METEOROLOGICAL OFFICE
London Road, Bracknell, Berks.

MET.O.15 INTERNAL REPORT

No. 73

THE DEVELOPMENT OF INSTANT OCCLUSIONS IN THE NORTH ATLANTIC

J B McGinnigle

Principal Forecast Office
HQ Strike Command

M V Young
M J Bader

Meteorological Office, Bracknell

March 1988

Cloud Physics Branch (Met.O.15)

THE DEVELOPMENT OF INSTANT OCCLUSIONS IN THE NORTH ATLANTIC

J B McGinnigle

Principal Forecast Office
HQ Strike Command

M V Young
M J Bader

Meteorological Office, Bracknell

March 1988

SUMMARY

The evolution of the traditionally interpreted 'instant occlusion' is explained using satellite and radar imagery, synoptic observations and numerical model diagnostics. An alternative analysis scheme is proposed for the cases studied in this paper. The main physical processes are described in the form of simple airflow models. Finally, forecasting guidelines are presented.

1. INTRODUCTION

In the north Atlantic, it is often necessary to predict the synoptic evolution and resulting weather distribution during interaction between a front and an approaching cold air vortex or polar trough. The two features, both of which are readily identified on satellite infra-red imagery may remain separate or merge. Where merging occurs it is conventional (Anderson et al., 1969, Fig. 1) to place an "instant occlusion" along the cloudband originally associated with the polar vortex since the cloud pattern resembles a classical occlusion, although its evolution and structure differ.

In an attempt to understand the mesoscale structure and development of such a system, Browning and Hill (BH,1985) devised a simple model (Fig. 2) relating the principal cloud features to ascending air flows or conveyor belts. They proposed that the polar trough may be analysed as a cold front if it has a significant temperature discontinuity across it, rather than an occlusion. In the cases studied in this paper, the cloudband of the polar trough is fed by a warm conveyor belt derived from a shallow moist zone behind the band rather than a flow orientated along its axis. The analysis proposed for the cases studied in this paper replaces the traditional "instant occlusion" by a warm front, and the secondary cold front, associated with the polar feature, becomes the more significant cold air boundary. This analysis is consistent with the thermal gradients which develop around the cold air system and describes the synoptic evolution more realistically. It resembles that proposed by Locatelli et al., 1982, (Fig. 3) in that the main frontal system is associated with the cold air vortex. The analysis therefore applies when the cold air vortex possesses significant baroclinicity before interaction with the polar front.

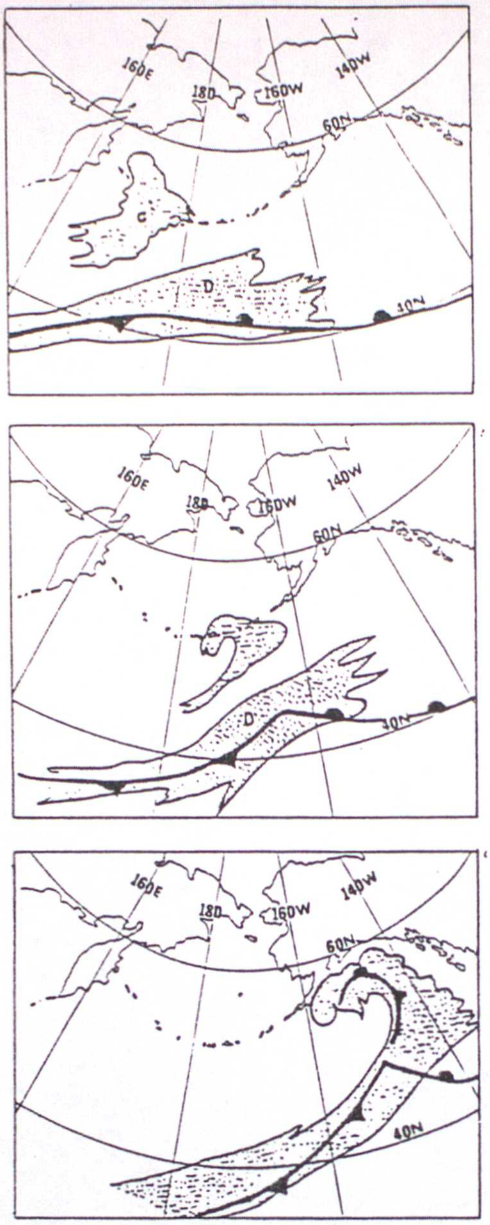
The study is based mainly on the case of 7-10 February 1987 and is supported by evidence from two other similar cases. We seek to

1. Describe the synoptic scale evolution by relating the features on the imagery to the surface and upper air analyses and the main dynamical processes.

2. Describe the sequence of surface weather.

3. Suggest a simple model of the principal airflows during the interaction and merging of the two cloud features.

4. Provide guidelines for the prediction of the development sequence.



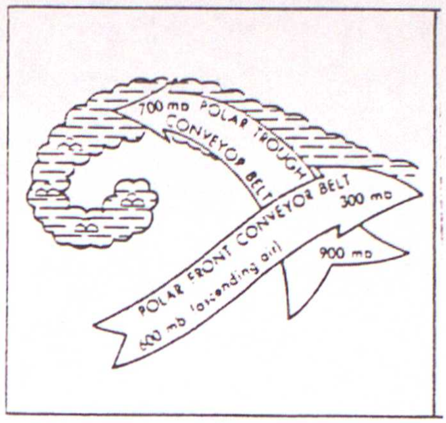


Figure 1 (left)

Evolution of cloud features resembling the instant occlusion as portrayed by Anderson et al. (1969), stippling representing upper cloud areas. Cloud labelled C is associated with the polar vortex, and D with the polar front.

Figure 2 (above)

Airflows giving rise to the instant occlusion relative to the motion of the cloudband associated with the polar trough. (Reproduced from Browning and Hill, 1985)

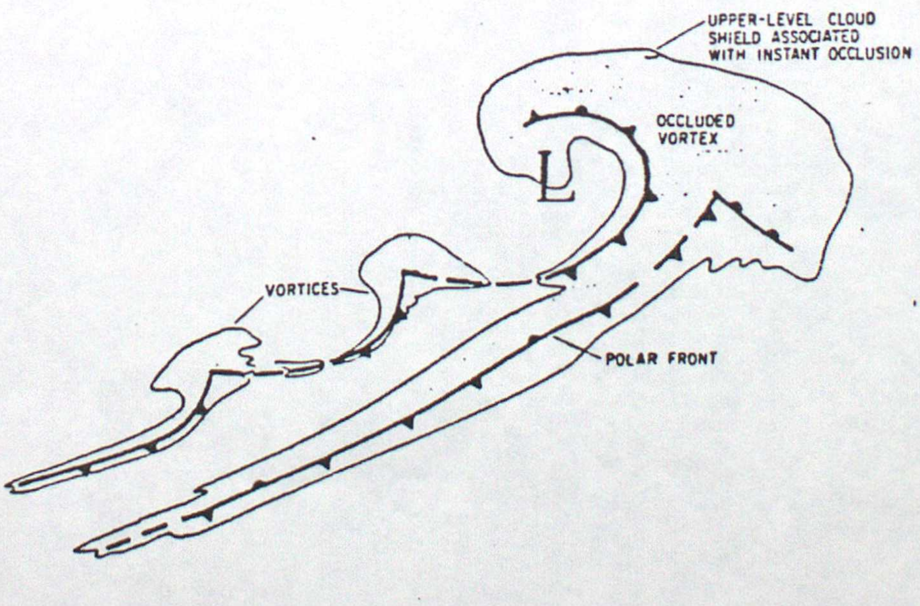


Figure 3

Schematic representation of polar vortex/polar front interaction reproduced from Locatelli et al, 1982.

2. THE SEQUENCE FROM SATELLITE IMAGERY AND SURFACE ANALYSIS

Fig 4 shows the sequence of events between 7th and 10th February, as seen from NOAA satellite imagery. On the 7th (Fig 4a) the significant features prior to interaction were as follows:

(i) A band of layer cloud F, with a sharp edge separating it from the polar air, extended from a mature system seen towards the top of the picture. F was a frontal system (Fig 5a), the cold front of which is referred to in this paper as the **forward cold front**.

(ii) Two areas of enhanced convection A and C were present in the polar air. They were accompanied by surface troughs (Fig 5a), identified from ship reports.

Examination of earlier satellite imagery and synoptic charts revealed that C originated from a front that had moved east over Canada and was analysed over Newfoundland as a weak occlusion. It then became engaged into a western Atlantic upper trough as a weak surface feature retaining some baroclinicity. Thus C inherited a gradient of wet-bulb potential temperature (WBPT) shown in Fig 5a and is therefore analysed as a cold front called the **rearward cold front** in this paper. In contrast, A had much less baroclinicity. A and C resemble the vortices shown in Fig. 3 which are detached from the polar front.

Area A moved quickly northeast (Figs 4a-d) accompanied by its surface trough which eventually came to lie close to the occluded front north of the British Isles where it lost its identity as a separate feature. The criterion that the polar vortex should approach the front to within 350 nautical miles to initiate interaction (Marshall 1982) was found not to be satisfied. In this case an instant occlusion did not form.

By the early morning of the 8th, C had moved northeast, approximately parallel to the northwestern edge of F, and evolved into two distinct clumps C1 and C2 (Fig 4b). The leading clump, C1, contained much layered cloud (with embedded convection) whilst C2 had more broken cloud. An indication of baroclinicity can be inferred from satellite imagery if the cold air feature contains dense layered cloud which can sometimes be leaf-shaped (Weldon, 1979), instead of being a small convective comma, characteristic of a positive vorticity advection (PVA) maximum.

