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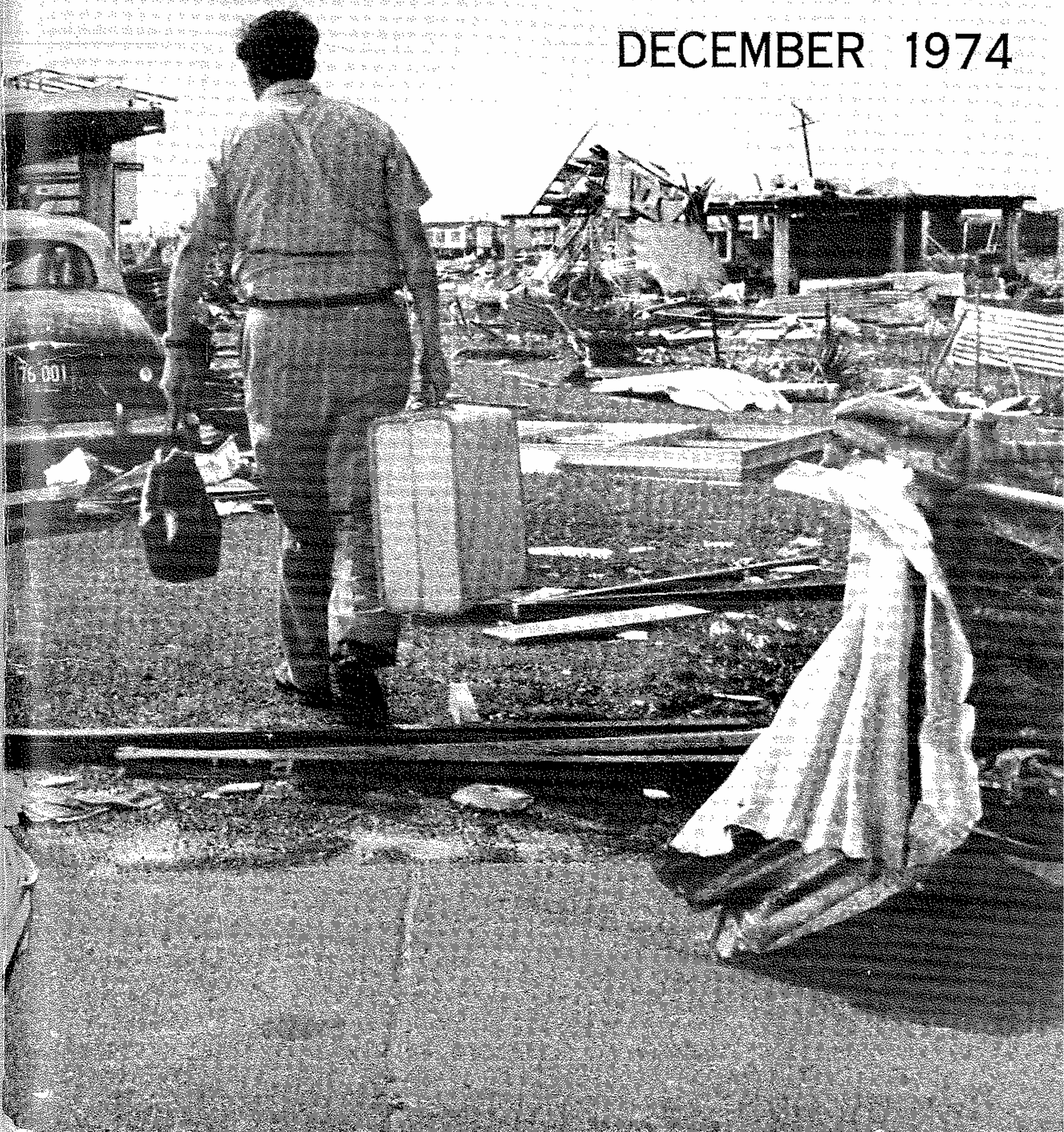
Special Services

DEPARTMENT OF SCIENCE
BUREAU OF METEOROLOGY

REPORT ON CYCLONE TRACY DECEMBER 1974



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REPORT ON CYCLONE TRACY DECEMBER 1974

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FOREWORD

After an event that profoundly affected not only Darwin, but the nation as a whole, it was considered essential to review the evidence presented in the interim report published in March 1975. A more comprehensive survey of the cyclone and its background is contained in this report.

I acknowledge with gratitude the assistance of authorities external to the Department, particularly Group Captain D. Hitchens and Squadron Leader B. Farrow of the RAAF, Mr L. Mace of the US National Environment Satellite Service Headquarters, Washington, and Lieutenant Colonel G. Atkinson of the Joint Typhoon Warning Center, Guam.

The report was prepared in the Head Office of the Bureau by Mr J. Mottram with the help of many other officers.

(W.J. GIBBS)
Director of Meteorology

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INTRODUCTION

The aim of this report is to present the results of investigation that have taken place since the preparation of the interim report (Australian Bureau of Meteorology 1975) and to incorporate wherever possible the findings of the initial report. Several investigations of various facets of Tracy by a number of organisations have highlighted uncertainties in defining basic parameters, particularly the wind field. New data and more refined techniques have enabled these parameters to be specified with greater confidence. The new data included higher quality satellite photographs, additional radar information, and the results of further aerial and ground surveys. Careful consistency checks have been undertaken. Also of particular assistance have been readings of a atmospheric pressure and rainfall taken by Bureau staff at Darwin airport during the passage of the eye. These readings were temporarily lost in the immediate aftermath of the cyclone.

The eye of the storm passed directly over Darwin, where a major meteorological installation was located. This provided a rare opportunity for obtaining detailed measurements inside such a storm, particularly by radar. Unfortunately, as is often the case in the severe meteorological conditions associated with tropical cyclones, some of the instruments malfunctioned or were put out of action by power failures or the impact of flying debris. Nevertheless, considerable data have been collected and besides providing information for this report, are being used as a basis for further research.

A chronology is presented at the commencement of the report to enable the reader to obtain a broad perspective of Tracy.* An examination is then made of the general synoptic background, isolating qualitatively a number of parameters considered to be important in the development of the cyclone. Subsequent sections examine Tracy in greater detail from the perspective of satellite and radar data. The behaviour and characteristics of the cyclone as it passed across Darwin are then described with particular reference to the wind profile, track, and extent of damage. To cater for a more general interest and to place Tracy in an historical perspective, a resume is given of cyclones in the Darwin area, including a comparison with a similar past storm and an analysis of return period.

The appendixes refer mainly to the tropical cyclone warning system, including an assessment of its performance. The operational warnings are presented in full in Appendix C. Although recurvature was not predicted, the first warning that Darwin itself was threatened came at 12.30 pm on 24 December, approximately 12 hours before the onset of destructive winds. Both mean winds and gusts were stronger than forecast, but the storm surge was accurately predicted. The objective assessment of mean position error presented in Appendix E confirms that the forecasts prepared by the Darwin Cyclone Warning Centre were, on average, appreciably better than normally achievable.

CHRONOLOGY OF CYCLONE TRACY

Tracy struck Darwin early on Christmas morning 1974, causing the deaths of 49 people and damage estimated at hundreds of millions of dollars. Another 16 people were posted as missing at sea. By global standards the cyclone was a very small but intense storm, the diameter of gale force winds being only about 100 km – in contrast to some north Pacific typhoons, which have had corresponding diameters of 1500 km (Dunn and Miller 1964). Its central pressure of 950 mb was close to the mean value observed in other tropical cyclones but because of its small site the peak pressure gradient was unusually high, at about 5.5 mb/km.

* Central Standard Time (CST) (Greenwich Mean Time plus 9.5 hours) is used throughout the report.

The passage of Tracy over Darwin resulted in a recorded surface wind speed of 217 km/h, which has been exceeded in Australia only by extreme gusts at Onslow, WA, of 232 km/h on 7 February 1963 and 246 km/h on 19 February 1975 (cyclone Trixie).

The broad track of the cyclone is shown in Fig 1 and rainfall at various places is listed in Table 1.

The first alert of the possibility of the development of a tropical cyclone was issued on 21 December 1974, more than 3 days before Tracy struck Darwin. Satellite pictures, weather watch radar, and automatic weather stations all played a vital part in detecting and monitoring the cyclone. The US meteorological satellites enabled early detection of the tropical disturbance and monitored the subsequent development of the cyclone. When the centre approached within range, the Bureau's weather watch radar gave accurate determinations of location and movement, while the automatic weather station at Cape Fourcroy on Bathurst Island reported the first measured values of the very strong winds and low pressure towards the centre. The shop *Lady Cynthia*, when located less than 90 km northwest of the position determined by the land based radar at Darwin airport. Reports from civil aircraft on routine flights also pinpointed the eye and one light aircraft flying at 300 m attempted to penetrate the storm but was forced to return when still some distance from the centre.

The following sequence of significant events occurred during the life cycle of cyclone Tracy:

20 December 1974

The precursor low which subsequently became cyclone Tracy developed near 8° s 135° E.

21 December 1974

Satellite photographs received during the morning showed the precursor low moving slowly southwestwards.

1600 CST
: The first tropical cyclone alert was issued, advising of the possibility of tropical cyclone development.

2130 CST
: On the basis of further development evident on the infrared satellite photographs It was decided that a tropical cyclone had formed. The Tropical Cyclone Warning Centre at Darwin issued a warning at 2200 CST and gave the cyclone the name Tracy.

22 December 1974

Satellite photographs, both in morning and evening, suggested rapid development and intensification of the system.

1030-1330 CST
: Continuous radar monitoring detected the first partial eye wall echoes.

1530 CST
: The eye was clearly defined on radar with a diameter of 37 km located just over 200 km north of Darwin and moving slowly southwest.

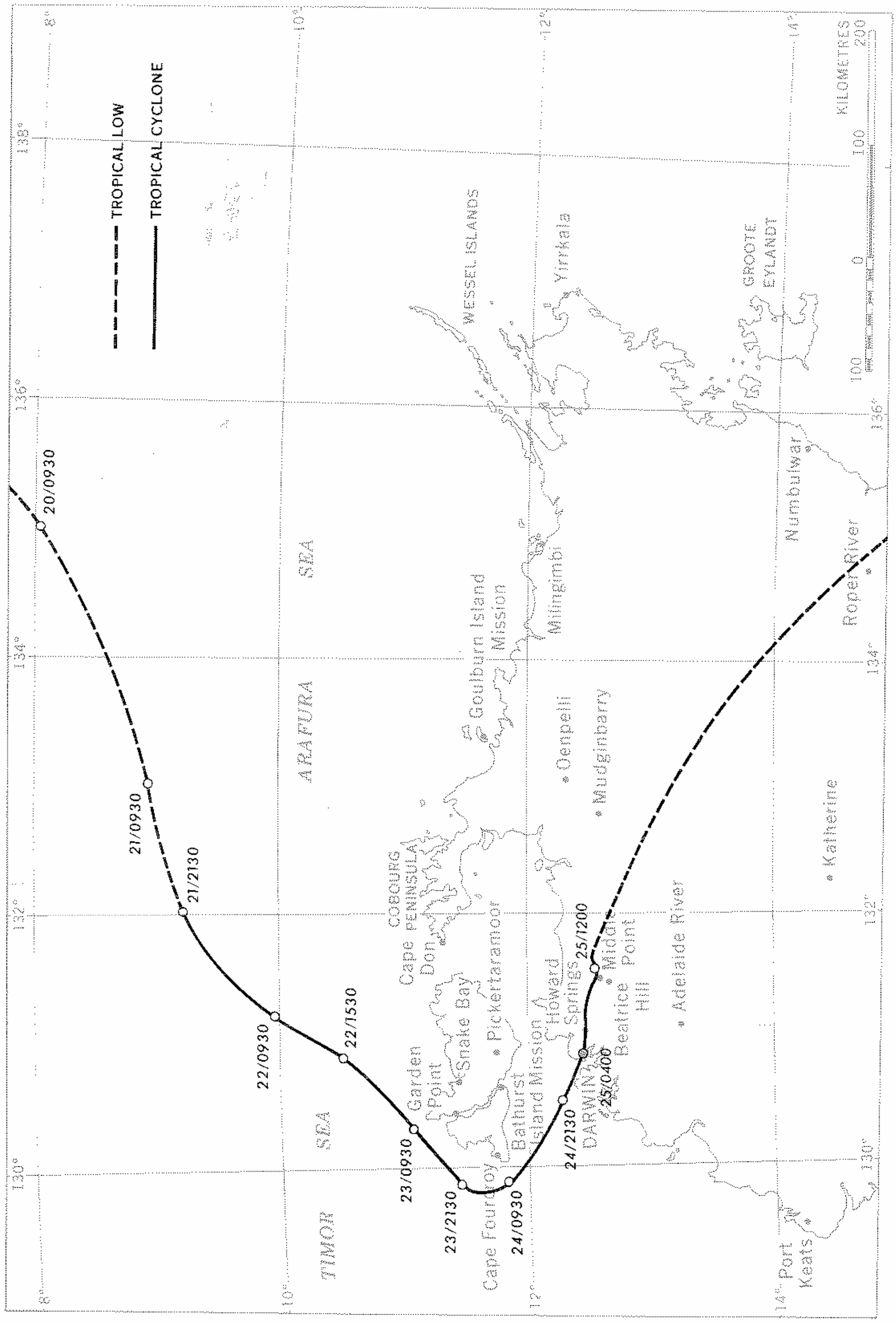

Fig 1 Track of Tracy. December 1974.

Table 1 3-hourly rainfall totals at selected stations (rainfall in millimetres): December 1974

Date/time (CST)	Snake Bay	Oenpelli	Katherine	Cape Don	Goulburn Is.	Garden Point	Darwin	Beatrice Hill	Bathurst Is.	Pickertaramoor
22/0001										
0300	0	0	0	0.4	0		0			
0600	1.2	0	0	1.0	0		0			
0900	1.6	0	0	3.8	0.4	20.0*†	0		(10 am) 35.4*†	0†
1200	8.4	0	0	4.2	2.2	(10 am)	0		(1 pm) 10.4*	
1500	0.6	0	0	0	2.8		0			
1800	2.4	0	0	0	0.2		0			
2100	0.2	0	0	0.8	0		0			
23/0001	1.6	0	0	0.8	0		0		0	
0300	19.0	0	0	0	0		0			
0600	37.8	0	0	0	0		0		31.6	
0900	18.6	0	0	7.8	6.8	138†	0.4			33.0†
1200	7.4	0	0	1.4	0		12.6		0	
1500	4.0	0	0	0	0.8		0		11.4	
1800	15.0	0	0	0	0.6		0		10.5	
2100	40.0	0	0	0	0		0		20.1	
24/0001	40.8	0	0	1.6	0		0			
0300	3.2	0	0	0	0		0.8			
0600	3.2	0	0	0	0		1.0		91.5	
0900	25.4	0.2	0	0	0	220.0†	1.4		20.0	35.2†
1200	4.0	0	0	0	0		2.2		(1 pm) 38.4*	
1500	13.0	11.5	0	1.2	1.4		2.2		(4 pm) 20.5*	
1800	0.8	0	4.0	0.2	0		8.6		25.6	
2100	17.2	0	0.8	0.4	0		12.0		21.1	
25/0001	2.8	0	0	0	0		26.0			
0300	2.0	0	0	0	0		(4 am) 144.2*			
0600	14.2	0	0	0	0					
0900	11.0	0.6	0	1.6	0	65.8†			236.4†	217.0†
1200	2.2		0	12.4	21.5					
1500	2.6	24.0*	0	1.8	7.0					
1800	0	0	0.4	0	5.6					
2100	3.6	0	0	0	0					
26/0900	16.0	69.8	36	25.6	13.6	32.0†		406§	41.4†	61.0†

* Non-standard readings. † 24-hour readings. § Total rainfall for period.

23 December 1974

0730 CST

The eye diameter had shrunk to about 12 km and the centre was just off the northern tip of Melville Island, still moving southwest.

0900 CST

Snake Bay on Melville Island reported mean winds of 65 km/h. Heavy rain was falling over Bathurst and Melville Islands and the western tip of Coburg Peninsula.

1500 CST

Mean winds at Snake Bay had increased to 75 km/h.

2400 CST

Radar observations showed that Tracy had changed direction and was moving southwards. Winds started to strengthen at the Bureau's automatic weather station at Cape Fourcroy on Bathurst Island.

24 December 1974

0300 CSt

Mean winds of 100 km/h were recorded at Cape Fourcroy.

0600-0900 CST

Winds at Carpe Fourcroy strengthened further. Wind direction backed from NNE to NW and mean speeds reached 120 km/h as the cyclone rounded the south-west corner of Bathurst Island and moved to within 20 km of the station.

1200 CST

Analysis of the noon chart and radar observations confirmed that Tracy had again changed course and heading southeast towards Darwin.

1230 CST

A top priority Flash Cyclone Warning was issued advising of Tracy's expected landfall early on Christmas morning.

25 December 1974

0000-0100 CST

Wind gusts in excess of 100 km/h commenced in Darwin.

0100-0300 CST

Numerous reports of severe damage in and around Darwin were received in the Bureau's Tropical Cyclone Warning Centre. Communications with the mass media were lost when both radio stations failed.

0305 CST

A peak gust of 217 km/h was recorded at Darwin airport.

0310 CST
The anemometer recording system failed.

0350 CST
A thirty-five minute period of calm commenced at the airport.

0400 CST
The Bureau's radar at Darwin airport showed that the eye was overhead. Rainfall recorded at the airport since midnight totalled 144.2 mm. Atmospheric pressure reading in the eye was 950 mb corrected to mean sea level.

0425 CST
The calm ended at the airport. Strong winds resumed from the southwest.

0430 CST
Radar tracking ceased.

0600 CST
Tracy's centre was located near Howard Springs.

0630 CST
Winds were abating in Darwin.

1100 CST
The cyclone was weakening as it passed the former CSIRO village, at Middle Point.

After crossing the Adelaide River about midday on the 25th, Tracy degenerated rapidly into rain depression and then moved slowly southeast across southern Arnhem Land into the Gulf country of Queensland.

Photographs showing the damage caused in Darwin are illustrated in Figs 2 to 6.

GENERAL METEOROLOGICAL BACKGROUND AND THE SYNOPTIC SITUATION

Terminology

In the Australian region the term ‘tropical cyclone’ is used only in reference to a closed cyclonic rotational system of tropical origin in which mean winds (10 min average) of at least gale force (63 km/h) occur, the belt maximum winds being in the vicinity of the centre. A ‘severe tropical cyclone’ is a tropical cyclone in which mean winds in the maximum wind belt exceed 120 km/h.

