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An evaluation of the penetrative convection scheme for the mesoscale model

by

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1. INTRODUCTION

Most convective parametrizations have been formulated for large scale models and address themselves primarily to the problem of heat and moisture transports. This aspect of a parametrization is of particular importance in the tropics.

A convective parametrization scheme in a mesoscale model must address itself to very different problems. The gridlength of such a model, typically 10-20 km, is comparable with the size of the largest cumulonimbus clouds and the time step of only one minute extremely short compared with the lifetime of a cloud cell. With only short period forecasts, the problem of transports becomes secondary to that of predicting rainfall from quantitatively described cloud units.

To that end, a new convective parametrization scheme was designed for the mesoscale model by Dr B Golding. This scheme models most of the features required of such a parametrization. It tests the model profile for instability by lifting layers to their lifting condensation level and comparing the resultant layer temperature with that of the environment at that level. If convection is initiated, the updraught parameters (height of top, mass flux, temperature and humidity, production of condensate) are determined by entraining parcel theory. A moist downdraught is also represented, the point of initiation being the mid-level of the cloud.

The cloud unit is allowed to be of variable area (proportion of the grid box) but is constrained in overall size by a mass flux term (AMUO), appropriate to a cloud of that height. A 'standard' cloud unit is considered to be 8000 m deep and as having a mass flux of 10^{11} Kg. AMUO is calculated as a fraction of that 'standard' mass flux according to the actual height of the cloud.

Clouds are considered to exist for one hour and sufficient cloud units, i.e. the number of cloud cells within the grid square (NCLOUD), are calculated to stabilise the column within that time. A scaling factor is then calculated, representing the total mass flux of all cloud units (AMUO * NCLOUD), subject to the constraint that this value can not exceed the available mass of air below cloud base. This term (AMUT) is then used to scale other parameters, such as amount of condensate produced, for final output by the scheme. Precipitation released during the life-time of the cloud is obtained from the total condensed water using an empirically determined efficiency.

The final stage of the scheme involves adjustments to the environment resulting from the convection process. A particular feature of this stage is the cooling of the surface layer by the downdraught, itself quite an important part of the process of re-initiation - or otherwise - of further convection.

A considerably more detailed explanation of the structure of the parametrization, and its computational details, is contained in Golding (1982).

2. TEST PROGRAMME

The purpose of the test programme was to investigate the performance of the parametrization in a variety of real data situations. It was felt that any such scheme should produce a realistic representation of the following:-

i. Cloud base and tops.

ii. Rain area, in an approximate manner.

iii. The entrainment process.

iv. Vertical velocities.

v. Rainfall rates.

vi. Modifications to the environment.

Note. For the purpose of these investigations, rain area was taken to be the area of the downdraught since this is the definition of rain area within the parametrization.

Occasions were chosen to represent a reasonable variety of degrees of convection from airstream showers in a maritime north westerly to deep thunderstorms in a slow moving southerly. Early tests were based on midday (radiosonde) soundings, the low level profile being modified for maximum temperatures.

Later tests were based on midnight soundings modified initially for dawn conditions and subsequently for daytime heating. When convection was initiated, however shallow, the profile was again modified according to the changes produced by the scheme, and further heating applied. This cycle was repeated until maximum temperatures were reached at the surface. It was felt that this process gave a much truer picture of what happened in reality where the effects of early morning (shallow) convection play some part in deciding the degree of convection that will occur later in the day.

Early work also tended to concentrate on the broader aspects of the scheme while later investigations involved re-running cases with slight changes to model formulations. Data were provided by Met O 8 that enabled an accurate comparison of hourly rainfall rates to be carried out; this was of particular value towards the end of the investigations when a degree of tuning was being considered. Dates considered were:-

Camborne	29 July 1980	Met O 15 supplied profile - Large CB.
Crawley/Hemsby	5 June 1982	Thunderstorms
Scotland)	3 July 1982	Showers
SE England)		Thunderstorms
SE England	12 July 1982	Thunderstorms from medium levels.
S England	13 October 1982	Showers in a south westerly.
S England)	17 October 1982	
N Ireland)		Medium level instability
Scotland	19 November 1982	Showers in a north westerly.

3. RESULTS

Results of the individual test cases will be discussed in Appendix I. However, the main areas of interest will be considered as described in Section 2.

i. Cloud base and tops

The parametrization gives a realistic indication of the base of clouds. The level of cloud base is thrown up to the next 50 mb level but the actual height of cloud base, the lifting condensation level, is calculated by the scheme. While the base level over estimates the height of base, the calculated base gives good agreement with observed/reported heights.

The cloud top suggested by the model is thrown down to the nearest 50 mb level below the level at which the vertical velocity of the updraught becomes negative. Since evidence suggests that most convective cloud tops lie between the T-Ø 'slice' method top and the T-Ø Parcel equilibrium level, the scheme may tend to give maximum rather than general cloud top heights.

ii. Rain area

In broad terms, the parametrization assumes that clouds that are large in height will also be large in area. The rain area is a function of updraught mass flux and shear. However, in all these experiments, the shear term was ignored, consequently, the controlling factor was the updraught mass flux, subject to the constraint described in Section 1.

Large CB clouds modelled by the scheme showed areas covering about one third of a ten kilometre square grid-box, suggesting cloud diameters of just over six kilometers. This agrees quite well with suggested sizes of such clouds reported in UK. Shallow shower clouds had rain areas of less than one tenth of a grid-box, suggesting clouds of about four kilometres in diameter.

