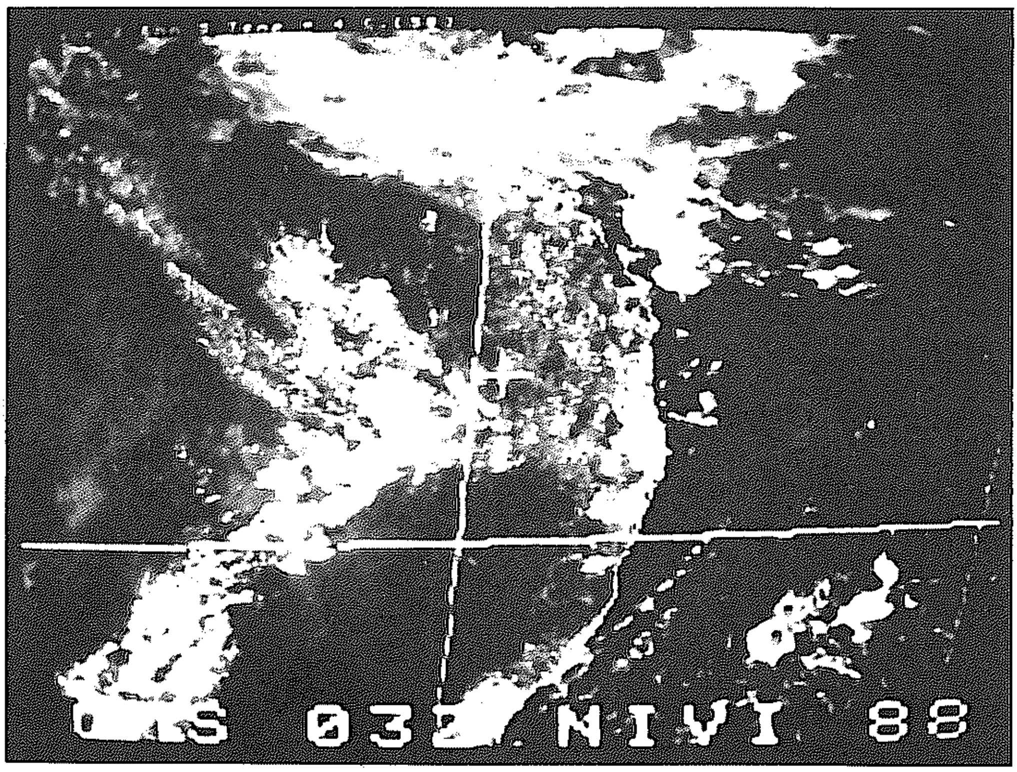
BUREAU OF METEOROLOGY
DEPARTMENT OF THE ARTS, SPORT, THE ENVIRONMENT, TOURISM AND TERRITORIES

REPORT ON THE COOYAR FLASH FLOOD

FEBRUARY 1988



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THE COOYAR FLASH FLOOD OF FEBRUARY 1988

J.J.Callaghan and J.T.Davidson
Severe Weather Section
Brisbane Regional Office

ABSTRACT

Within the constraints of the available data, an investigation was conducted into meteorological aspects of a flash flood event which devastated the village of Cooyar, some 130 kilometres west-northwest of Brisbane. The event occurred around 1400 UTC 12 February 1988 (midnight local time). Torrential thunderstorm rain fell in the catchment area above the village in the 4 or so hours before midnight.

The aim of the study was to document meteorological conditions surrounding the event and attempt to identify possible focussing mechanisms which concentrated such exceptionally high rainfall in a relatively small area. At the time several features generally associated with flash flood events were in evidence. To complete the analysis, rainfall data was examined from both a spatial and temporal perspective.

INTRODUCTION

During the late evening of 12 February 1988, thunderstorm activity brought torrential rain to the Cooyar Creek catchment. This deluge caused rapid rises in the Cooyar, Logyard and Back Creeks which merge behind the village of Cooyar. Water to a depth of 2 metres is reported to have swept through Cooyar around midnight destroying at least 3 houses, the local shop and the town hall. One person was confirmed drowned while another is presumed drowned. Shortly after the event, the Queensland State Government declared Cooyar a disaster area. Some appreciation of the damage wrought by the surge of water can be obtained from the various scenes in Fig. 1.

Figure 2 is a location map showing Cooyar, elevation contours and place names used in the text. The Cooyar Creek catchment is situated in the northwest corner of the Brisbane River catchment and is bounded by the Main Divide to the west, by the Cooyar Range to the northwest and by the Blackbutt Range to the southeast. The catchment area is approximately 156 square kilometres.

Rainfall isohyets for the 24-hour period from 2200 UTC 11 February to 2200 UTC 12 February 1988 are displayed in Fig. 3. The highest verifiable totals were 249 mm and 246 mm at 2 recording sites on 'Vincentvale' station. 'Trevanna' station which is nearby registered 240 mm. Between 8 pm and midnight (local time) the rainfall was observed by local residents to be at its most intense.

In this paper, the synoptic-scale evolution surrounding the event is described together with commentary on atmospheric stability. Further, the role of satellite and radar imagery in monitoring development is discussed. Vertical motion and the sub-synoptic scale environment are then examined in some detail. Features common to flash floods are later identified and parallels drawn with the Cooyar event.

Fig. 1(a) Cooyar destruction.

Fig. 1(b) Damaged house Cooyar.

Fig. 1(c) Demolished house, Cooyar.

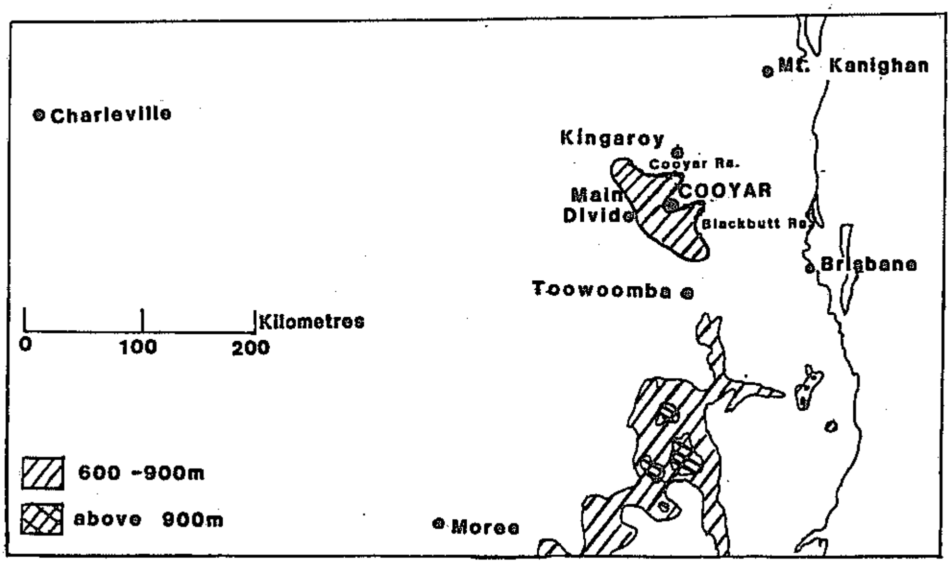

Fig. 2 Location map.

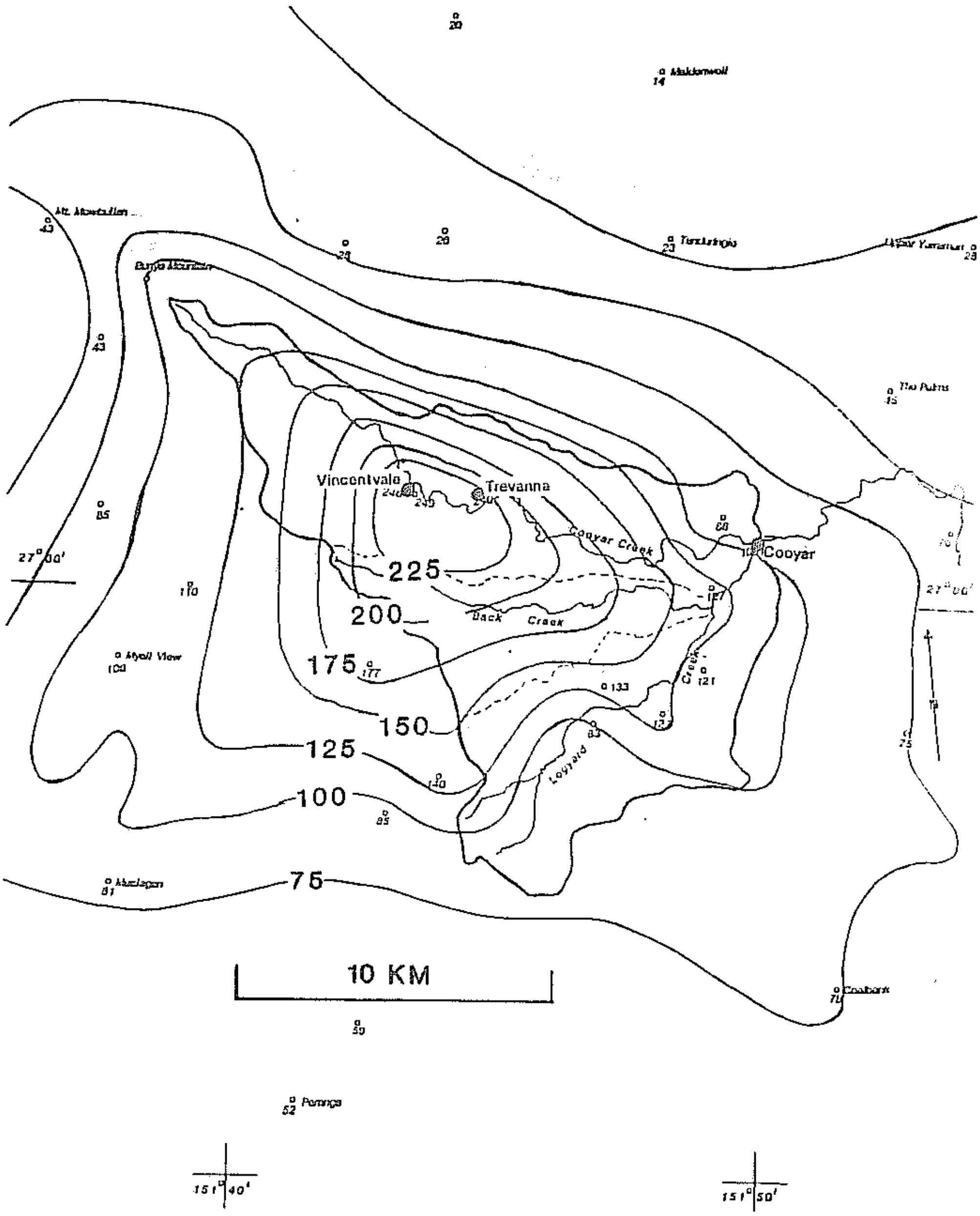

Fig. 3 Rainfall isohyets for period 2200 UTC 11 February 1988 to 2200 UTC 12 February 1988 (millimetres).