During the morning, new cloud G formed between C1 and F (Fig 4c). By 12GMT, a minor wave had formed on the forward cold front (Fig 5b). A new low of 1011mb had developed at 47N 22W located at the northern end of the rearward cold front. Tightening of the 850mb WBPT gradient north of this new low suggests that warm frontogenesis was taking place. These features are shown in Fig 6 along with the surface observations as verification. By the afternoon, the tops of G had

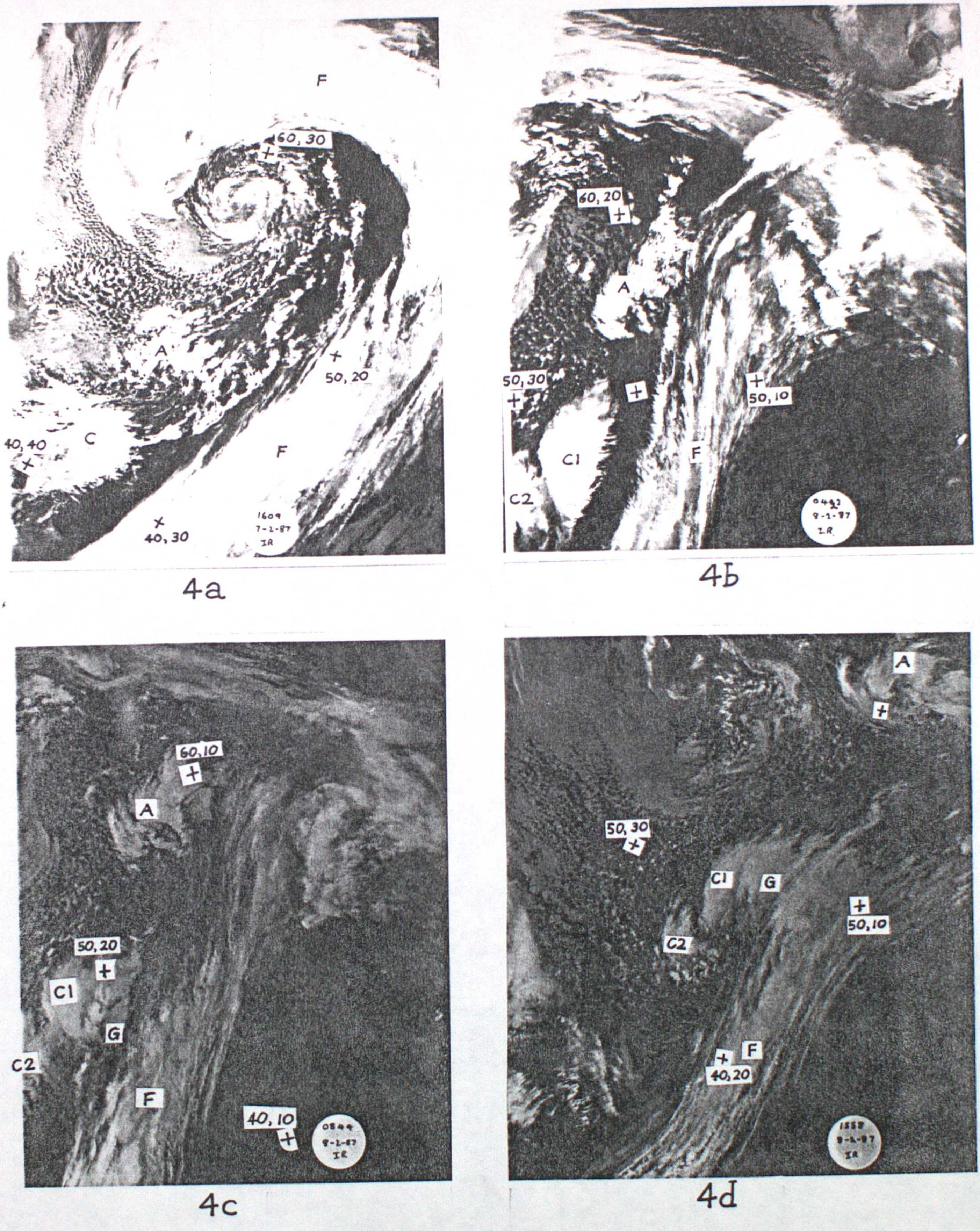
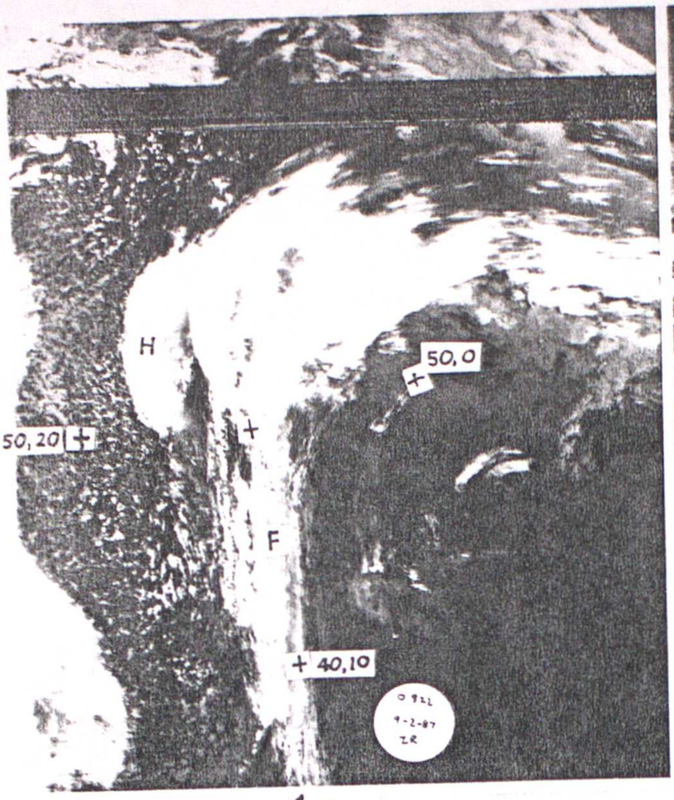


Figure 4

NOAA infra-red imagery for 7-10 February 1987. (a) 1609GMT 7th , (b) 0442GMT 8th, (c) 0844GMT 8th, (d) 1558GMT 8th, (e) 0822GMT 9th, (f) 0800GMT 10th. All times are equator crossing times. Cloud areas A, C, C1, C2, F, G, H are referred to in the text. Selected latitude/longitude intersections are shown by a cross. (Photographs courtesy of University of Dundee Electronics Laboratory)



4e

4f

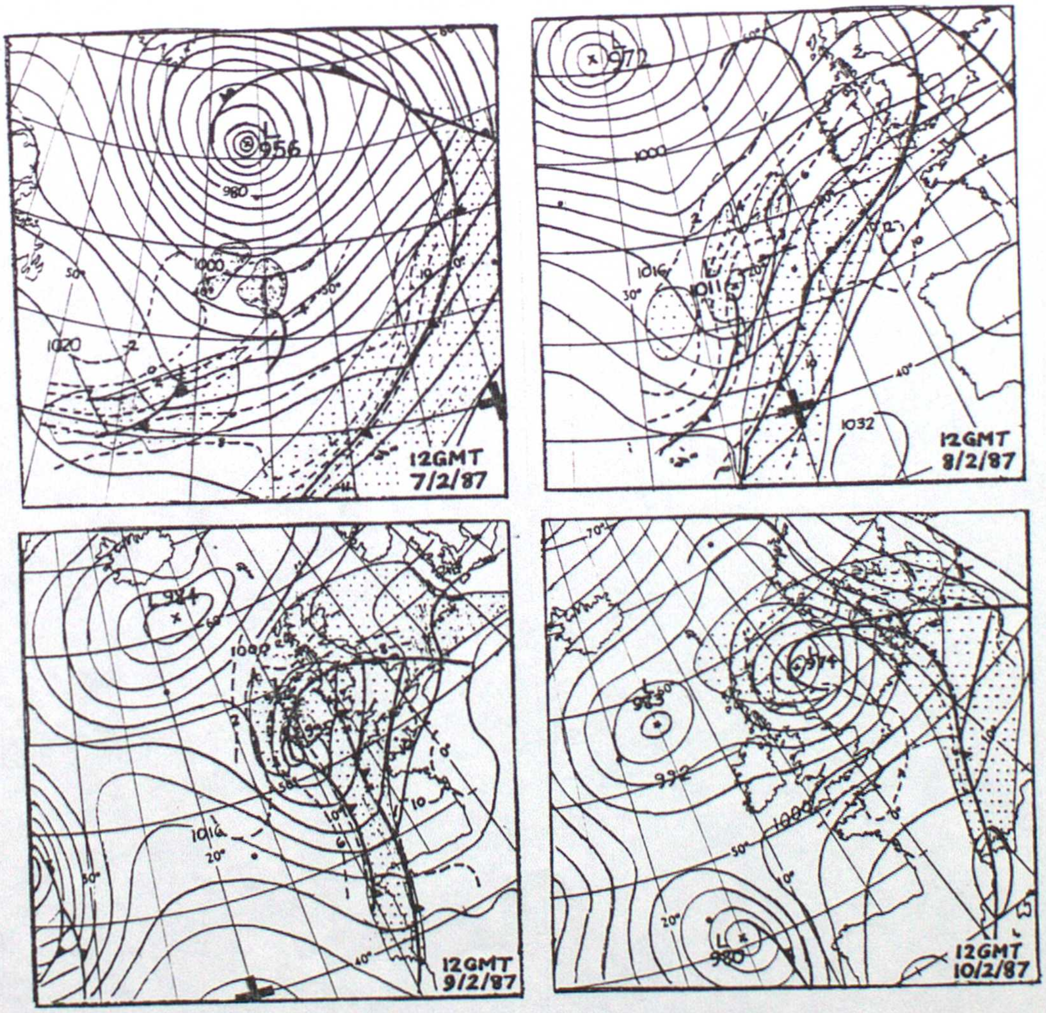


Figure 5

Analyses of sea level pressure and frontal position, model analysed 850mb WBPT (dashed lines), and upper cloud areas (stippled) derived from available NOAA and Meteosat imagery for (a) 12GMT 7th February 1987, (b) 8th, (c) 9th, (d) 10th February 1987. The bold line on (a) is a surface trough.

grown to form a nearly continuous cloud mass between C1 and F (Fig 4d). The upper cloud appeared to rotate cyclonically to form hook H (Fig. 4e) which advanced **ahead** of the rearward cold front. Meanwhile the originally well-defined southern tail of C1 became increasingly fragmented (Fig 4c) and difficult to identify. G and H together gave the appearance of an "instant occlusion" linked to a wave(see Fig. 1).

On the 9th (Fig 4e), the wave and hook remained identifiable but the frontal cloud to the south narrowed and became more fragmented. By 12GMT on the 9th, the frontal wave had moved quickly northeast to Northern Ireland (Fig 5c) deepening to 996mb while the cold air low had deepened to 995mb. This low became colocated with the cloud-free slot near southwest Ireland (Fig 4e) whilst the forward cold front progressively lost its identity. As the complex low pressure area over the British Isles transferred eastwards it steadily deepened, consolidating into one centre forward of the cold air low which soon lost its identity.