At present there is no common international usage with regard to definitions for tropical disturbances of various intensities. For example, the United States meteorological services define a ‘tropical storm’ as a warm core cyclonic wind circulation in which the maximum sustained wind (1 min average) is 63 km/h or greater. Tropical storms in which the maximum wind equals or exceeds 119 km/h are called ‘hurricanes’ east of 180 degrees longitude and ‘typhoons’ when they occur west of 180 degrees longitude (Joint Typhoon Warning Centre (JTWC) 1974).

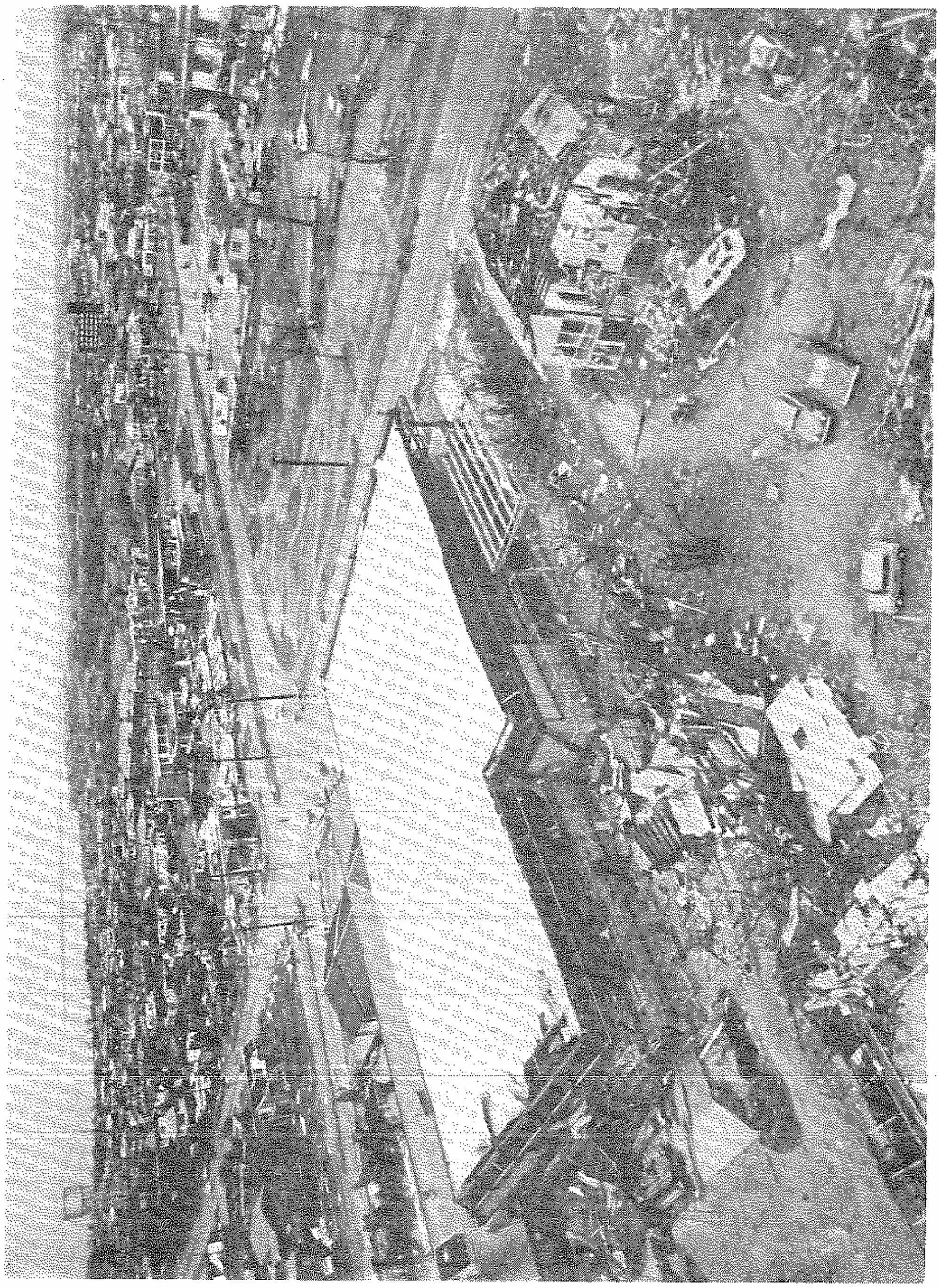

Fig 2 General view of widespread damage in suburbs, showing the almost complete devastation of buildings and the stripping of leaves from trees. (Courtesy of Herald and Weekly Times).

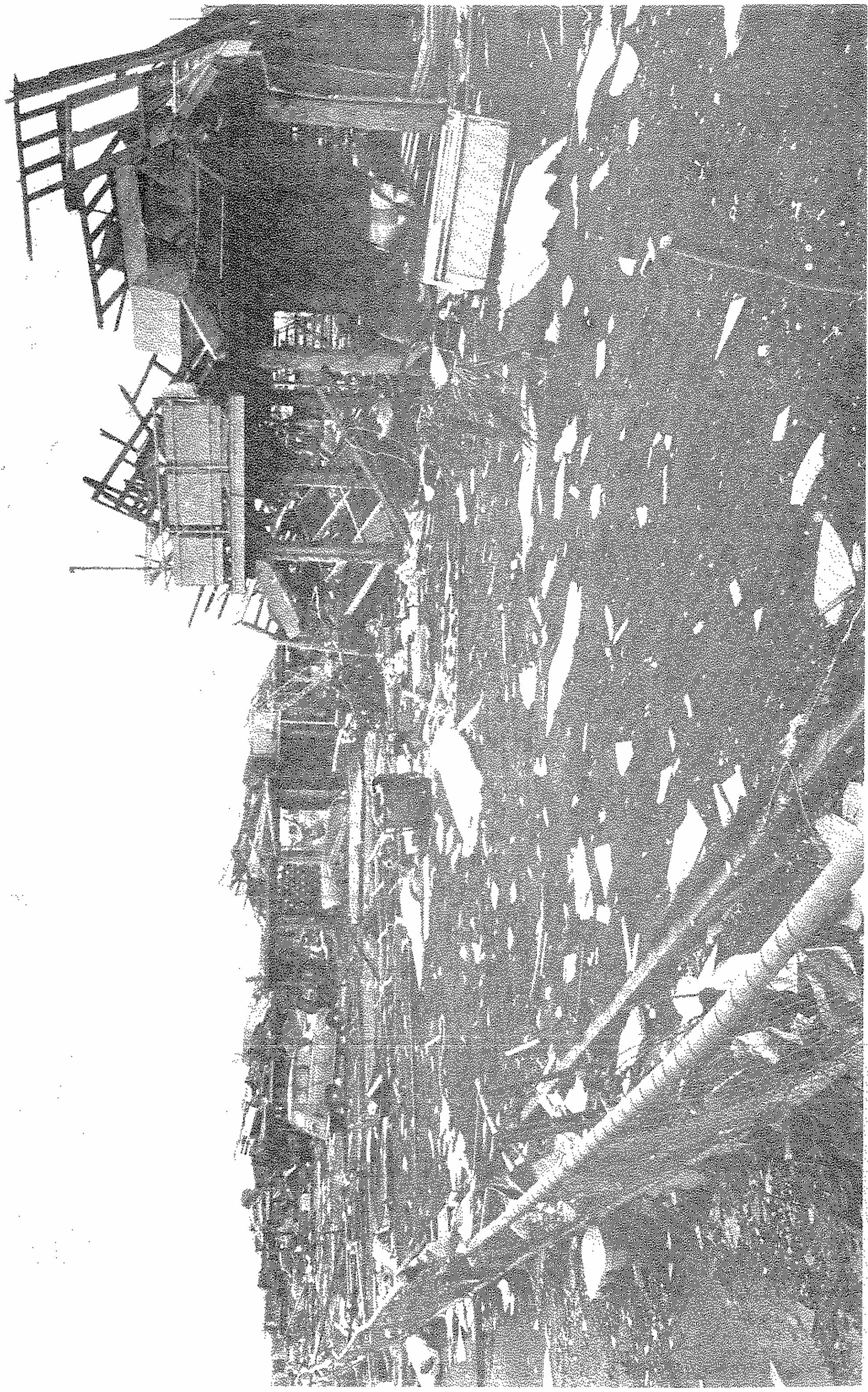

Fig 3 A street of devastated houses showing the complete destruction of upper storeys. (Courtesy of Herald and Weekly Times).

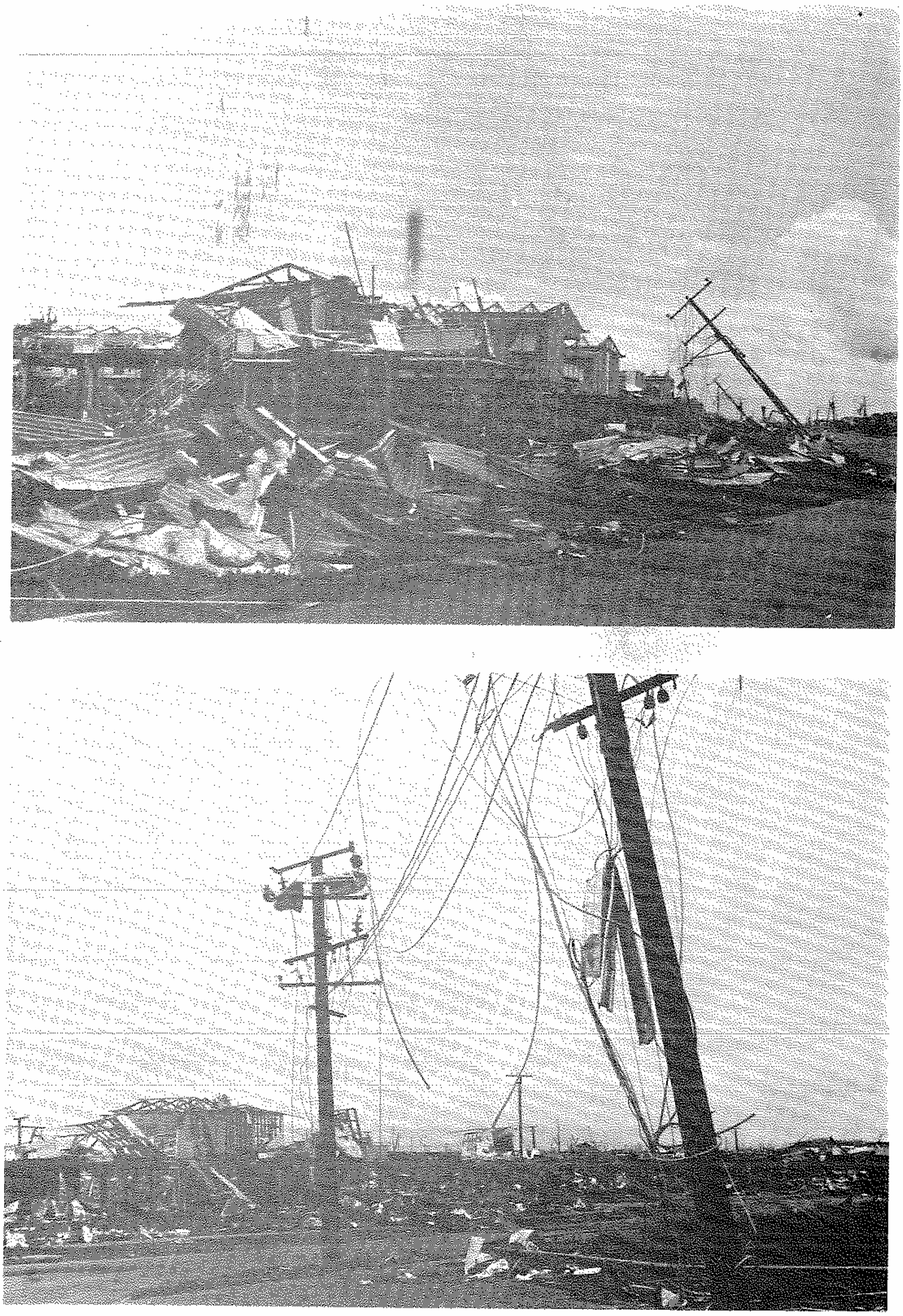

Fig 4 Detail views showing accumulation of debris and damage to transmission lines and poles.

Fig 5 Damage in Darwin city area (Courtesy of News Ltd.)

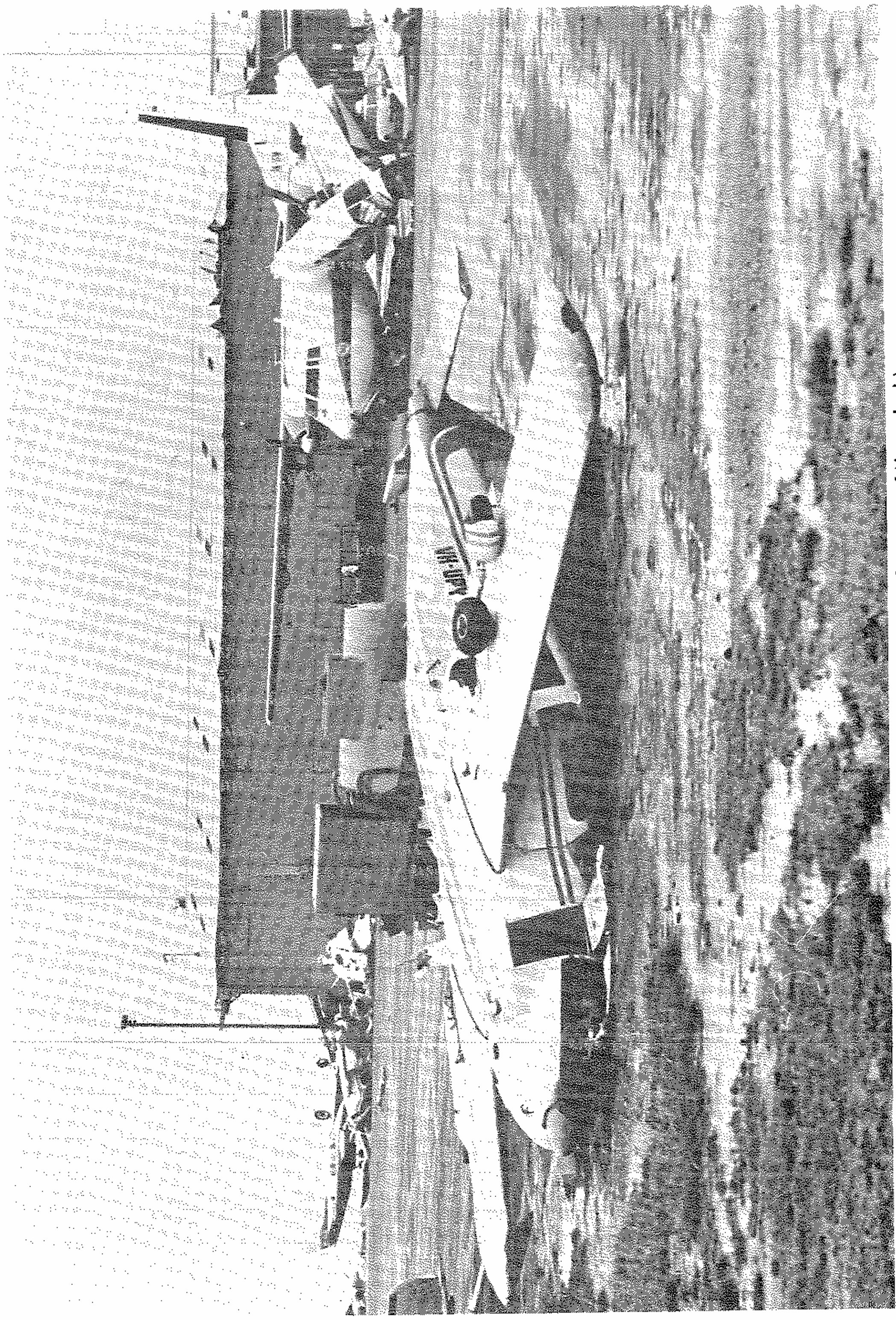

Fig 6 Damaged aircraft at Darwin Airport (Courtesy of News Ltd.).

Other countries with tropical areas of responsibility such as Japan, France, and Mauritius, all have their own different terminology. Atkinson (1971) has made a comprehensive review of their classification systems. In this report the Australian terminology is implied in reference to Tracy.

Climatology

On a global scale, parameters defined by Gray (1975) and explained below delineate well the areas of cyclone genesis shown in Fig 7 (after Gray 1975). In the Australian region, which accounts for approximately 18 per cent of the global total, tropical cyclones form over waters to the north of Australia in practically every year during the months from November to April. The Statistics in Fig 8, which reflect movement as genesis, show that the areas most frequently affected by tropical cyclones lie northeast and northwest of the Australian continent. As a breeding ground the most favoured regions are found over the Timor and Coral Seas and genesis becomes more frequent in these areas as the season advances. A less frequent but still significant breeding ground is also to be found in the Arafura Sea between Timor and West Irian and it was in this area that Tracy had its origin near 8°s 135°E, on 20 December 1974.

Development of Tracy

The broadscale surface analysis for 0930 CST 20 December 1974 is depicted in Fig 9 and shows the tropical low, between Timor and West Irian, which was the precursor of cyclone Tracy. The ‘doldrum trough’ (particularly active on both sides of the equator) contained several lows, including another developing tropical depression over the Indian Ocean. The two lows over northern Australia were partly due to surface heating, but the one in the northwest had a circulation pattern and vertical extent which would suggest it was more of a dynamic than thermal system. The mid-latitude high south of the Great Australian Bight had developed over the previous day or so and was the dominating influence affecting the Australian continent at this stage. In the northern hemisphere tropical storm Kit (10.5°N 128.5°E in Fig 9) was perhaps the most important feature.

The intertropical convergence zone (ITCZ) was evident on satellite photographs of previous days as an almost continuous band of cloud stretching from about 120° E to 180° E between 10°S and the equator. At the time of the analysis in Fig 9 it had fragmented considerably and one these fragments, which appeared to be a cumulonimbus cluster about 4° wide, was associated with the precursor low to Tracy. Gray (1968) has shown that approximately 85 per cent of all tropical cyclones originate in a similar position, namely in or just poleward of the ITCZ, where the vertical shear of the wind is small.

The precursor low matured rapidly after moving only a degree or so southwards from its position in Fig 9 and on the basis of satellite evidence was analysed as a tropical cyclone at 2130 CST on 21 December 1974. The path of the storm is illustrated in the inset to Fig 9. The broad change in direction that occurred along the track can be associated with the movement of a high level outflow centre evident on the upper air analysis.

