it (Table 1) which clearly distinguished the two dimensional case (a) from the other more typical cases with multiple line elements. Moreover, the element structure of line convection did not appear to bear any obvious relationship to topography. Fig 5, for example, shows that, for case (c) no gross modification of the elemental pattern occurred throughout the 3½ hour period the front took to cross the mountains of S Wales. In a study of orographic rain (Browning et al (1975)), including cases (a) and (b), it was also found that the intensity of the surface rainfall during the passage of the line convection was negligibly influenced by topography. The lack of effects due to topography might seem surprising in view of the fact that line convection is a low-level phenomenon which in every case studied so far has been restricted to the lowest 2 or 3 km (Table 1).

4 SURFACE WEATHER ASSOCIATED WITH ELEMENTS AND GAPS IN THE LINE CONVECTION

In this section one of the cases is analysed to show how surface observations are related to the line convection elements. Fig 6 shows the line element structure at approximately 1-h intervals as cold front (f) crossed southwest Wales. This portion of the front was characterised by multiple line elements separated by gaps. Most of the gaps were small but one (labelled gh) was as large as 70 km (as defined in the inset of Fig 4). Surface autographic records are shown in Fig 7 for the six stations identified in Fig 6. Three of the stations (C, R and P) were affected by line elements; the other three (A, B and M) were affected by the large gap gh. Notable features of Fig 7 are as follows:

i Rainfall

The autographic rainfall charts from Port Talbot (P) and Rhoose (R) each show a short burst of rain of intensity greater than 15 mm h^{-1} corresponding to the passage of a line element overhead. The records from Brawdy (B) and Aberporth (A) show no such burst and are consistent with the large gap gh having passed over them.

ii Wind

The anemograph traces from Cilfynydd (C), Rhoose (R) and Port Talbot (P) show an abrupt wind veer, about 60° in less than 5 minutes, and a rapid decrease in speed. The remainder show a slow veer, and the wind speed dropping over a period of nearly an hour. Comparison of Fig 6 with Fig 7 shows that the very sharp veer and decrease in speed occurred when an element passed over a station and that the slower veer and decrease in speed occurred where a gap passed over a station.

iii Pressure

The barograph records show that stations over which elements passed experienced an abrupt pressure jump of about 1 mb. The corresponding temperature drop at the surface was 1 to 2°C but above 700 mb the passage of the surface cold front was not accompanied by any significant changes in temperature. A radiosonde ascent at Castlemartin (near M in

Fig 6) released 25 mins before the passage of the front, gave a 1000-700 mb thickness of 2861 m and another released 25 mins after the passage of the front, gave 2850 m. The change of -11 m corresponds to a surface pressure change of +1.3 mb which is rather larger than the value of +0.8 mb actually observed to occur abruptly during the passage of the line elements at Castlemartin. The difference is partly attributable to the slow synoptic-scale fall in pressure occurring during the period. Table 1 lists, for all of the six days studied in detail, the largest observed pressure kick within 100 km of the radiosonde site together with the change in pressure attributable to the change in 1000-700 mb thickness calculated using ascents normally one hour apart.

Some of the above findings are summarised in Fig 8, which shows schematically the nature of the transition zone associated with a sharp cold front. If an element passes overhead then all changes occur abruptly within 5 min. Boundary layer convergence produces a narrow band of intense updraft and a burst of heavy precipitation. However, if a gap passes overhead these changes can take up to an hour. In this case, the convergence is diffused over a larger area and nothing more than light to moderate rain occurs.

5 APPLICATION TO FORECASTING

The value of radar in providing forecasts of precipitation for very short periods ahead will depend upon the recognition of well defined patterns in the precipitation and the extrapolation of their movement based upon their recent motion. Successful extrapolation in turn depends on the persistence of the features observed. The present study has shown that the line convection is certainly a well defined phenomenon and that the larger features move in a fairly predictable manner, being largely unaffected by topography. The predictability of line element motion was tested quantitatively on the five days with the best radar data. The data on each of these days were divided into two equal time intervals and the direction of motion of the elements in the first period was used to forecast the movement of the elements which were observed at the end of that period. The predictability was evaluated in terms of the ability to forecast correctly whether a given location would be affected by the passage of a line element or a gap. The results are shown in Fig 9. On average the percentage success fell to 65% after about 1 h. The errors for such short forecast times were mainly attributable to changes in the size or direction of motion of the smaller features; the motion of the large features, especially the gaps, was well predicted.

The association of line convection with sharp surface cold fronts means that the location of such fronts can be identified precisely by radar in areas that are otherwise data-sparse, for instance over the sea and in some hilly regions. Knowledge of the exact location of the surface cold front is particularly important in hilly regions because the front demarcates zones of greatly differing orographic rainfall enhancement (Browning, Pardoe and Hill (1975)). Sometimes, also, the observation of line convection enables the identification of waves on cold fronts which especially over the sea can escape identification and upset the forecast time of arrival of the cold front. Even over the land, the availability of a radar display of line convection can be valuable in ascertaining the precise position of a waving cold front. A case in point was the cold front of 1 December 1975 (depicted in Fig 2).

The presence of large 'steps' in the surface cold front creates some difficulty, even when a frontal passage is imminent, in predicting the precise time of passage of a cold front on the basis of routine surface observations alone. Fig 10 shows the cumulative distribution of the distance of the line convection from the synoptic front, taken to be a smooth line through the midpoint of each element. Also shown is the cumulative distribution of the corresponding error in time of passage of the fronts attributable to this cause. The figure shows that the time error is in fact generally less than 10 min; however, in about 1% of cases it can exceed 20 min and, for case f in Fig 6, the step corresponds to a time step of nearly 1 h, which is equivalent to a time error of $\frac{1}{2}$ h (ie $\frac{1}{2}$ h either side of a smooth line drawn through the elements. The identification and tracking of such steps by radar can reduce this source of error to a few minutes.