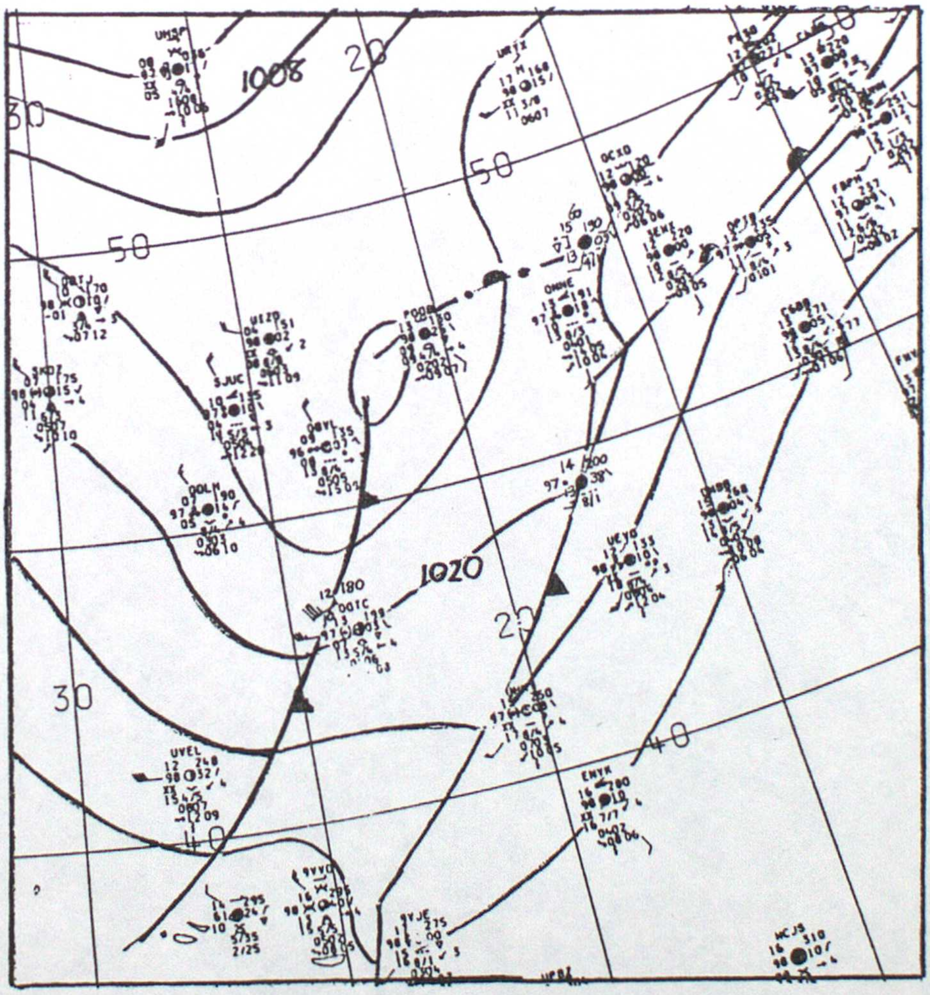


Figure 6

Surface analysis and observations for 12GMT 8 February 1987.

3. UPPER AIR AND DYNAMICAL CONSIDERATIONS

The 300mb winds and contours are presented in Fig.7a(i), b(i) and c(i) for 12GMT on 7,8 and 9 February. Areas of ascent, descent and thermal advection analysed by the U.K. Meteorological Office Fine Mesh model (Gadd, 1985) are shown in Figs 7a(ii), b(ii) and c(ii) for the same times. The main cloud areas derived from satellite imagery are superimposed on all the fields. The model can be used to explain the dynamics because its cloud and humidity fields were consistent with the satellite imagery over the area of interest even though analysis of the cloud-free slot and hook at 12GMT on 9 February was a little too far east.

At 12GMT on 7th, cloud areas A and C were situated on the forward side of broad upper troughing covering the western half of the North Atlantic (Fig 7a(i)) and were colocated with ascent in the lower and middle troposphere (Fig 7a(ii)). This ascent resulted from PVA induced by short wave troughs within the flow. Area A did not develop because it did not lie in a favourable part of the upper air pattern.

By 12GMT on the 8th, the main troughing had moved east (Fig 7b(i)), and C1 remained within a PVA maximum ahead of the trough. (C2, near the base of the trough, moved quickly towards Iberia and the cloud became broken (see Fig 4d)). Meanwhile ascent was colocated with C1; this expanded, intensified and extended towards the forward frontal cloud to the east.The region of ascending motion between the two cloud areas corresponded to the right entrance region of the jet, inferred from the upper level wind observations on Fig. 7b(i). Very little WBPT contrast now remained on the forward cold front due to advection of high WBPT between C and F. (On the forward side of the extending upper trough, another wave was carried eastward towards Iberia, embedded in the large area of ascent (Fig 7b(ii) and 7c(ii)), along with the remnants of C2.)

Following merging of C and F after 12GMT on the 8th February, the upper trough continued eastwards (Fig 7c(i)) and a large area of warm advection giving ascent resulted in the cloud over the north of the British Isles (Fig 7c(ii)). Within the frontal cloud to the south and near the hook, there was slight descent, (Figs 4d and 4e) giving thinning and warming of the cloud tops.

Figure 7 (overleaf)

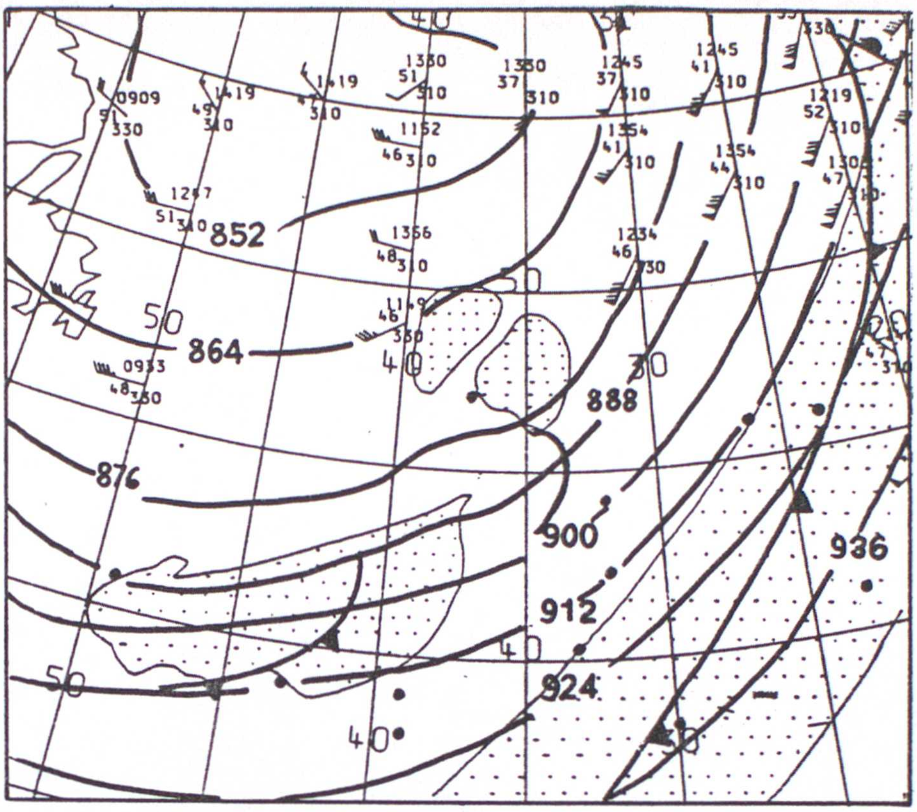
Upper air pattern, model diagnostics, and upper cloud areas (stippled) for 7-9 February 1987; (a) 12GMT 7th, (b) 12GMT 8th , (c) 12GMT 9th. Surface fronts are shown conventionally and troughs are bold lines.

Figs. 7a(i)-7c(i) show 300mb heights in decameters (thin continuous lines) and upper cloud areas deduced from METEOSAT imagery. Wind reports at 300mb from synoptic stations and aircraft near that level are shown. (Other observation locations are marked by a dot)

Figs. 7a(ii)-7c(ii) show upper cloud areas (stippled) and fronts superimposed on fine mesh model analyses of vertical velocity and thermal advection averaged over the 850-500mb layer. Open circles represent descent more than 6mb/hr; closed circles, ascent more than 6mb/hr, asterisks, ascent more than 12mb/hr. The isopleths are thermal advection in degs.C per 6 hours, continuous lines representing warm advection, and dashed, cold advection.

Fig 7a

(i)



(ii)

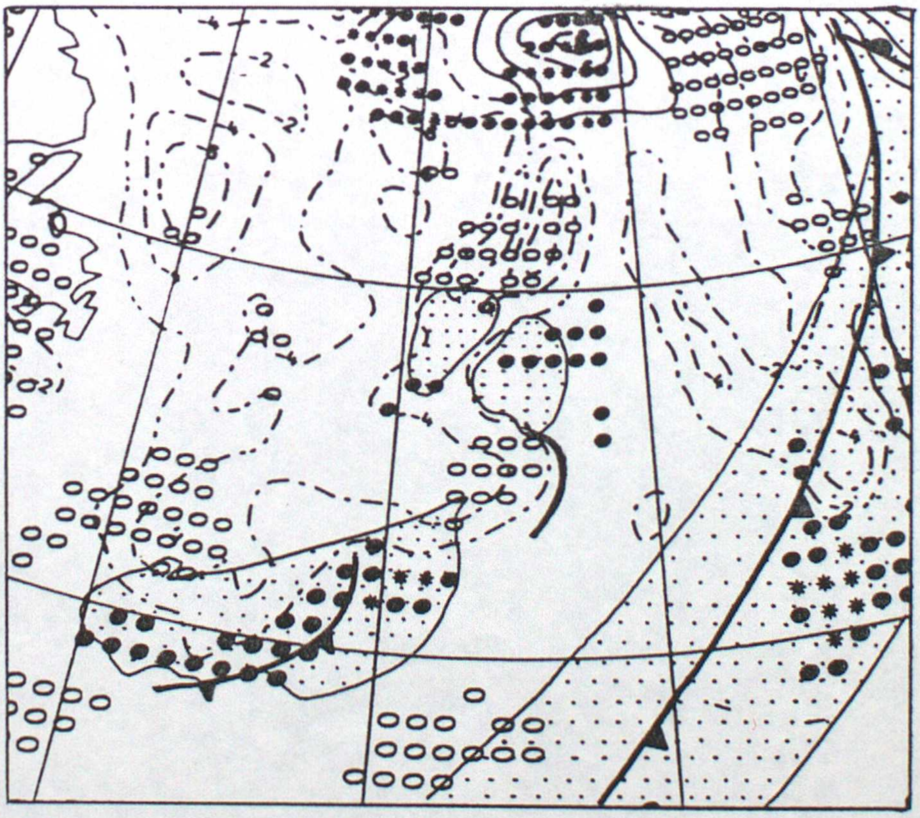
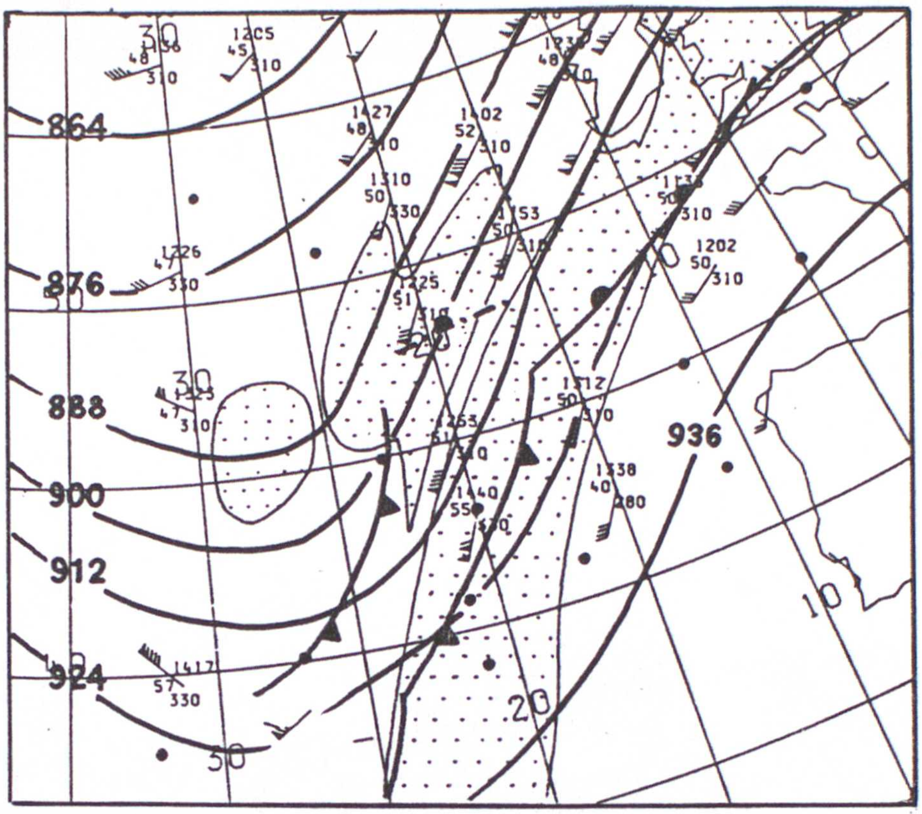