Tropical cyclone formation

The formation (or genesis) and intensification of Tracy can be viewed in the light of the existence and sequential coupling of a number of environmental parameters. In considering formation, Gray (1975) has combined six of these into a Seasonal Genesis Parameter, which can be thought of as the product of the dynamic and thermal potentials of the ocean/atmosphere system to produce tropical cyclones.
The primary component parameters are related to:

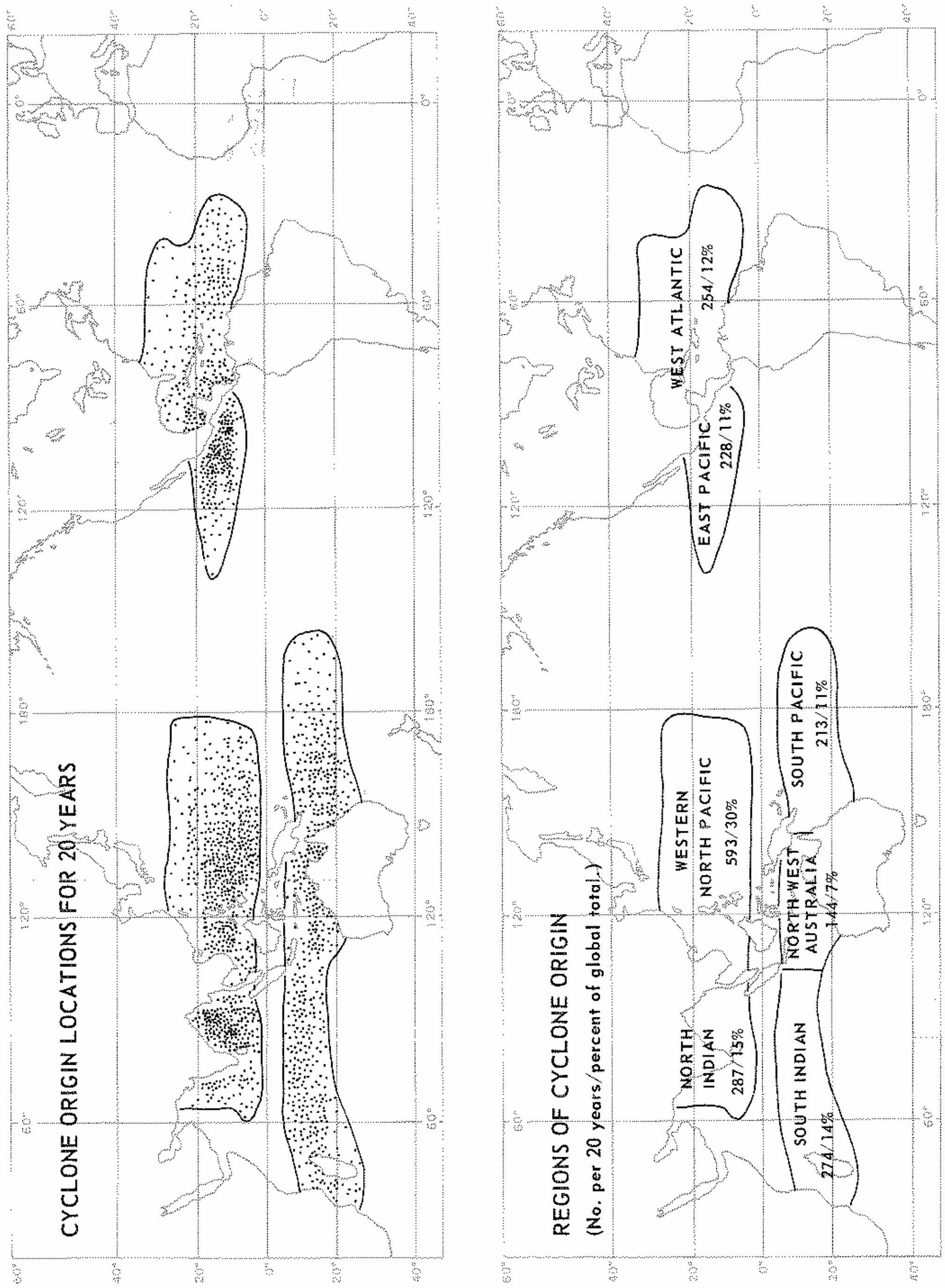

Fig 7 Regions and origin locations of tropical cyclone genesis during the period 1952–1971 (after Gray, 1975).

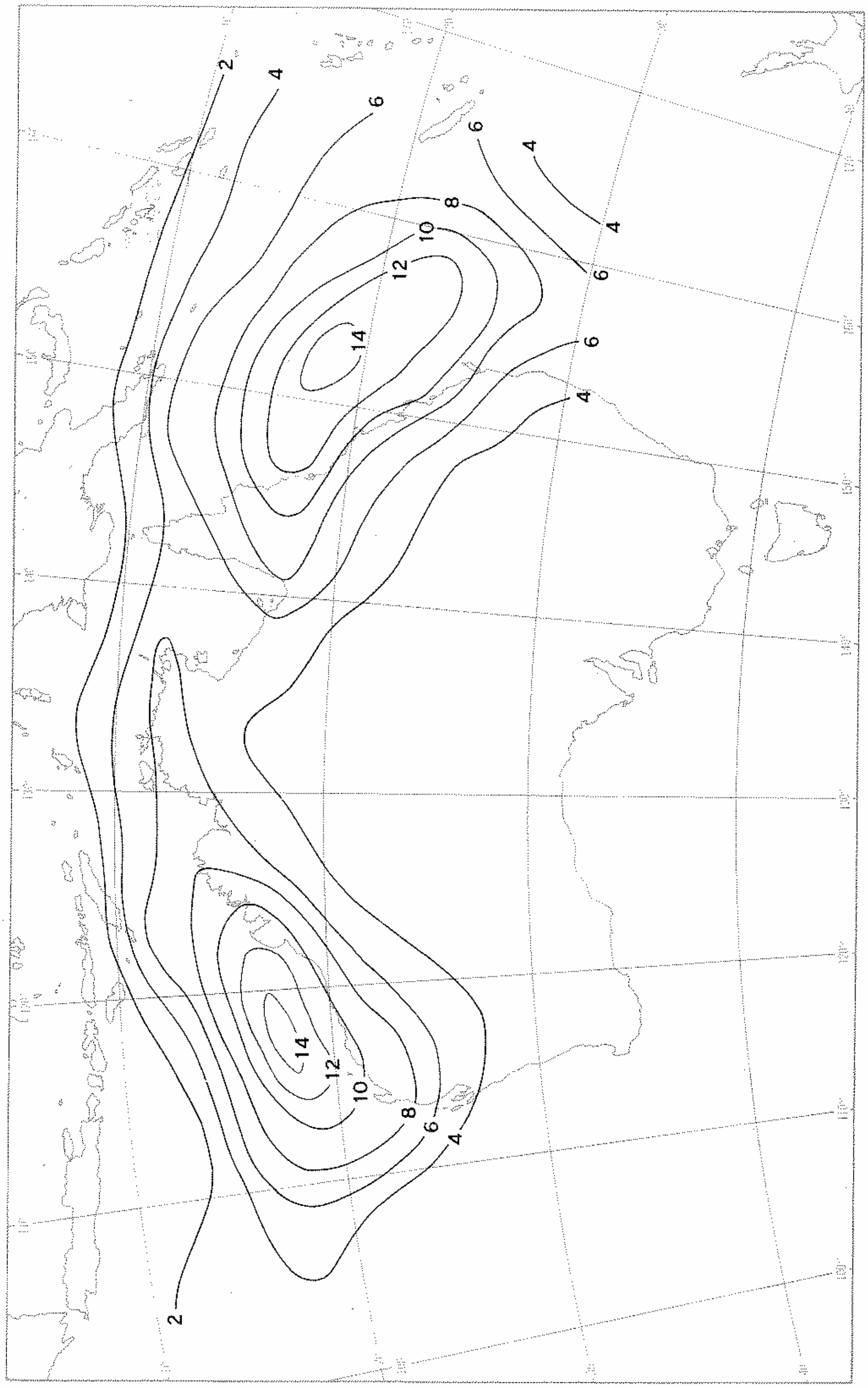

Fig 8 Average frequency of tropical cyclones crossing 5° latitude-longitude squares per 10 years for season (December-April).

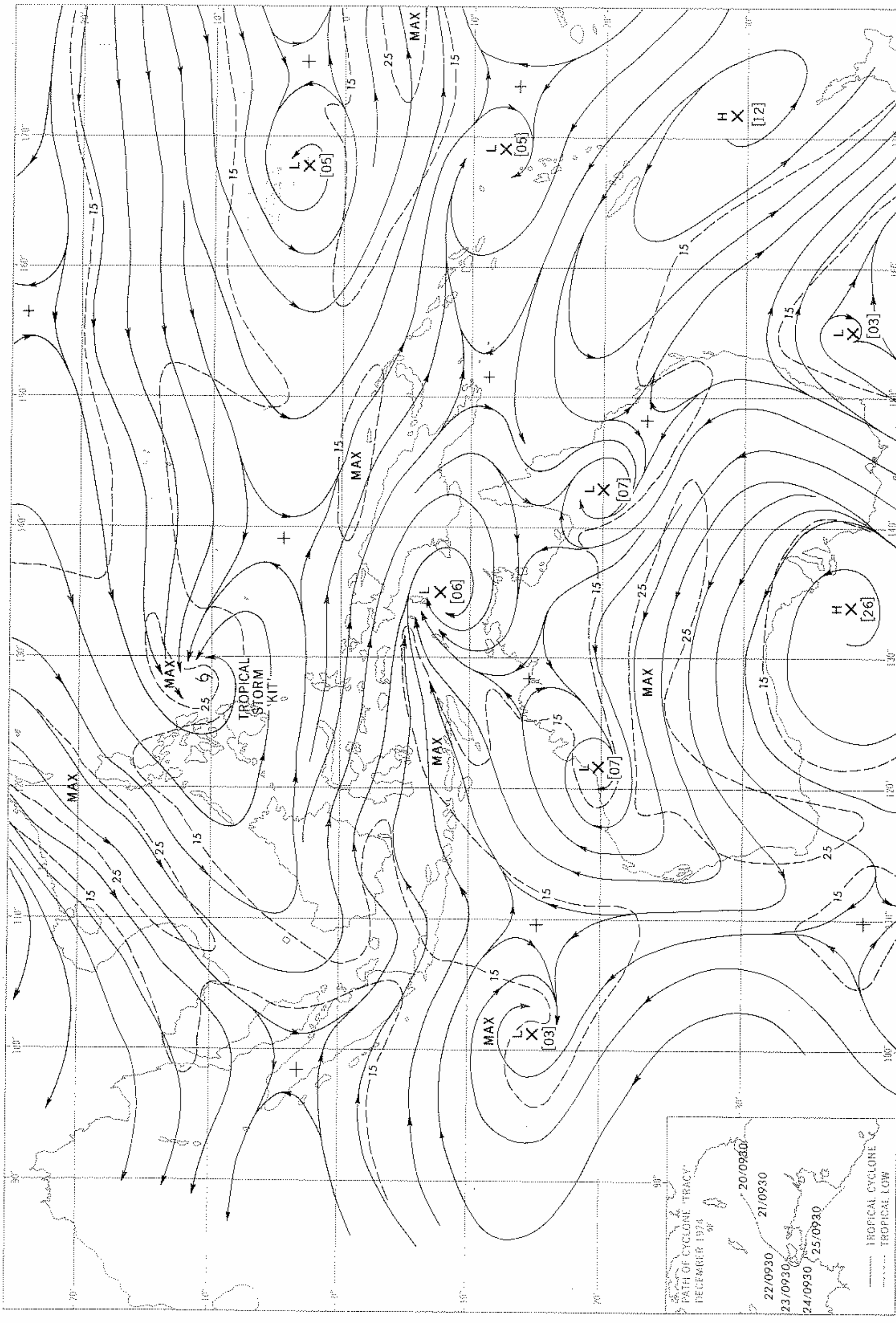

Fig 9 Surface streamline-isotach pattern for 0930 CST 20 December 1974 illustrating the broadscale synoptic environment in which Tracy formed. The inset shows the storm's subsequent path with positions at 24 hourly intervals.

1. *Low level relative vorticity*: which can be shown to be proportional to the frictional veering of the boundary layer wind, which in turn produces the low level mass, moisture, and momentum convergence necessary for development.

2. *Coriolis parameter*: which reflects the role of the earth's rotation in establishing the initial circulation. It must be greater than a certain minimum value as observational evidence shows that cyclones do not form within 4 to 5° of the equator in either hemisphere.

3. *Vertical shear of the horizontal wind between the lower and upper troposphere*: conditions of minimum vertical shear are most favourable for development as this allows warming to be concentrated over a moving disturbance, i.e., the ventilation of upper tropospheric energy is inhibited.

4. *Ocean thermal energy:* follows from the well established criterion discussed by Palmen (1956) that the sea surface temperature must be at least 26°C.

5. *Vertical gradient of temperature and moisture between the surface and the mid troposphere:* must be sufficient to maintain the moist buoyancy of a parcel of surface air when lifted up to heights of at least 12 km. Tropical cyclones do not occur unless there is a well established vertical coupling of the lower and upper tropospheric flow patterns and the primary mechanism for this coupling is cumulonimbus convection.

6. *High values of middle tropospheric humidity:* lead to increased precipitation efficiency and the greater likelihood of the enthalpy increase necessary for development.

It can be shown or inferred that each of these parameters was making a significant contribution to the genesis of Tracy.

Although only a very small proportion of cumulonimbus clusters develop into tropical cyclones, their existence necessarily infers the presence of several favourable environmental parameters for genesis. Conditions of moist buoyancy and mid tropospheric humidity (numbers 5 and 6 or Gray's parameters) are obviously satisfied. Ocean thermal energy (parameter number 4) is related to sea surface temperatures and analysis of these is regularly performed in the National Meteorological Analysis Centre, Melbourne. Five day mean sea surface isotherms are regularly constructed from all available ship reports in the appropriate period and these are considered to give a superior indication of sea surface temperature patterns than might otherwise be obtained from one or two isolated synoptic reports. The sea surface temperature analysis for 18 to 22 December 1974 (inclusive) showed values between 29 and 30°C over waters where Tracy developed, which would have been more than sufficient to maintain large sea to air energy transfers.

The vertical shear of wind (parameter number 3) over the initial surface disturbance appeared to be small on the basis of upper air analyses and satellite evidence. Accurate determination was not possible in the absence of proximate data; however, the location of the surface feature with respect to the ITCZ would also suggest conditions of minimum vertical shear.

The coriolis force (parameter number 2) was obviously sufficient at latitude 8°S and warrants little further discussion. In addition, however, a contribution form low level relative vorticity (parameter number 1) is also required and it is necessary to assess the features that could have increased the low level relative vorticity in the area.

The initial presence of a low pressure disturbance (such as the low at 8°S 135°E in Fig 9) is generally accepted as a precursor to cyclone development Matano and Sekioka (1974) have shown that such a pre-existing low is necessary t provide a field of relative vorticity in which the tropical cyclone forms. They further suggest that this pre-existing low maintains its identity, undergoing a life cycle of its own even after the tropical cyclone develops; this last aspect has not been documented for cyclones in the Australian region, nor could it be confirmed as being associated with Tracy.

Another feature which could be thought of as having some influence on Tracy's genesis was tropical storm Kit, located at 10.5°N 128.5°E (see Fig 9). Its existence could be interpreted as leading to increased equatorial westerly flow, which in turn could have increased the low level relative vorticity in the vicinity of the precursor low. It is difficult to sustain this argument in view of the fact that Kit was not a very intense system and appeared on satellite photos as quite a small storm. Indeed there is no evidence of its circulation extending over a sufficiently large enough area to have appreciably caused such an effect.

There is evidence to suggest that southern hemisphere influences may well have provided the major contribution. A marked strengthening in the low level southwesterly wind flow can be noted near Timor in Fig 9. This low level wind surge, which seems to have been generated by the dynamic systems operating in higher latitudes over the Australian region, resulted in the only appreciable strengthening of wind currents in the 'doldrum trough' that could be detected prior to Tracy's development; and is seen as playing an important role in increasing the low level relative vorticity for the area and augmenting its tropical cyclone genesis potential.

Another traditional ingredient, not favoured by Gray, is the existence of upper level divergence to produce the initial pressure falls at the surface. This has several controversial aspects and it should be noted that Gray (1986) has previously rejected its primacy and supports Charney and Eliassen's (1964) Conditional Instability of the Second Kind (CISK) hypothesis, and views development and the resulting upper tropospheric outflow as but a consequence of a lower tropospheric convergence that is frictionally forced. The role of initial upper level divergence as a factor in Tracy's genesis could not be reliably determined due to the sparsity of data.

Tracy's movement and upper air analyses

All tropical cyclones have a tendency to move poleward and come increasingly under the influence of mid latitude features. This influence is normally reflected as a change in direction of movement, which is termed recurvature. Recurvature is usually regarded as an effect due to changes in the broad upper tropospheric wind currents in the vicinity of the storm, which exert a steering influence on the movement of the tropical cyclone, and has long been recognised as a feature of tropical cyclone movement (e.g., Fiehl 1954 and Dunn and Miller 1964). In some instances when the upper steering influence is weak, only 'partial recurvature' is achieved and the cyclone may resume its former direction of movement. In other cases, the upper steering influence is first broken and then reinforced, producing what is often termed 'multiple recurvature'. Tracy's path (see inset to Fig 9) is an example of 'complete recurvature', which was accomplished as the storm passed Bathurst Island

Predicting recurvature is a difficult problem as essentially only a subjective assessment of the steering forces is possible in an operational environment. Satellite information can provide useful guidance and this will be discussed in a later section, but at this stage it is interesting to note that the upper air analyses reveal a synoptic scale system that can be associated with Tracy's recurvature. The 300 mb analysis for 0930 CST 22 December 1974 is shown in exerting an initial steering influence on Tracy, as it seems to have maintained the upper easterlies in its vicinity.

The more important steering influence is attributed to the 300 mb outflow centre situated off the northwest coast of Australia. This upper anticyclone was a discrete feature that maintained its identity as it moved regularly east-ward. Its track is shown in the inset to Fig 10. Recurvature commenced late on 23 December, when Tracy first moved into the northwest quadrant relative to this 300 mb outflow centre. The 300 mb analysis for 2130 CST 24 December 1974, following recurvature, is shown in Fig 11 and it can be seen that the steering influence of the southern hemisphere system was clearly dominant.