The strong cyclonic shear associated with line convection, like that encountered along thunderstorm gust fronts, is important to aviators. Table 1 lists the maximum vector wind shear observed as elements passed over anemometers at 10 m on each of the days. Also given is the effective width of the line convection found by multiplying the speed of the front by the time taken for the wind to change (this effective width and the shear are subject to large errors owing to difficulty in resolving short times on the anemograph traces). Detailed Doppler data obtained on 3 October 1967 (Browning and Harrold (1970)) indicate that the shear across line convection at a height of 500 m can be a factor of two greater than the value at 10 m. Thus it is thought that it is not uncommon for mean horizontal shears as great as

$10^{-2} sec^{-1}$ (ie a vector change of $25ms^{-1}$ over 1.5 km) to occur across the elements of line convection. Such large shears present a hazard to aircraft landing or taking off when their airspeed is only a few tens of knots above their stall speed. The recognition of line convection on radar screens will enable this particular hazard to be anticipated. Since some essentially sharp cold fronts evidently have gaps in them tens of kilometres in extent which are devoid of sharp frontal characteristics, it is possible for observations from a small sample of surface stations to give a misleading impression of the type of front. The availability of radar data showing the location of the line elements and gaps will help the analyst reconcile any such apparently contradictory surface observations.

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TABLE 1: CHARACTERISTICS OF SIX COLD FRONTS AS THEY PASSED THE HOURLY RADIOSONDE SITE

CASE	(a)	(b)	(c)	(d)	(e)	(f)
DATE	11 Nov 1970	9 Nov 1972	27 Nov 1972	6 Dec 1972	26 Jan 1974	19 Jan 1975
SITE	Isles of Scilly	Defford, Worcs	Defford, Worcs	Defford, Worcs	Castlemartin, Dyfed	Castlemartin, Dyfed
Velocity of front normal to its length (ms^{-1})	5.3	7.8	11.1	18.6	10.8	10.3
Component of velocity of line elements parallel to front (ms^{-1})	6.1	8.4	10.7	24.7	17.3	15.3
Maximum wind speed within low-level jet just ahead of front (ms^{-1})	27 $\pm$ 2	31 $\pm$ 2	26 $\pm$ 2	26 $\pm$ 2	35 $\pm$ 2	34 $\pm$ 2
Decrease in wind speed immediately above low level jet maximum (ms^{-1})	9 $\pm$ 3	7 $\pm$ 3	9 $\pm$ 3	>2	8 $\pm$ 3	10 $\pm$ 3
Height of low-level jet maximum (m)	800 $\pm$ 200	1000 $\pm$ 200	1000 $\pm$ 200	1600 $\pm$ 200	800 $\pm$ 200	600 $\pm$ 200
Wind speed at a height of 1 km behind the front (ms^{-1})	-	9 $\pm$ 2	6 $\pm$ 2	16 $\pm$ 2	9 $\pm$ 2	9 $\pm$ 2
Maximum observed wind shear across an element at 10 m height, $(10^{-2}.s^{-1})$	1.2 $\pm$ 0.4	0.6 $\pm$ 0.2	0.8 $\pm$ 0.4	0.3 $\pm$ 0.1	0.6 $\pm$ 0.3	0.4 $\pm$ 0.1
corresponding vector wind change, (ms^{-1})	19	14	15	13	12	12
and effective width of line convection (km)	1.6 $\pm$ 0.5	2.3 $\pm$ 0.7	2.0 $\pm$ 1.0	4.5 $\pm$ 1.7	1.9 $\pm$ 0.9	3.1 $\pm$ 0.9
Highest θ_w in low-level jet just ahead of surface cold front (°C)	12.5	11.0	6.6	8.7	9.5	8.8
Lowest θ_w in cold air within 50 km of surface cold front (°C)	6.4	6.2	3.8	5.6	6.4	5.5
Change in 1000-700 mb thickness across front, within $\pm$ 50 km of surface cold front (m)	-23	-15	-18	-20	-12	-11
Change in surface pressure across front corresponding to observed change in 1000-700 mb thickness (mb)	+2.8	+1.8	+2.2	+2.4	+1.4	+1.3
Largest observed pressure kick within 100 km of radiosonde site (mb)	+1.2 $\pm$ 0.2	+1.9 $\pm$ 0.2	+0.8 $\pm$ 0.2	+1.7 $\pm$ 0.2	+1.6 $\pm$ 0.2	+0.8 $\pm$ 0.2
Depth of line convection derived from θ_w analysis (km)	2.5 $\pm$ 0.4	2.8 $\pm$ 0.4	2.5 $\pm$ 0.3	>2.5	>2.8	2.4 $\pm$ 0.5