One particular case is worth attention at this point. A late autumn WNW (polar maritime) airstream showed a very unstable profile, cloud tops suggested to 7000 m (level 13). However, since the airmass was cold and moist, the condensation level was low. Consequently the overriding mass flux constraint ensured that while cloud tops were high, the rain area was small. This contradicts the general rule. However, it makes sense synoptically since many cold airstream showers are frequent, and quite heavy but relatively small in area.

It would seem therefore that the use of mass flux constraints to determine or control the size of cloud units is a most suitable criterion and that the scheme produces realistic rain areas.

iii. Entrainment

The representation of the updraught appears reasonable in all cases tested. The degree of cooling due to entrainment of environment air as the parcel ascends is very closely related to the humidity of that environmental air. The amount of air actually entrained into the rising parcel is sufficient to double the mass of the parcel by the time it reaches the top of the cloud; this amount is substantiated by observations. (See Fritsch and Chappel (1981)).

iv. Vertical velocities

Maximum vertical velocities range from about eight metres/second for early morning convection, i.e. shallow, to near 20 m/s in large CB clouds where a moderate shower may be occurring. In some examples of thunderstorms, with intense rainfall rates, vertical velocities of over 40 m/s were predicted by the model.

While these seem somewhat excessive, they play no part in scaling any other factor within the parametrization. They are used solely to calculate the cloud top during the entrainment process. Hence, although it is fair to assume that the absolute values may not be correct, they give a good indication of the intensity of convection.

(At the base of the cloud, a vertical velocity of two metres/second is prescribed). Vertical velocities are largely dependent on the buoyancy of the parcel i.e. the temperature difference between the parcel and the environment. Consequently, any errors in the entrainment process - itself almost certainly a simplification of very complex interactions - will produce errors in the vertical velocities.

v. Rainfall Rates

The parametrization calculates rainfall rate as a function of the total condensate produced. It is given as a rainfall "total" for the whole ten kilometre grid box. However, the rain area for the cloud is also calculated. If the rainfall amount is related to the actual rain area, a more realistic and meaningful rate of rainfall value is obtained.

Initial experiments were not examined too critically with regard to rates of rain. Most clouds produced rates over the rain area appropriate to a moderate shower i.e. up to ten mm hr^{-1}. Some of the later experiments involving very unstable situations produced rates of 15-20 mm hr^{-1} and even over 20 mm hr^{-1} on isolated occasions. These later cases were compared with combined raingauge/radar rainfall analyses prepared by Met O 8 for hourly periods on the dates under investigation. A favourable comparison of rates was found. This suggests that the production of rainfall by the scheme is realistic and capable of producing reasonable indications of rates not only for ordinary showers but also large thunderstorms.

vi. Modifications to the Environment

Environmental modifications from winter cases, based on midday profiles, produced reasonable profile structures. However, when the scheme was run on markedly unstable summer profiles, an undue amount of warming was noted in the modified profile at mid-levels (750-500 mb). This produced a grossly over-stabilised profile which would not reconvect without a totally unrealistic heat input at the surface.

It was felt that the more realistic process of initiating convection earlier in the day, i.e. with a lower convection temperature, from a dawn modified midnight profile should be explored. Experiments based on this concept showed no excessive warming in the final modified profiles, equivalent to convection at maximum temperature. There may have been four cycles - though more generally three - from dawn to maximum temperature, each modified profile reconvecting after an input of surface heating equivalent to about one to two hours. For example, convection initiated by warming from dawn to 0900, and lasting one hour, could be re-initiated by midday and again with maximum temperatures between 1400 and 1500.

There is a consistent drying of the profile at middle levels. Condensed moisture is summed over the depth of the cloud and then either rained out or held as cloud water. The non-precipitated cloud water is partitioned between the cloud levels with a greater amount in the top half to simulate anvil outflow.

The modified environment level designated as that of the cloud top is always saturated with a marked cooling compared with the original environment profile.

At the surface, there is a cooling of the environment due to the replacement of air by the cold downdraught. The amount of cooling is dependent on the area of the downdraught: small clouds produce a cooling of only 0.1 to 0.5°C while very large clouds produce a cooling of around 1.5°C. It is realised that these temperature drops do not accurately model the very large drops that may accompany thunderstorms in reality. There is usually a decrease in HMR at the surface, but sometimes HMR actually increases. The net result of the changes in temperature and HMR is usually a decrease in relative humidity at the surface. This is because the decrease in HMR is large compared with the decrease in temperature. However, in very unstable cases where there is a more marked cooling, the relative humidity actually rises after convection.

These effects are apparently balanced quite critically and it is therefore imprudent to draw too many generalised conclusions. However, the concept of a moist, cool downdraught affecting the surface layer after/during convection is represented to some extent.

References

Golding, B.W. 1980 A penetrative convection scheme for the mesoscale model. Met O 11 Working Paper No. 46.

Fritsch, J.M. and Chappell, C.F. 1980 Numerical prediction of convectively driven mesoscale pressure system, Pt I, convection Parametrization. J. At. Sc. 37, pp 1722-1733.

APPENDIX I - NOTES ON FIGURES

Fig 1. This is one of the early test cases. It is for a profile based on combined Hemsby and Crawley 12Z soundings. The situation (3 July 1982) was a slack North westerly flow over UK with isolated showers developing, some of these growing into thunderstorms later in the afternoon. Upper levels were cooling from 00Z to 12Z and no doubt this cooling continued through the afternoon.