Supplementary surface charts

Discussion of Tracy has so far concentrated on aspects that could be determined from broadscale synoptic and environmental considerations. Detailed surface analyses provided further insights into the storm and can be used to illustrate its small diameter and the intense nature of the pressure gradients that existed near the centre. The mean sea level isobaric analysis for 0600 CST 24 December 1974 as Tracy rounded the southwest corner of Bathurst Island is depicted in Fig 12. Such analyses were prepared each 3 hours in the Darwin Tropical Cyclone Warning Centre during the period of the cyclone and were based on reports from the normal and emergency surface network for the area, supplemented by a small number of ship reports. These analyses, used in conjunction with radar positioning of the centre, showed that gale force winds over the sea had a radial extent of only about 50 km. It will be shown subsequently that at the time of the analysis in Fig 12, Tracy was at or near peak intensity and its central pressure must have been about 950 mb. The intensity of pressure gradients near the centre of the storm is clearly illustrated by the fact that the value of the innermost closed isobar in Fig 12 is over 40 mb higher than the estimated central pressure.

FEATURES OF TRACY REVEALED BY WEATHER SATELLITES

The preceding chapter dealt with the broader aspects of Tracy's genesis, intensity, and movement, which were largely determined from conventional synoptic analyses. Photographs from weather satellites are accepted as an important data source for the synoptic analysis of all types of weather systems, and this is particularly so in the southern hemisphere where there is almost a complete absence of reports from reconnaissance aircraft and weather ships. In the case of tropical cyclones, the photographs enable a more complete description of a storm's growth and intensity and can provide indications of future movement.

Tracy's analysis and prediction was an example of the extreme value of satellite information. Meteorologists were able to detect the cyclone in its infancy and follow its development and movement over the entire period from 20 December until 26 December, when it degenerated into a rain depression.

Available data and general distribution

The Bureau's readout station in Darwin received photographs at the time from the United States weather satellites ESSA 8 and NOAA 4 each day. ESSA 8 (which has since failed) provided pictures from a television camera system. In the case of NOAA 4, visual imagery is produced by a scanning radiometer with sensors in the

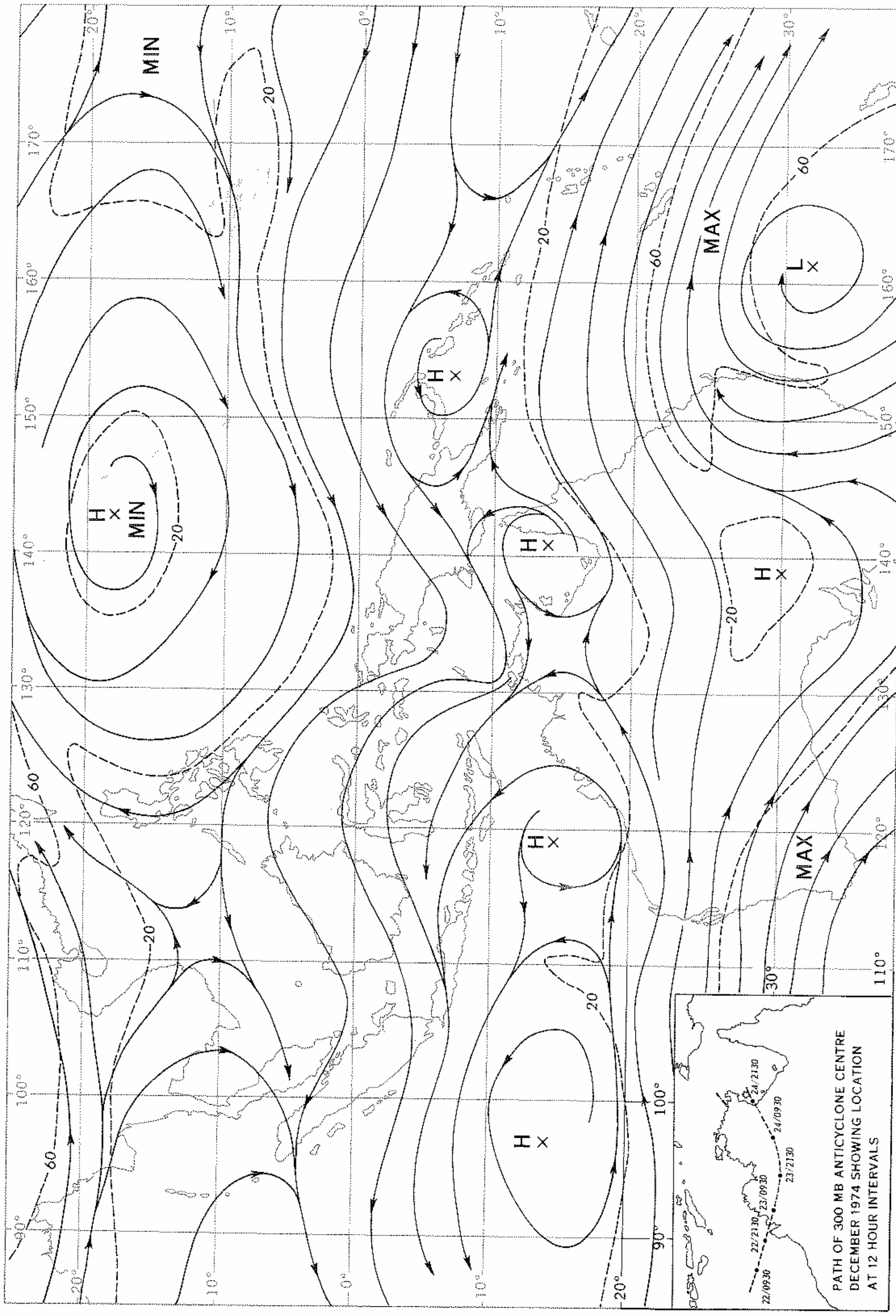

Fig 10 300 mb streamline-isotach pattern for 0930 CST 22 December 1974 illustrating upper air features prior to Tracy's recurvature. The inset shows the subsequent movement of the anticyclone centred off the NW coast of Australia.

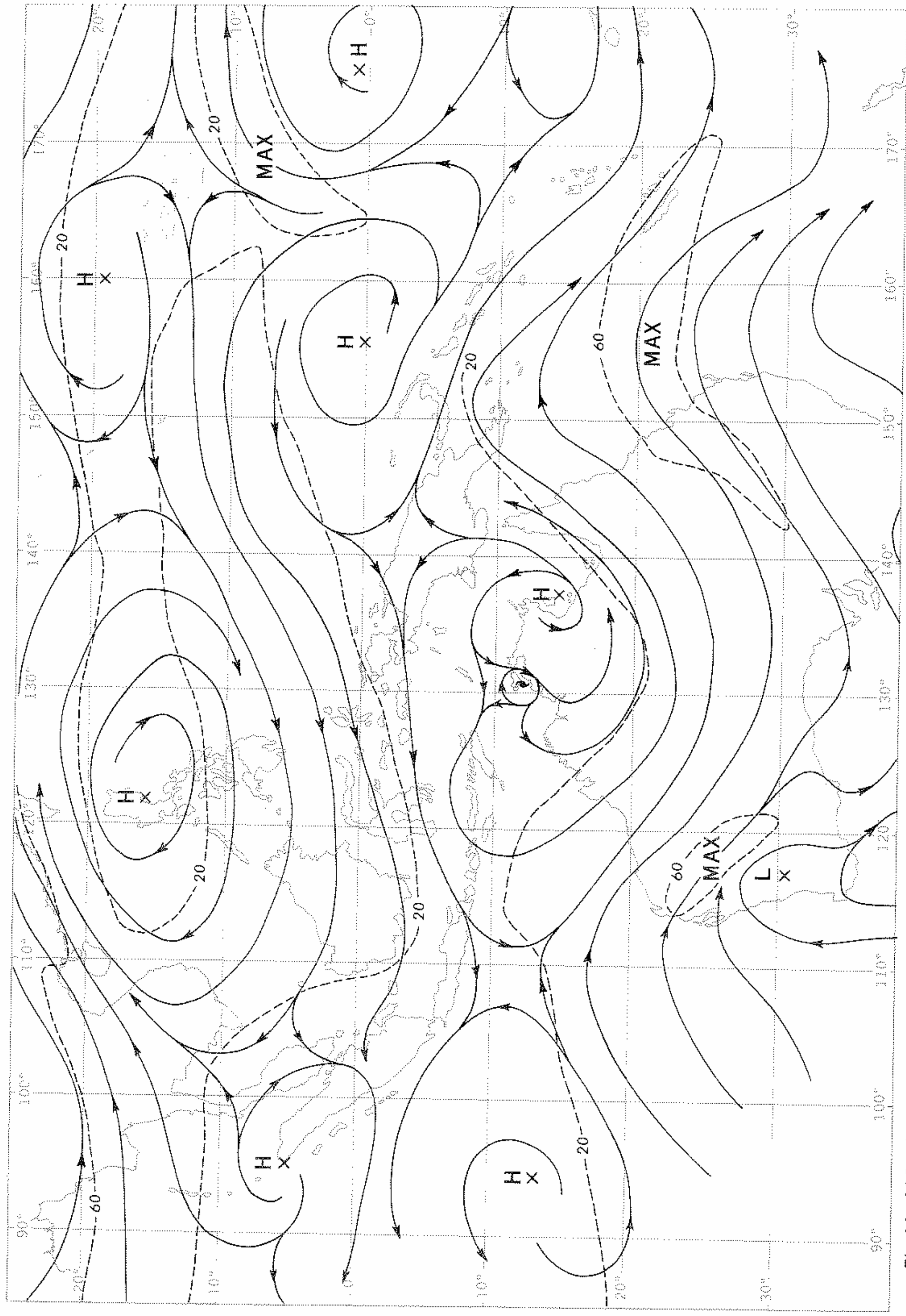

Fig 11 300 mb streamline-isotach pattern for 2130 CST 24 December 1974 illustrating upper air features following Tracy's recurvature.

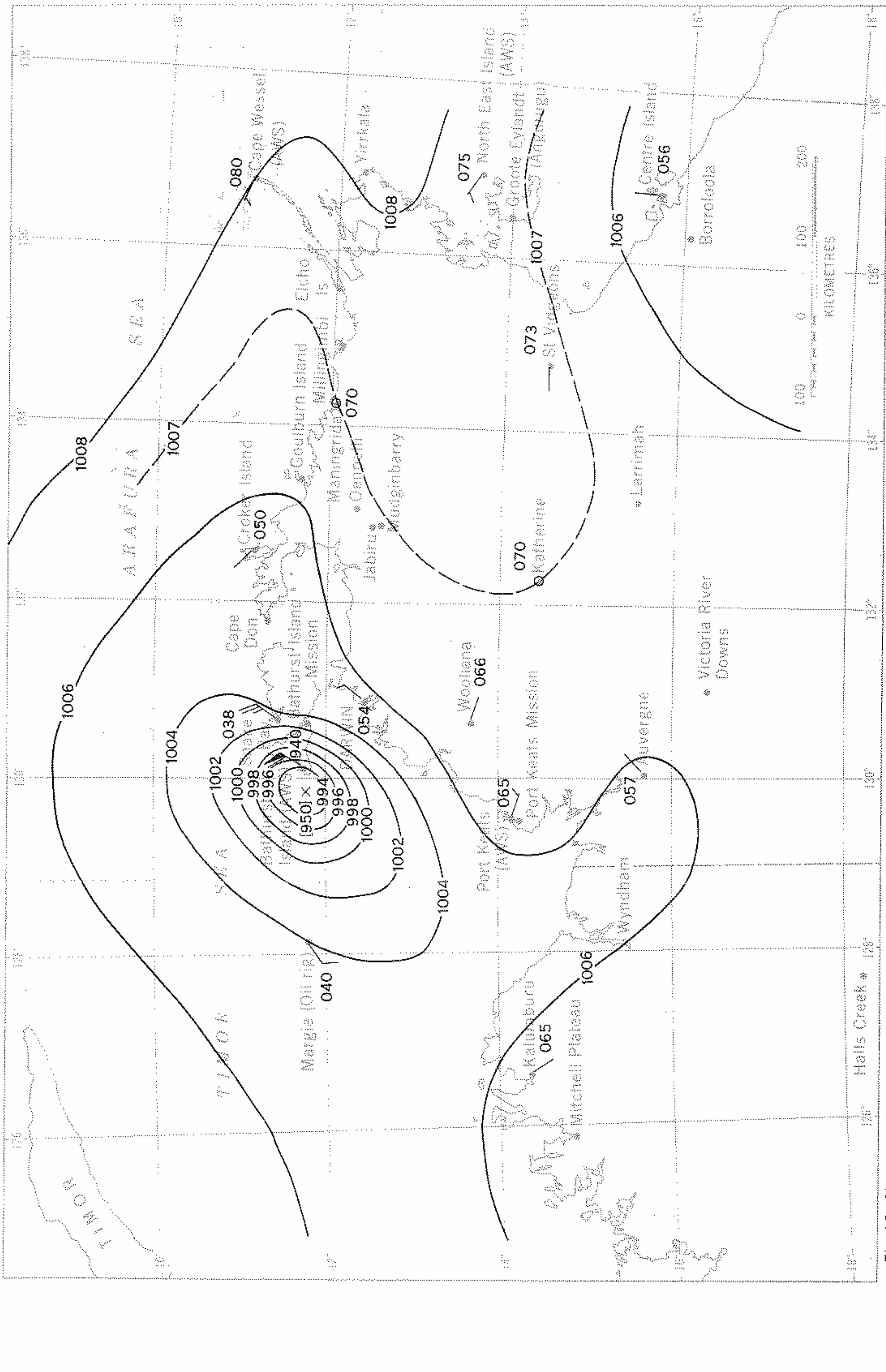

Fig 12 Mean sea level isobaric pattern for 0600 CST 24 December 1974. The last closed isobar is 994 mb and Tracy's central pressure is estimated to have been near 950 mb at this stage. Places illustrated comprised the normal and emergency surface reporting network for the area.

visible and infrared (IR) range. The IR information is received twice daily and maintains the vigilance during the hours of darkness.

Additional data for the period have since been made available from the National Environmental Satellite Service (NESS) Headquarters in Washington and the Joint Typhoon Warning Centre (JTWC), Guam in the form of selected Defence Meteorological Satellite Program (DMSP) photographs and fully rectified NOAA 4 imagery. These pictures are of superior quality to those normally available to operational staff in Australia and facilitate the application of the latest analysis techniques. Post application of satellite data to Tracy involved experienced meteorologists from the National Meteorological Analysis Centre, Melbourne and used the better data made available from the United States. Essentially the rectified visual NOAA 4 imagery supplied the basis for the analysis and as recommended by Dvorak (1975), the IR data were used to confirm trends established by the more reliable daytime indications.

Intensity analysis

The feasibility of applying satellite observations to estimate the intensities of tropical cyclones was recognised early in the meteorological satellite program of the 1960s. The findings of several authors provided the basis for an intensity classification system developed by NESS towards the end of the decade and described by Oliver (1969).

More recently Dvorak (1975) devised systematic procedures for both the analysis and forecasting of tropical cyclone intensities. This technique combined the interpretation of satellite imagery with a model of tropical cyclone development, and generally gave superior results to previous methods. Later refinements by Dvorak (1975) have resulted in further improvement. He quotes independent tests on west Pacific cyclones during the 1972 season that compared maximum winds estimated using the technique with official post season figures and showed a reduction of mean deviation to 15 km/h and root mean square error to 22 km./h.

The latest scheme also makes allowance for unusual rates of change, by which a cyclone’s development may be identified as rapid, typical, or slow. The appropriate curve for a particular storm is determined from the changes in its central dense features and outer banding features that have occurred between successive satellite observations.

It was found that Tracy’s development pattern fitted extremely well to the rapid curve of Fig 13 (after Dvorak 1975). The T numbers on the mantissa classify the various stages of development and are directly related to the adjacent figures on the left in smaller type, which signify corresponding maximum wind speed.

Imagery form NOAA 4 at 1002 CST 21 December (Fig 14) indicated that Tracy had reached stage T2. After this it developed rapidly and at 0902 CST 22 December 1974 the cyclone’s appearance was much more organised (Fig 15). Deep layer convection occurring near the centre had produced a central dense overcast area in which there were faint indications of an eye; however, a clearly defined eye was never observed by satellite. The cirrus steamers extending from the outer cloud band suggested that at this stage the main upper level outflow was concentrated to the northwest of the circulation centre. Such asymmetry in the outflow layer is typical of many tropical cyclones (Anthes 1974) The intensity analysis of this photograph classified Tracy at T3.5 and thus placed development along the rapid curve of Fig 13.

Careful analysis of the subsequent IR and visual photographs confirmed the selection of the rapid development curve and indicated that Tracy attained maximum development at T5.5 when NOAA 4 was overhead at 2218 CST 23 December 1974.
The photograph for this time is shown in Fig 16.