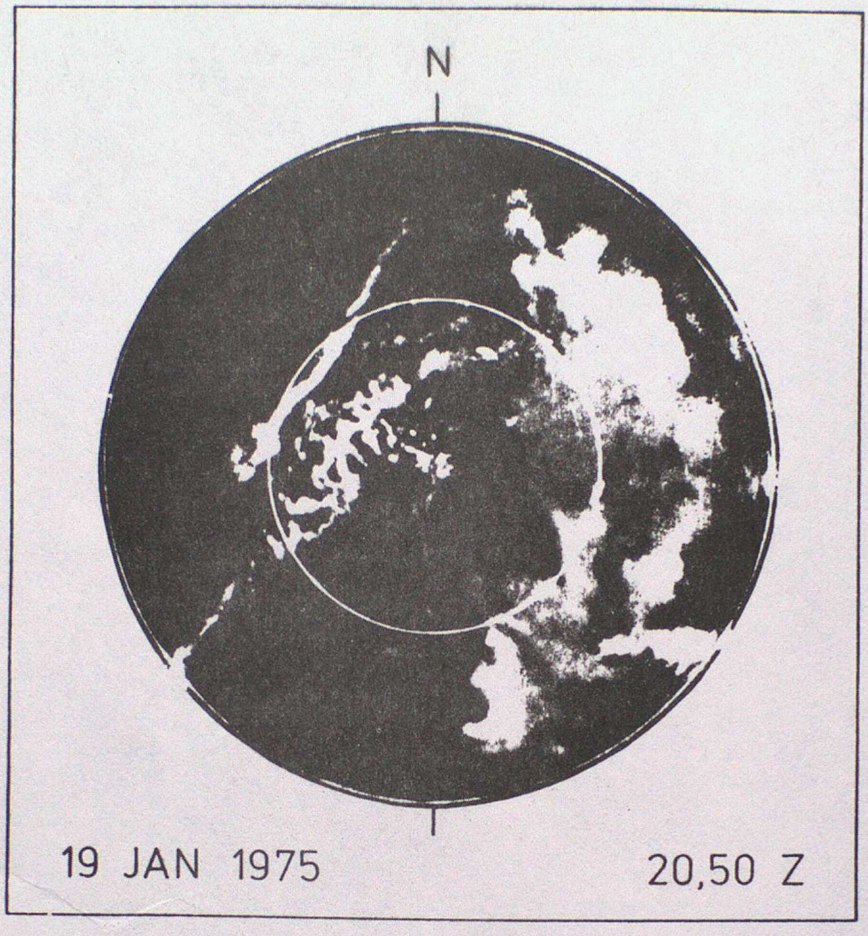

Fig 1 Photograph of the PPI display of a 43S weather radar at Castlemartin, Dyfed at 2050 GMT on 19 January 1975. The range rings are at 50 km and 100 km respectively. The grey echo is equivalent to a rainfall rate greater than about 1 mm h^{-1} and the white echo is equivalent to a rate greater than about 5 mm h^{-1}. The white echo lying SW to NE about 50 km NW of Castlemartin is from the heavy rain associated with line convection. The white echo 80 km to the SE of the radar site is permanent echo from the N coast of Devon. The remaining echo is from irregularly shaped areas of rain in the warm sector.

fig 1

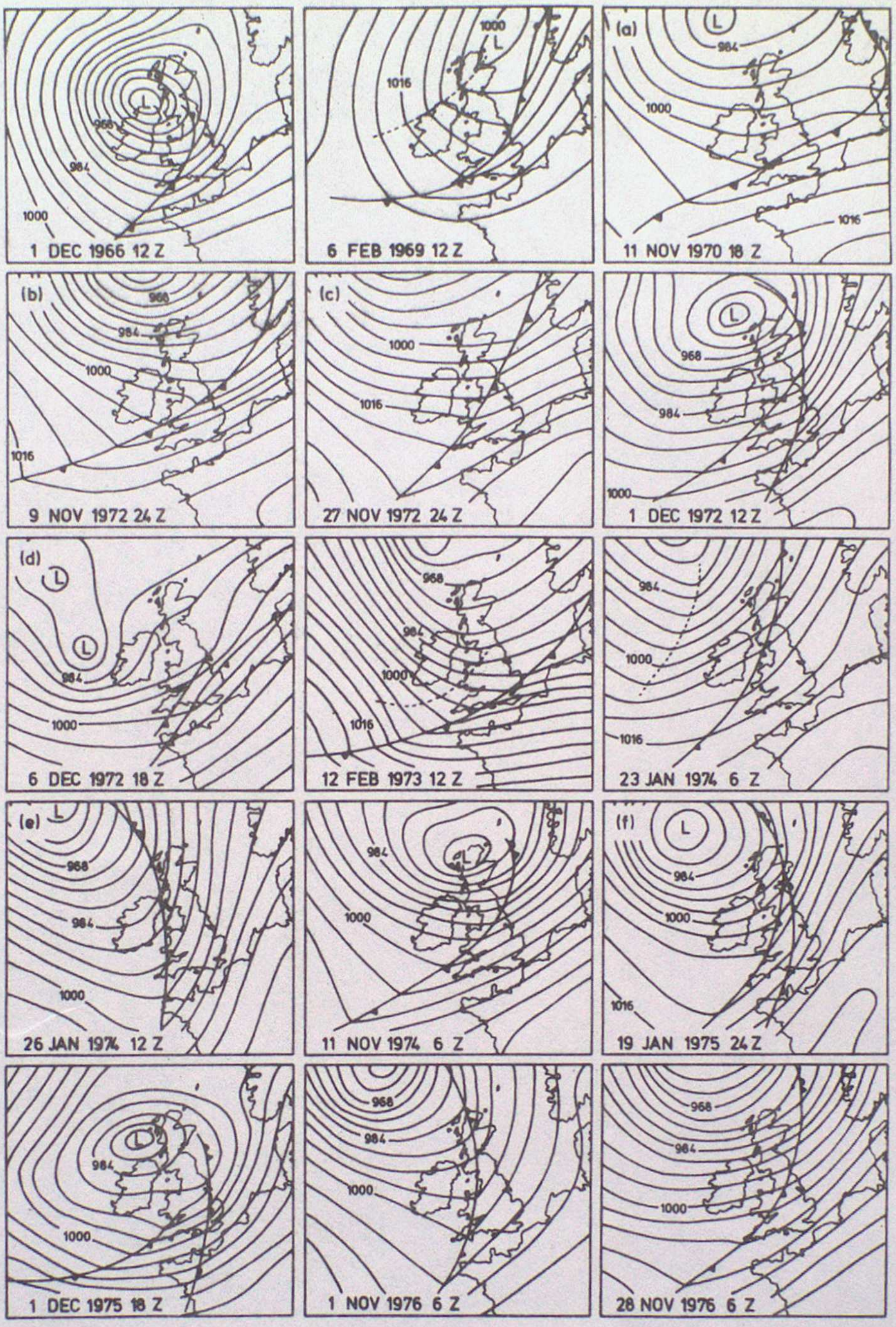

Fig 2 The synoptic situation for 15 days on which line convection was observed by radar. The 6 days listed in Table 1 are labelled (a) through (f).