Results from a 'Probable Maximum Precipitation' analysis for the catchment are provided and a 'Design Rainfall Intensity' display interpreted. Lastly and in brief, the performance of the Bureau's operational Finest model at that time is evaluated.

SYNOPTIC-SCALE CONSIDERATIONS

In Fig. 4 a sequence of mean sea level (MSL) analyses is presented with superimposed 1000-500 hPa thickness contours spanning the period 0000 UTC 11 February to 0000 UTC 13 February 1988. Synoptic features include an intense slow-moving depression in the Tasman Sea and a low pressure area associated with a weakening thermal trough moving northeastward through New South Wales. At the same time, a high in the Southern Ocean was travelling eastward towards Tasmania. The pressure pattern at 0000 UTC 12 February 1988 points to synoptic-scale confluence existing over inland parts to the west of Brisbane.

Sequences of streamlines at 6-hourly intervals for 4 levels from 850 hPa to 250 hPa are produced in Fig. 5. The following features relevant to the event at Cooyar are noted:

850 hPa A confluent zone on the eastern flank of an area of inflow moved towards Cooyar (denoted by the dark circle) and became quasi-stationary over inland southeast Queensland.

700 hPa A ridge east of a major trough was located over Cooyar and moved slowly east to be oriented along the coast by the end of the period. This ridge is considered crucial to the observed rainfall distribution and is discussed in more detail later.

500 hPa A major trough dominated the middle levels and extended into northwest Australia. However a smaller scale trough with a tilt towards the northeast and located to the near west of Cooyar evolved during the period.

250 hPa Likely influences are difficult to diagnose. The lack of data to the east of Cooyar makes calculations of upper divergence unreliable. Using the barotropic vorticity equation (Palmen and Newton 1969) upper divergence zones can be approximately defined by areas of cyclonic vorticity advection. Cooyar lay east of a 250 hPa trough so that changes in flow curvature would contribute to cyclonic vorticity advection. However an obstacle is determining whether the local wind speed maximum is located north or south of Cooyar at 0400 UTC and 1000 UTC 12 February 1988. This would be critical in calculating the contribution to cyclonic vorticity advection by changes in horizontal wind shear.

SATELLITE IMAGERY

Very little cloud existed over southeast Queensland during the morning of 12 February 1988 (not shown) with the effect of the approaching middle-level system yet to be felt. The evolution and scale of the precipitation area is best illustrated by a sequence of visible and enhanced infrared geostationary meteorological satellite (GMS) imagery (Fig. 6).

A mass of (cold) high cloud over southeast Queensland can be seen to spread from convective cells. In Figs 6 (c) and 6 (d), temperatures colder than about -40°C (delineating the higher cloud tops) are shaded black. This temperature value corresponds to a height of about 10 km. The relative decrease in extent of high

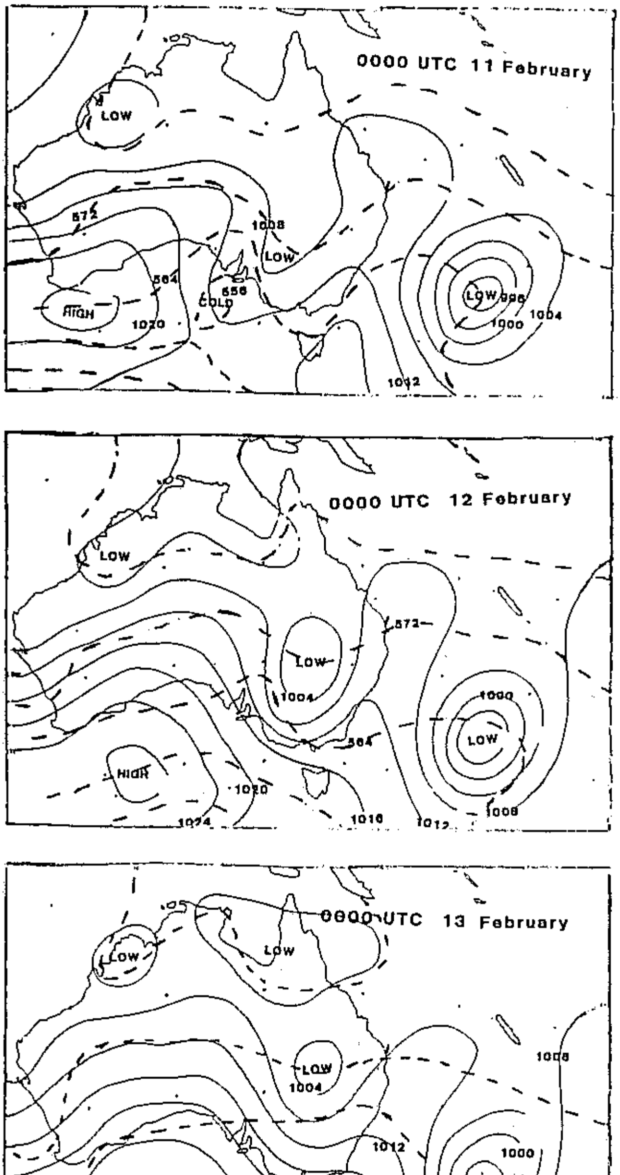

Fig. 4 MSL analyses with superimposed 1000-500 hPa thickness contours.

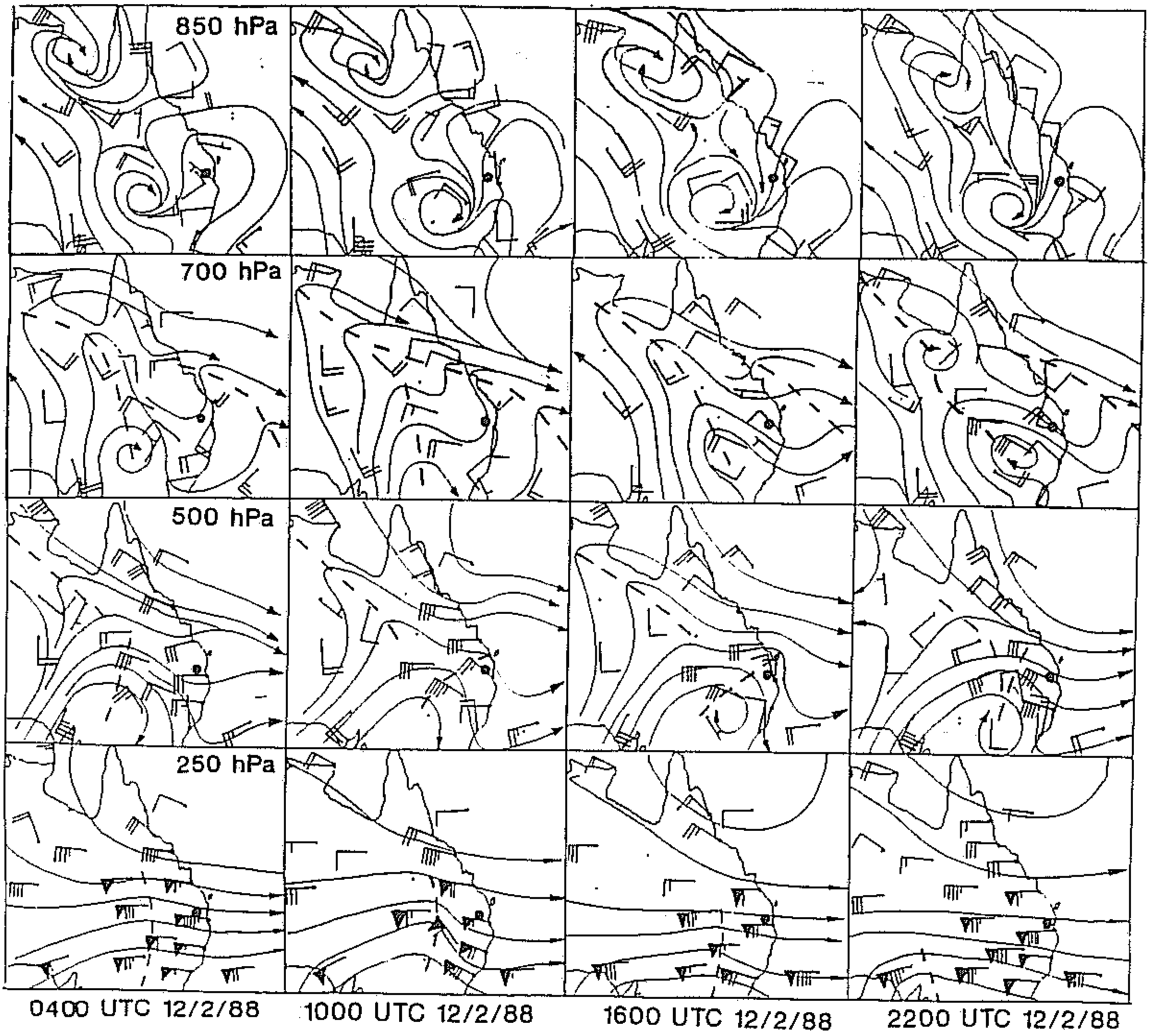

Fig. 5 Sequence of streamlines at 850, 700, 500 and 250 hPa for period 0400 UTC to 2200 UTC 12 February 1988.

Flags, barbs and half barbs on the wind photo represent 25 m/s, 5 m/s and 2.5 m/s respectively.

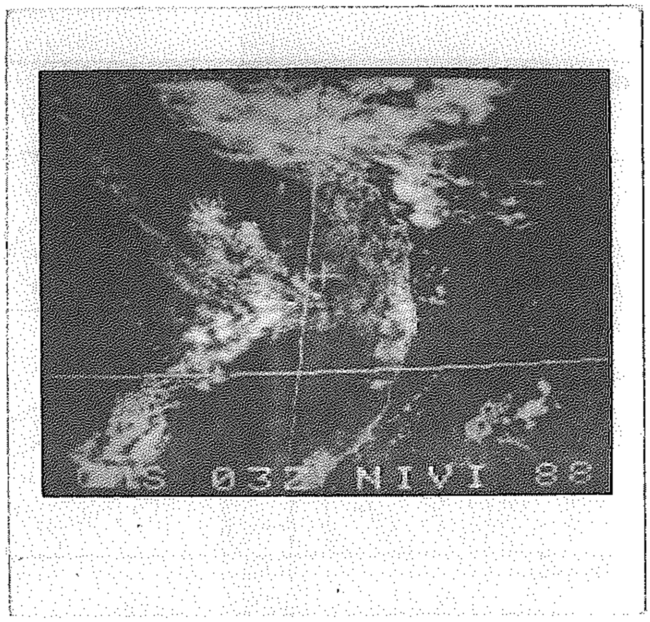

Fig. 6(a) Visible wavelengths GMS-3. Satellite photograph 0300 UTC 12 February 1988.