Fig 7b

(i)



(ii)

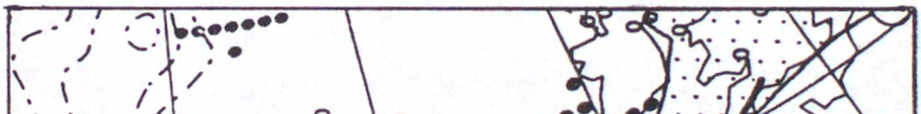
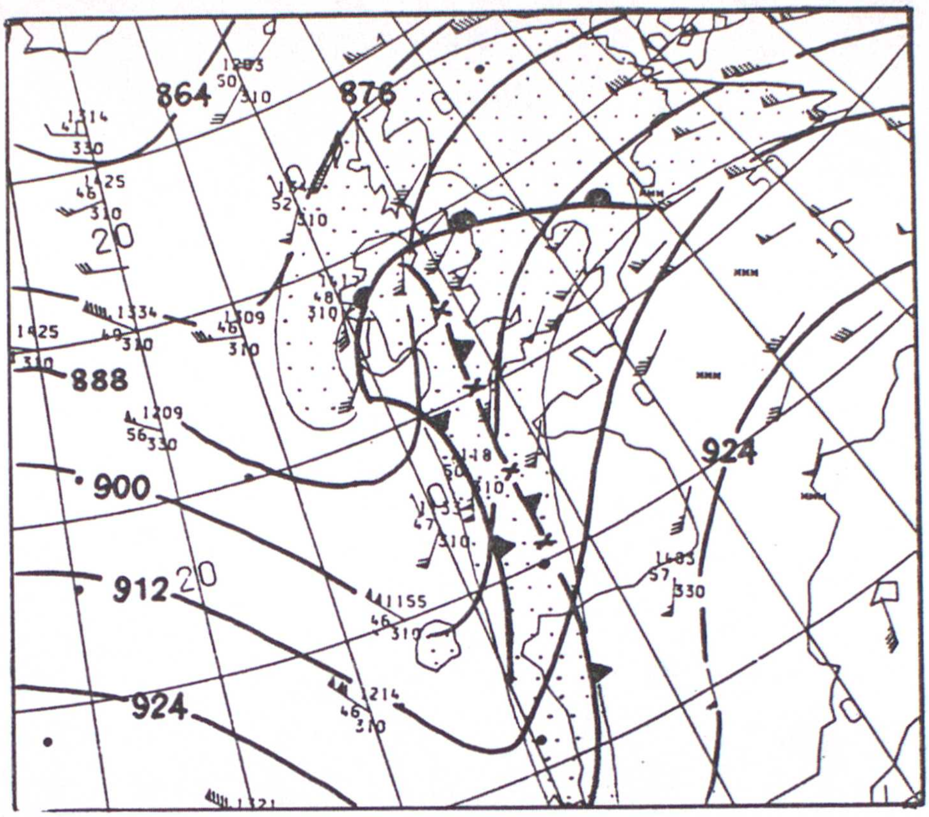
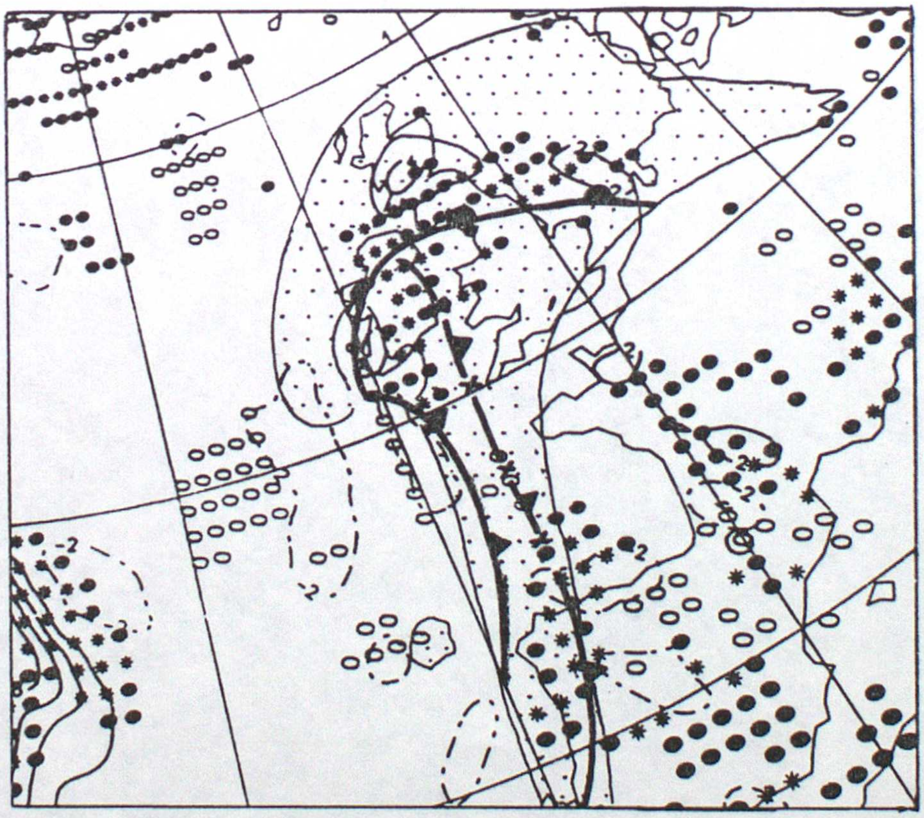


Fig 7c

(i)



(ii)



This case is one of several in which the relationship between the imagery, upper air pattern, and surface analyses were similar. For instance, Fig 8 shows analyses of 500mb height and 1000-500mb thickness with added major cloud areas derived from imagery for 10-11 November 1986, 7-8 December 1986 and the present case. Later in this paper, the implications of the similarities are exploited to produce general forecasting guidelines. For interaction to be possible, the cloud system in the polar air needs to be embedded in a strong upper flow that carries it towards the forward front. Any earlier cyclogenesis in the cold air upstream which distorts the flow would prevent interaction between the two systems.

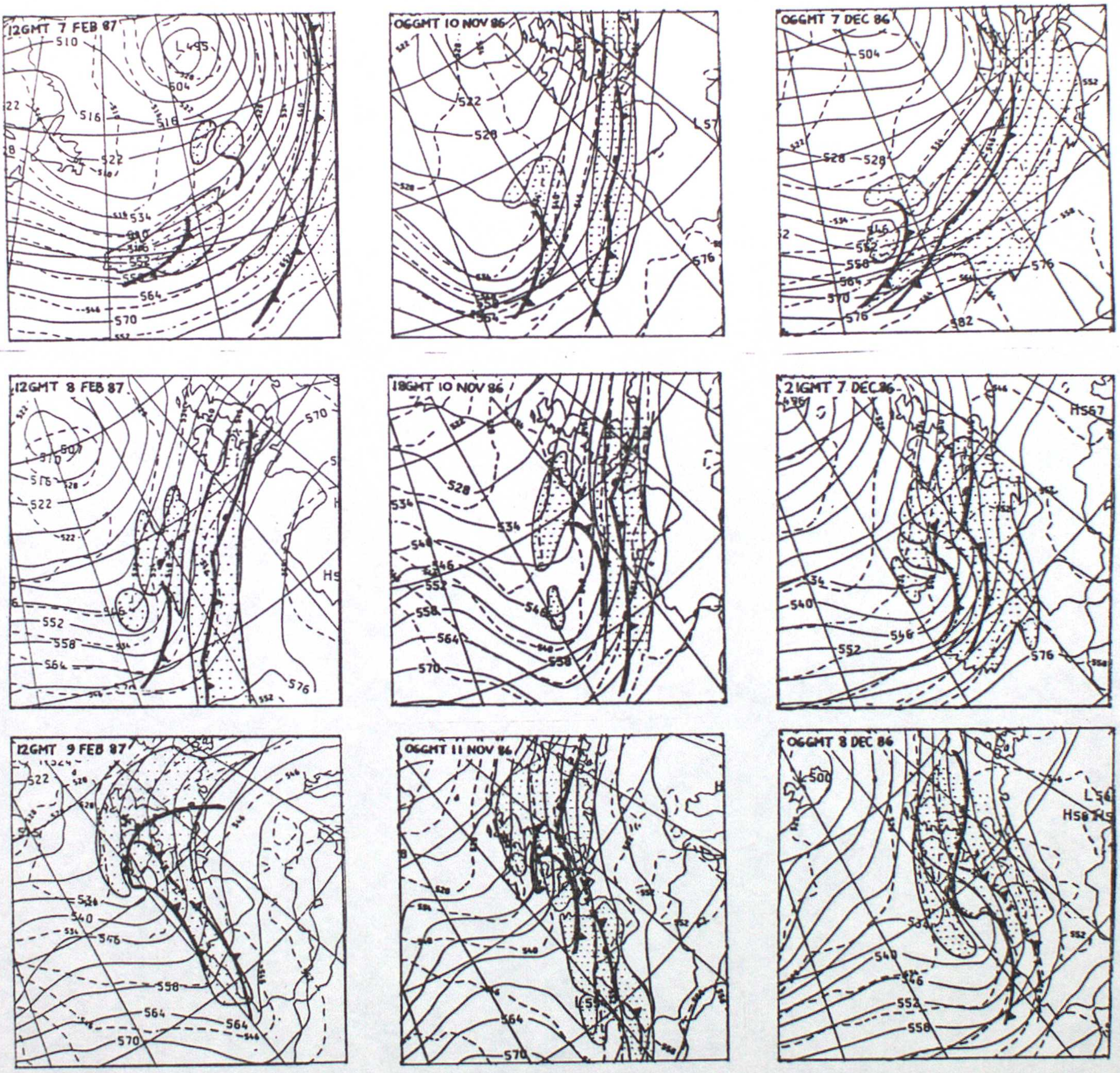


Figure 8

Sequences of upper air analyses derived from the fine mesh model for (a) 7-9 February 1987, (b) 10-11 November 1986, (c) 7-8 December 1986. Continuous lines are 500mb heights, and dashed lines are 1000-500mb thicknesses in decametres. Upper cloud areas are stippled and frontal locations are shown conventionally. In each case the cold air feature which eventually merged with the frontal cloudband was associated with a short wave trough embedded in a strong upper level flow.