fig 2

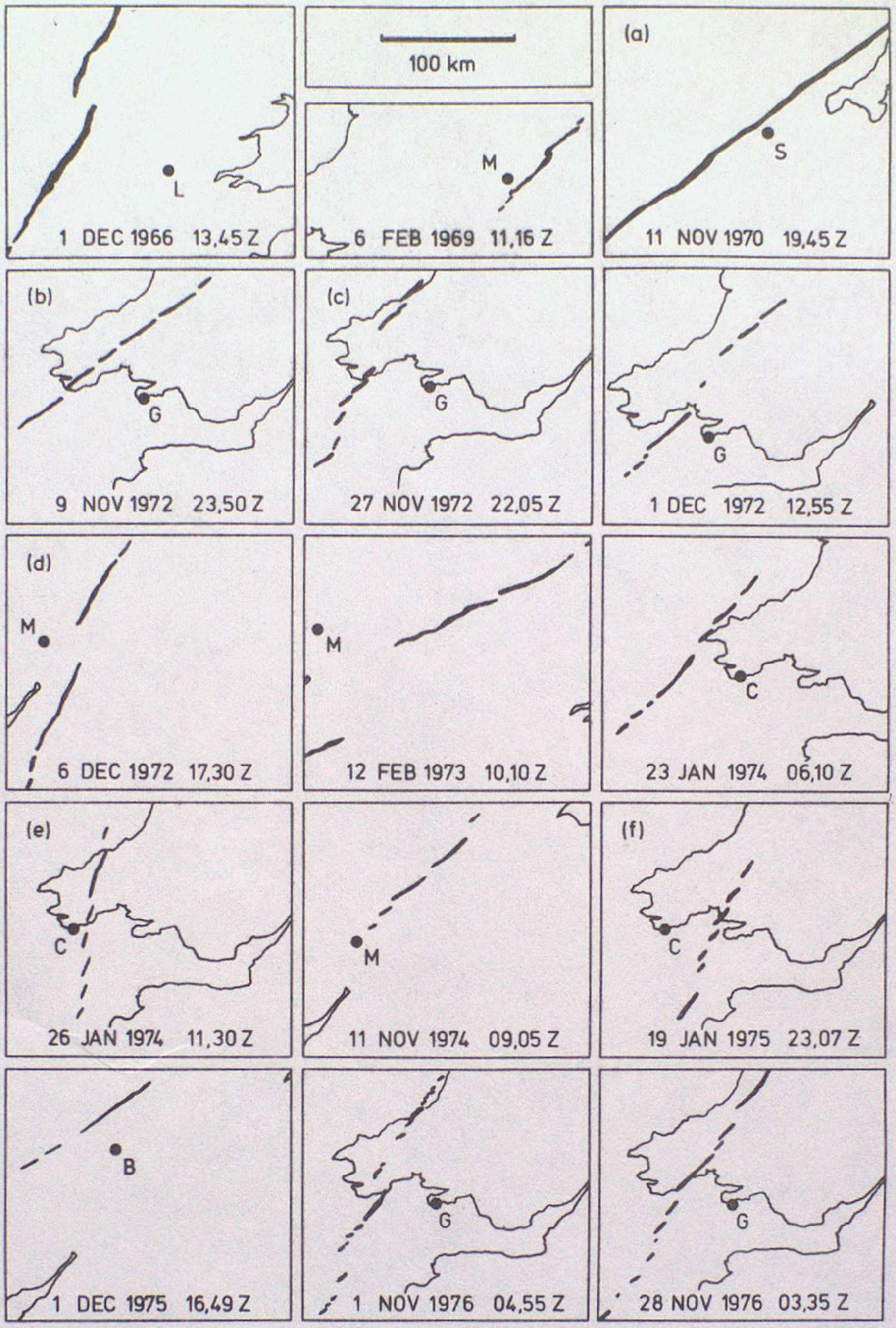

Fig 3 Tracings of echoes from line convection observed on PPI displays on each of the 15 days. Echo from weaker precipitation and from the ground has been omitted. The radars were sited at London (L), Malvern (M), Isles of Scilly (S), Gower (G), Castlemartin (C) and Birmingham (B).