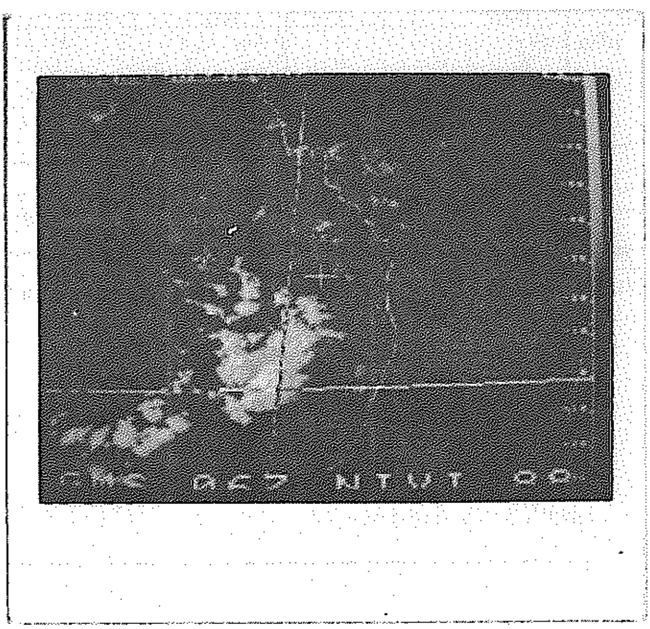

Fig. 6(b) Visible wavelengths GMS-3. Satellite photograph 0600 UTC 12 February 1988.

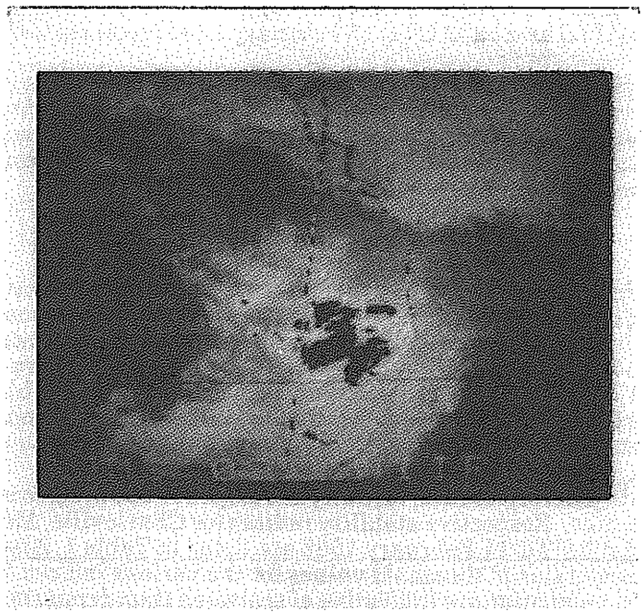

Fig. 6(c) Infrared wavelengths GMS-3. Enhanced satellite photograph 0900 UTC 12 February 1988.

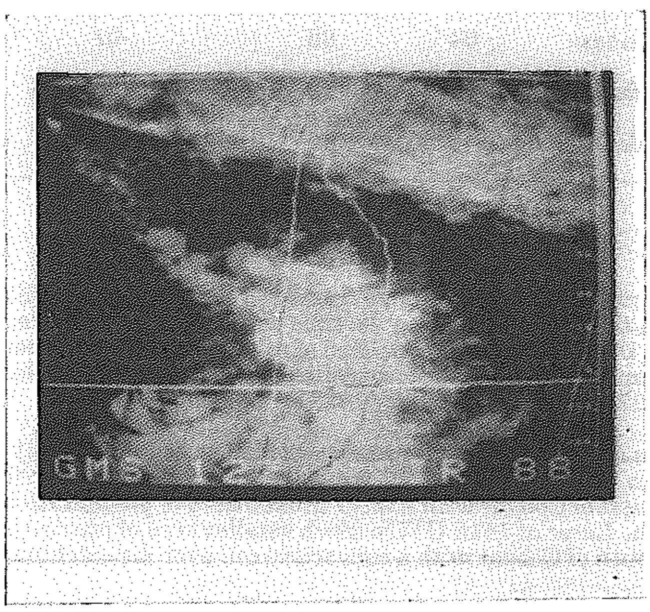

Fig. 6(d) Infrared wavelengths GMS-3. Enhanced satellite photograph 1200 UTC 12 February 1988.

cloud - equivalent to a reduction in mean depth of the convective complex - between 0900 UTC and 1200 UTC 12 February 1988 is clearly visible.

About 0900 UTC, Toowoomba experienced a severe thunderstorm with 4 cm diameter hail and a 33 mm downpour. Note that the heavy rain around Cooyar occurred several hours later. Many who experienced heavy rain reported hearing occasional thunder. It is worth noting that the high cloud mass south of latitude 30 degrees had little significant precipitation associated with it.

ATMOSPHERIC STABILITY

The first evidence of convection on satellite imagery appeared between the upper-air observing stations of Charleville and Moree just before noon on 12 February 1988. From the 0100 UTC synoptic reports, the dry-bulb temperature in the area was around 34°C and the dew-point near 18°C. If these values are applied to the 2200 UTC 11 February 1988 radiosonde traces in Figs 7(a) and (b), parcel theory would support convective cell development to an elevation of almost 11 km (neglecting entrainment).

The main convective cells initially developed in the broad confluence zone referred to earlier. Respective stability indices for Charleville, Moree and Brisbane at 2200 UTC 11 February 1988 are listed in Table 1. Also included are 'scattered thunderstorm' threshold values for the various indices. The indices at Charleville in particular are indicative of scattered thunderstorm activity.

Table 1. Stability indices at 2200 UTC 11 February 1988

	Brisbane	Moree	Charleville	Threshold
Showalter Index	04	03	-01	0
Whiting Index	10	23	39	35
Total - Totals Index	40	45	48	48

RADAR RECORDS

Radar observations were available from both Brisbane and Mt Kanighan throughout the episode. During the time the catchment area was being inundated, the precipitation consisted of rain from stratiform cloud with heavier falls from embedded thunderstorm cells. Skies had generally cleared around Cooyar by 2200 UTC 12 February 1988.

Brisbane weather watch radar reports have been manually plotted and displayed in Fig. 8. At 0930 UTC strong cellular echoes were evident just west and southwest of Cooyar with a large broken area of precipitation extending well to the south. Later at 1115 UTC a much smaller area of precipitation could be seen just south of Cooyar with a convective cell over the catchment region.

Figure 9 is a representation of Mount Kanighan digitised radar imagery for 1150 UTC (35 minutes after Fig. 8). A cellular echo (stippled for clarity) is now much closer to Cooyar representing a cell velocity of about 45 km/h towards the east-northeast. Although the ambient middle-level flow was westerly, thunderstorms in the southeast of the state are regularly observed to track to the

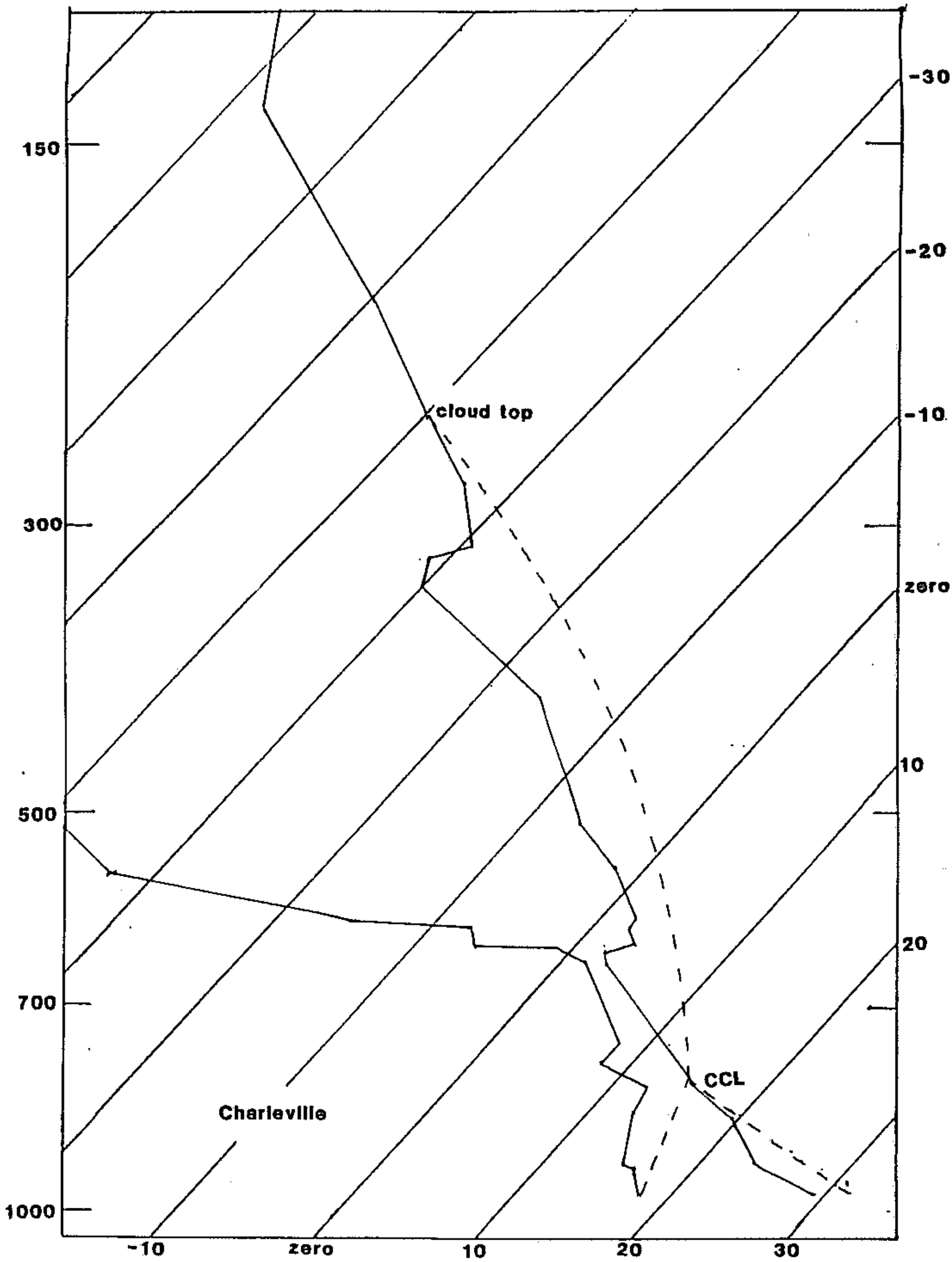

Fig. 7(a) Vertical temperature (°C) and dew-point (°C) sounding for 2200 UTC 11 February 1988 at Charleville.