4. MESOSCALE WEATHER DISTRIBUTION

The features on the imagery can be related in more detail to the frontal analysis as they crossed the British Isles network on 9th February, soon after the NOAA image in Fig 4e. More frequent imagery from METEOSAT and the UK weather radar network is presented in false colour in Fig 9a-f.

The main features in the METEOSAT infra-red image for 11GMT (Fig 9a) have already been identified in Section 2 except for some convective cloud, labelled T, over the southwest tip of Ireland in the originally cloud-free slot between the decaying forward cold front and the hook. This convection developed rapidly under a tongue of dry air aloft, clearly shown on the water vapour imagery (Fig 9b) which depicts the distribution of moisture at about 400mb (Eyre 1981). The dry air was observed above 470mb in the radio-sonde sounding from Valentia (Fig 10), the location of which is shown in Fig 9b; the air was also unstable and, according to the numerical model diagnostics (Fig 7c(ii)), was rising ahead of the surface low near southwest Ireland (allowing for the slight longitudinal phase error in the model's analysis). Fig. 9e shows convection having closed the gap between the hook and forward cold front.

Other features of interest from the satellite and radar imagery are as follows.

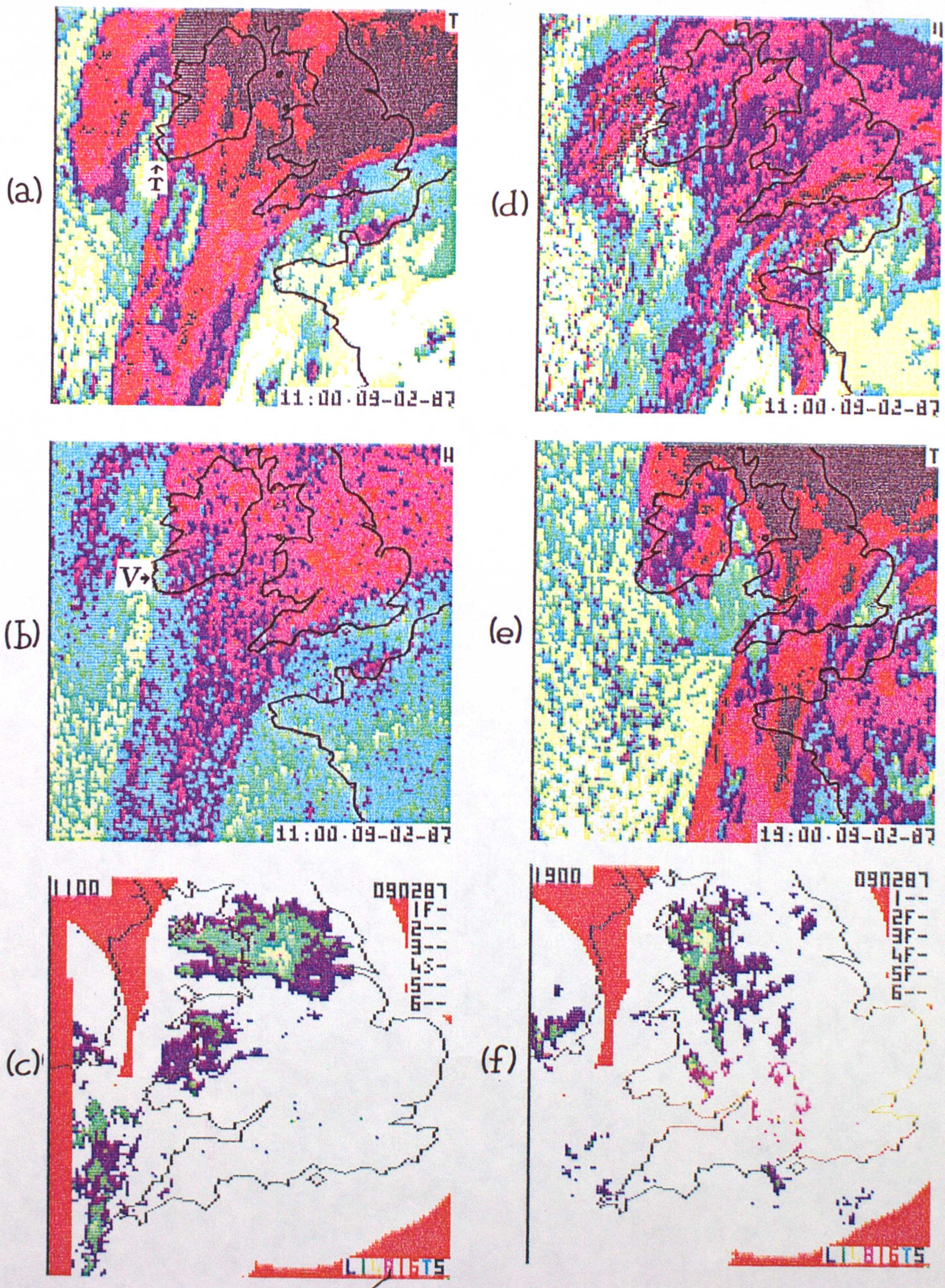
(i) There was a narrow band of rain to the west of England and Wales, associated with the forward cold front (Fig 9c). This corresponded with the band of thicker cloud in the visible image (Fig 9d). The rain gradually decayed as it moved east, especially over the southern half of the UK (Figs 9c,f). The band of heavy rain over the Irish Sea and north Wales is thought to have resulted from mid-level convection which had developed earlier behind the forward cold front.

Figure 9 (overleaf)

False colour METEOSAT and radar imagery for 9 February 1987.
(a) Infra- red image for 11GMT. The colour scheme represents temperature slicing as follows: black, colder than -40deg.C, red -30 to -40, mauve -20 to -30, purple -10 to -20, pale blue 0 to -10, green 0 to 5, yellow 5 to 10, white, warmer than 10. T is an area of growing convection referred to in the text.
(b) Water vapour image for 11GMT. This shows the amount of moisture in the mid and upper troposphere, centred around 400mb (Eyre, 1981). The colour sequence is as previous figure, and represents increasing dryness of the air, red being moistest, yellow being driest. V marks the location of Valentia.
(c) Radar network imagery for 11GMT. Purple represents rainfall rate of less than 1mm/hour, green 1-4mm/hr, yellow, over 4mm/hr. The apparent gap over southwest Wales is because of the radars not seeing rainfall at long range.

(d) Visible image for 11GMT. The colour sequence is as in the infra-red picture, representing decreasing reflectivity, black being the densest, most reflective cloud. Yellow and white are predominantly cloudfree areas.
(e) Infra red image for 19GMT. Colour slicing as in (a).
(f) Radar network imagery for 19GMT. Colour slicing as in (c).

Fig. 9


(a)
T
11:00 09-02-87
(d)
H
11:00 09-02-87
(b)
V
H
11:00 09-02-87
(e)
T
19:00 09-02-87
(c)
1100
090287
1F-
2--
3--
4S-
5--
6--
(f)
1900
090287
1--
2F-
3F-
4F-
5F-
6--

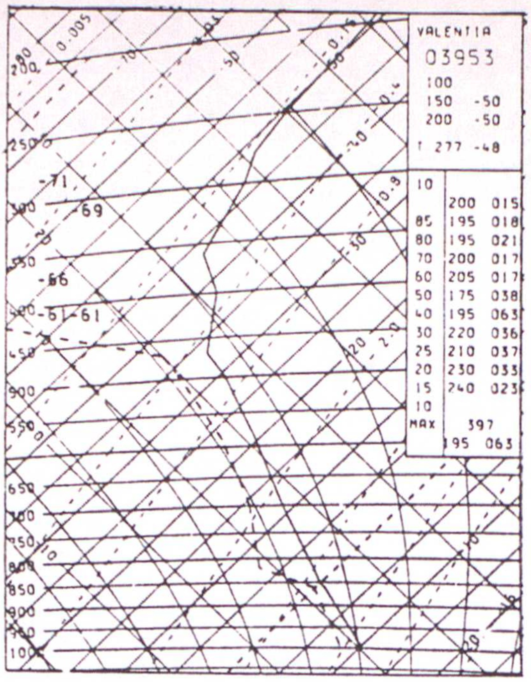


Figure 10 (left)

Upper air sounding at 12GMT 9 February 1987 for Valentia, the location of which is marked V on Fig. 9b.