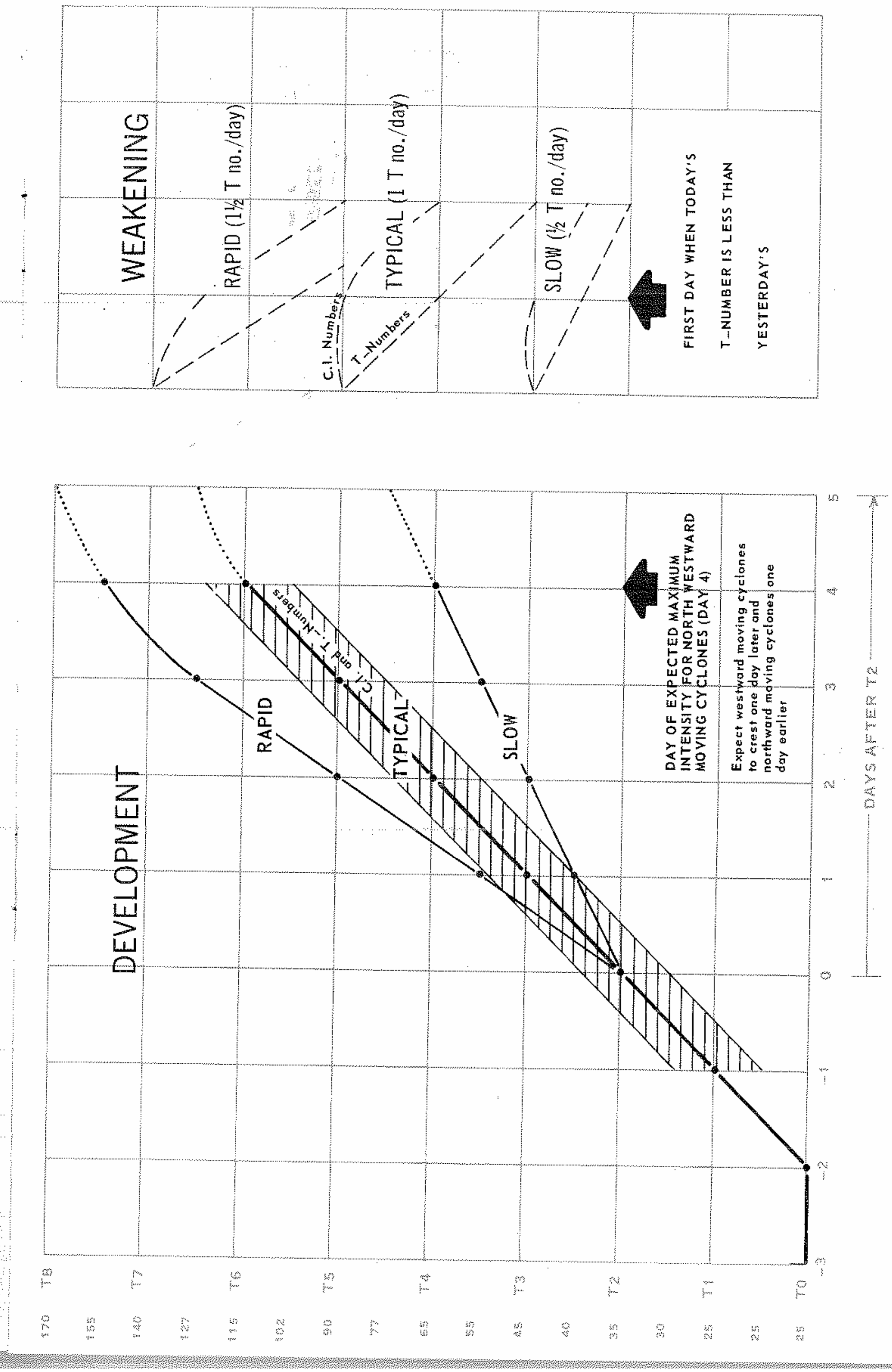

Fig 13 Modelled tropical cyclone intensity change curves for use in conjunction with satellite imagery (after Dvorak 1975).
Note: Block comments referring to directions of movement are for northern hemisphere storms.

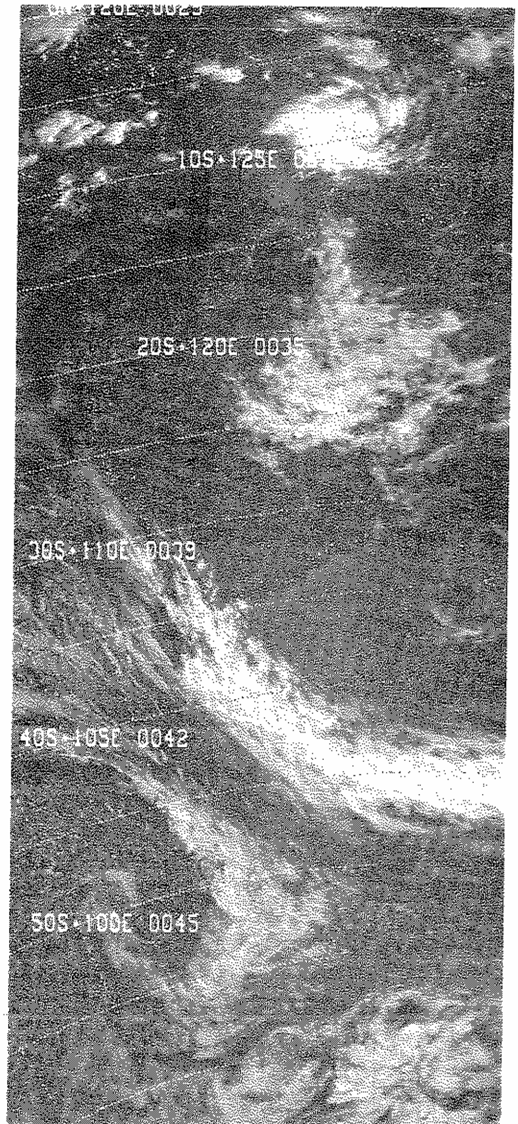

Fig 14

Satellite picture of Tracy at 1002 CST 21 December 1974 produced from NOAA 4 visual imagery. (Courtesy of NESS). The storm is in its early formative stages corresponding to T2 of Dvorak's classifications.

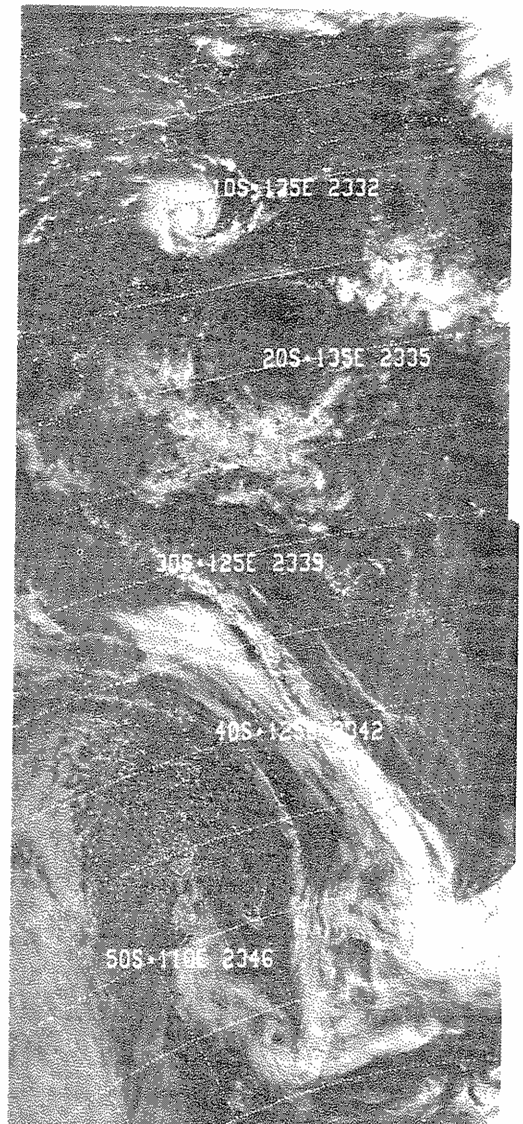

Fig 15

Satellite picture of Tracy at 0902 CST 22 December 1974 produced from NOAA 4 visual imagery. (Courtesy of NESS). The increased banding of cloud features and development of the central dense overcast is indicative of rapid intensification.

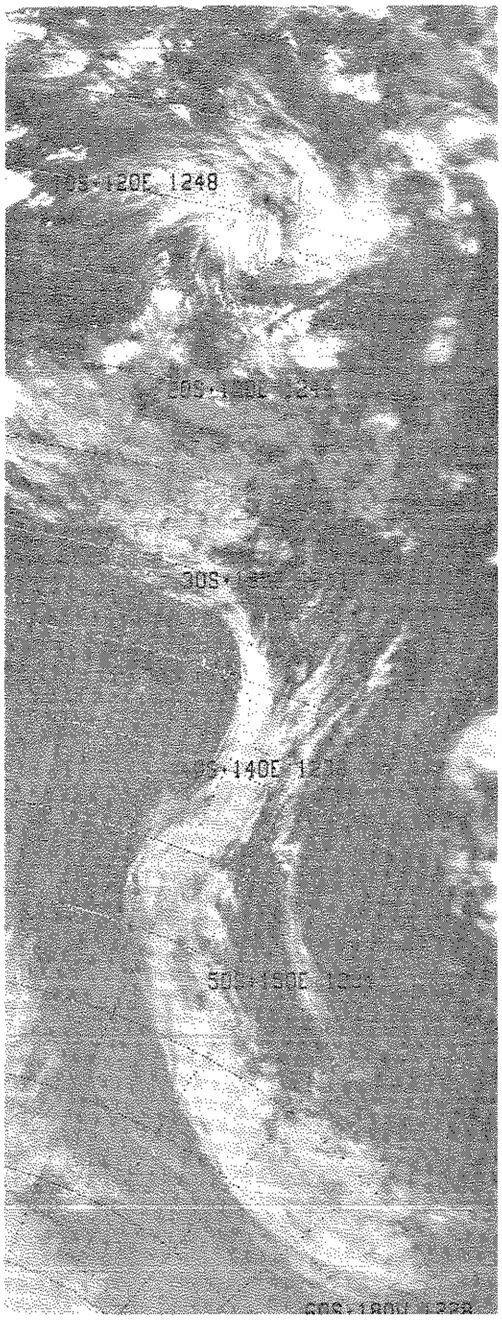

Fig 16

Satellite picture of Tracy at 2218 CST 23 December 1974 produced from NOAA 4 I.R. imagery. (Courtesy of NESS). This shows Tracy's appearance as it reached peak intensity corresponding to T5.5 of Dvorak s clas sifications.

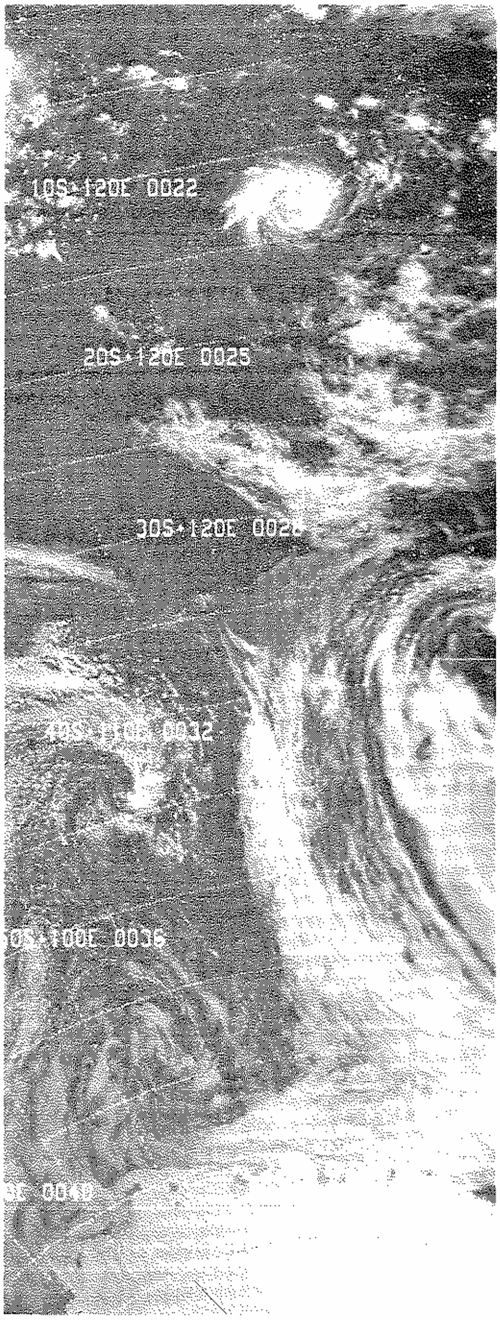

Fig 17

Satellite picture of Tracy at 0952 CST 25 December 1974 produced from NOAA 4 visual imagery. (Courtesy of NESS). The storm is inland at this stage. Weakening is indicated by the reduced size of the central dense overcast.

Thereafter the cloud features showed a reversal of the previous trends and Dvorak suggests that such arrested development is frequently associated with recurvature. This was indeed the case with Tracy.

The picture at 0952 CST 25 December 1974 in Fig 17 shows the cyclone south-east of Darwin, beginning the rapid decay typical of many tropical cyclones once they cross the coast.

In one respect, the satellite data have achieved even greater importance subsequent to the event. Wind measurements in the cyclone over Darwin were deficient due to instrument failure brought about by effects of the storm; and the use of satellite information is a method which provides estimates of maximum winds up to the time of landfall. The analysis technique allows for factors not directly related to cloud features. It incorporates the use of a Current Intensity (CI) number which accounts for the observed delay in the reduction of maximum wind speed after cloud features have indicated weakening and the cresting of the cyclone's winds between visual satellite observations 24 hours apart. For developing storms the CI number is the same as the T number, but once weakening trends are established it is the CI number (and not the T number) that relates directly to the maximum wind speeds. The relationship between CI numbers and T numbers for weakening storms is illustrated on the right hand side of Fig 13 and the results of the analysis of the full sequence of satellite photographs are shown in Table 2.

Table 2 Results of Dvorak (1975) analysis applied to tropical cyclone Tracy (December 1974): satellite system NOAA 4

Date/time	Type of data	T number	CI number	Maximum wind speed (1 min average)
				km/h
21/1002	VIS	2.0	2.0	56
21/2223	Night IR	2.5	2.5	65
22/0902	VIS	3.5	3.5	102
22/2123	Night IR	4.0	4.0	120
23/0957	VIS	5.0	5.0	167
23/2218	Night IR	5.5	5.5	189
24/0857	VIS	5.0	5.5	189
24/2313	Night IR	4.5	5.5	189
25/0952	VIS	Cyclone over land		

These results suggest that Tracy was at a peak intensity corresponding to a maximum sustained wind speed of 189 km/h (102 kn) at 2218 CST 23 December 1974. They further suggest that this wind strength was maintained for another 24 hours and the storm was still at or near peak intensity as it entered Darwin.

The maximum wind speeds shown in Table 2 and obtained from Fig 13 refer to a one minute average wind. The maximum speed of 189 km/h must be multiplied by a factor of 1.25 to estimate the peak gust that would be recorded on a Dines anemograph similar to the one in Darwin at the time. This yielded an estimate of 236 km/h. The choice of 1.25 as the appropriate gust factor is discussed further later in this report.

Direction of movement

Forecasting the movement of tropical cyclones is one of the most difficult and challenging tasks faced by meteorologists. Generally a combination of subjective and objective techniques is used; however, it has long been felt that ongoing processes visible in satellite photographs must provide clues to the storm's future behaviour. Intensity changes have been well documented as discussed in the previous section but techniques for forecasting movement form satellite data have not been so forthcoming.

In an effort to determine a relationship between the direction of movement of tropical cyclones and the structure of their cloud systems, Lajoie and Nicholls (1974) studied over one hundred pictures of 26 well-defined tropical cyclones in the Australian region. Their study revealed that:

(a) A tropical cyclone does not move towards a sector that is devoid of massive cumulonimbus clusters. This sector can be defined as extending from the edge of the central cloud mass to about 600 km from the centre.

(b) Outer cloud bands are entities separate from the central could mass of a tropical cyclone and generally end abruptly in the southern quadrants some 200 to 600 km from the vortex centre.

(c) Cumulonimbus clouds are more developed at or near the down-stream end (in a cyclonic sense) of the outer cloud band.

(d) A tropical cyclone moves or curves within 12 hours of picture time towards a direction given by a line joining the vortex centre to the most developed cumulonimbus cluster at or near the downstream end of the outer cloud band.

Lajoie (1976) has applied these finding to the sequence of photographs covering the Tracy period. It was found that skilled application of the technique gave excellent indications of the storm's direction of movement and, in particular, the recurvature as it neared Bathurst Island.

FEATURES OF TRACY REVEALED BY RADAR

Available data

Tracy was under radar surveillance from early on 22 December 1974 until failure of the power to the radar just after 0430 CST 25 December 1974. The radar observations were of the Plan Position Indicator (PPI) display, which present a plan view of the echoes from the rain associated with Tracy. During the occurrence of Tracy the prime function of the observations was to assess the cyclone movement from consecutive positions of the cyclone eye. Inferences as to structure, intensity, and position of the maximum winds have been made in the post analysis of the photographic records of the PPI echoes.

Photographs of the PPI available for post analysis covered the period 0320 CST on 22 December to 0415 CST on 25 December, with intervals between photographs of between 30 and 60 minutes.

A selection of photographs taken during this time are shown in Appendix F. Individual photographs in this set will be referred to later in this section

Other data sources associated with the radar were:

(a) a descriptive log of cyclone observations, including an assessment of the eye position, completed hourly by a duty observer at the radar;

(b) manually produced overlay tracings of PPI echoes at 30-minute intervals.

Major radar features of Tracy

The main radar echo feature of Tracy was the central region containing the eye. The classical echo formation is shown by Tracy in Fig 18(a). Indicated in this figure is an echo free area, often virtually cloud free, bounded by an eye wall echo of approximately circular shape. Other radar observed features exhibited by Tracy and common to most other cyclones were the presence of a rain shield area and spiral rain bands as shown in Fig 18 (a), (b), and (c).

The unusually small size of Tracy compared with other tropical cyclones was reflected in the small area covered by the radar echoes. The diameter of the main echo area was about 150 km. As a comparison the values for Althea (Townsville radar, 1971) and Trixie (Port Hedland radar, 1975) were 400 km and 250 km, respectively.

The overall radar pattern of Tracy showed a fair degree of asymmetry with most of the spiral bands converging in an area to the left of the storm's path (e.g., Pic 49). This is consistent with observed asymmetries in most other tropical cyclones. (In the northern hemisphere the maximum echo coverage is to the right of the path.)

Eye characteristics of Tracy

The radar eye of Tracy was small, being about 12 km in diameter. Typical inner diameters of the eyes of tropical cyclones are 10 to 60 km and an 'average' size would be about 30 km. Several times during Tracy's approach to the coast the eye was elliptical in shape (Fig 18 (b) and also a second concentric eye wall was observed (Fig 18 (c)), a possible indication of increased intensity.

A partial eye wall echo first appeared at 1030 CST on 22 December (Pic 8) and this was more obvious at 1330 CST (Pic 12), when the eye diameter was determined as 37 km at a range of 204 km from the radar. Intensification of Tracy over the period from 1330 CST on 22 December to 1745 CST on 23 December (Pic 49) can be inferred from:

(a) A gradual decrease in eye diameter from 37 km to less than 10 km (Fig 19). Such a decrease in eye size should generally indicate deepening of a cyclone (Palmen and Newton 1969).

(b) The formation of a complete, almost circular eye wall separated from the rest of the storm by an area free of echoes (Pic 43). At various times a concentric 'double eye' configuration was observed as the first rainband outwards from the eye completely enclosed the inner eye wall (Pic 49). Such 'double eyes' are often associated with the most intense stage of a tropical cyclone's development (Hoose and Colon 1970) but there is not enough evidence available to make this a general rule.