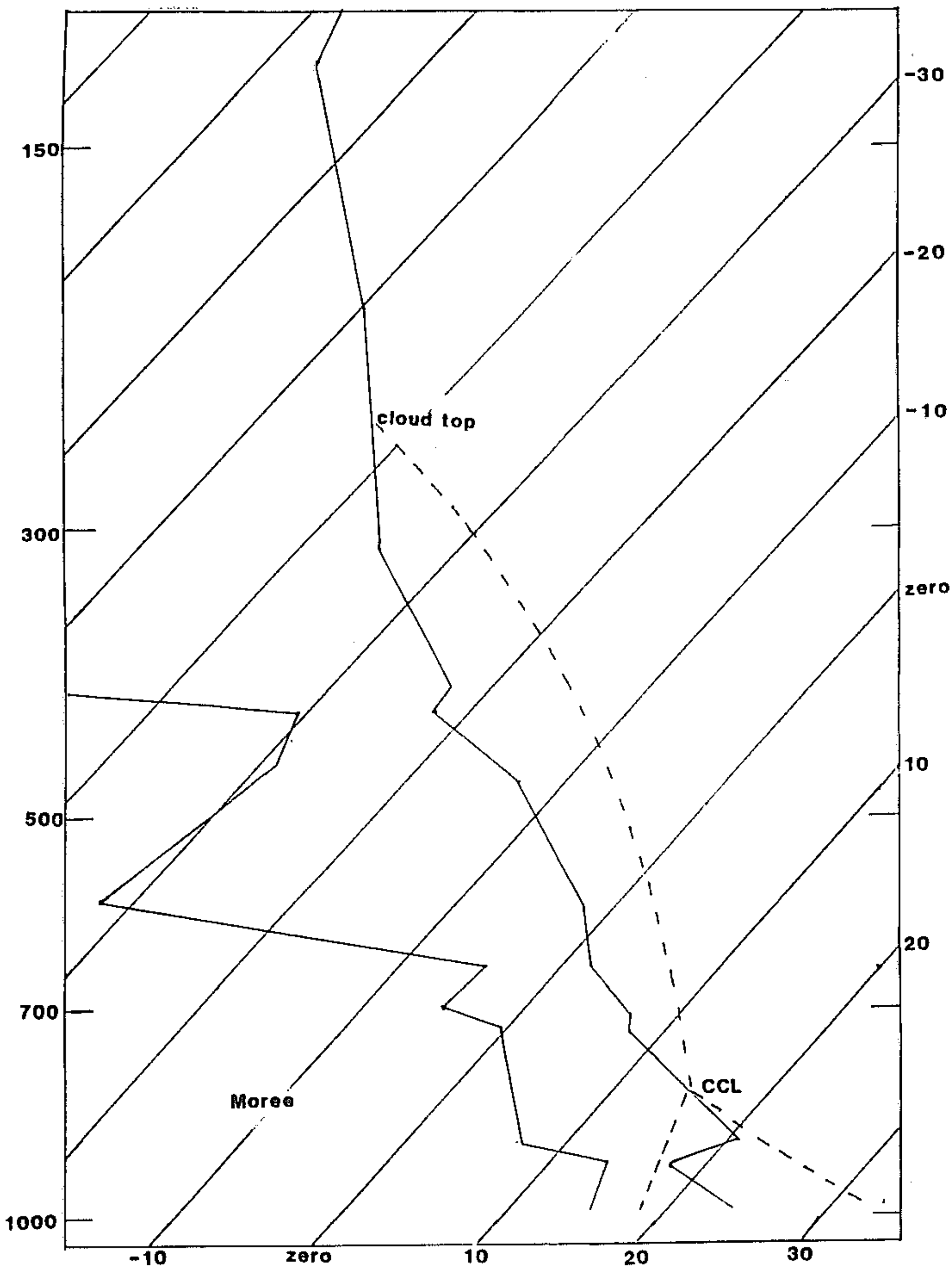

Fig. 7(b) Vertical temperature (°C) and dew-point (°C) sounding for 2200 UTC 11 February 1988 atMoree.

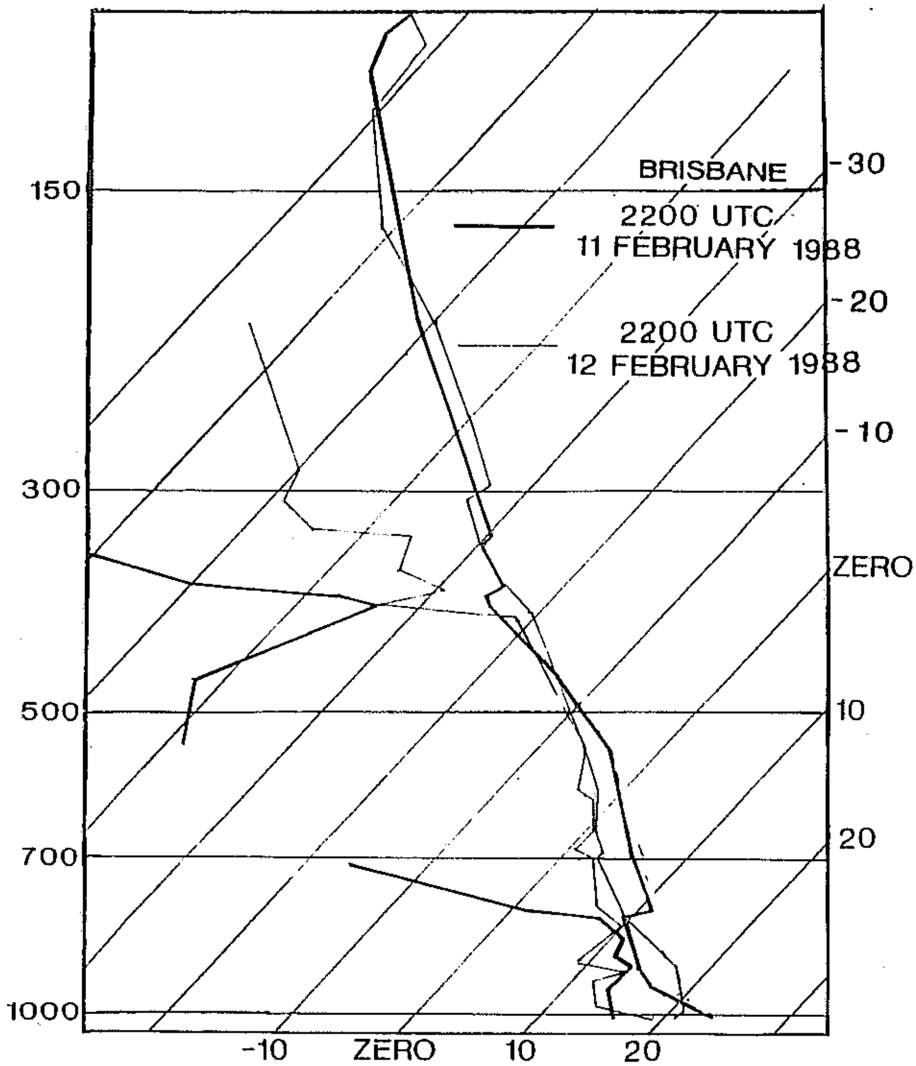

Fig. 7(c) Vertical temperature (°C) and dew-point (°C) sounding for 2200 UTC 11 February 1988and 12 February 1988 at Brisbane.

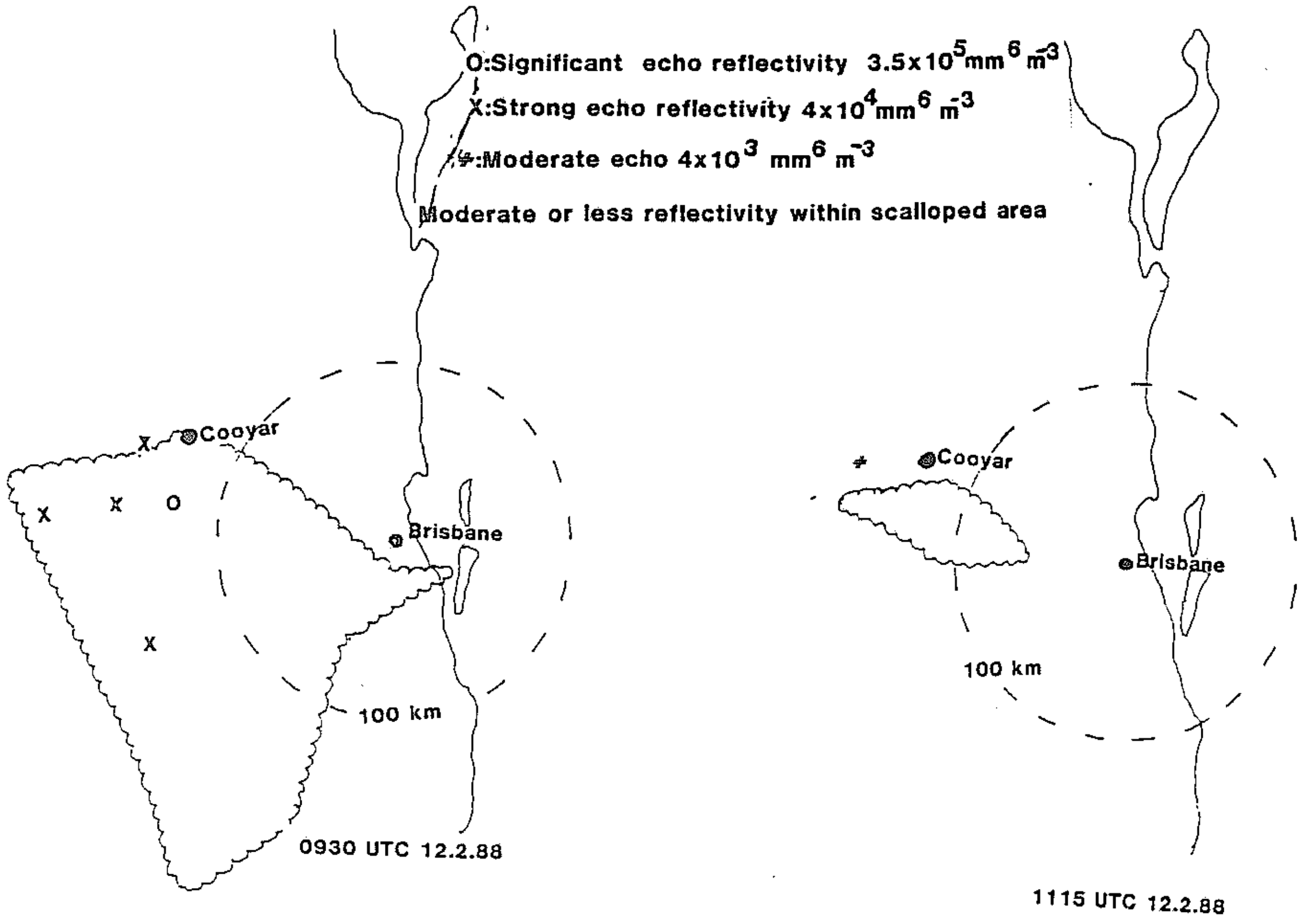

Fig. 8 Plotted radar reports from Brisbane.