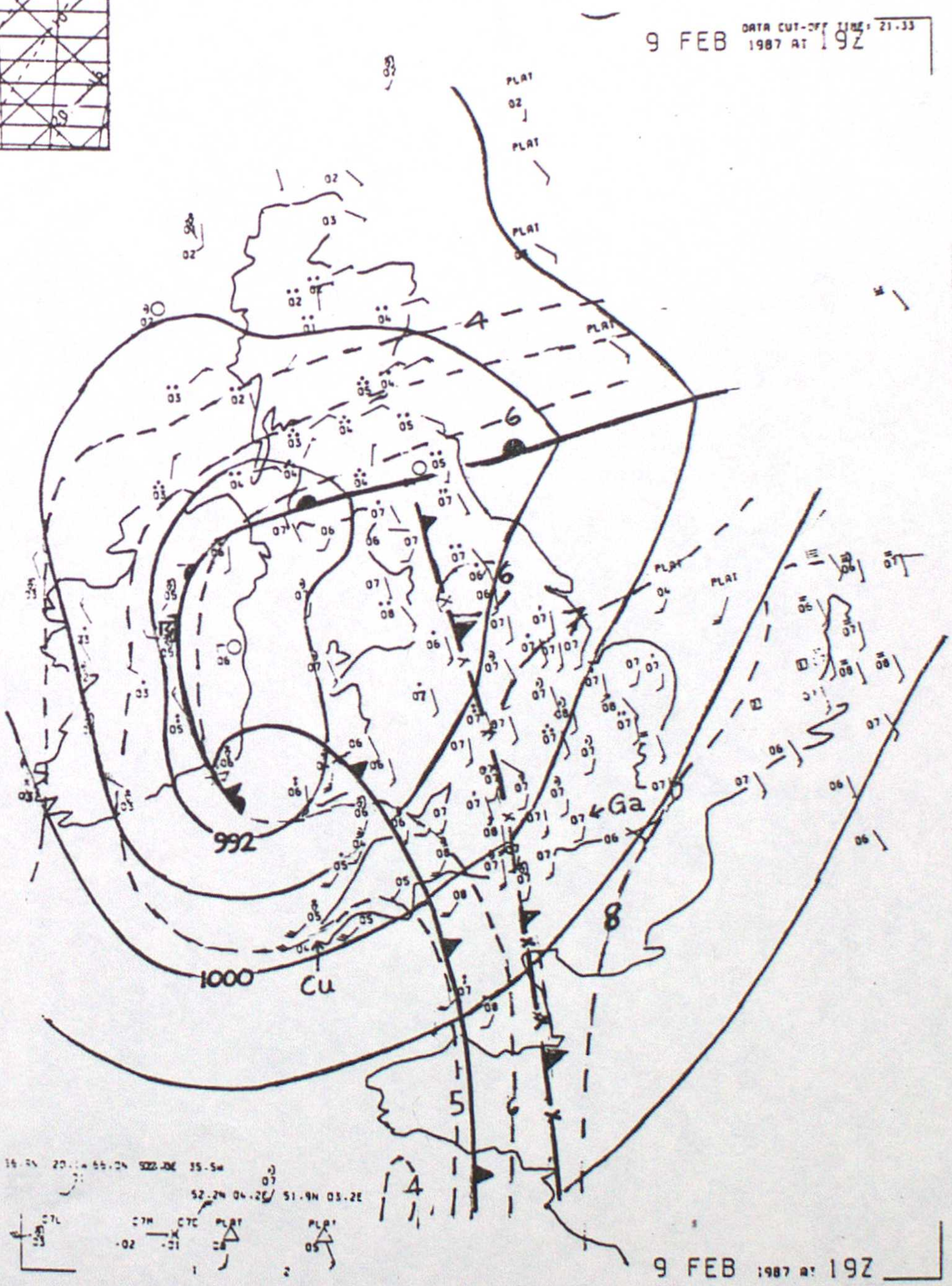


Figure 11

Surface synoptic analysis for 19GMT 9 February 1987. Plotted observations show present weather, wind, and dewpoint. The locations of Gatwick and Culdrose are marked by Ga, and Cu respectively. 850mb WBPT isopleths (deg. C) derived from a model analysis at 18GMT are shown as pecked lines.

(ii) The thicker cloud on the eastern side of the hook shown in the visible image (Fig. 9d) corresponded to warmer tops in the infra-red image. Rainfall here was probably heavier and more widespread than further west where the cloud was thinner. Cloud warmed and decayed in the southern tip of the hook (Fig 9a,e).

(iii) The area of rain over northern England was associated with ascent due mainly to warm air advection (Fig 7c(ii)) north of the warm front.

(iv) The rearward cold front was difficult to identify from the visible and infra-red imagery.

The surface analysis corresponding to the time of the imagery in Fig. 9e and 9f is shown in Fig. 11. The forward cold front has been drawn though the line of patchy rain which could be followed on radar imagery, but there was little change of wind or dew-point across it. The thunderstorm reported over Ireland was within the region of convective activity identified in Fig. 9e. The main airmass change was at the rearward cold front where the dew-point fell significantly, the cloud base lifted but only patchy rain occurred. Fig. 12 is a time sequence of hourly observations from two stations in southern England, one coastal and one inland, showing that the basic characteristics of the two fronts were preserved whilst crossing southern England. The warm front in Fig. 11 has been analysed along the warm side of the surface wet-bulb temperature gradient.

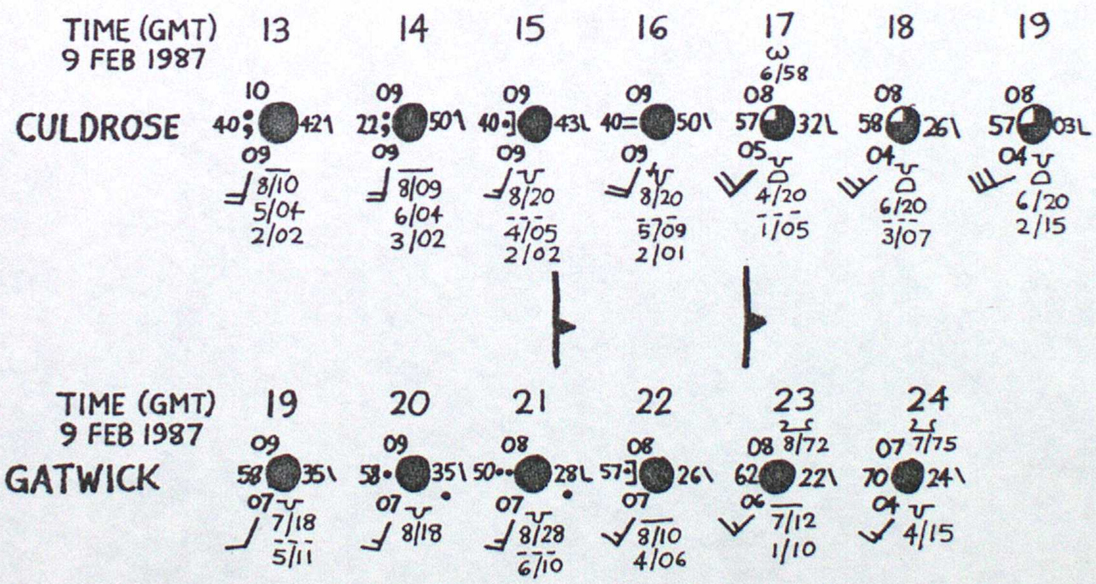


Figure 12

Sequence of hourly surface observations from Gatwick and Culdrose, (labelled Ga and Cu respectively in Fig. 11) between 13GMT and 24GMT 9 February 1987. The cold fronts are marked in a position corresponding to the time of passage across each station.

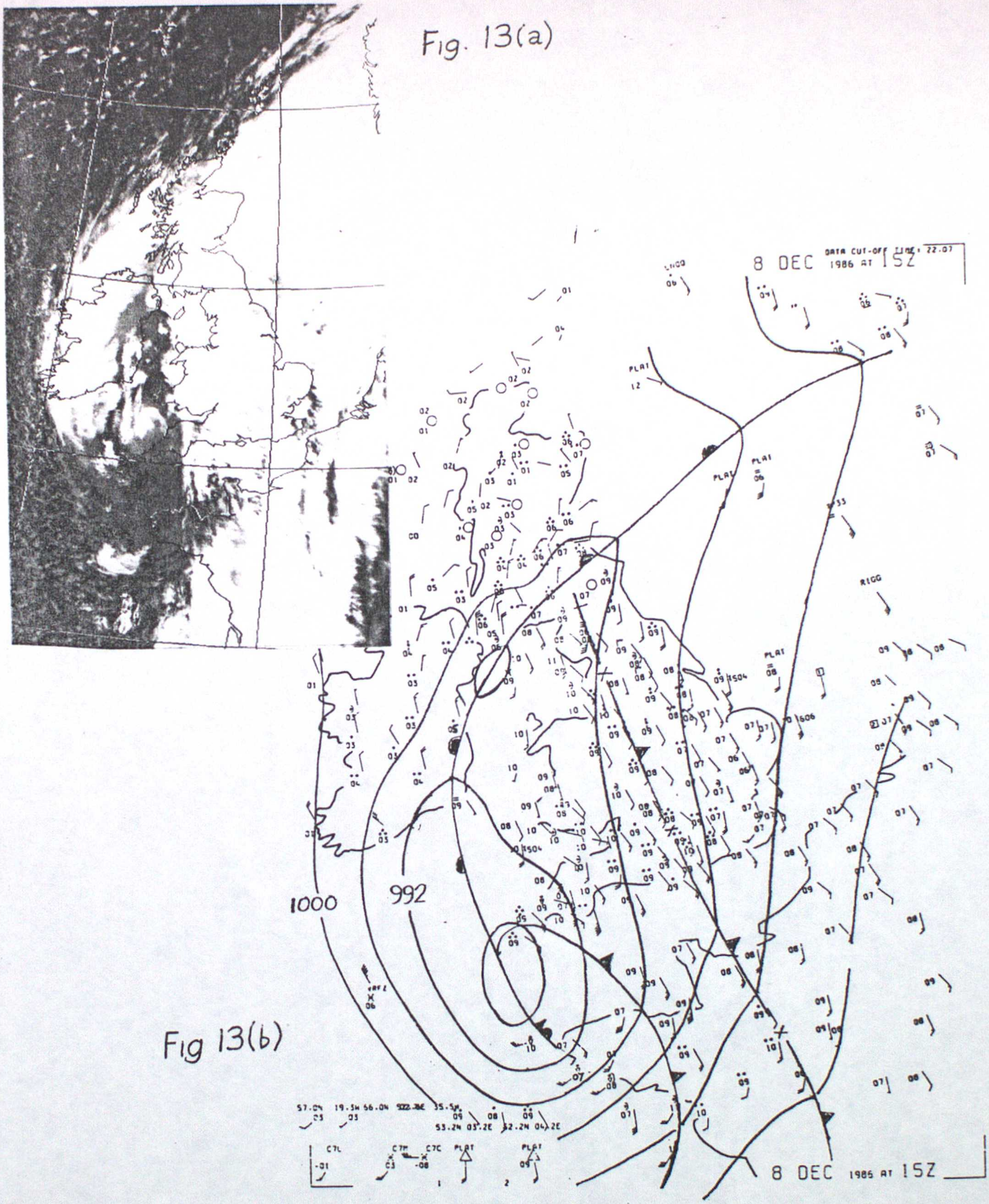


Figure 13

NOAA 9 infra-red imagery (a), and surface analysis (b), for 15GMT 8 December 1986. The symbols on the surface analysis are as in Fig. 11. As on 9 February 1987, there was deep convection immediately north of the cold air vortex, and lower dewpoints followed the rearward cold front. The forward cold front was marked by a progressively weakening rainband.

This case is one of several (eg. 8 December 1986 shown in Fig. 13) in which the evolution was similar. A schematic diagram showing cloud outlines, frontal analysis and weather is presented in Fig. 14, which will be used in section 6 for forecasting guidelines.

The subsequent behaviour of the system following the stage depicted in Fig. 14 is governed by the large scale upper flow pattern. The cold air surface vortex will in most cases be situated so near the upper trough axis (Fig. 8) that it will undergo little further development and will soon begin to fill. The most favourable development area is found several degrees forward of the upper trough (ie. well ahead of the original cold air vortex) and this is where any further cyclogenesis would occur.