Much of the CU and CB reported was at a base of around 3000 ft - the scheme suggested 3300 ft. The presence of thunderstorms suggests tops rather above those predicted by the model though the rate of rainfall over the rain area certainly points to moderate or heavy showers, if not thunderstorms.

The surface temperature used in this run of the model was 18°C, the temperature at which showers and thunderstorms were apparently triggered.

There is an unrealistic warming of the modified profile between 850 and 650 mb.

Fig 2. This is a modified version of the profile in Fig 1, with an attempt at producing a dawn modified 00Z ascent. The surface temperature was set at 15.5°C, the lowest temperature at which convection was initiated. The modified profile was then further heated, simulating continued diurnal heating and this new profile rerun in the model with a surface temperature of 18°C, as in Fig 1. The first and second modified profiles are labelled accordingly.

A comparison of profile 2 in this figure with the modified profile in Fig 1 shows that the unrealistic warming has been removed and was not so much a feature of the parametrization scheme itself rather the unsuitable mode of the test.

There is only one cloud unit in the example of Fig 2 while the original of Fig 1 had two cloud units. Rainfall and rain area are reduced pro rata while the rate of rain over the rain area remains the same.

It was felt that the use of actual 00Z data would not be representative in view of the destabilisation taking place due to cooling aloft.

Fig 3. This profile was a combined ascent based on Shanwell and Stornoway (which were very similar), 3 July 1982, 12Z data. The general level of temperatures was lower in Scotland than in SE England; the flow was considerably stronger and markedly cyclonic. The model produced a lower suggested base than in SE England but reported bases were also lower viz 2500 ft observed c.f. 2300 ft in the model. The model cloud top of 350 mb is rather higher than observations would suggest since there are no thunderstorms reported, only showers.

Despite the height of the cloud, it is relatively small due to the constraint of available mass of air below cloud base. AMUT is noticeably smaller than in the Fig 1 case, despite the cloud top being considerably higher.

Maximum vertical velocity is rather large.

Fig 4. On this date, a small low centre lay just south of Cork (at 1500Z, 13 October 1982) with an unstable southwesterly flow over S England. This airstream was to the rear of a cold front which had brought thunderstorms to the area. The low centre was moving steadily East.

The profile was a combined ascent for Larkhill and Crawley, 12Z data. Reported cloud bases were around 2500 ft whereas the model suggests 2800 ft. The suggested model cloud top (level 12, 20,000 ft) seems on the high side since only light showers were being reported. Coupled with this, the rainfall rate for the rain area (13 mm hr^{-1}) is also inconsistent with light showers. In reality, it may be that very few parcels rose above the warm bulge in the profile at 700 mb, more generally producing tops around 11000 ft.

Again coupled with an over large cloud, there is evidence of over stabilisation of the modified profile between 900 mb and 650 mb.

Fig 5. This is an example of convection within a cold showery airstream, again with strong cyclonic flow. With low temperatures, the cloud bases reported were low, typically 1500 ft. This was well indicated by the model, 1100 ft. The most important aspect of this profile is the overriding constraint of available mass below the cloud. Although the cloud top is high and the AMUO value is large, the scaling factor AMUT is small because of the low cloud base. The rain area is therefore also small while the rainfall rate for the rain area is quite reasonable.

Modifications to the profile are small and only minimal cooling aloft would re-initiate further convection, correctly modelling the idea of frequent, fast moving showers.

Fig 6. This example is again based on a 00Z profile, modified for dawn temperatures and then heated at the surface, the heat being added into the lower layers (forming a DALR) until convection was initiated. This actually occurred with a surface temperature of 26°C, the value subsequently used in the model.

Observations suggest temperatures may have reached that value during the late morning but thunder storms did not break out until midday. (Temperatures were reported to 29°C with no showers or thunderstorms).

Bases reported were varied, 3500 to 4500 ft; the model indication of 4100 ft seems in agreement. The "cloud" was in fact so large that there was no indicated top other than the top of the model. At that level, vertical velocities were large, positive and still increasing: the updraught was still buoyant.

The AMUO factor of 0.1148E12 shows that the model cloud is larger than the standard model cloud of 8000 m (mass flux 10^{11} or 0.1E12 Kg). The profile is quite moist so the rainfall amount is large. There is no constraint on the size of the cloud (other than the limitation of the top level of the model) so the scaling factor AMUT is large. Hence the rain area covers almost a third of a grid square.

The rainfall rate for the rain area is 23 mm hr^{-1}. To verify the possibility of this value, an analysis of combined raingauge/radar data was obtained from Met O 8, see Fig 7. As can be seen, two points show computed hourly falls of 23 mm. Although there may be some error in the absolute values, they give a good indication that local rates in the range 20-30 mm hr^{-1} occurred during this afternoon. Hence, the predicted model value "verifies" well.

Once again, the maximum vertical velocity is too large.