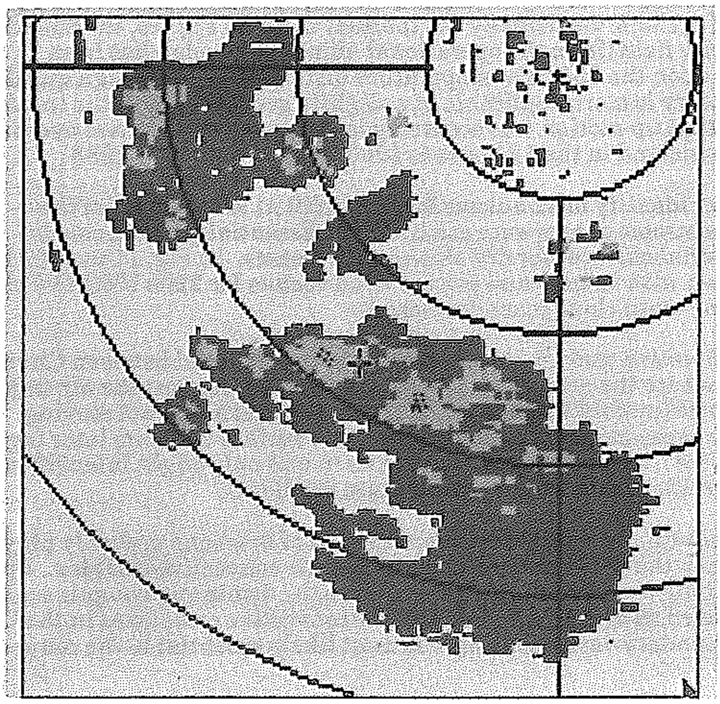

Fig. 9 Digitised radar imagery at 1150 UTC 12 February 1988, from Mt. Kanighan radar. Range rings at 50 km intervals and cross marks location of Cooyar.

left of the mean flow. Note that the scales for Figs 8 and 9 are quite different. From subsequent radar data the general rain area remained roughly orientated northwest-southeast through Cooyar until at least 1800 UTC the next morning.

Radar data suggests a multicellular convective complex became anchored over the catchment. Individual thunderstorm cells did track towards Cooyar and then dissipate after passing out of the rain band and moving off the eastern escarpment of the Great Divide. It is interesting to note that Kingaroy, some 50 km north of Cooyar, received only 3 mm of rain during the entire period.

VERTICAL MOTION

From quasi-geostrophic theory (Trenberth 1978), up-motion exists in the presence of advection of cyclonic vorticity by the thermal wind. In Fig. 10, the 850 hPa relative vorticity field (from the operational numerical model) has been superimposed upon the 850 hPa temperature distribution. Although quasi-geostrophic theory is more applicable at a slightly greater height, the inference can be drawn that up-motion was occurring in the lower troposphere over inland southeast Queensland in the 12 hours to 1200 UTC 12 February 1988.

To further identify mechanisms forcing uplift at lower levels of the atmosphere isentropic charts were constructed. Essentially, these charts represent material surfaces for dry abiabatic processes. In Fig. 11 the 303 K surface is shown with isobars and plotted wind vectors for 2200 UTC 11 February 1988 (before the main cloud mass developed).

Warm advection and up-motion is implied in a channel between Charleville and Brisbane where the orientation of the wind vectors suggest the air trajectory would rise approximately 100 hPa if the pressure pattern was not moving eastward. The pressure distribution on the same surface 24 hours later (again Fig. 11) indicates little movement in the pattern and only slight intensification in the pressure gradient (and hence temperature gradient).

Ascending air and warm air advection west of Brisbane probably played an important role in the development of the mesoscale convective complex. Doswell (1985) cited strong low-level warm advection as the dominant synoptic scale feature associated with similar multicellular convective complexes in the U.S.A. In this case, boundary-layer heating was most likely essential to the convective processes.

SUBSYNOPTIC-SCALE PARAMETERS

A major forecasting difficulty in Queensland is whether or not thunderstorms will develop over southeast coastal districts. It is not uncommon in summer for cumulonimbus clouds, extending up to 15 km or more, to collapse after descending off the ranges to the lower equivalent potential temperature (Theta E) region along the coastal plains.

Local research isolates two parameters as being strongly associated with the collapse of such storms. A detailed investigation is being carried out by this section into 200 storm events during a ten-year period in the area broadly covered by the regional MSL analysis in Fig. 12. Another study by J. N. Butler of the Brisbane Airport Meteorological Office (unpublished) covered a different ten-year period.

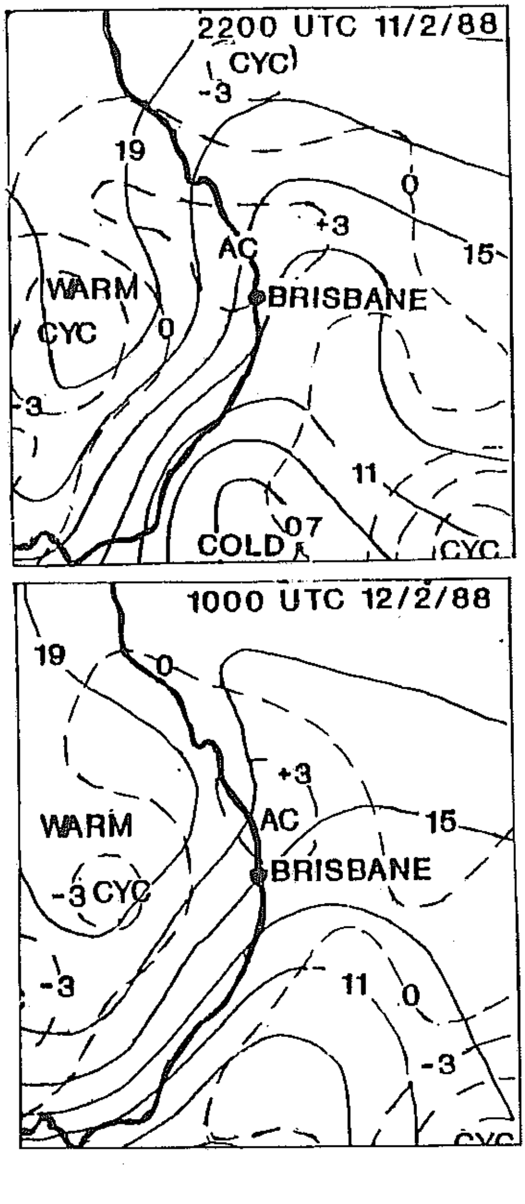

Fig. 10 850 hPa analyses for 2200 UTC 11 February 1988 and 1000 UTC 12 February 1988. Full lines temperature in degrees celsius. Dashed lines vorticity in $sec^{-1} \times 10^{-5}$.

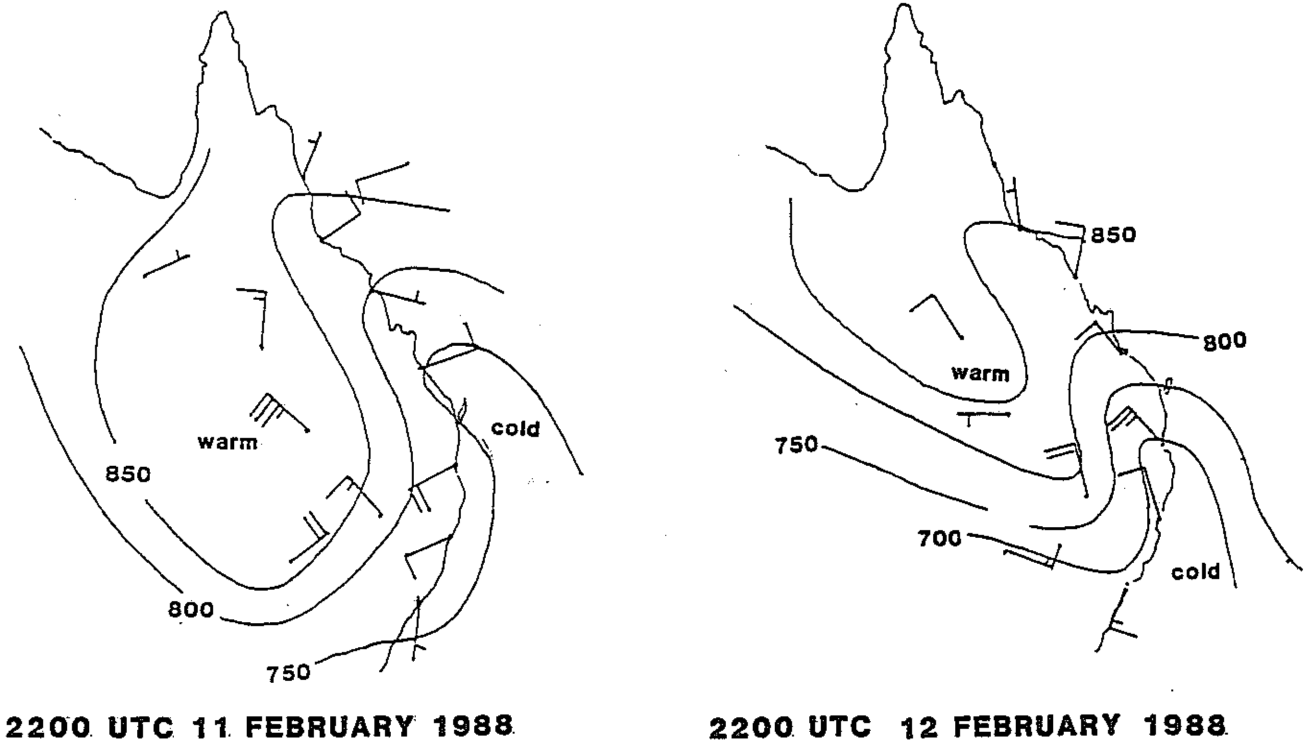

Fig. 11 Pressure (hPa) analyses on the 303K isentropic surface. Wind plotting convention as in Fig. 5.