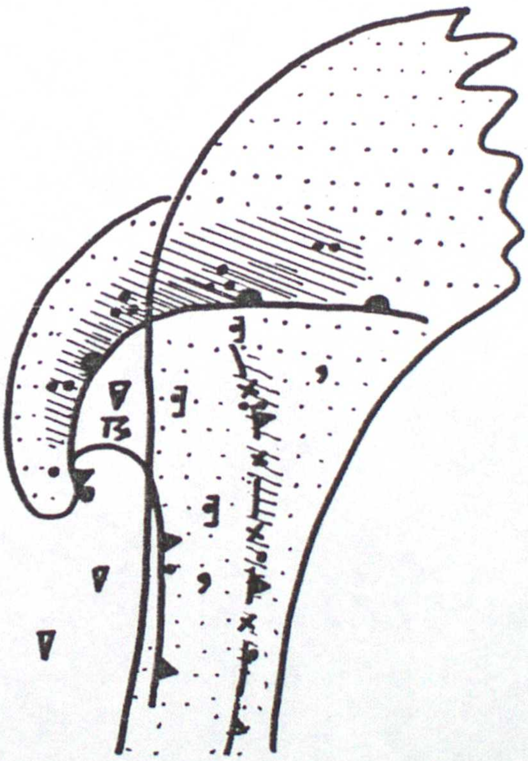


Figure 14

Schematic representation of upper level cloud (stippled), and rainfall (hatched) in the mature system as it crossed the British Isles. Dense hatching represents moderate or heavy rain, light hatching, light rain. Current weather symbols are used to depict observations characteristic of various parts of the system. The area bounded by the forward and rearward cold fronts and the hook, is characterised by moist air near the surface and extensive low cloud, giving showery outbreaks of rain and drizzle. Within the colder, drier air west of the rearward cold front, cloud becomes more broken and convective. Deep convection may develop between the hook and the forward frontal band.

Fig. 15

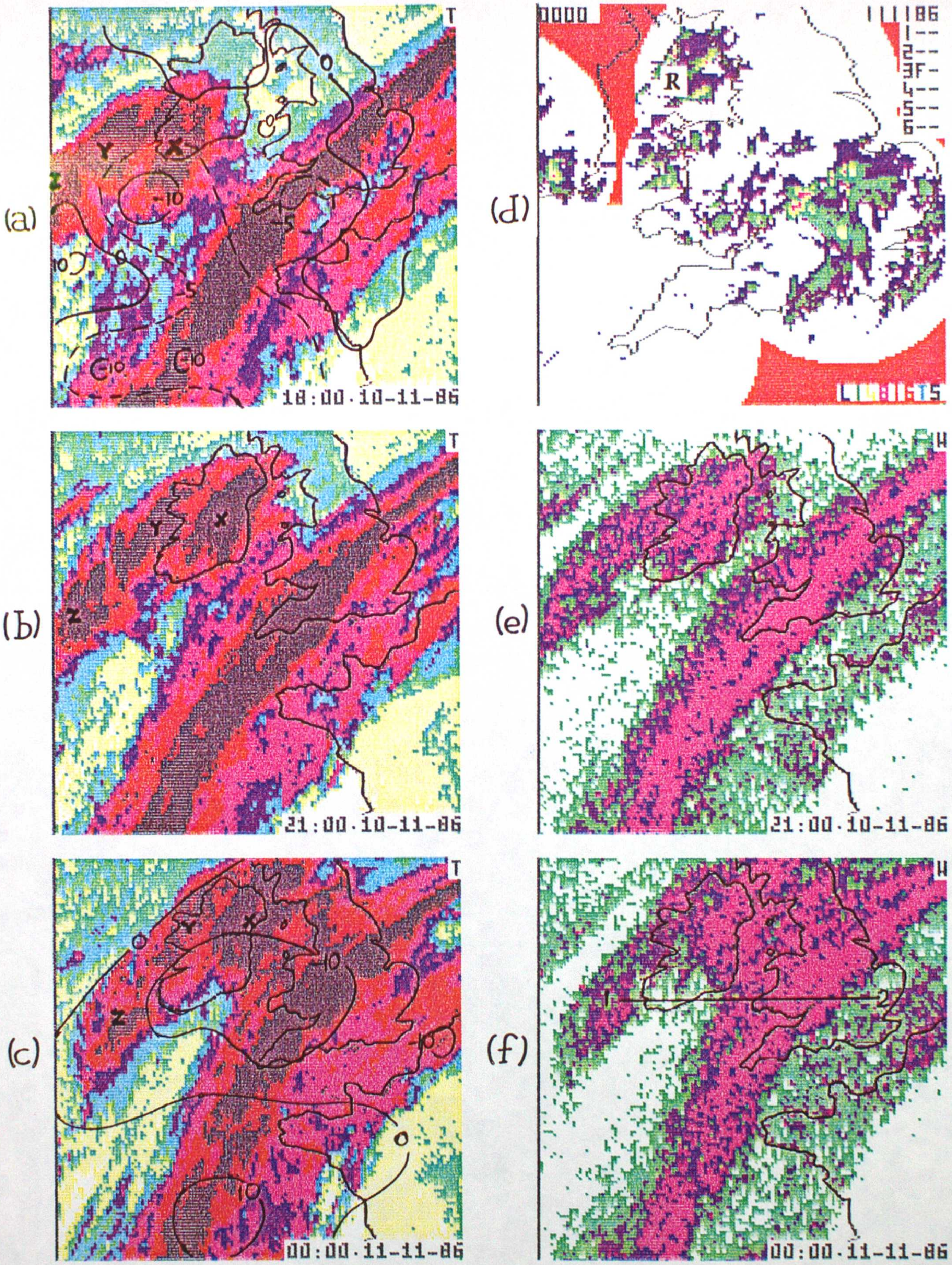

(a)
(b)
(c)
(d)
(e)
(f)
T
H
X
Y
Z
R
18:00 10-11-86
21:00 10-11-86
00:00 11-11-86
00:00 11-11-86
111186

Figure 15 (previous page)

Sequence of Meteosat and radar images for 10-11 November 1986 showing merging of a cold air vortex and frontal cloudband over the British Isles. Infra-red images are shown for (a) 18GMT and (b) 21GMT 10 November, and (c) 00GMT 11 November, with the same colour scheme as in Fig 9a, except with green 0-10 deg. C, yellow 10-15, white warmer than 15. Isopleths of vertical velocity (mb/hr) at 600mb derived from model analyses are superimposed on (a) and (c), negative values representing upward motion. The letters X,Y,Z, mark the convective elements referred to in the text. (d) is a radar network image for 00GMT 11 November, the colours as in Fig. 9c. R is the rainfall area referred to in the text. (e) and (f) are water vapour images for 21GMT 10 November and 00GMT 11 November respectively, white representing driest upper tropospheric air, and green, purple, pink, successively moister air. On (f) 1-2 is the line of the cross-section in Fig. 16.

5. CONCEPTUAL MODEL

Of the three cases already presented, that of 10th-11th November 1986 provides the best opportunity of detailed understanding of the merging process since this took place in a data-rich area over the British Isles. Fig 15 shows the merging of the two systems using a sequence of 3-hourly METEOSAT infra-red and water vapour images. The cooling of the cloud tops can be seen in the former gap between the cold air vortex and the forward frontal band with rapid moistening at upper levels. The pockets of locally heavy rain (labelled R) over the Irish Sea, seen in the radar image occurred within this area of cloud growth, and amalgamated into an area of heavy rain over northern England shortly afterwards.

The hook consisted of three separate mesoscale convective elements labelled X,Y and Z. Region X expanded as it moved NE, whilst Y and Z dissipated and warmed. The differential motion of X,Y and Z produced the apparent rotation of the cloud envelope associated with the cold air vortex.

Vertical velocities derived from fine mesh analyses are also shown in Fig 15. Prior to merging, a band of upward motion extended across from the cold air vortex to the forward frontal cloud with a separate maximum on each, then consolidated into a single region of ascent by 00GMT 11 November.

Fig 16 is a fine mesh model cross-section of WBPT taken along line 1-2 in Fig 15f. In the layer 950-700mb between 5 deg W and 8 deg W, immediately upwind of the region of rapid cloud growth, the air was potentially unstable. Therefore, merging appears to have been a reponse to large-scale forcing within a potentially unstable environment.