fig 3

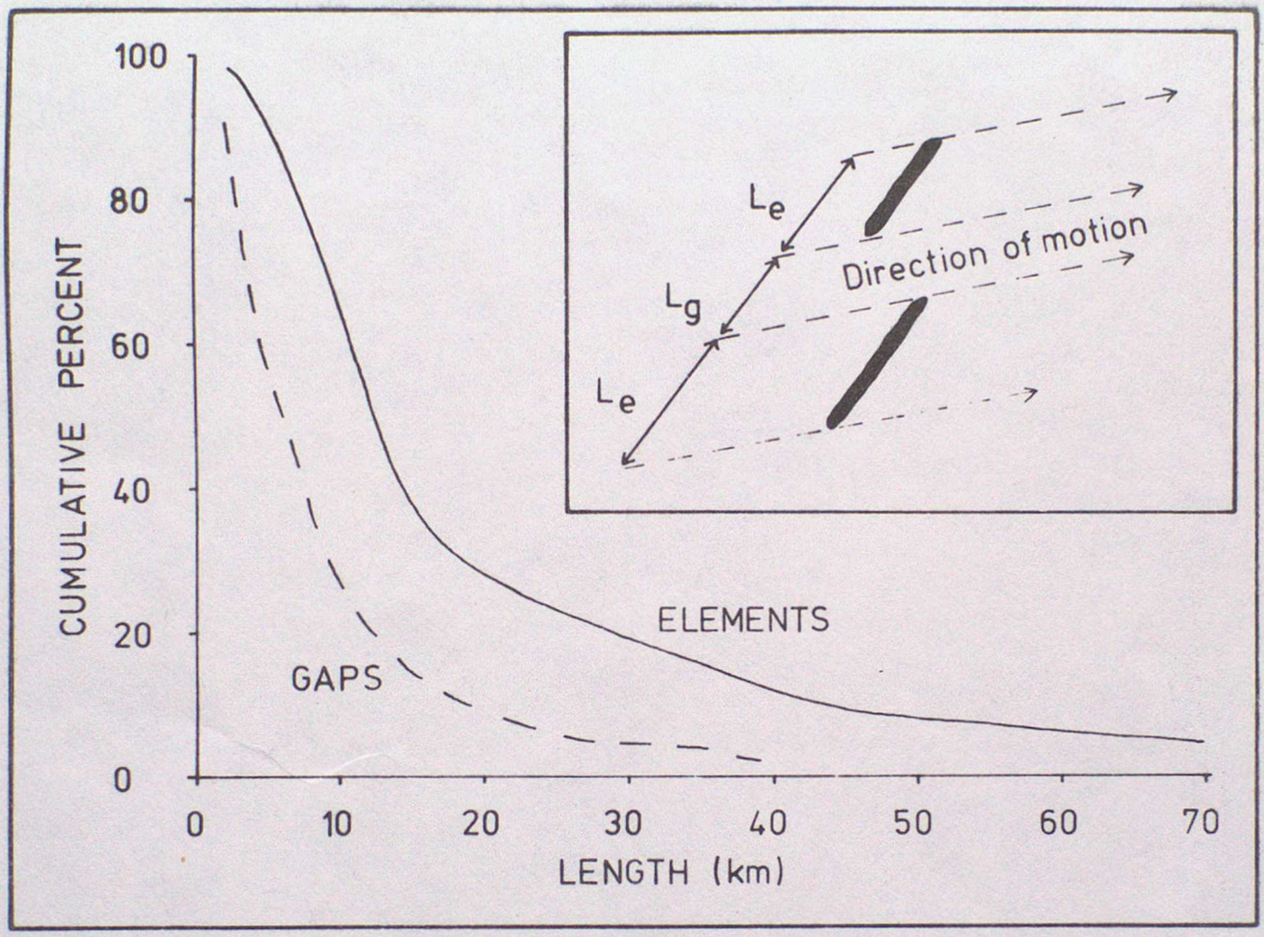

Fig 4 The cumulative frequency distributions of the observed lengths of line convection elements (full line) and gaps (dashed line). The lengths are defined as shown in the inset. The total length of front that was observed was 3130 km, 71% being element, 29% gap. The mean length ($\bar{\ell}_e$) of an element was 22 km and the most probable length 11 km; the corresponding figures for gaps were 9 km and less than 5 km.

fig 4

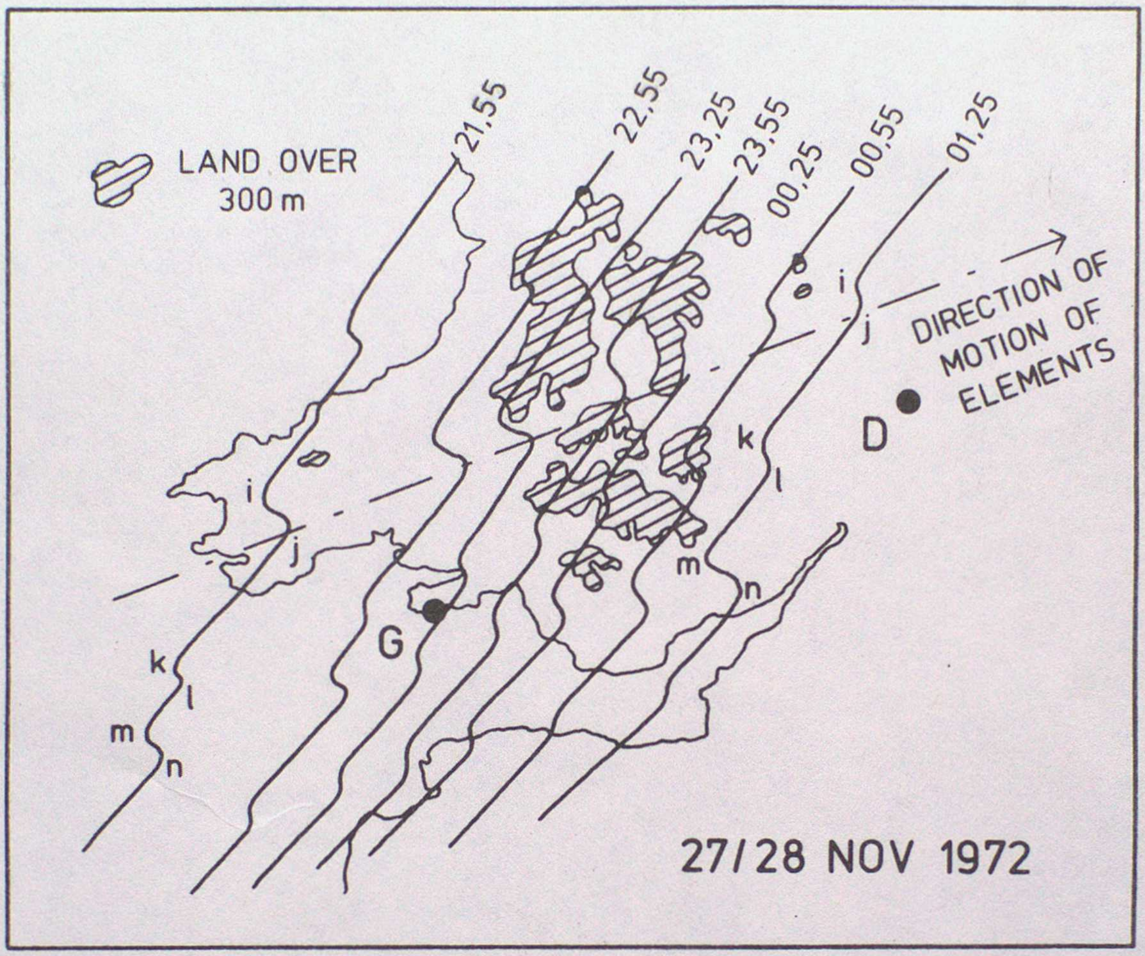

Fig 5 The detailed shape of the surface cold front observed on 27/28 November 1972 (Case (c)). A solid line is drawn through line convection elements observed at each of a sequence of 7 times. Large gaps appear as steps in the solid line. The line convection was observed by radars situated on the Gower (G) and at Defford, Worcs (D). At 0025 GMT the northern portion of the front was obscured by ground returns.