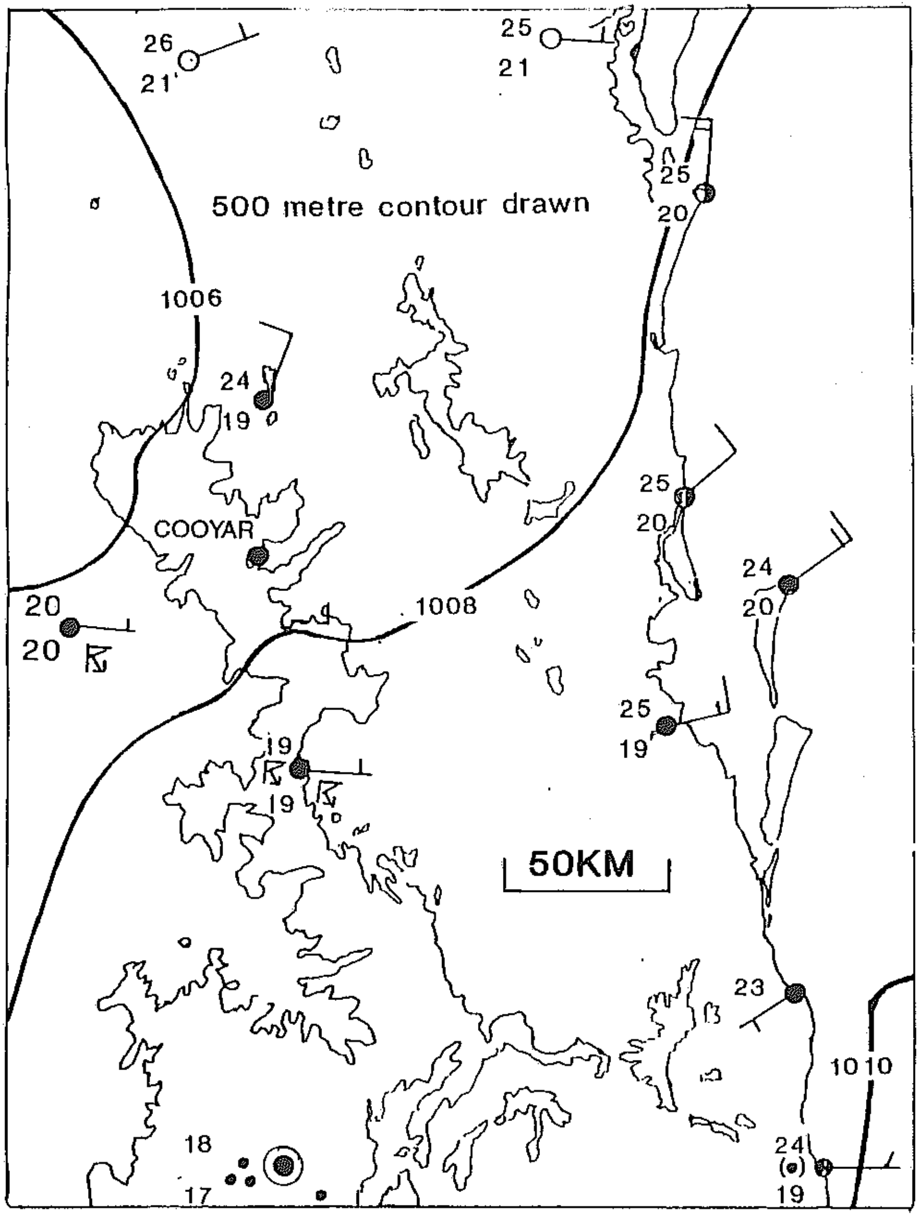

Fig. 12 Regional MSL analysis for 1100 UTC 12 February 1988.

Parameter 1: Vertical Wind Structure
If storms which arrive on strong cold fronts are neglected, there exists a favorable vertical wind structure for the advection of storms off the ranges to the coast. This structure consists of backing winds with height (warm air advection) from northerly to northwesterly near 900 hPa up to west-northwesterly to west-southwesterly winds at 700 hPa.

Parameter 2: Coastal Theta E
The other important parameter is the coastal Theta E ahead of the approaching storms. It has been found that in many cases when storms collapsed the observed coastal temperatures were less than the convective temperature at the same time. This convective temperature can be calculated graphically from the coastal temperatures and dewpoints at the time of collapse and the morning radiosonde trace.

A schematic vertical cross-section (Fig. 13) of the path of the convective complex which deluged Cooyar shows upslope motion to the top of the Great Divide. East of the Divide where the cells dissipated there is a sudden drop in elevation to the Brisbane River Valley.

A time section of the upper winds at Brisbane (Fig. 14(a)) shows the effects of the 700 hPa ridging mentioned earlier. At 0400 UTC and 1000 UTC 12 February 1988, south-southwesterly to southwesterly winds were observed in a layer centred at 700 hPa. At 900 hPa the winds were almost from the opposite direction and represented a vertical wind structure not conducive to the advection of storms off the ranges. It should be noted that by 2200 UTC warm advection predominated in the lower half of the troposphere as the ridge moved seawards. About this time the rain band which had previously remained quasi-stationary along the ranges had almost reached Brisbane.

A vertical temperature profile to represent the region just east of the Great Divide near Cooyar (Fig. 14(b)) at the time of the heavy rain was constructed from radiosonde and upper wind data at Brisbane. Details of its derivation is provided in Appendix 1.

The nearest observation to Cooyar east of the Divide at the time of the heavy rain was Kingaroy which is the station just north of Cooyar in Fig. 12. This station's temperature and dew-point were used to calculate the lifted condensation level in Fig. 14(b). It can be seen that a mechanism would need to be present to produce uplift to 850 hPa so that convective cloud could develop east of the Divide. As mentioned above little rain was recorded at Kingaroy during the event.

Therefore it appears that dynamic and thermodynamic factors combined to ensure that the convective complex could not propagate off the Great Divide. At the same time a low-level confluent (and presumably convergent) zone remained quasi-stationary in the general area to initiate redevelopment of cells.

FEATURES COMMON TO FLASH FLOOD EVENTS

Maddox et al. (1979) studied 151 flash floods and noted 8 features common to most of the events. These features with comment on their applicability to the Cooyar event are now presented:

(1) Flash floods were associated with convective storms.

- Certainly the case at Cooyar.

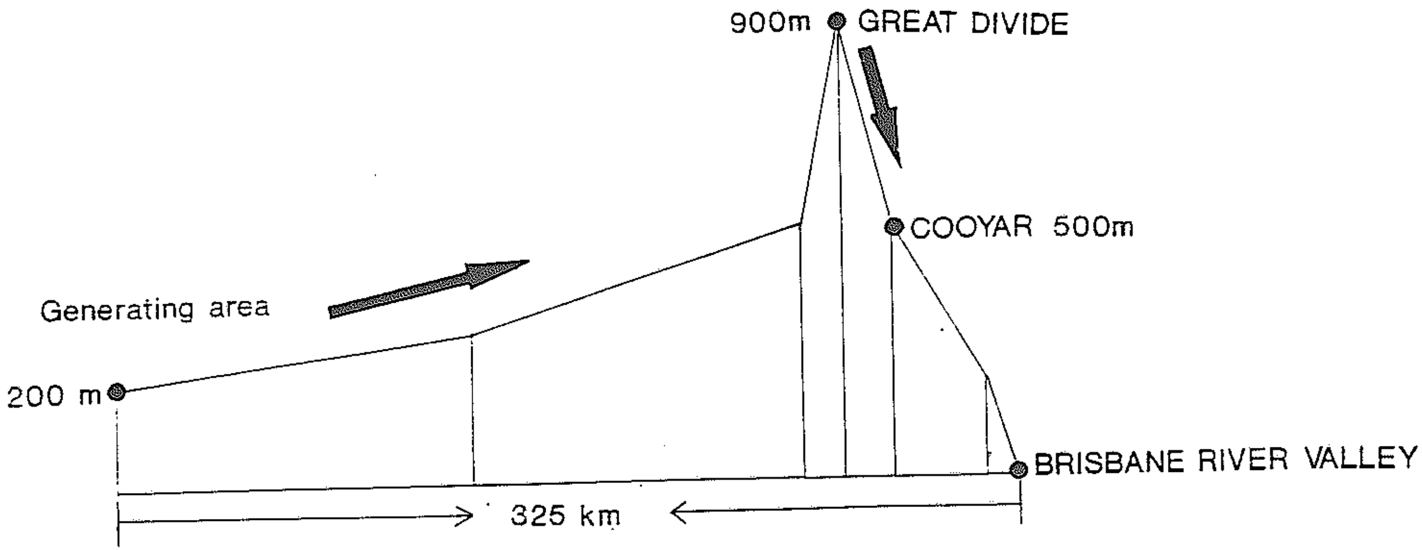

Fig. 13 Vertical cross-section of path of convective complex on 12 February 1988.

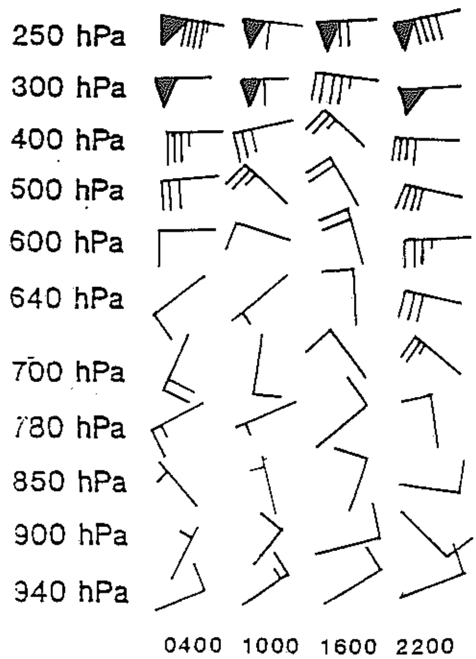

Fig. 14(a) Upper winds Brisbane 12 February 1988 (UTC). Wind plotting convention as in Fig. 5.

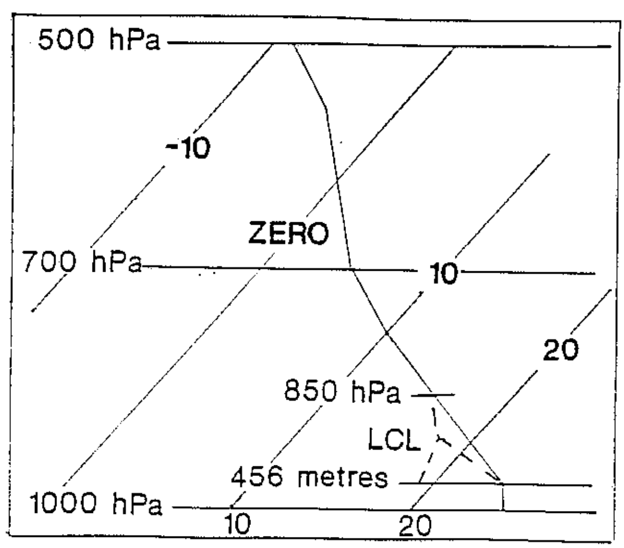

Fig. 14(b) Vertical temperature (°C) 1100 UTC 12 February 1988 near Kingaroy.

(2) Storms occurred in the regions with high surface dew-point temperatures.

● Prior to convective development, surface dew-points were in the 17/20C range which is quite high for inland parts of southeast Queensland.

(3) Relatively high moisture content was present through a deep tropospheric layer.

● From Fig. 7, the respective radiosonde traces are not particularly moist, so this condition was probably not so relevant to the Cooyar event.

(4) Weak to moderate vertical shear of the horizontal wind was present through the cloud depth layer.

● The closest rawinsonde station to Cooyar is Brisbane. About the time of the heavy rain (1200 UTC), the vertical wind shear there was generally weak to at least 400 hPa (Table 2). The relationship of vertical wind shear to precipitation efficiency is discussed in a later section.

(5) Convective storms and/or cells repeatedly form and move over the same region.

● Evidence presented earlier leaves little doubt that this was the case. As noted by Doswell (1985), it is often the succession of moving cells, passing over the same area at about the same heavily-precipitating stage in their life cycle (the so-called 'train effect'), that creates the high localised rainfalls seen in flash floods.

Table 2. Upper winds (m/s) at Brisbane Airport 1000 UTC 12 February 1988

200 hPa	270	44	600 hPa	290	5
250 hPa	280	31	700 hPa	195	6
300 hPa	270	31	800 hPa	245	2
400 hPa	260	16	850 hPa	345	2
500 hPa	315	12	900 hPa	040	6

Vertical Shears

800 to 300 hPa	$3.3 \times 10^{-3}\ s^{-1}$
800 to 400 hPa	$2.0 \times 10^{-3}\ s^{-1}$

(6) A weak mid-tropospheric mesoscale trough helped trigger and focus the storms.