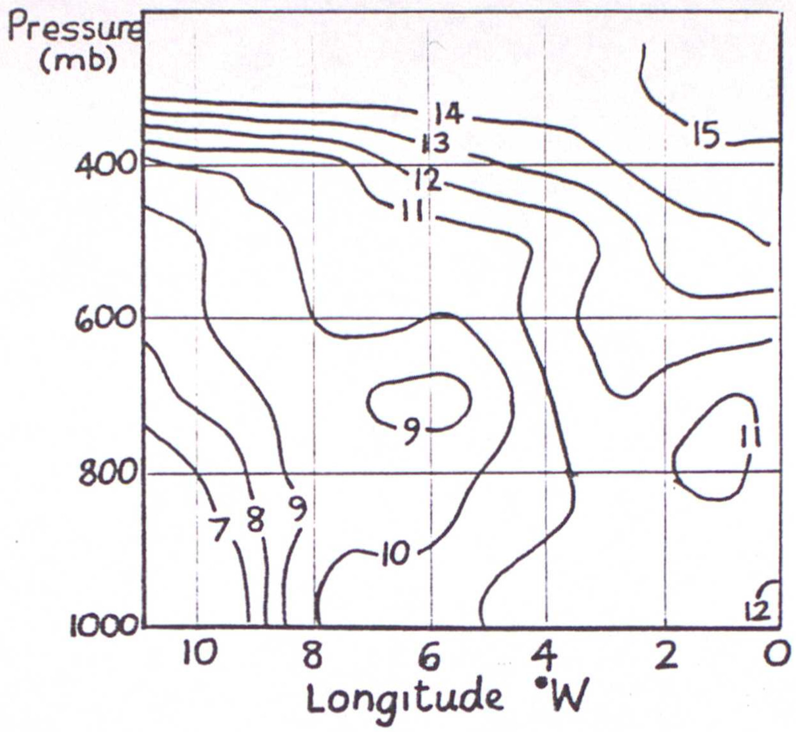


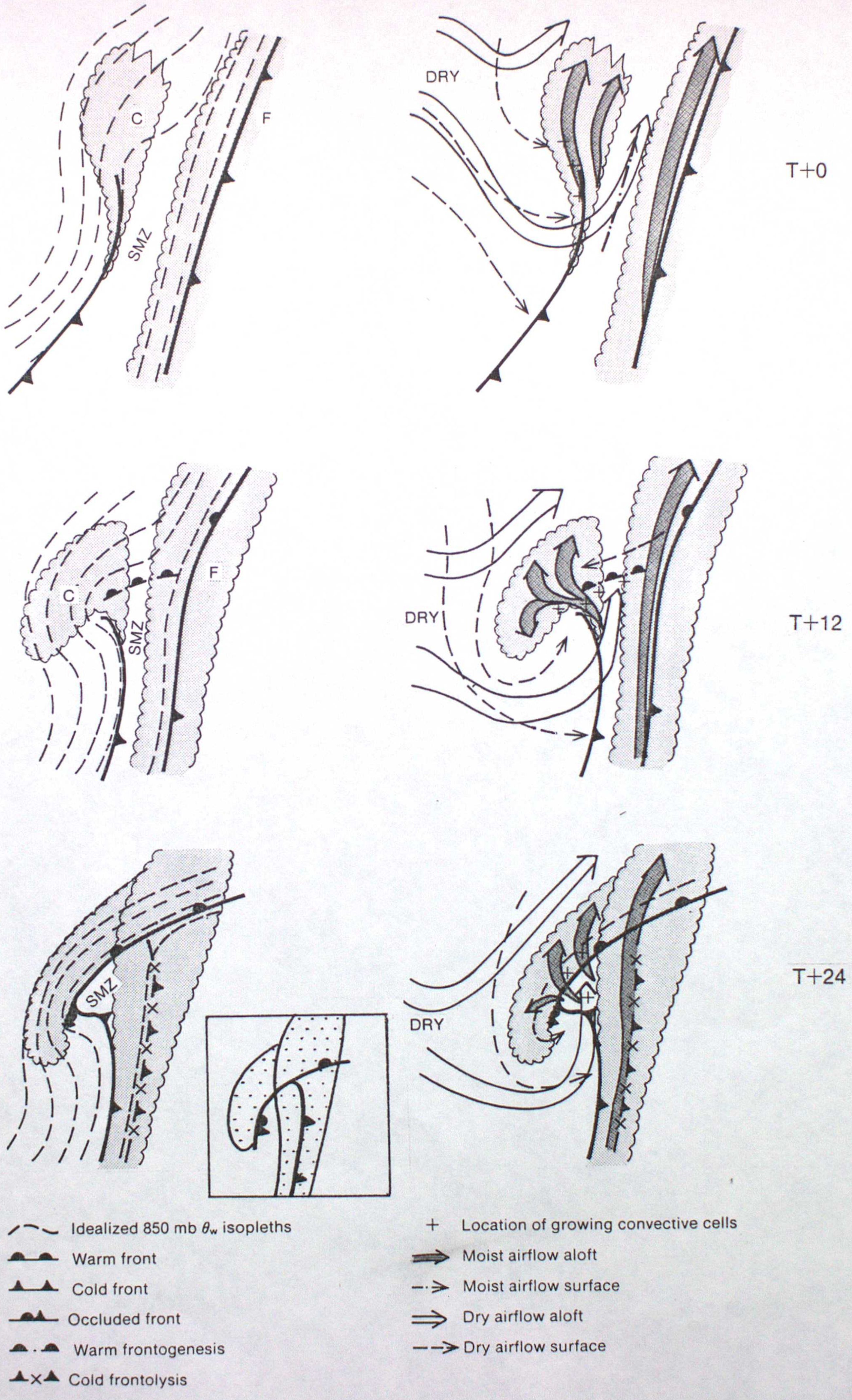
Figure 16

Cross-section of WBPT (deg. C) along the line 1-2 in Fig. 15f derived from a fine mesh analysis for 00GMT 11 November.

The airflow model presented in Fig 17 proposes to account for merging of the cold air vortex and frontal cloud band, formation and maintenance of WBPT gradients and the precipitation distribution. The model has been derived using rapid movieloop sequences of half-hourly METEOSAT images, along with fine mesh model diagnostics (isentropic analysis, vertical velocities and 850mb WBPT). The evolution is described in three separate stages.

Stage 1 (Pre-merging stage)

The cold air feature C, coincident with a PVA maximum, approaches a cold frontal zone F. At this stage C is composed of a series of convective cells generated at its rear edge, with anvils combining to produce the upper cloud shield. At low levels, air of low WBPT follows the cold front at the rear of C. At middle and upper levels, dry air moves around the base of the trough within the strong upper flow, overrunning the tail of C, then travelling parallel to the sharp edge of F. At low levels, warm, moist air is advected ahead of C, weakening the thermal contrast associated with F and generating potential instability within a new shallow moist zone (SMZ) between C and F. This contrasts with the case of BH in which the cold air feature possessed little baroclinicity and so the thermal gradient was retained on the polar front. (In such cases, any cyclogenesis would occur on the forward front rather than on the rearward frontal zone.)



C
F
SMZ
DRY
T+0
C
F
SMZ
DRY
T+12
SMZ
DRY
T+24
Idealized 850 mb θ_w isopleths
Warm front
Cold front
Occluded front
Warm frontogenesis
Cold frontolysis
+ Location of growing convective cells
Moist airflow aloft
Moist airflow surface
Dry airflow aloft
Dry airflow surface

Figure 17 (previous page)

Life cycle model showing the interaction between a polar air cloud feature C and polar frontal cloud F at approximately 12 hourly intervals. Such an interaction is conventionally interpreted as an 'instant occlusion' but a revised frontal analysis is presented here. Stippling denotes upper cloud. Broadening and narrowing arrows show ascending and descending air respectively. SMZ denotes shallow moist zone. Inset shows the conventional analysis corresponding to stage three.

Stage 2 (The merging stage)

C appears to rotate rapidly leaving behind a trailing low-level WBPT boundary. Convective cells continue to be generated at the southern rear edge of C, with a series of anvils carried forward, and dissipating upon encountering the dry air to the rear of F. The potential instability already created between C and F may be then released as ascending motion is imposed upon this region by a combination of warm air advection and PVA. Rapid cloud growth then proceeds in the gap. Warm advection ahead of C generates a thermal gradient on its northern side and a low level flow is established from F towards C ahead of this nascent frontal zone.

Stage 3 (the mature stage)

C and F have linked, thus completing the instant occlusion process as traditionally interpreted. The new front has been placed along the inside edge of the hook-shaped cloud C on the warm side of the 850mb WBPT gradient. The edge of the cold frontal cloud band may still be apparent above the hook and normally corresponds to the upper level jet axis. (Since the temperature gradient along the rearward cold front occupies a shallow layer, the jet axis will normally remain ahead of it, tied to the forward front which, at upper levels retains some thermal structure.) C becomes aligned with the upper trough (Fig 7c(i)) and, having stopped rotating, may appear unchanged for many hours. Warm, moist boundary layer air from the SMZ ascends along the new frontal slope, producing a band of rain along the inside of the hook-shaped cloud C. Since this region is overrun by dry low WBPT air some convection cells will also be generated. Continued but less rapid ascent associated with the newly-formed baroclinic zone produces progressively colder cloud tops towards the outside of the hook but with lighter rainfall. Deep convection may occur anywhere within the SMZ, but is most likely to become concentrated just ahead of the cold air low where strong PVA is acting upon an environment that is destablising due to cold advection aloft.

The mature system corresponding to stage 3 differs from BH in that cloudband C is fed by air with high WBPT from a SMZ behind it instead of a flow predominantly along its axis. The presence of this flow originating from a potentially unstable SMZ is crucial in determining whether new cloud growth and possibly heavy rain will occur within the previously cloud-free gap. Conversely, in cases where this flow is absent, (eg. in Fig. 2), precipitation intensity is suppressed near the intersection of the two cloudbands.

The analysis shown in Fig. 17 reflects the thermal and weather distributions more realistically than the commonly used "instant occlusion" analysis, which is shown in the inset of the figure for comparison. The overall shape of the system corresponding to stage 3 resembles the 'cloud head' frequently observed prior to explosive cyclogenesis (Bottger et al., 1975, Monk and Bader, 1988). Indeed, an analysis scheme similar to that proposed in Fig. 17 probably also applies in such cases (Monk, personal communication). The vertical section (Fig. 16) across the two cold fronts as represented by stages 2 and 3 of Fig. 17 is similar to the split front model (eg. Young et al., 1987). The weakening forward front acts as the "upper cold front" as it still possesses an upper level moisture boundary despite very little surface temperature contrast. Meanwhile, the rearward front acts as the surface cold front.

6. FORECASTING GUIDELINES

(1) An "instant occlusion" of the type described in Fig. 17 may form if all the criteria (a)-(c) below are satisfied:

(a) A cold air cloud cluster, which may be leaf-shaped, contains dense layered cloud.

(b) Surface observations or numerical model diagnostics (eg. 850mb WBPT) show that a thermal gradient is associated with this cloud.

(c) The cloud is embedded in a strong upper flow that will carry it to within 350 nautical miles of the polar front (Marshall, 1982).

(2) Having satisfied the criteria in (1), and if the cold air cluster rotates (indicating cyclogenesis), merging of the cold air cluster and the polar frontal cloud band normally follows.

(3) During "merging", cloud develops rapidly ahead of the rearward cold front producing rain which may be heavy. This front trails behind its original upper cloud. The resulting hook-shaped cloud canopy then moves parallel to the orientation of the forward cold front.

(4) After merging (see Fig. 14):

(a) The heaviest rain falls at the inside of the hook.

(b) The main airmass boundary is along the rearward cold front, the forward cold front becoming difficult to identify at the surface.

(c) Convection may develop anywhere between the hook and the forward cold front, but it is particularly likely to be deep (perhaps with thunder) immediately ahead of the cold air surface low.

(d) As the cold air surface low occludes and starts to fill, any further cyclogenesis will take place on its forward side.

ACKNOWLEDGEMENTS

We would like to thank K.A. Browning, M.E. Hardman, P. Jonas, G.A. Monk, R.M. Morris, P. Salter, G. Shutts, P. Wickham, and A. Woodroffe for helpful comments on the first manuscript, D. Cranidge who wrote the software for the movieloop satellite image display, and R. Hardy for bringing this case to our attention.

REFERENCES

Anderson, R.K.,Ashman, J.P.,Bittner, F.,Farr, G.R., Ferguson, E.W., Oliver, V.J., and Smith, A.H., 1969: Application of meteorological satellite data in analysis and forecasting. Tech. Rpt. 212, Air Weather Service, Washington.

Bottger, H., Eckardt, M., Katergiannakis, U., 1975: Forecasting extratropical storms with hurricane intensity using satellite information. J. App. Met.,14, 1259-1265.

Browning, K.A. and Hill F.F.,1985: Mesoscale analysis of a polar trough interacting with a polar front. Quart. J. R. Met. Soc.,111, 445-462

Eyre, J.R., 1981: Meteosat water vapour imagery. Met. Mag.,110, 345-351

Gadd, A.J., 1985: The 15-level weather prediction model. Met. Mag.,114, 222-226

Locatelli, J.D., Hobbs, P.V., and Werth, J.A., 1982: Mesoscale structures of vortices in polar air streams. Mon. Wea. Rev.,110, 1417-1433

Monk, G.A., and Bader, M.J., 1988: Satellite images of the development of the storm of 15-16 October 1987. Weather,43, 130-135.

Marshall, Capt. T.A., 1982: 'Weather satellite picture interpretation', Vol.2. NP411(2), DNOM memo no 1/82. Pub. by Directorate of Naval Oceanography & Met.,MOD,London.

Weldon, R.B., 1979: Cloud patterns and the upper air wind field. National Weather Service Training Notes, part IV, 62-79. Unpublished manuscript available from Applications Division, NOAA NESDIS, U.S. Dept. of Commerce.

Young, M.V., Waters, A.J., Browning, K.A., and Bader, M.J., 1987: Application of satellite imagery in nowcasting and very short range forecasting: some examples for cold fronts. Satellite and radar imagery interpretation, preprints for Workshop, Reading, England, 20-24 July 1987, 163-178.