FIG. 1

DATE: 3 July 82
TIME: 12Z
LOCATION: 'SE England'

Convection Initiated from level 1
ZBASE 1008m. 3300ft   Base at level 4
Top level 10
NCLOUD 2
AMUO 0.4675 E11
AMUT 0.9351 E11

Rainfall over whole grid 2.97 mm
Rain area 0.26 of grid square
Rainfall rate over rain area 11 mm/h
Maximum vertical velocity 16 m sec⁻¹

Initial temp profile	•———•
Initial HMR profile	x-----x
Modified temp profile	⊙———⊙
Modified HMR profile	⊗-----⊗
Updraught temp profile	x— —x

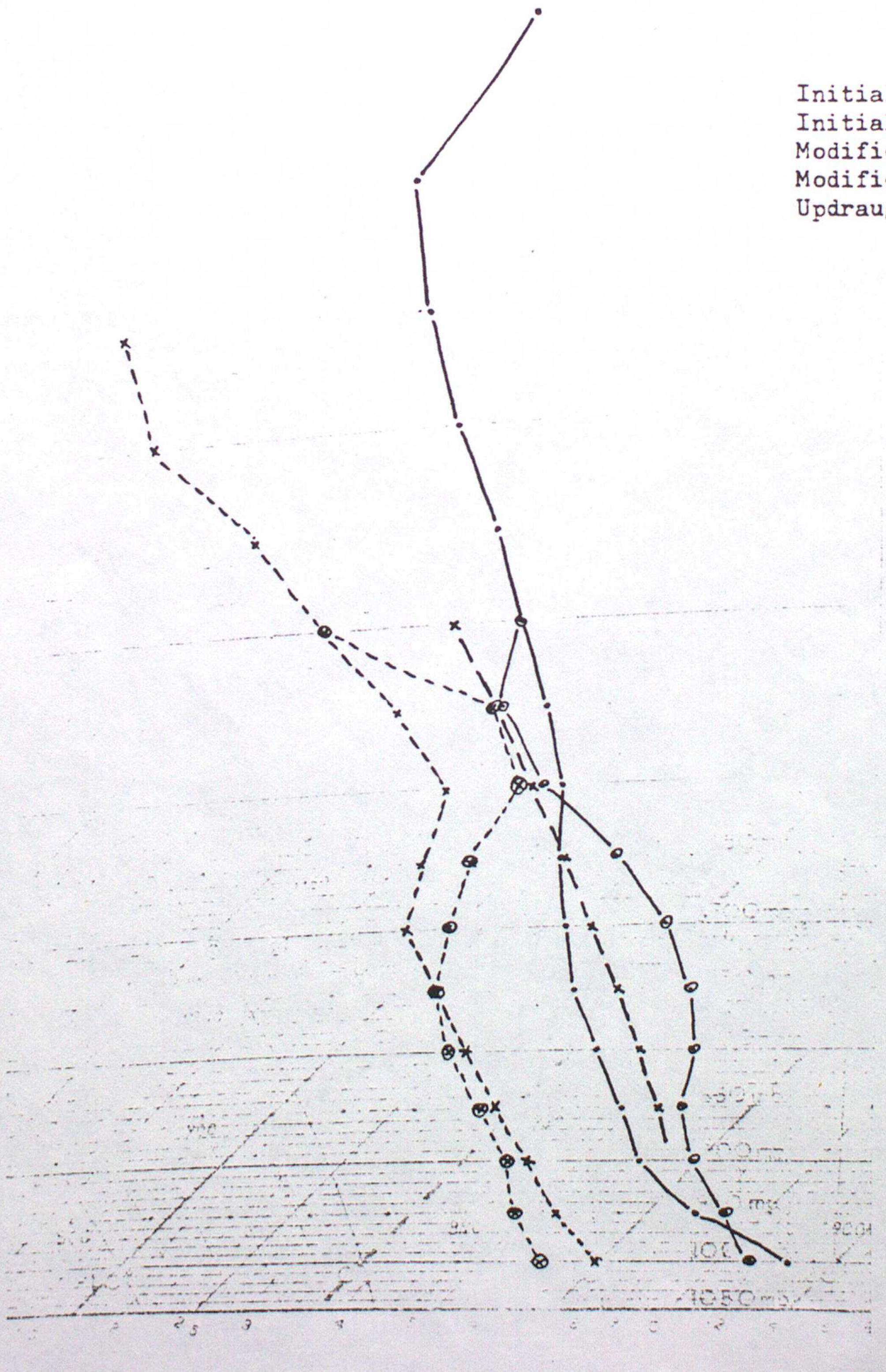


FIG.2

DATE: 3 July 82

TIME: Pseudo 00Z

LOCATION: 'SE. England'

Convection Initiated from level 1

ZBASE 1009m 3300ft

Base at level 4

Top level 10

NCLOUD 1

AMUO 0.4635 e1

AMUT 0.4635 e1

Rainfall over whole grid 1.5 mm

Rain area 0.13 of grid square

Rainfall rate over rain area 11 mm/hr

Maximum vertical velocity 12 m/sec

Initial temp profile •———•
Initial HMR profile x-----x
Modified temp profile ⊙———⊙
Modified HMR profile ⊗-----⊗
Updraught temp profile x—— ——x