● At 1000 UTC 12 February 1988, a 500 hPa trough and cyclonic curvature were being analysed west of Brisbane (Fig. 5). Whereas the cyclonic curvature had not been an identifiable feature prior to that time, the major trough near Charleville had been evident for some 24 hours.

(7) The storm area was very near the mid-trospospheric large scale ridge position.

- The analyses for 1000 UTC 12 February 1988 (Fig. 5) confirms the presence of a ridge, especially at 700 hPa. In contrast to the Cooyar area, thunderstorm cells entering this region soon collapsed in the rather benign setting. Other factors obviously contributed to the collapse as shown earlier.

(8) Storms often occurred during the night-time hours.

- Needless to say, the heavier rain in this case fell during the night.

Upslope air flow over topography was noted as an important mechanism in some events (Caracena and Fritsch 1983). Moreover, Doswell (1985) defines the role of topography as being one of providing a fixed source of lift which, under the right circumstances, produces the propagation required to make systems quasi-stationary.

The location of Cooyar in relation to the surrounding ranges would ensure that moist low-level northeast winds supplied plentiful moisture for convective development. The regional MSL chart for 1000 UTC 12 February 1988 shows the moist northeast airflow into the Cooyar region (Fig. 12).

RAINFALL ANALYSES

Intensity-frequency-duration (IFD) curves for Cooyar were prepared by the Hydrology Branch Bureau of Meteorology (Fig. 15 (a)). These IFD curves are based on a generalised analysis of rainfall data and derived by using the nearest computer grid-point to the location of the station. At 'Vincentvale' station, 220 mm was registered in a 2 1/2 hour period between 1100 UTC and 1330 UTC. This is well in excess of the rainfall corresponding to a 100 year average recurrence interval (ARI) and could approach a 500 year ARI for 'point' rainfall.

The mean catchment rainfall for the 24 hours to 2200 UTC 12 February 1988 was estimated at 149.1 mm. The temporal pattern appearing as Fig. 15 (b) was constructed, based on the Maclagan pluviograph record and the 'Vincentvale' rainfall reports. For the most intense rainfall period (1100 UTC to 1400 UTC), the mean catchment rainfall for Cooyar Creek to Cooyar village is estimated to be 126 mm.

For durations up to 6 hours and areas up to 1000 square kilometres, probable maximum precipitation (PMP) is estimated using the method detailed in Bureau of Meteorology 1984 [1]. This technique had been modified following the extraordinary flash flood near Dapto in New South Wales in February 1984 (Shepherd and Colquhoun 1985). The method can be directly applied to the Cooyar event as most of the rain fell in a 3 to 4-hour window and the catchment size is approximately 156 square kilometres. PMP estimates for the Cooyar Creek catchment are listed in Table 3. In broad terms, these values exceed by a factor of 3 to 4 the average rainfall rates recorded on this occasion.

Foote and Fankhauser (1973) demonstrated that precipitation efficiency in thunderstorms is (crudely) inversely proportional to vertical wind shear through the principal cloud-bearing layer. With a shear value of about $1.5 \times 10^{-3}\ s^{-1}$, the precipitation efficiency was shown to be close to 100 per cent. At 1000 UTC 12 February 1988 the vertical wind shear between 800 and 400 hPa at Brisbane was $2.0 \times 10^{-3}\ s^{-1}$. Although not conducive to maximum efficiency, the comparatively

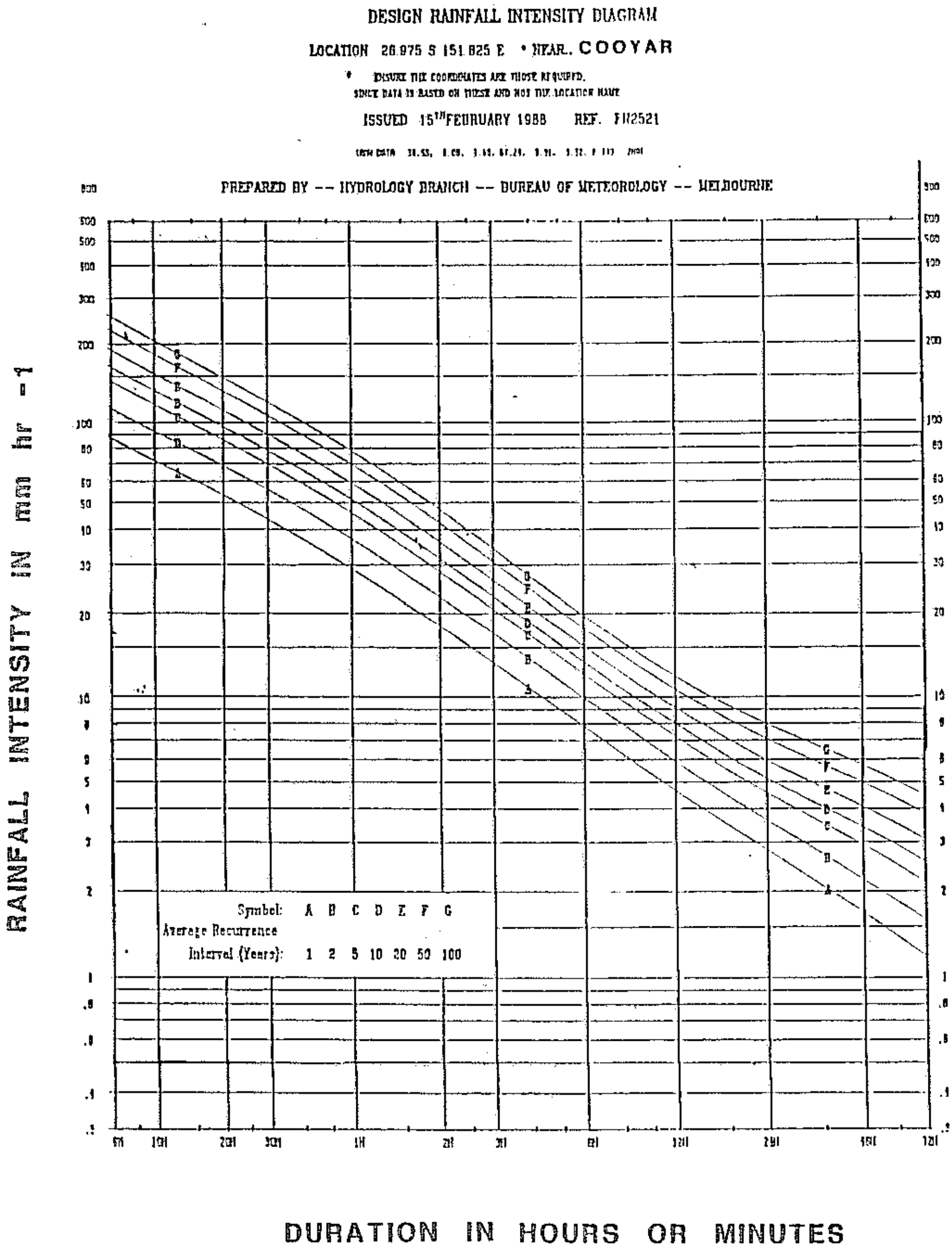

Fig. 15(a) Design rainfall intensity diagram for Cooyar.

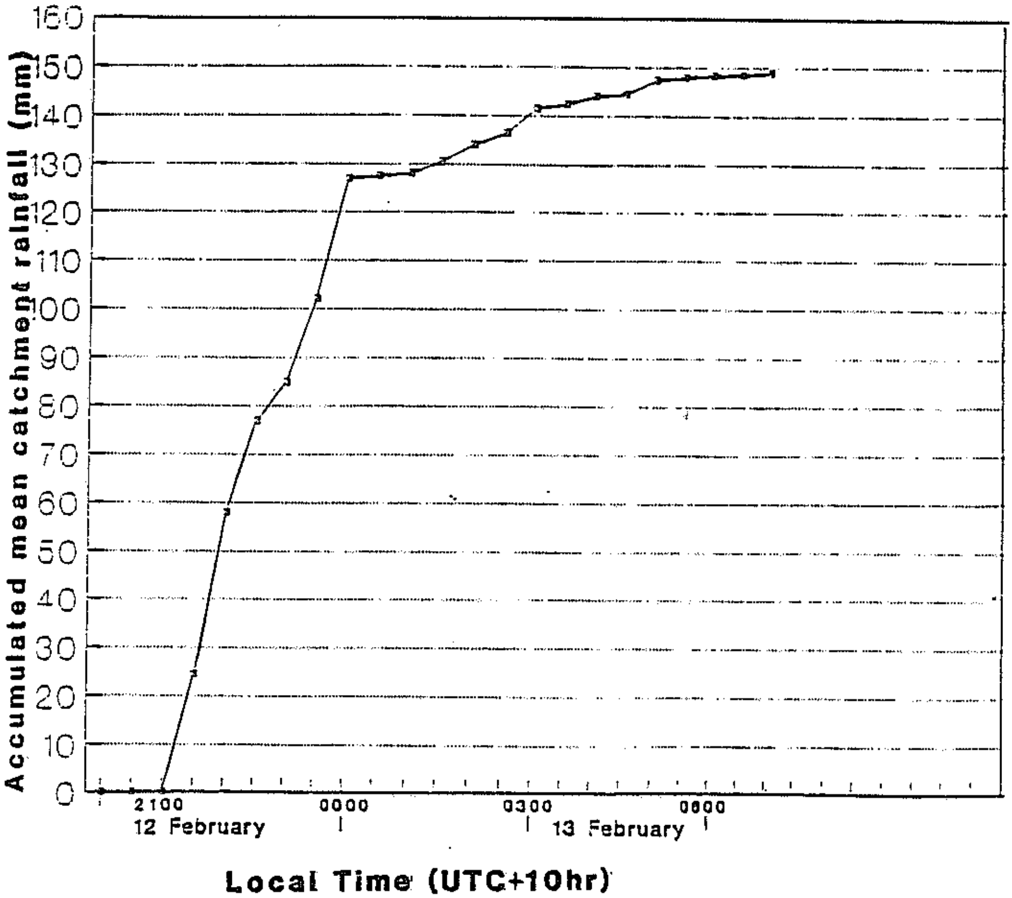

Fig. 15(b) Cooyar Creek to Cooyar estimated temporal pattern 12-13 February 1988.