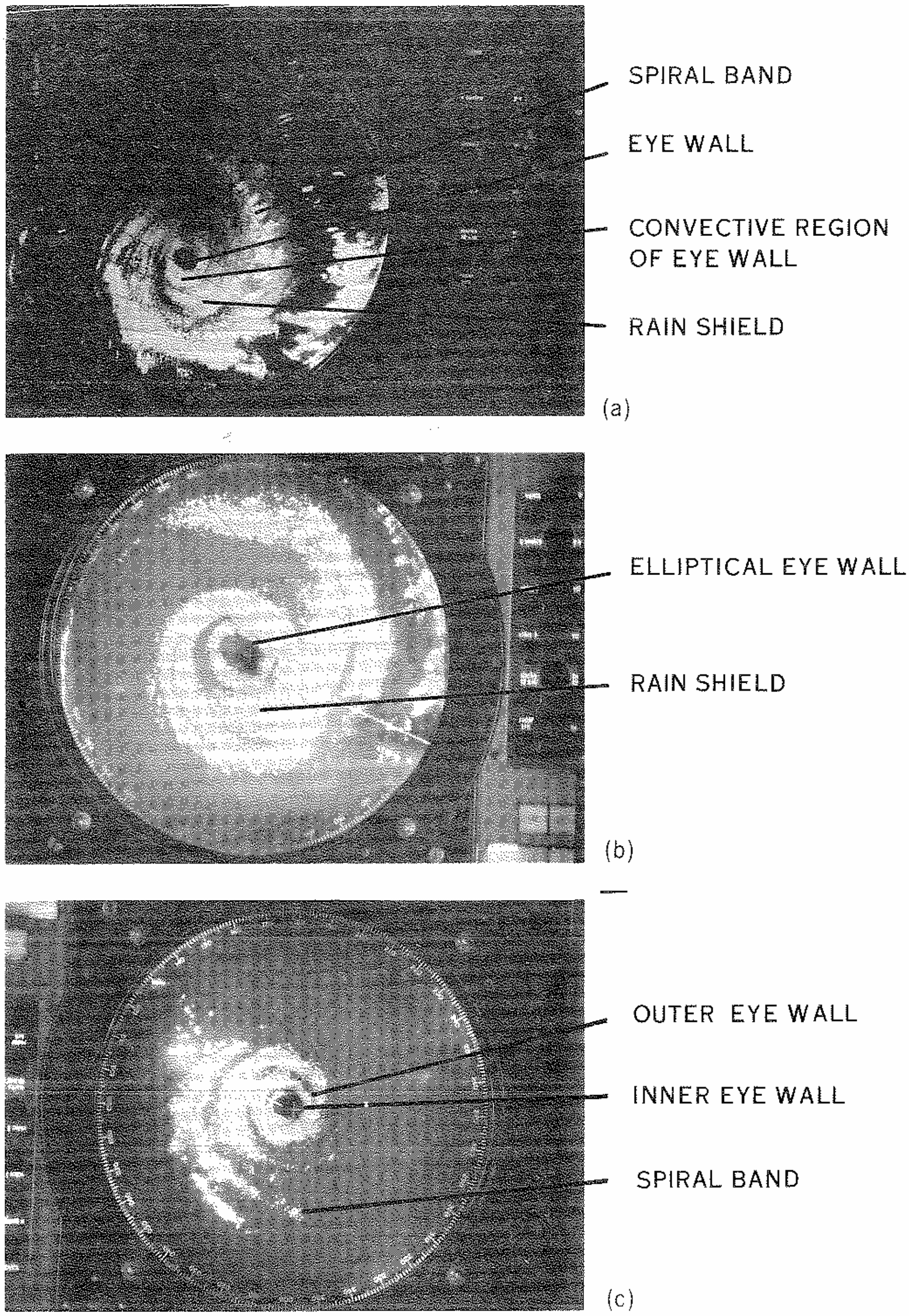

Fig 18(a), (b) & (c) Photographs of the Darwin Airport radar screen illustrating the main features of Tracy's echo structure.

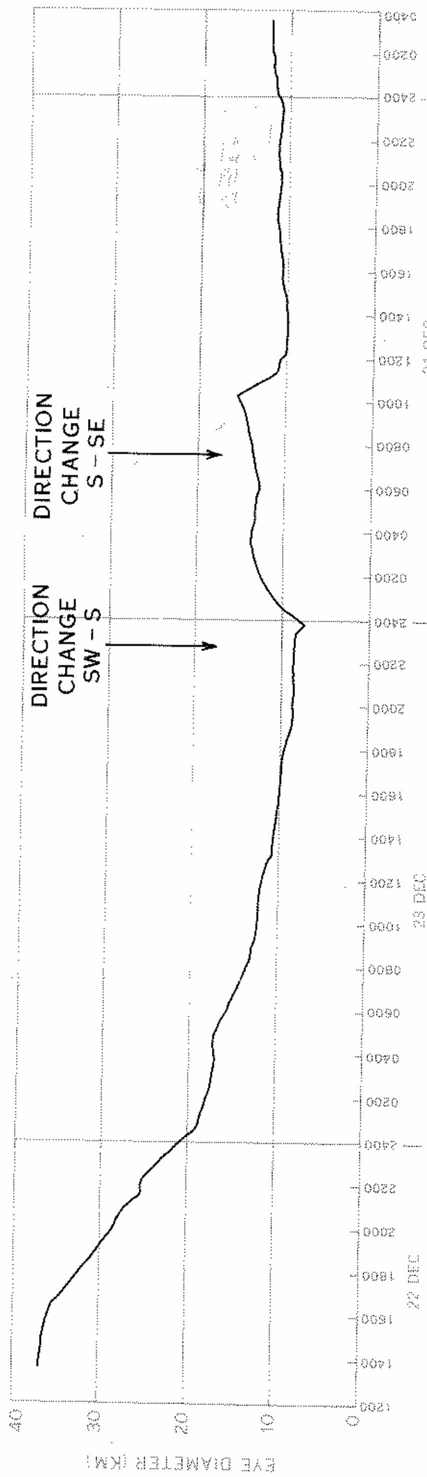

Fig 19(a) The variation of Tracy's radar eye diameter.

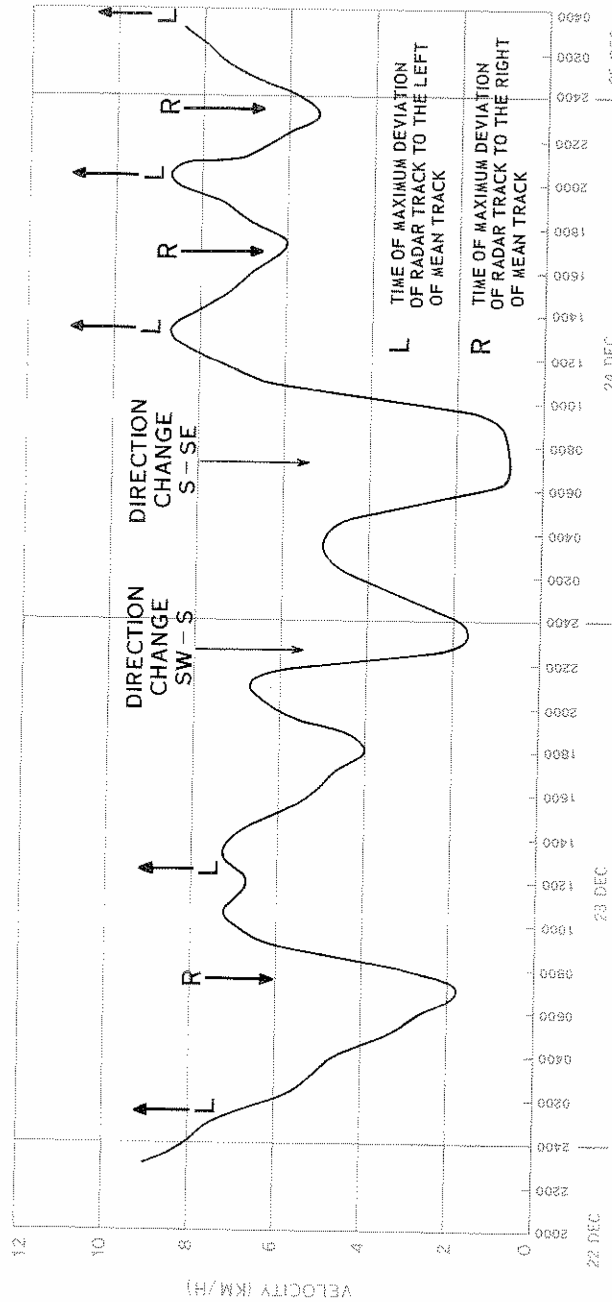

Fig 19(b) Speed of movement during the period of radar observations.

During the period 2100 CST on 23 December to 0900 CST on 24 December there was generally only a partial eye wall echo present, the eye being open on the western flank (Pic 77). Also during this period the eye diameter increased to around 14 km (Fig 19 (a)) and the speed of Tracy’s movement reduced (Fig 19 (b)) as it changed direction from southwestwards to southwards and finally to southeastwards (Fig 20).

After 0900 CST on 24 December, Figs 19 and 20 indicate that as Tracy moved in the direction of Darwin its speed increased, its eye diameter steadied at about 12 km, and the eye wall reverted to a closed circular configuration.

Tracy at landfall

The radar photograph at 0315 CST on 25 December (Pic 140) showed Tracy’s eye as making landfall at a distance of approximately 7.5 km from the radar. This observation indicates that the inner edge of the eye wall was very near the airport area.

Research into hurricanes by Shea and Gray (1973), Black et al. (1972), Simpson (1966), Jordan et al. (1960) indicate that for mature storms the maximum cyclonic winds occur within the inner eye wall. Fig 21 (Shea and Gray 1973) shows that the radius of maximum wind can be quite variable but account must be taken of the fact that the data include aircraft wind measurements from hurricanes at high latitudes where intensities can be lower and more variable. For a mature well developed cyclone the maximum winds are likely to occur within 6 km of the inner eye wall, with a possibility of a second but probably lower maximum in the outer eye wall region.

The ring of heaviest precipitation, where convergence and ascent are greatest, can be identified with the strongest winds in the storm (Palmen and Newton 1969); and furthermore the largest ascending vertical motions are concentrated in a narrow area at the radius of maximum winds (Shea 1972). A manual tracing of the PPI echoes at 0300 CST 25 December showed the band of most intense precipitation to be almost over the airport.

While some allowance must be made for small errors in detail involved in the manual tracing, the conclusion nevertheless follows that the radius of maximum winds most likely must have reached the airport between 0245 and 0315 CST on 25 December. The eye itself would have been very close to being over the radar at 0400 CST 25 December.

The major factors affecting a cyclone when it passes over the land are increased friction and the removal of the heat source from the sea. Miller (1966) indicates that the removal of the latent heat source of the sea makes the most important contribution to the ‘filling’ process of a cyclone once the central region reaches land. The ‘filling’ process is seen on the radar as a loss of distinct spiral bands; the previously clear eye region fills with rain and the circulation of the echoes diminishes until the system appears as a large conglomeration of rain echoes Observations of Tracy ceased due to power failure soon after landfall and therefore no major indication of filling of the cyclone was observed. The observations at 0345 CST on 25 December (Pic 142) and 0415 on 25 December (Pic 144) showed some ingress of rain into the previously clear eye region.

Track of Tracy

While the central region of a tropical cyclone is within radar range, the radar provides the best means of determining the track. The centre of a tropical cyclone is taken to be the geometrical centre of the echo free area within the eye wall echo and radar observations of this feature of Tracy, mainly at one hour intervals, have been used to determine the position of the centre during the post analysis. The continuous radar track of the cyclone centre is shown in Fig 20.

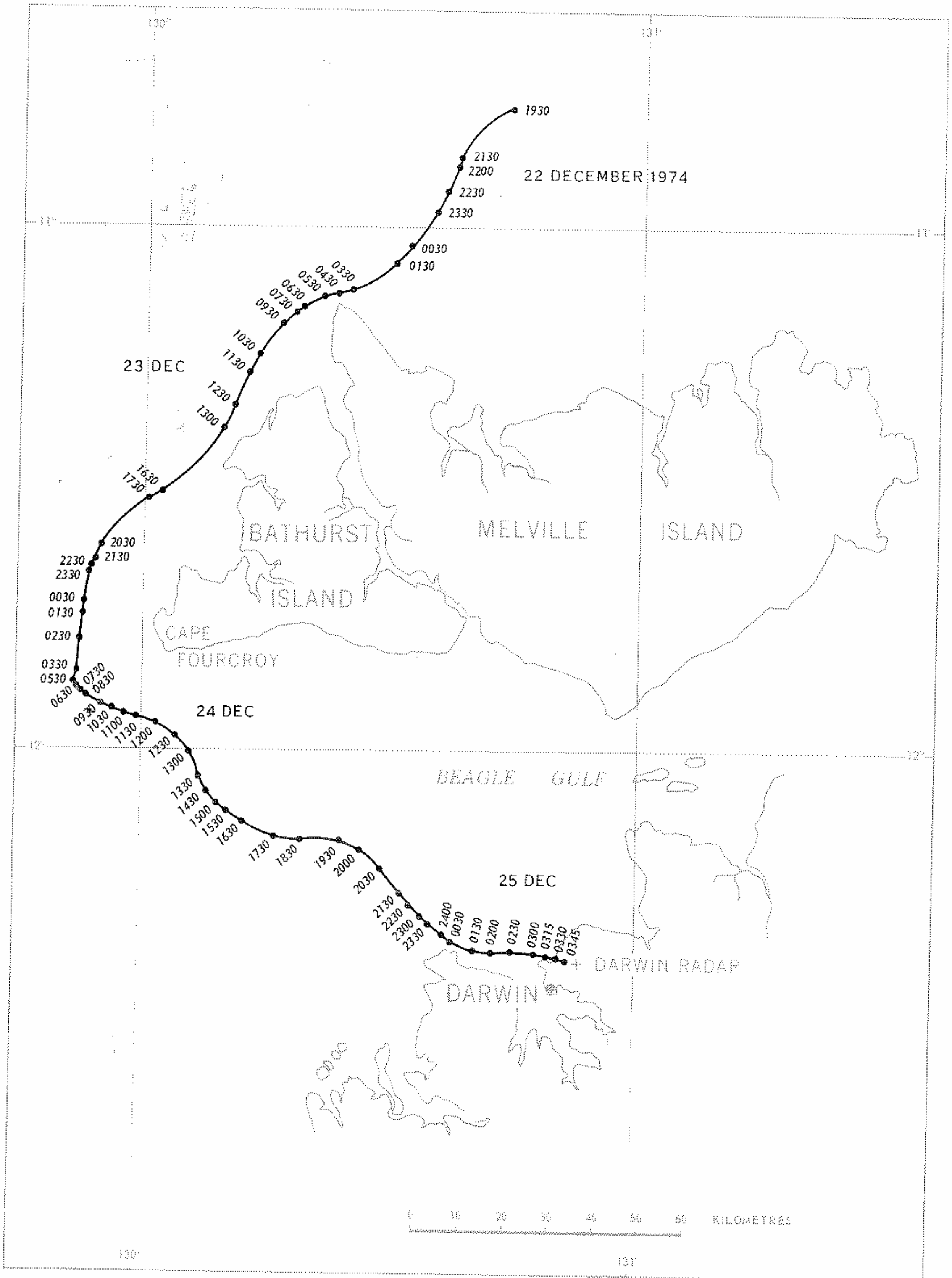

Fig 20 The track of cyclone Tracy as determined by successive positions of the centre of the radar eye.

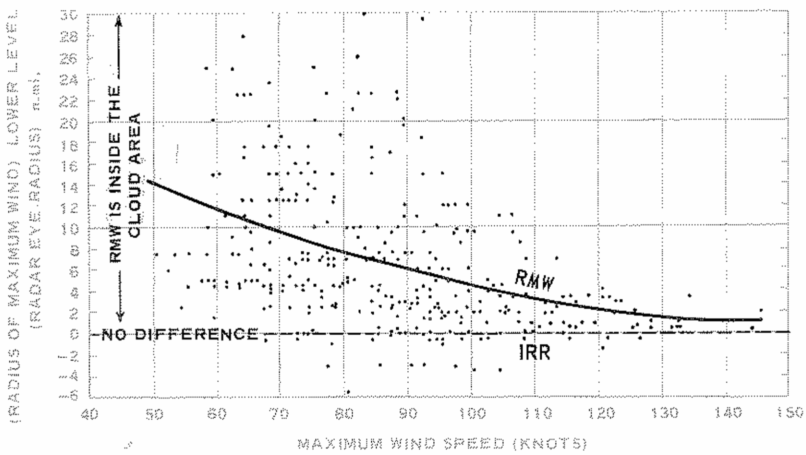

Fig 21 Difference between the radius of maximum wind and the radar eye radius versus maximum wind speed for some Atlantic hurricanes. The best fit curve is indicated by the heavy line. (After SHEA (1972)).

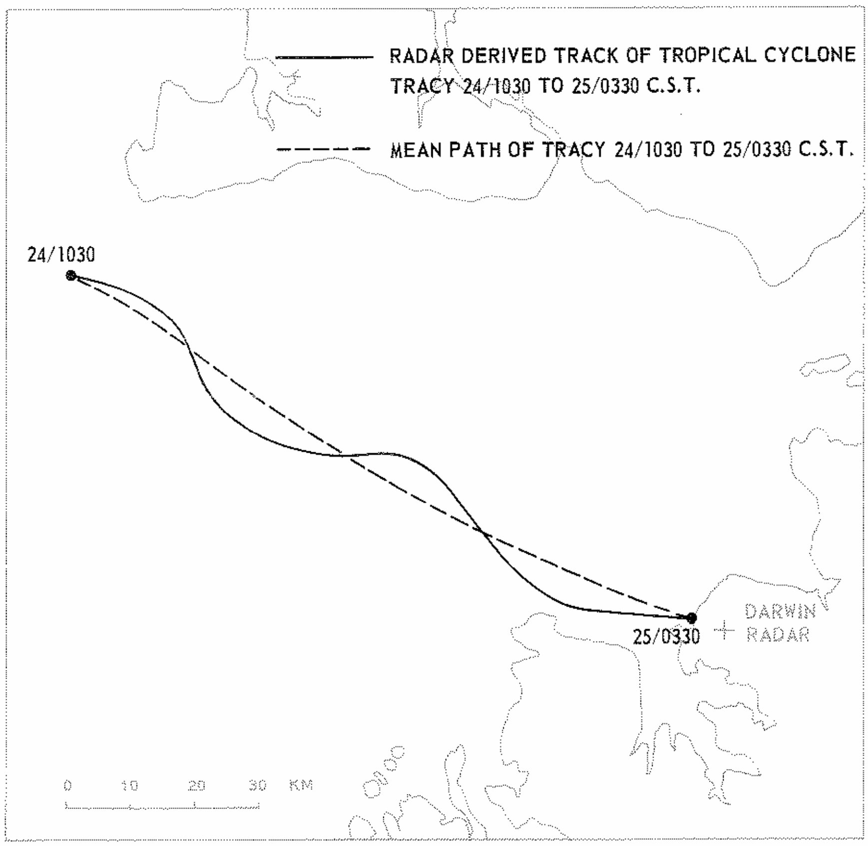

Fig 22 The radar track (solid line) and the mean path of Tracy (dashed line) during the last 17 hours before landfall.