fig 5

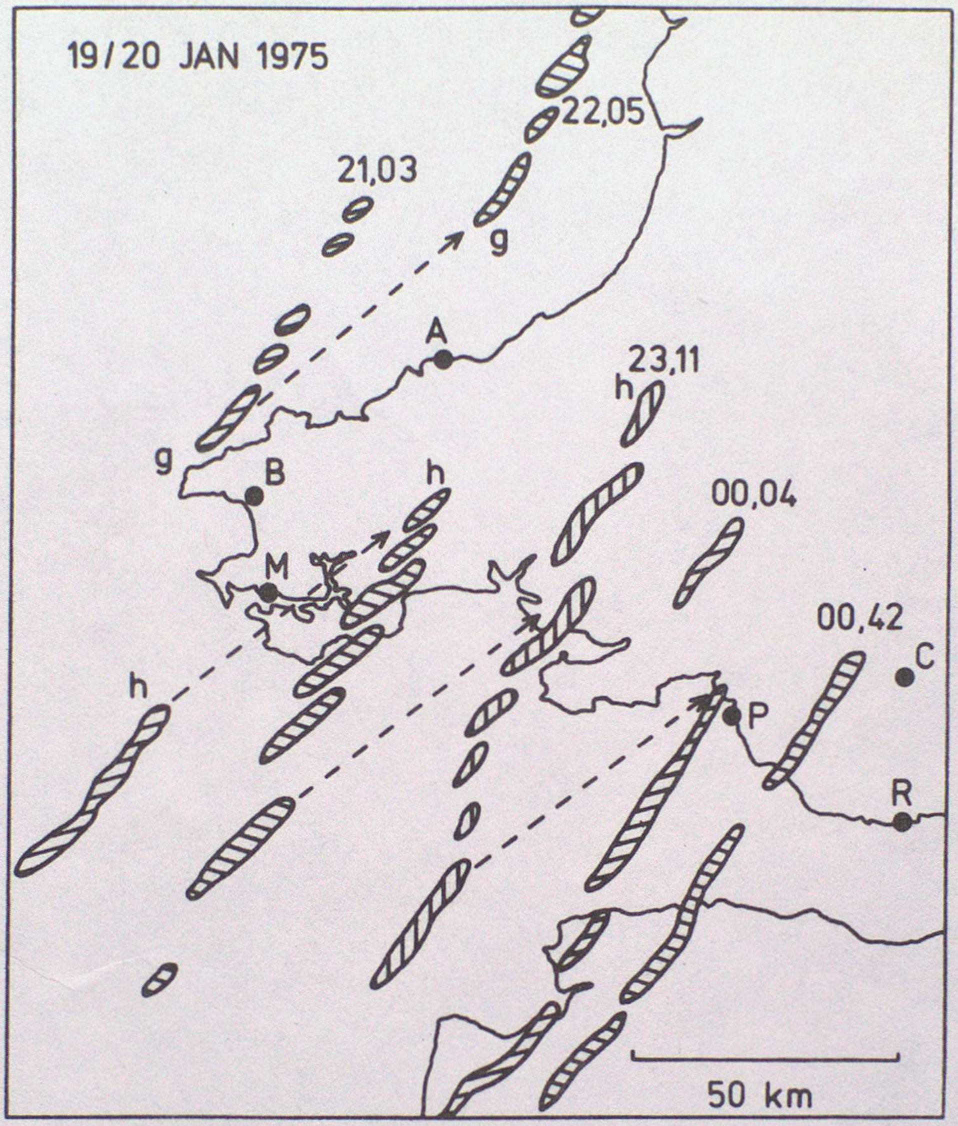

Fig 6 Tracings of the line convection echoes at a number of times on 19 January 1975 (Case (f)). Different shadings are associated with different times. The dashed lines indicate the direction of motion of the elements. A large gap between the elements is identified by gh. The lettered dots indicate stations whose autographic records are display in Fig 7: A is Aberporth, B Brawdy, M Milford Haven, P Port Talbot, C Cilfynydd and R Rhoose.