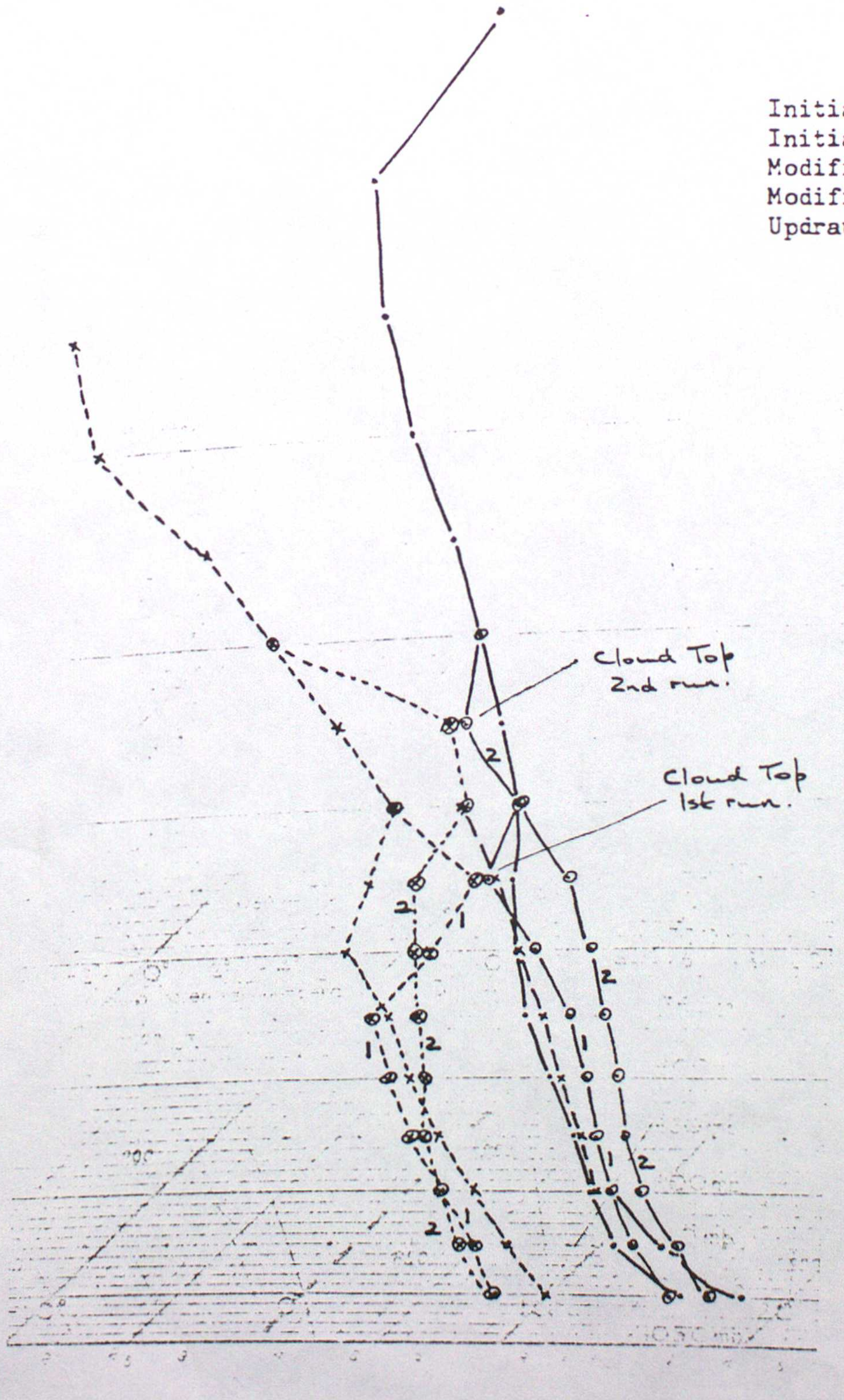


FIG.3

DATE: 3 July 82.

TIME: 12 Z

LOCATION: 'Scotland'

Convection Initiated from level 1

ZBASE 697m 2200ft

Base at level 3

Top level 14

NCLOUD 2

AMUO 0.3955 E

AMUT 0.6969 E

Rainfall over whole grid 3.1 mm.