Previous radar observations of tropical cyclones have often shown that the centre appears to move in an irregular fashion with sudden accelerations and sideways deviations and even with small loops or cusps in the track. Senn (1961) concluded from an analysis of small scale track variations for a number of hurricanes observed by radar that rapid lateral variations in the centre position of up to 3 n mile (5.5 km) in 5 minutes could occur. However, since the eye wall echo structure is rarely perfectly circular and since changes in the eye wall echo configuration do occur over short periods of time, such track variations must be viewed with considerable caution It is very unlikely that the tropical cyclone system as a whole undergoes such irregularities of movement. Also, for a tropical cyclone with an eye diameter of 25 n mile (46 km), a variation of 3 n mile (5.5 km), given the inherent variability of the eye wall structure, would be within the area of uncertainty in determining the centre position. Conover (1962) overcame some the of the centre determination difficulties by applying a circular eye configuration to the most reliable portion of the eye wall observed and by applying a reasonable amount of judgement in weighing continuity with each centre fix made. The track of Tracy shown in Fig 20 was obtained using a similar procedure. When the echo structure around the eye is clearly defined, as for example at 1045 CST on 24 December (Pic 101), and small in size, as was the case with Tracy, the task of constructing a track is relatively easy, although care is still needed, particularly in interpreting any irregularities or deviations that may appear to occur in the eye positions about a mean track. Not all photographs used, some of which were at 30-minute intervals, are depicted on the track shown in Fig 20.

The two noteworthy features of the cyclone's path are:

(a) There were two major direction changes; from southwesterly to southerly around 2230 CST on 23 December; and from southerly to southeasterly around 0730 CST on 24 December. Fig 19 (b), which shows the speed variations of Tracy, indicates that significant reductions in speed occurred simultaneously with these direction changes.

(b) Regular oscillations occurred in the track with a period of about 8 hours and an amplitude of 6 km. These oscillations are considered a real feature of Tracy's track and must not be confused with short period fluctuations mentioned previously.

The track oscillation amplitude is of the same order as the eye diameter and hence eye positioning errors, which would not exceed 2 km, do not explain the oscillation. Coupled with the track oscillation is the centre speed variation mentioned above. In general the speed is greater with the track deviations to the left and less with deviations to the right. One complete oscillation must therefore be observed, involving measurements of speed and position of the centre, before confidence can be placed in statements of the mean speed of the storm along a *mean* path. The radar track, and the mean forward movement of Tracy over the 17 hours before landfall is shown in Fig 22. Note the difference between speed along the radar track, between 5.3 and 8.7 km/h, and speed along the *mean* track for the same period of 6.3 km/h. A trochoidal motion of the vortex would give speed variations in the same sense as those observed for Tracy. Explanations of such track oscillations involving the notion of a vortex embedded in a basic steering current (Yeh 1950, Kuo 1969, Khandekar and Rao 1975) are of particular relevance to this aspect.

Spiral band and individual echo movement

Emphasis has been placed on the radar track derived from observations of the radar eye only because observations of other echo features give little or no indication of the movement of the system as a whole. In particular, spiral bands have been shown to originate near the cyclone eye and propagate outwards as they develop and dissipate (Hardy et al. 1964). Measurements of the outwards speeds of some spiral band segments of Tracy shoed them to be moving at speeds comparable with the foreward movement of the system as a whole, but in different directions to the foreward storm movement.

Individual echoes tended to move in an almost circular path around Tracy’s centre, reflecting the general low level wind pattern of the system. Therefore, the movement of such echoes cannot be used to determine the overall movement of the system.

BEHAVIOUR AND CHARACTERISTICS NEAR DARWIN

Track through Darwin and eye reports

The path of cyclone Tracy through the built-up areas of Darwin is shown in Fig 23. This was constructed from radar data provided up to 0430 CST and incorporates numerous eyewitness reports of lulls or calms. It is consistent with barograph and anemometer recordings, damage patterns apparent on photomaps produced by the Royal Australian Survey Corps from aerial photographs made by the RAAF on 29 December 1974 and 2 January 1975, and is in good accord with an independent debris and lull survey conducted by Leicester and Reardon (1975).

Tracy’s centre reached East Point at 0315 CST and crossed the coast just north of Fannie Bay a quarter of an hour later. It then moved directly towards the airport at approximately 11 km/h and was centred over the radar at 0400 CST. From the airport the centre moved south of Winnellie and Berrimah and then recrossed the Stuart Highway just south of Knuckeys Siding shortly after 0430 CST. Two reliable reports of the actual period of the calm were obtained from Fannie Bay and the RAAF log at Darwin airport. The period of ‘complete calm’ at Fannie Bay was from 0320 CST until 0355 CST, while at the airport it extended from 0350 CST until 0425 CST.

The boundary of the radar eye as depicted on the PPI overlays at 0330 CST and 0400 CST was transposed onto the figure and several interesting points emerged. First, the approximate boundary of lulls or calms corresponded very closely (within 1 km) with the edge of the eye wall. Second, it was possible to explain the timing of events at both Fannie Bay and Darwin airport, which at first appeared somewhat anomalous.

At Fannie Bay particularly, the ‘centre’ of the eye was much closer at the beginning of the calm that it was when the calm ended. If, however, we assume that the rain echoes visible on the radar were an accurate reflection of the inner wind field in which they were embedded, then it can be seen in Fig 23 that at 0330 CST the inner wind field was ‘distorted’ and the onset of the calm was delayed by the ‘distortion’. This ‘distortion’ appears to have been a transitory phenomenon associated with the eye making landfall. Indeed, by 0400 CST when the trailing edge had crossed the coast the eye, although smaller, had assumed a more regular elliptical shape.

The actual radar photograph for 0415 CST (Pic 144) showed a number of small rain elements inside the eye wall at this time, and it would appear that increased frictional convergence was bringing peripheral winds into what had previously been a calm centre.

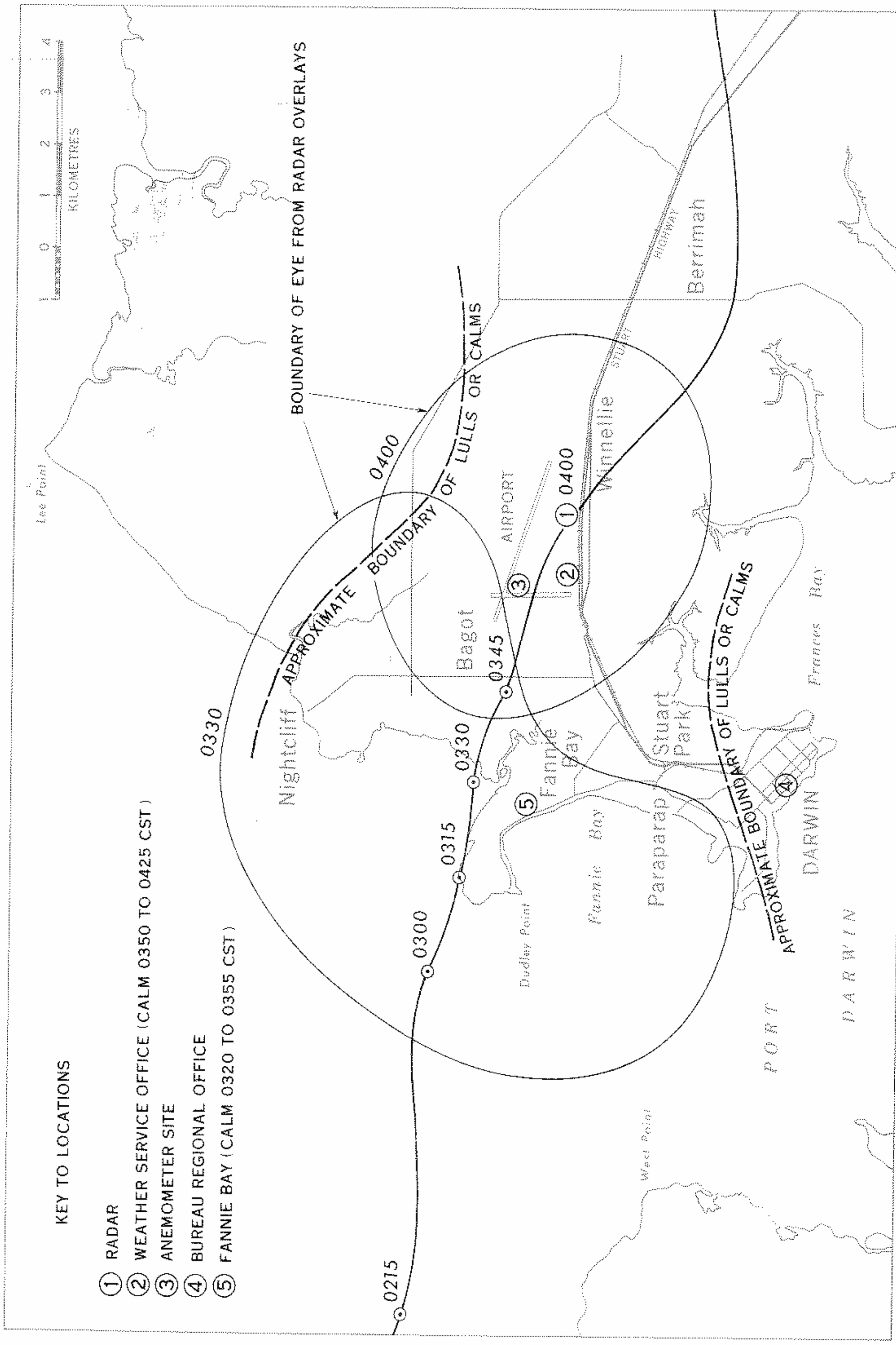

Fig 23 Path of cyclone Tracy through the built-up areas of Darwin showing approximate boundaries of surveyed lulls or calms and their close relationship to the eye as determined by radar. Key locations referred to in the text are also indicated.

Central pressure

The first accurate measurements of atmospheric pressure near or in the cyclone's eye were made over Darwin itself. The Bureau's installations in Darwin are shown in Fig 23. The Regional Office and the airport Weather Service Office were each equipped with a mercury barometer and a weekly barograph. Half hourly pressure values throughout Tracy's passage were read from the mercury barometer in the Regional Office and are listed in Table 3. The lowest discrete reading was obtained at 0335 CST when the pressure, corrected to mean sea level, was 956.5 mb. The barograph traces are shown in Fig 24(a) and (b) and have been the subject of a thorough investigation. The timing on the Weather Service Office barograph trace has proved to be approximately 30 minutes fast while the timing on the Regional Office traces was similarly in error. It was found that the Regional Office trace did not 'bottom' and, even though an ink smudge somewhat masked the trace, the minimum station level pressure of 948.5 mb was correctly recorded. This is equivalent to 954.5 mb when corrected to mean sea level, and agrees well with the lowest discrete reading at 0335 CST in Table 3.

Table 3 Pressure readings of the mercury barometer, Darwin Regional Office, 25 December 1974

Time (CST)	Pressure at -	
	Station level	Mean sea level
	mb	mb
Midnight	990.4	996.4
0030	987.8	993.8
0100	985.6	991.6
0130	982.4	988.4
0200	978.5	984.5
0230	973.0	979.0
0300	962.9	968.9
0335	950.5	956.5
0400	953.5	959.5
0430	961.0	967.0
0500	975.6	981.6
0530	981.0	987.0
0600	986.5	992.5

The mercury barometer at the Weather Service Office was read each half hour up to about 0300 CST, when the building was severely damaged. One further reading was made during the calm at approximately 0400 CST in the middle of the cyclone's eye. The value then obtained was 950.4 mb corrected to mean sea level. This was consistent with the minimum pressure recorded in the Regional Office (on the basis of measured pressure gradients and the distance that the Regional Office was outside the eye) and firmly established Tracy's minimum pressure corrected to mean sea level over Darwin as 950 mb.

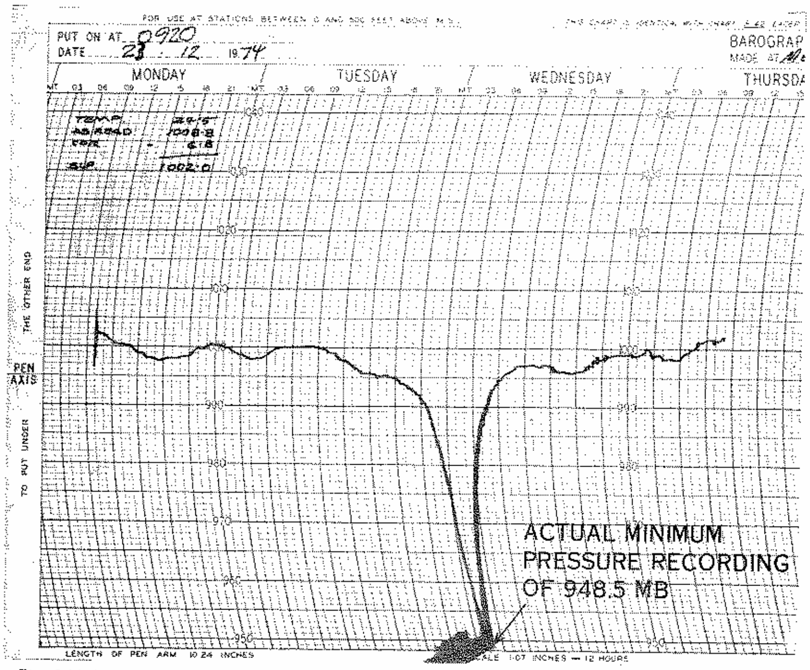

Fig 24(a) Barograph trace at Darwin City Regional Office, 23–26 December 1974 (Station level pressure).

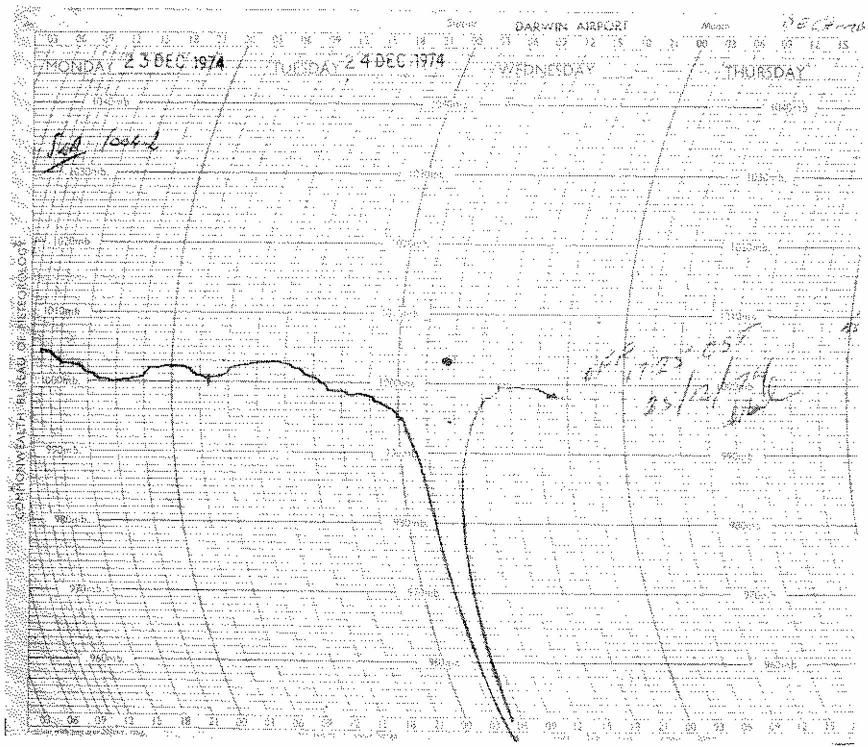

Fig 24(b) Barograph trace at Darwin Airport, 23–25 December 1974. (Station level pressure).

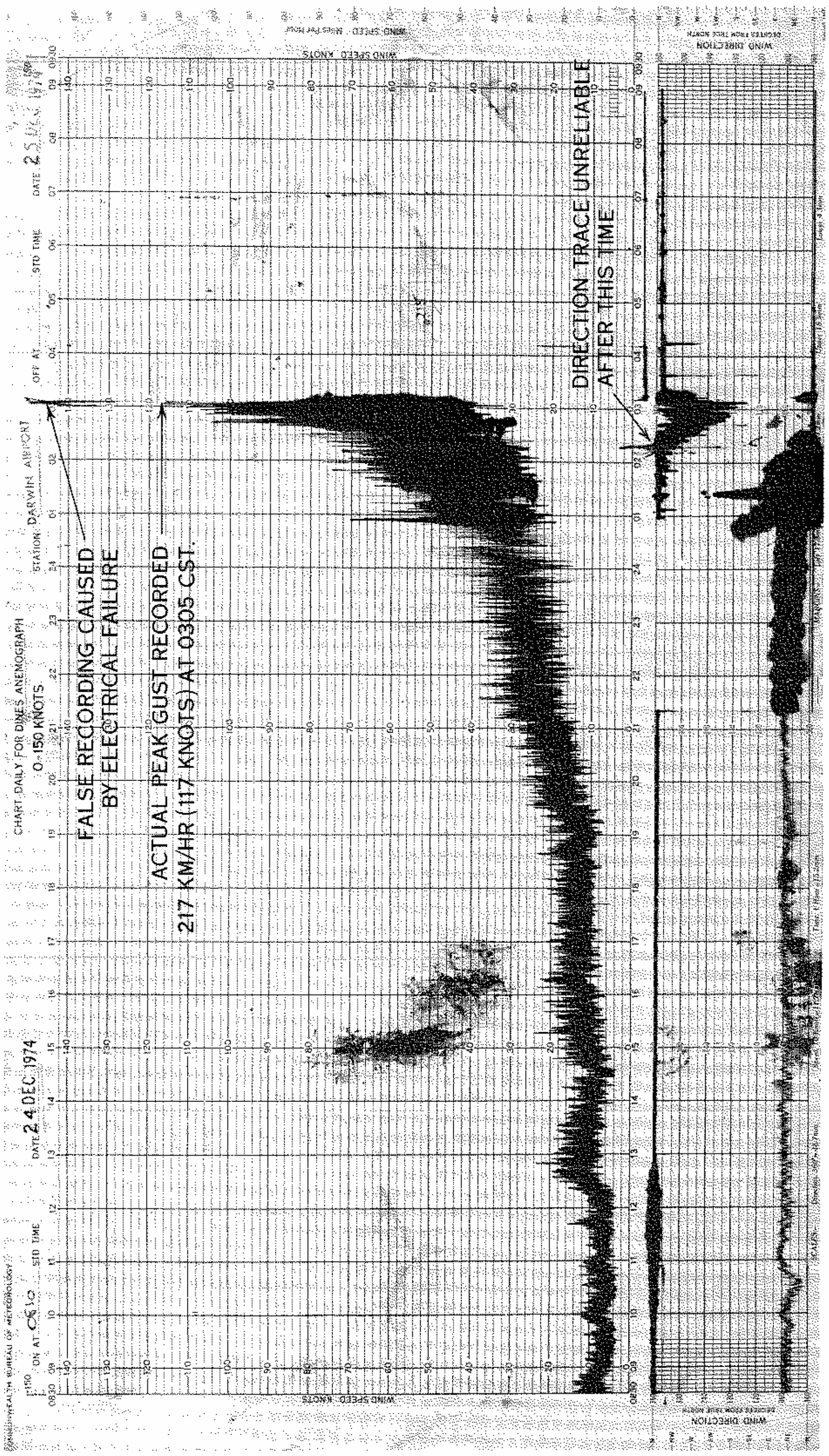

Fig 25 Dines anemograph trace at Darwin Airport, 24–25 December 1974.