fig 6

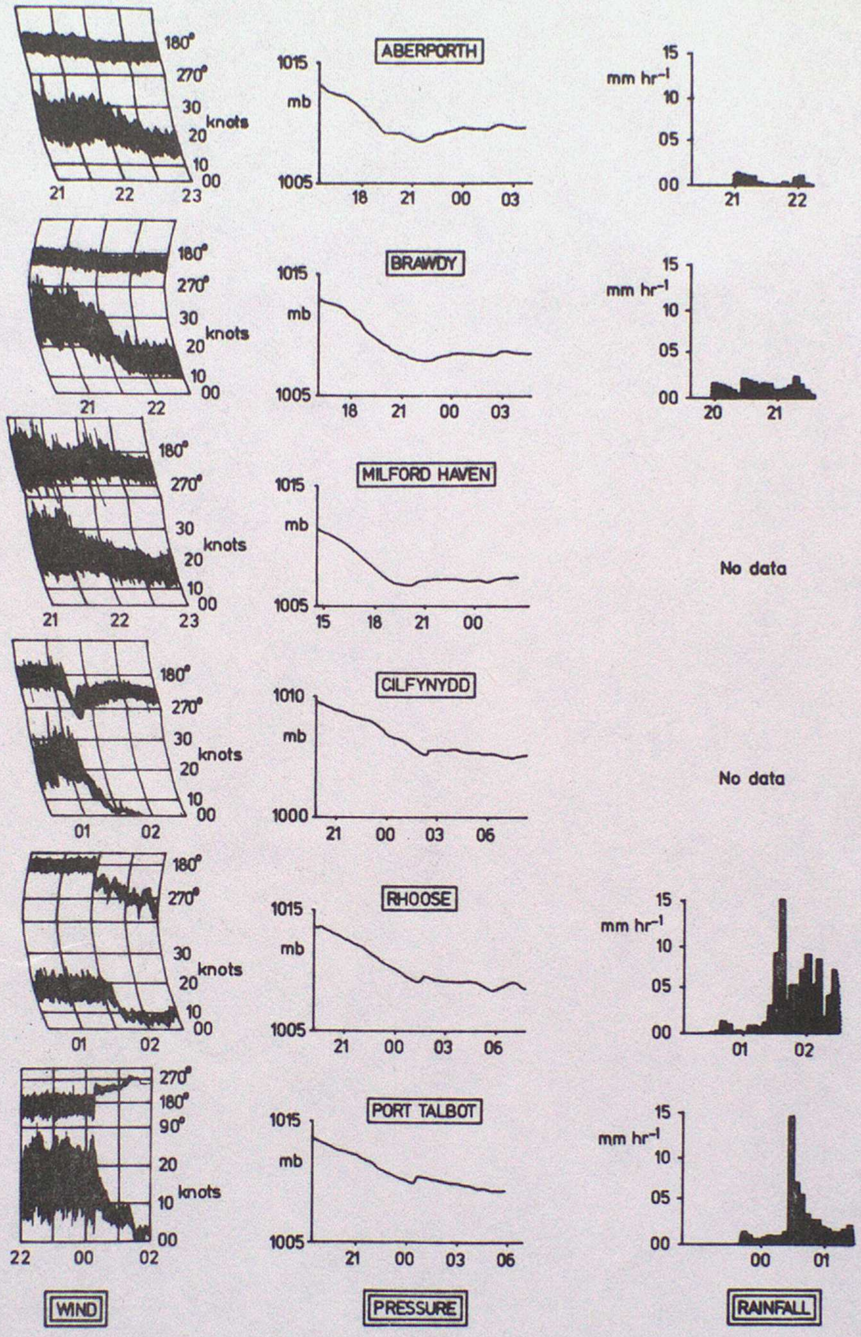

Fig 7 Autographic records of wind, pressure and rainfall on 19 January 1975 for stations indicated by letters in Fig 6.

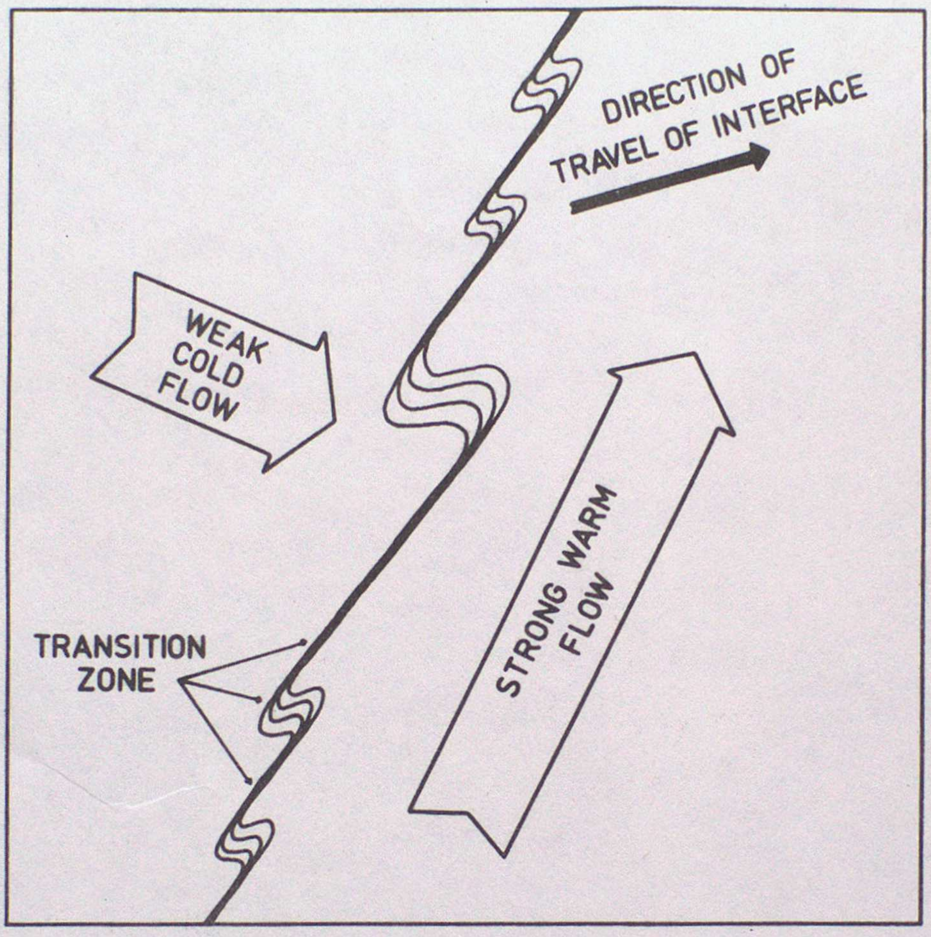

Fig 8 Schematic model of the transition zone at a sharp surface cold front. Line elements with strong updraughts and heavy precipitation occur in the regions with a narrow transition zone. The broad arrows representing the cold and warm flows on either side of the interface are drawn relative to the ground.