Rain area 0.19 of grid square

Rainfall rate over rain area 16 mm/h

Maximum vertical velocity 37 m sec

Initial temp profile •——•

Initial HMR profile x-----x

Modified temp profile ⊙——⊙

Modified HMR profile ⊗-----⊗

Updraught temp profile x— —x

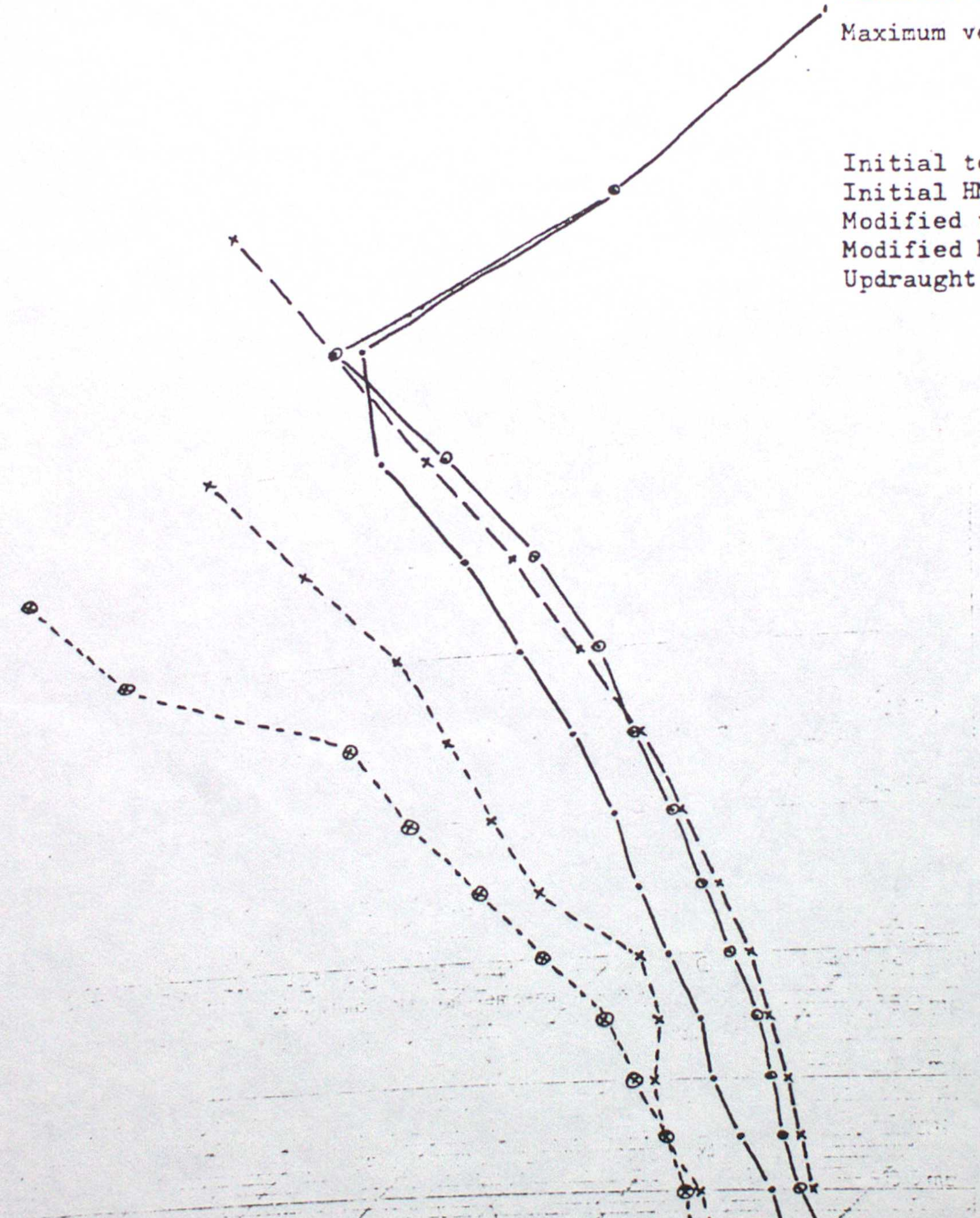


FIG.4

DATE: 13 OCTOBER 82

TIME: 12 Z

LOCATION: S. ENGLAND

Convection Initiated from level 1

ZBASE 863 m
2800 FT

Base at level 3

Top level 1

NCLOUD 1

AMUO 0.6618 E11

AMUT 0.6618 E11

Rainfall over whole grid 2.4 mm

Rain area 0.18 of grid square.

Rainfall rate over rain area 13 mm hr^{-1}

Maximum vertical velocity 16 m sec^{-1}

Initial temp profile •——•
Initial HMR profile x-----x
Modified temp profile ⊙——⊙
Modified HMR profile ⊗-----⊗
Updraught temp profile x— —x