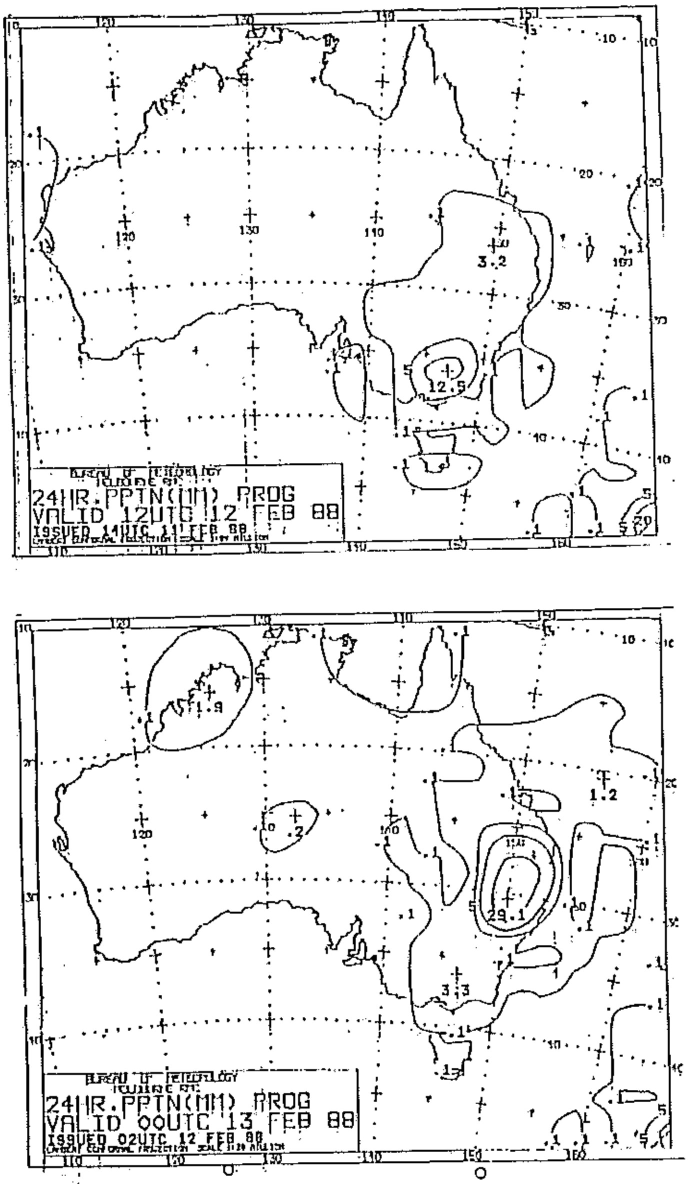

Fig. 16 24-hour precipitation prognoses.

600/400 hPa shear				
700/500 hPa shear	Colder to west	Colder to west	Colder to west	Near thermal trough
850/600 hPa shear	Warmer to west	Near thermal ridge	Warmer to east	Warmer to east
900/700 hPa shear	Warmer to west	Warmer to west	Warmer to east	Warmer to east
	120400	121000	121600	122200

Fig 17 Time section of vertical wind shears at Brisbane 0400 UTC to 2200 UTC on 12 February 1988.

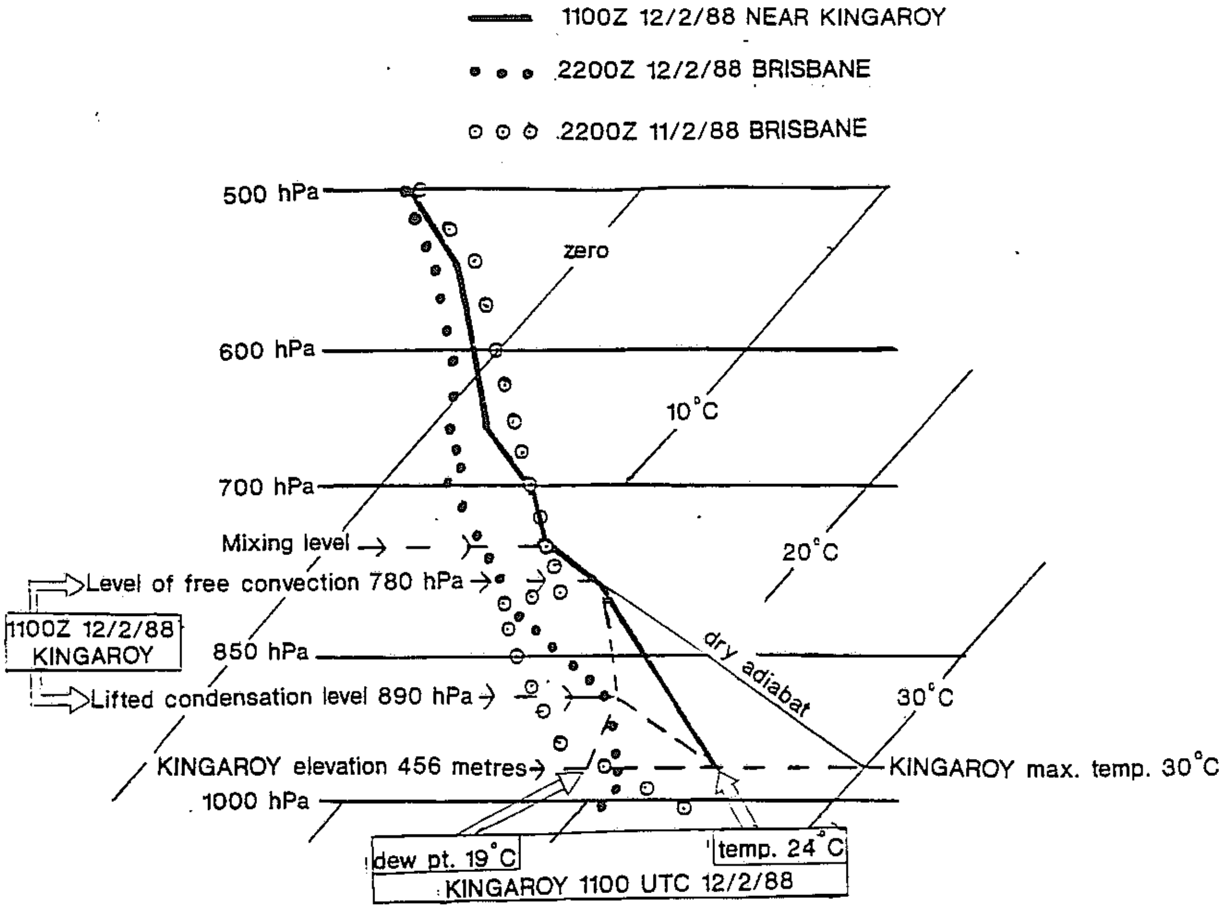

Fig. 18 Derivation of temperature profile near Cooyar/Kingaroy.

weak vertical shear would have contributed to the exceptional rainfall rates observed.

Numerical precipitation prognoses (from the Finest model) are received in the Brisbane Regional Forecast Centre at 12-hourly intervals. Included as Fig. 16 are the 24 hour total precipitation prognoses for both 1200 UTC 12 February 1988 and 0000 UTC 13 February 1988. Rainfall is forecast for southeast Queensland with a 29.1 mm maximum somewhat southwest of Cooyar on the 0000 UTC display. To convert this 'areal' (22500 square kilometres) forecast to a 'point' value, a factor of 4 is appropriately applied (Bureau of Meteorology 1984 [2]). Even 116 mm is significantly less than the 240 mm plus which fell during that night.

Table 3 . PMP for Cooyar Creek catchment

15min	30min	1hr	2hrs	3hrs	4hrs
120mm	180mm	280mm	360mm	410mm	460mm

CONCLUSION

The problem of establishing a flash flood threat is very similar to determining the likelihood of a severe thunderstorm. Various meteorological processes interact on several scales of motion to produce heavy rain in a particular area. As Maddox et al state 'Data indicate that, as in severe thunderstorm situations, marginal values of one important parameter may be compensated by more intense values of another parameter.'

Any attempt at this time to construct a logical decision tree for flash flood forecasting would be thwarted by the scarcity of reliable meteorological data on the sub-synoptic scale. Nevertheless, certain quantifiable features have been identified as common to many flash flood events and these should receive due consideration in the forecast and warning process.

As the range of numerical diagnoses and prognoses available to the forecaster is enlarged and the resolution of the model is reduced, there will likely be a commensurate increase in understanding of focussing mechanisms for heavy thunderstorm rains. Also the pending installation of a surface mesonet in southeast Queensland should provide researchers with high quality data on a sufficiently small scale to perform detailed analyses and design theoretical models.

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REFERENCES

Bureau of Meteorology 1984[1]. **The estimation of probable maximum precipitation in Australia for short durations and small areas.** Bull. 51, AGPS, Canberra, 35pp.

Bureau of Meteorology 1984[2]. **Manual for the estimation of Probable Maximum Precipitation.**

Caracena, F. and Fritsch, J.M. 1983. Focussing mechanisms in the Texas hill country flash floods of 1978. **Mon. Weath. Rev.**, 111, 2319-32.

Doswell III, C.A. 1985. **The Operational Meteorology of Convective Weather Volume II: Storm Scale Analysis.** NOAA Technical Memorandum ERL ESG-15.

Foote, G.B. and Fankhauser, J.C. 1973. Airflow and moisture budget beneath a northeast Colorado hailstorm. **Jnl Appl. Met.**, 12, 1330-53.

Maddox, R.A., Chappell, C.F. and Hoxit, L.R. 1979. Synoptic and mesoalpha scale aspects of flash flood events. **Bull. Am. Met. Soc.**, **60**, 115-23.

Palmen,E. and Newton C.W. 1969. **Atmospheric Circulation Systems.** Academic Press London.

Shepherd, D.J. and Colquhoun, J.R. 1985. Meteorological aspects of an extraordinary flash flood event near Dapto, New South Wales. **Aust. Met. Mag.**, **33**, 87-102.

Trenberth, K.E. 1978. On the interpretation of the diagnostic Quasi-geostrophic omega equation. **Mon. Weath. Rev.**, **106**, 131-137.

APPENDIX

CONSTRUCTION OF A VERTICAL TEMPERATURE PROFILE NEAR COOYAR

With reference to Fig. 7(c), in the 24 hours from 2200 UTC 11 February to 2200 UTC 12 February 1988, the temperature at Brisbane warmed at low-levels and cooled significantly between 800 hPa and 450 hPa. In Fig. 17 the vertical wind shears at various levels in the 24 hour period were plotted to investigate these temperature changes. A low-level thermal ridge passed through Brisbane between 1000 UTC and 1600 UTC while near 700 hPa a thermal ridge was evident in the Brisbane area at 1000 UTC.

This thermal ridge extended down to somewhere between 780 hPa and 850 hPa as this was the level at 0400 UTC and 1000 UTC the winds changed direction with height to produce the southwesterly shear observed east of the thermal ridge. The maximum temperature reached 30 degrees at Kingaroy on 12 February 1988 so that the mixing level would have been above the top of the inversion at 790 hPa observed on the Brisbane radiosonde trace at 2200 UTC 11 February 1988. Therefore the layer below the inversion would have been heated during the day by convective mixing of surface heating while the top of the inversion was heated by the approach of the thermal ridge.

Refer to Fig. 18. The temperature trace taken to represent the area east of the Great Divide at 1100 UTC 12 February 1988 was drawn from the temperature at 790 hPa (top of inversion) that morning on the Brisbane trace to 24 degrees at an elevation of 456 m. This last level is the elevation of Kingaroy and the temperature was the actual recording at 1100 UTC 12 February 1988. At the top of this layer the environmental temperatures were probably warmer and the lapse rate less than plotted. This would make the trace even more stable and would not destroy the reasoning presented above.

The thermal trough producing the cooling arrived at Brisbane at 600 hPa at the end of the 24 hour period. Above about 700 hPa cooling was occurring for most of the 24 hour period so that here a linear interpolation was applied to arrive at the constructed trace.