fig 8

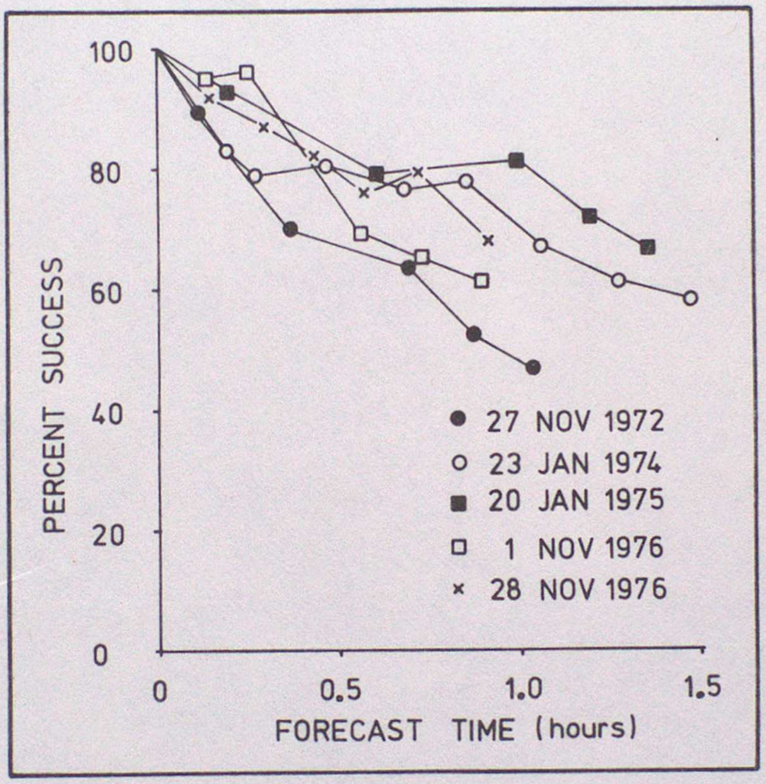

Fig 9 The percentage success of forecasts of the passage of line elements as a function of time for 5 of the days. A success is defined as the correct prediction of either an element or a gap passing over a given location. For more details see text.

fig 9

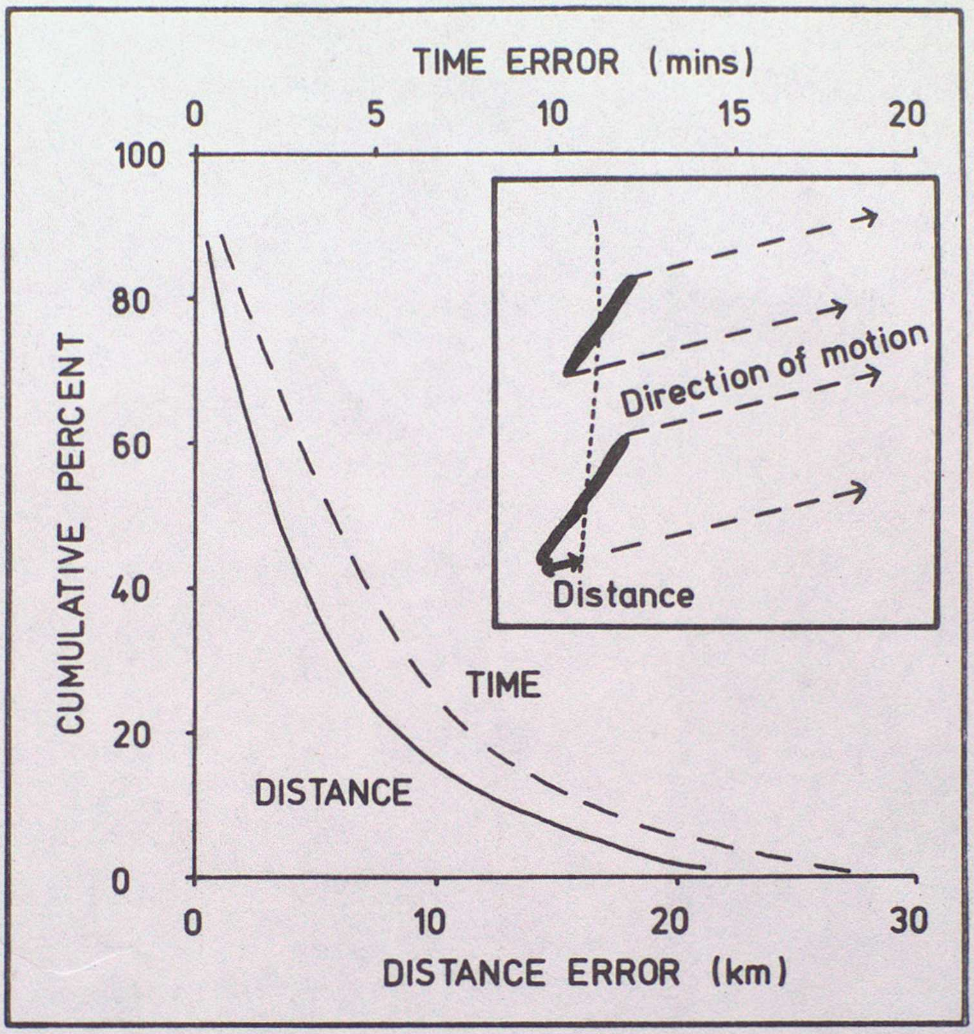

Fig 10 The cumulative frequency distributions of the observed distance of the line elements from the synoptic front (defined as a smooth line drawn through the elements) and of the equivalent departure in time. The departure in distance is defined as shown in the inset and the departure in time is found by dividing this distance by the speed of the elements.

fig 10

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