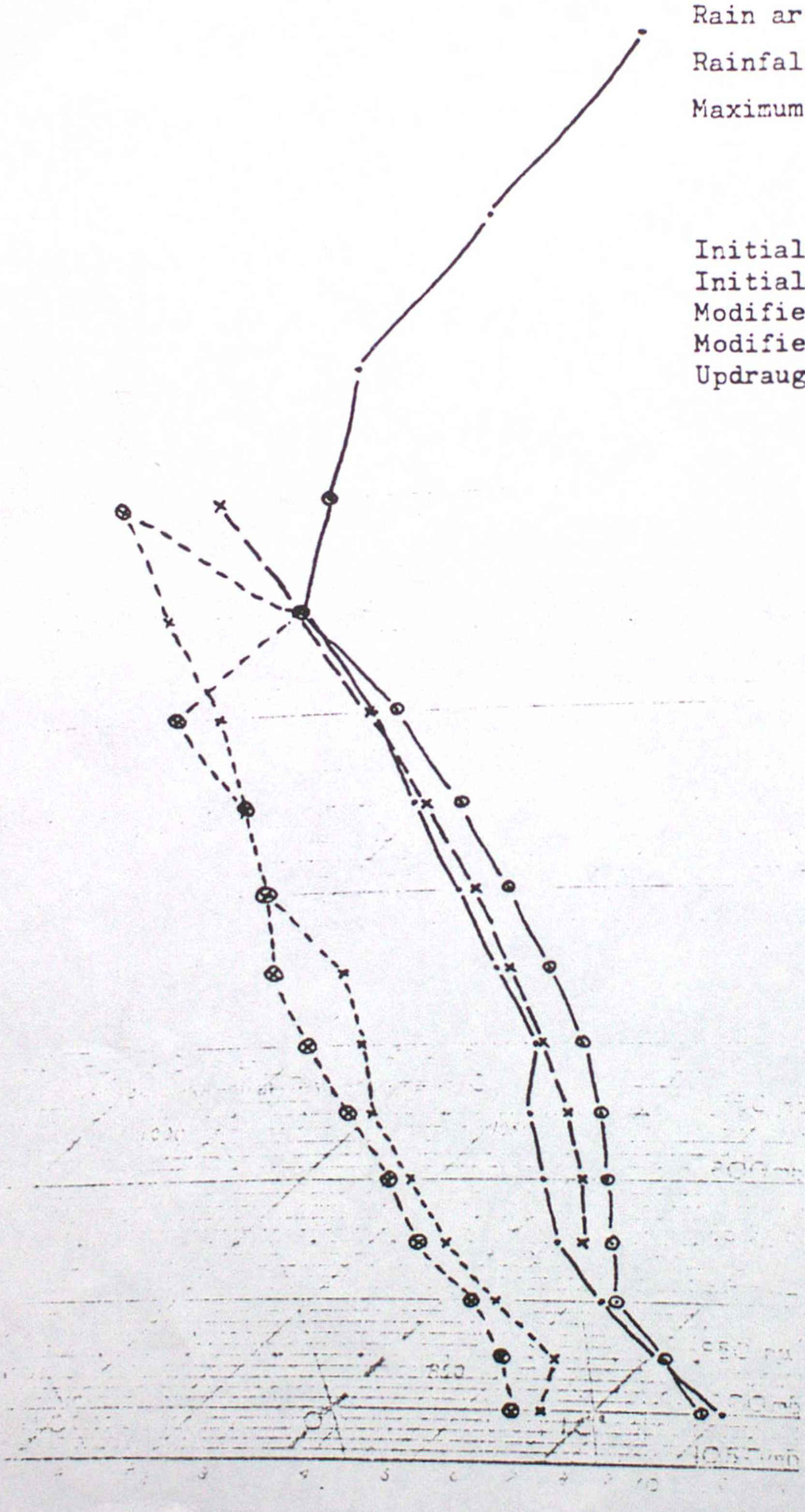


FIG.5

DATE: 19 Nov 82

TIME: 12Z

LOCATION: STORNOWAY

Convection Initiated from level 1

ZBASE 329m
1100ft

Base at level 2

Top level 13

NCLOUD 1

AMUO 0.8121 E1

AMUT 0.3286 E1

Rainfall over whole grid 1.1 mm

Rain area 0.09 of grid square

Rainfall rate over rain area 12 mm

Maximum vertical velocity 11 m sec⁻¹

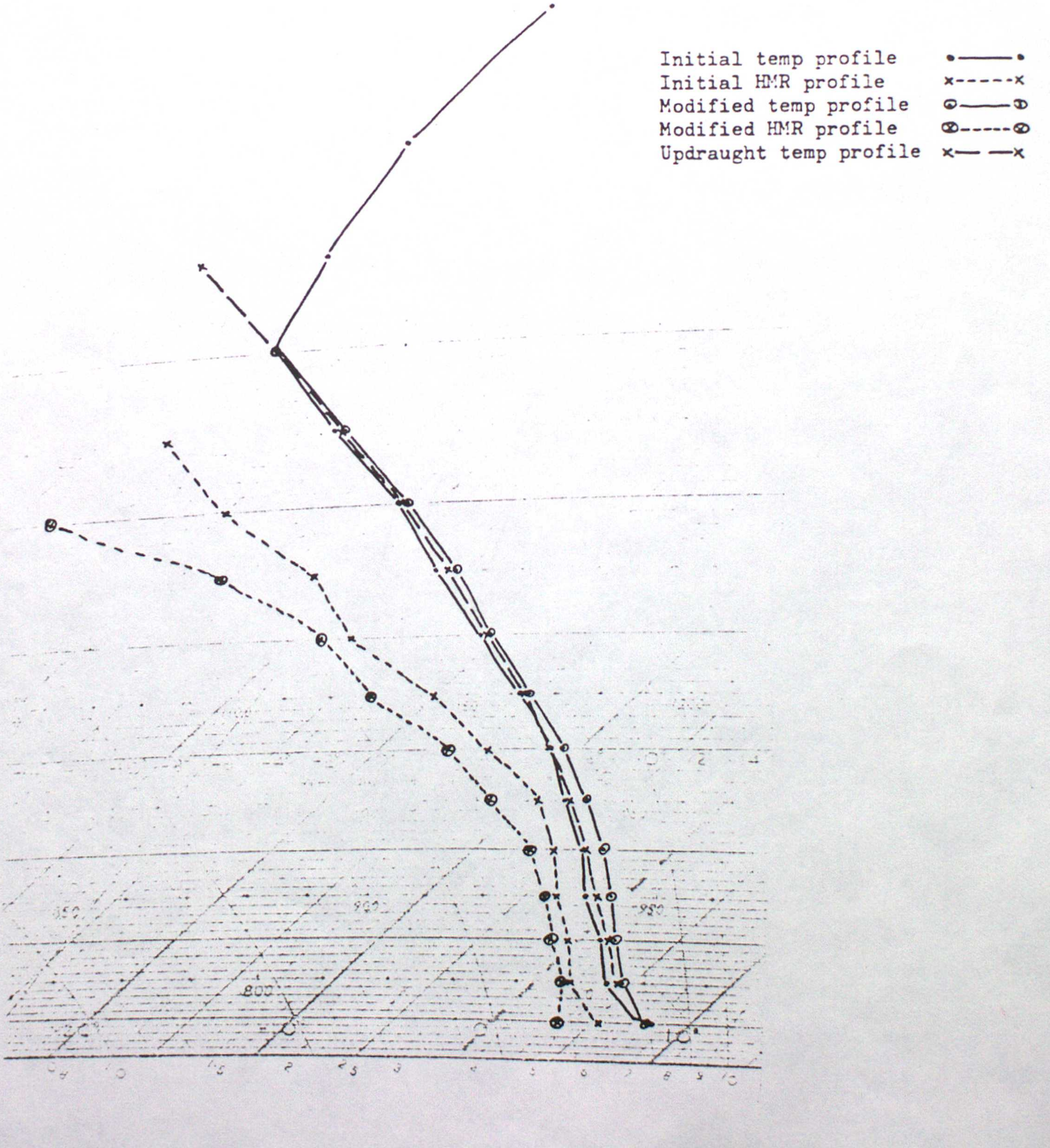


FIG.6

DATE: 5 JUNE 82

TIME: 00Z

LOCATION: HEMSBY.

Convection Initiated from level

ZBASE 1259m
4100ft

Base at level 4

Top level 16

NCLOUD 1

AMUO 0·1148 E

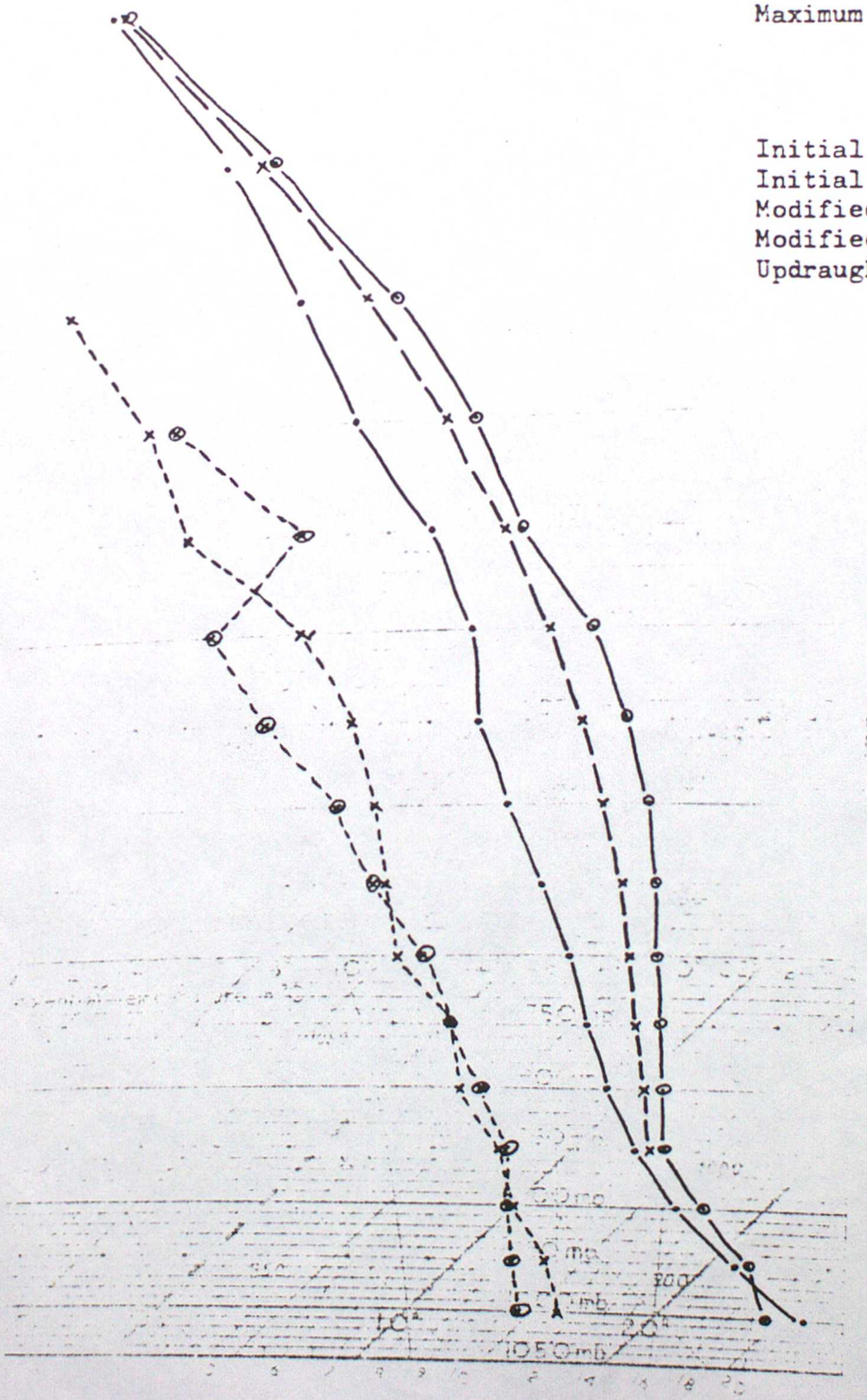
AMUT 0 1148 E

Rainfall over whole grid 7·3 mm

Rain area 0·32 of grid square

Rainfall rate over rain area 23 mm

Maximum vertical velocity 45 m/s



Initial temp profile •——•
Initial HMR profile x-----x
Modified temp profile ⊙——⊙
Modified HMR profile ⊗-----⊗
Updraught temp profile x—— ——x

FIG.7 COMBINED RAIN-GAUGE/RADAR ANALYSIS.

(Hourly values in tenths of mm.)