Rainfall

The Dines tilting siphon pluviograph at Darwin airport was damaged and stopped recording after the passage of the eye of the cyclone soon after 0400 CST 25 December 1974. Water had previously entered the outer case and damaged the chart, so that the record was faint and fragmentary after midnight. A reconstruction of the chart has been made with some confidence and shows good agreement with observations of the ordinary rain gauge, the readings of which are listed in Table 4.

Table 4 Rainfall totals at Darwin airport

Date	Time CST	Standard gauge	Pluviograph
		mm	mm
24 December 1974	0900-1200	2.2	1.7
	1200-1500	2.2	1.5
	1500-1800	8.6	8.4
	1800-2100	12.0	11.9
	2100-2400	26.0	23.8
25 December 1974	0000-0400	144.2	145.0

Rainfall intensity increased substantially after 0230 CST, reaching a maximum of approximately 105 mm per hour between 0245 and 0315 CST. An abrupt decrease in intensity occurred just before 0330 CST and rain appeared to have ceased just after 0345 CST. This agreed well with the timing of the arrival of the cyclone's eye. An attempt was made to estimate the rainfall up to 0830 CST, when rain ceased according to verbal reports. Based on a period without rain while the eye passed over, followed by half an hour of rainfall of similar peak intensity to before the eye, then steadily decreasing intensity thereafter, the estimate yielded a total of about 280 mm for the 24-hour period to 0900 CST 25 December 1974.

In strong winds most rain gauges record rainfall rates lower than the representative area average because of the flow of wind over the funnel. The Australian Bureau of Meteorology (1976) found that the error increases with wind speed, and is substantial, certainly more than 10 per cent, at 40 km/h.

Wind and the anemometer record

The most complete wind record for cyclone Tracy was obtained by a Dines anemograph, which was part of the Bureau's meteorological installation at Darwin airport. The anemograph was a special model designed to record winds up to 240 km/h and was capable of measuring strong wind gusts with periods as short as 2 or 3 seconds duration. The sensors were exposed at 10 m elevation near the centre of the airport (see Fig 23) and the record was made in the Weather Service Office via a telemetry link.

A copy of the record is shown in Fig 25. The record was terminated at about 0310 CST when the telemetry from the instrument failed. Subsequent investigation has shown that most of the record is reliable. Some interpretation is needed for the last two hours because water damaged the record and the direction recording system was also damaged.

The peak gust recorded was 217 km/h at approximately 0305 CST. The apparent record of stronger winds was due to an electrical failure and apart from this isolated record of greater than 217 km/h the wind speed record was reliable to within about 5 km/h.

The wind direction record was reliable, as far as it could be read through smudged ink, until 0200 CST. For some hours before 0100 CST the wind direction was 060 to 050 degrees and by 0200 CST the had shifted to nearly 360 degrees. After 0200 CST the nature of the trace suggested that a fault had developed in the direction recording system. This was presumed to be in the mechanical linkage near the vane, but its exact nature could not be determined because the vane was lost when the instrument was destroyed by flying debris after the passage of the eye. Lack of correspondence between wind direction and radar positioning of the cyclone's centre confirmed the unreliability of the direction trace after 0200 CST.

The timing accuracy of the trace has since been confirmed and the mean wind from 0300 to 0310 CST was 140 km/h with gustiness in this period ranging from 60 to 217 km/h. Subsequent subjective estimates of the wind were made by RAAF and trained Bureau personnel. The Bureau staff estimated that winds prior to the cyclone's eye did not get much, if at all, stronger after the anemometer failed. However, very strong winds persisted until only 5 minutes or so before the calm, which was recorded in the RAAF log as commencing at 0350 CST and finishing at 0425 CST when strong winds returned from the southwest. Two subsequent estimates of wind were entered in the RAAF log, namely, at 0455 CST 'Wind estimated up to 140 km/h' and at 0630 CST 'Wind abating – estimate 60 km/h'.

Radar information suggested that the radius of maximum winds reached the airport between 0245 and 0315 CST. Since the anemometer was recording during most of the period, the strongest gust of 217 km/h at 0305 CST must therefore be considered as a possible measurement of the peak gust prior to the eye.

There were some subjective estimates that the strongest winds were after the eye. Generally, these opinions were based on the response of structures and the sound of the wind, both of which would have been largely dependent on the amount of previous damage and exposure. It is therefore difficult to determine what reliability should be placed on these estimates as investigation has yielded no meteorological evidence to support them. However, studies of other tropical cyclones have shown that the strongest winds are normally found to the left (southern hemisphere) of the cyclone's direction of movement (Shea 1972). In Tracy's case such asymmetry means that places north of the track, which would also include the anemometer site, probably experienced the strongest winds in the cyclone both before and after the passage of the eye.

Pressure gradients and gradient wind profile

The radar fixes on Tracy's centre and the pressure data over Darwin enable calculation of the pressure gradients in the cyclone and the gradient wind profile near the eye and provide an independent check on the anemometer measurement. The pressure data used were the Weather Service Office barograph trace (Fig 24 (b)) and the mercury barometer readings from the Regional Office (Table 3). A photographic enlargement of the trace shown in Fig 24 (b) was made to attain adequate accuracy for readings to be taken at consecutive half hourly intervals. Wherever possible these were checked for consistency with the available Weather Service Office mercury barometer readings.

$$V_m = 12.4\,(1010 - P_c)^{0{\cdot}644}$$

It was assumed that the cyclone was in a steady state during its approach towards landfall, i.e.

$$\frac{dp}{dt} = \frac{\partial p}{\partial t} + V.\nabla p = 0$$

$$\text{i.e.} \quad \frac{\partial p}{\partial t} = V.\nabla p$$

where $\frac{\partial p}{\partial t}$ is the pressure change measured by a barograph, ∇p the pressure gradient in the cyclone and V its speed of approach towards the observation point.

Using finite differences, let Δp be the pressure drop (mb) during the time Δt that the cyclone approached a distance ΔR (km). Consecutive overlapping pressure falls were read from the Weather Service Office barograph trace. The corresponding values of ΔR were determined from the radar data. The pressure gradients, approximated by $\frac{\Delta p}{\Delta R}$, were assigned to a radius R from the storm's centre by the use of centred differences. The results are shown in Table 5, together with values based on Regional Office mercury barometer readings. Corresponding values of the gradient wind, Vg, also shown in Table 5, were derived in the following manner.

The cyclostrophic wind equation may be written as

$$\frac{Vc^2}{R} = \frac{1}{\rho}\frac{\partial p}{\partial R} \qquad \ldots 1$$

where Vc is the cyclostrophic wind speed, R the distance from the centre of the cyclone, ρ the density of the air and $\frac{\partial p}{\partial R}$ the pressure gradient.

It can also be shown that the difference between Vc and the gradient wind speed (Vg) may be expressed in the form

$$Vc - Vg = \frac{RfVg}{Vc+Vg} \qquad \ldots 2$$

where f is the Coriolis parameter.

Using an approach similar to that of Wilkie and Gourlay (1971), it is assumed that $|Vc + Vg| >> |Vc - Vg|$. Thus it may be assumed that $Vc \simeq Vg$ and from Eqn 2

$$Vc - Vg \simeq R\ (f/2) \qquad \ldots 3$$

Combining Eqn 3 and 1 and substituting finite differences for the derivatives, the gradient wind values were calculated from

$$Vg = \left(\frac{R}{\rho}\frac{\Delta p}{\Delta R}\right)^{\frac{1}{2}} - R\ (f/2) \qquad \ldots 4$$

where the air density was assumed constant at $\rho = 1.15 \times 10^{-3}$g cm^{-3} and the coriolis parameter was also assumed constant at f = 0.1091 hr^{-1} (lat. 12°S). Converting the values of Vg in Table 5 to knots and plotting them on the anemometer trace at the time when the cyclone was the corresponding distance R from the anemometer, yielded the results in Fig 26. There was good agreement between the values obtained from both data sources and a dotted line joining all the points yielded an approximate gust envelope.

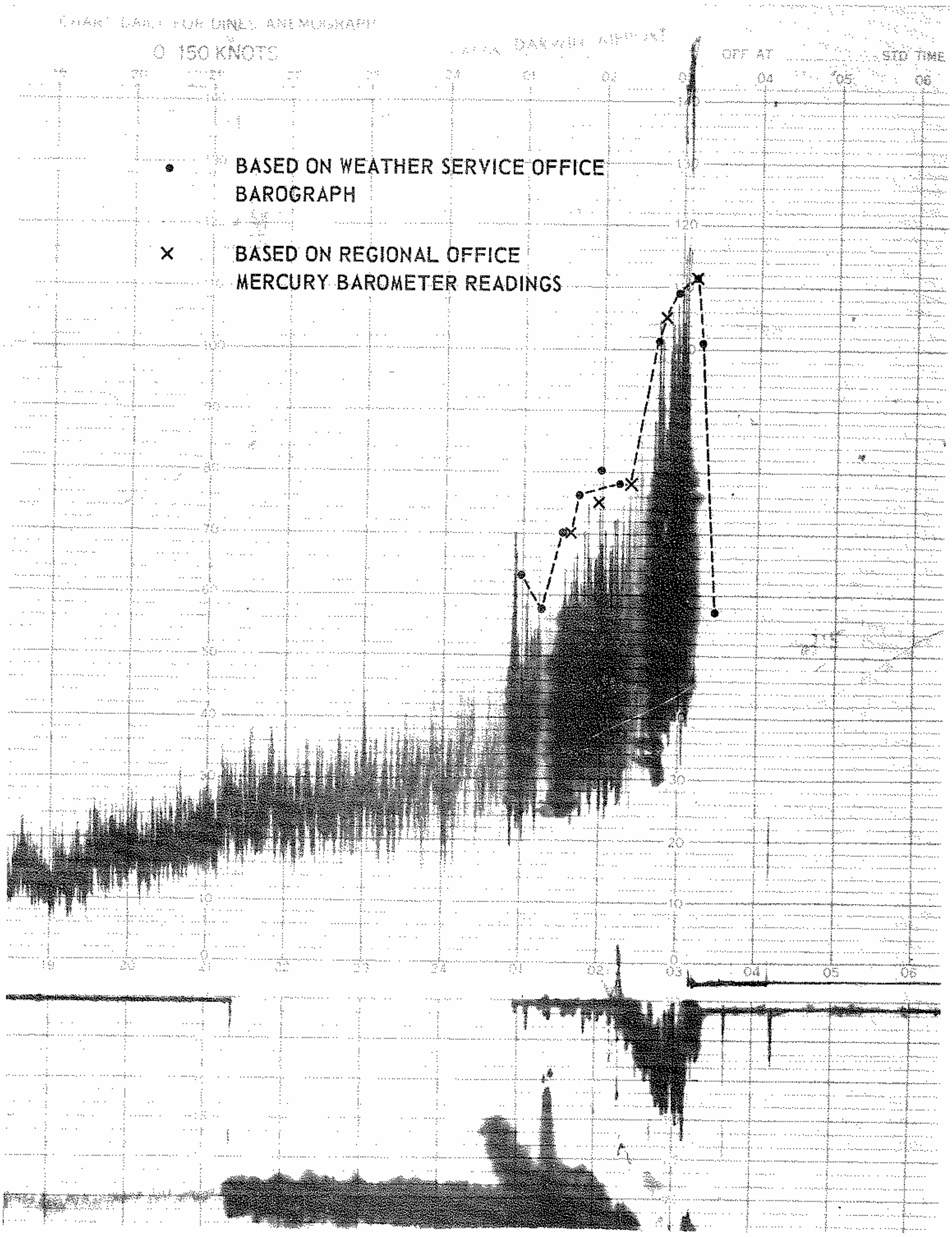

Fig 26 Tracy's calculated gradient wind profile plotted on a section of the anemograph trace of fig 25. Values of Vg (the gradient wind) were determined using radar data and atmospheric pressure readings at the Darwin Regional Office and the Airport Weather Service Office.

Table 5 Variation with time of geostrophic wind, related to changes in pressure and cyclone displacement for Darwin Regional Office and Weather Service Office

Office and time (CST)	ΔP	ΔR	R	Vg
	mb	km	km	km/h
Weather Service Office -				
0045-0115	1.8	3.5	24.4	117
0100-0130	2.1	4.6	22.2	105
0115-0145	3.4	4.6	20.4	129
0130-0200	3.6	3.7	18.1	141
0145-0215	4.5	3.7	16.3	148
0200-0230	5.3	4.1	14.2	144
0215-0245	8.5	4.6	12.0	157
0230-0300	13.2	4.3	10.0	189
0245-0315	16.1	3.5	7.9	202
0300-0330	15.5	3.7	6.1	168
0315-0345	9.2	3.9	4.3	105
Regional Office -				
0100-0130	3.2	4.3	20.2	129
0130-0200	3.9	3.7	16.3	139
0200-0230	5.5	3.7	12.6	144
0230-0300	10.1	2.8	9.3	194
0300-0335	12.4	2.2	6.8	207

Inspection of the figures in Table 5 shows that the radius of maximum winds was approximately 7 km and pressure gradients in its vicinity reached about 5.5 mb/km. The anemometer was recording when the cyclone's centre was about this distance away, and the shape of the dotted envelope in Fig 26 confirms that the anemometer was recording very close to,if not at, the radius of maximum winds.

It should be noted that similarly extreme pressure gradients and associated winds in the eye wall and a rapid decrease in winds outwards from the eye wall were observed in Hurricane Inez (1966) (Hawkins and Imbembo 1976).

The gradient wind profile supports the hypothesis that the anemometer was recording in the belt of maximum winds and the maximum gust of 217 km/h at 0305 CST was a good estimate of the peak winds in the cyclone. This figure is not inconsistent with the satellite information, which gave an estimate of 236 km/h as the peak gust, in that both estimates fall within reasonable limits of error.

Estimation of maximum wind by use of an empirical relationship

Another approach that may be used to substantiate the gust estimates entails the use of a proper relationship between the minimum surface pressure and the maximum sustained surface wind speed.

Numerous equations have been developed over the past 30 or 40 years but have generally failed to stand the test of time in operational usage, due mainly to the difficulty of measuring surface winds and of obtaining coincident central pressure values. Atkinson and Holliday (1975) derived a new relationship between minimum central pressure and maximum sustained wind (averaged over one minute). In deriving this relationship they applied rigorous selection criteria to their data and restricted their maximum wind values to peak gust observations taken at stations with recording anemometers, as these were considered the most reliable wind observations during strong wind periods.They further reduced these observations to a standard elevation of 10 m by means of a standard formula and, by use of appropriate gust factors, to one minute averages. The resulting equation has been adopted for operational use in the Joint Typhoon Warning Centre, Guam. It takes the form:

$$Vm = 12.4\ (1010 - Pc)\ ^{\circ} \cdot 644 \qquad \ldots 5$$

where Vm is the maximum one minute average wind speed (km/h) and Pc is the minimum mean sea level pressure (mb). The authors suggest that most of the usable data collected over the northwest Pacific since the Second World War have been applied in the derivation of this equation and in cases where Pc is accurately known they advise against departures of more than ± 20 km/h from the value obtained by its use.

Assuming that the constants derived from the northwest Pacific data are applicable to the contiguous Australian region, the central pressure of Tracy (950 mb) put into Eqn 5 yields

$$Vm - 173 \text{ km/h}$$

To compare this value of Tracy's maximum wind with the other estimates made above it must first be converted to a peak gust. Atkinson (1974) found that gust factors (i.e., the ratio of the peak gust to the mean wind occurring during the same period of time) applicable to one minute average winds in strong wind situations varied between 1.20 and 1.25. Taking the higher figure of 1.25, which for winds of this strength is also consistent with gust tables in current operational use in the Joint Typhoon Warning Centre, Guam (Atkinson and Holliday 1975), yields a peak gust estimate of 217 km/h.

Estimates based on anemometer readings, pressure gradients, and satellite data are thus well supported and the consistency of these different approaches leads to the conclusion that peak gusts associated with Tracy were most likely in the range 217 to 240 km/h, corresponding to maximum mean winds (10 minute average) over Darwin of 140 to 150 km/h.

Storm surge

In the destructive and death dealing features of tropical cyclones, wind ranks third behind sea action and flood (Dunn and Miller 1964). When a tropical cyclone approaches or crosses a coastline, the very low atmospheric pressure and the stress of the strong winds on the sea surface produce a rise in sea level above the normal tide level. This is known as the storm surge, and its effect can be amplified by the shape of the sea bed and features of the coastline. The storm surge, particularly if accompanying a high tide, can cause inundation of coastal areas resulting in major damage and loss of life. An extremely disastrous case occurred in November 1970, when a tropical cyclone in the Bay of Bengal caused the deaths of more than 100 000 people.

Fortunately 24-25 December 1974 was a period of neap tides in Darwin and even though the maximum storm surge was associated with a high tide, the water level did not rise high enough to be a problem. The maximum height of the storm surge, measured in the Darwin Harbour and reported by Hopley (1975), was 1.6 m at about 0215 CST. He also reported that in Fannie Bay indirect evidence indicated a surge of 1.7 to 2.0 m. Fig 27 was compiled from Hopley's report by courtesy of the James Cook University of North Queensland and displays Tracy's storm surge as measured in Darwin Harbour.

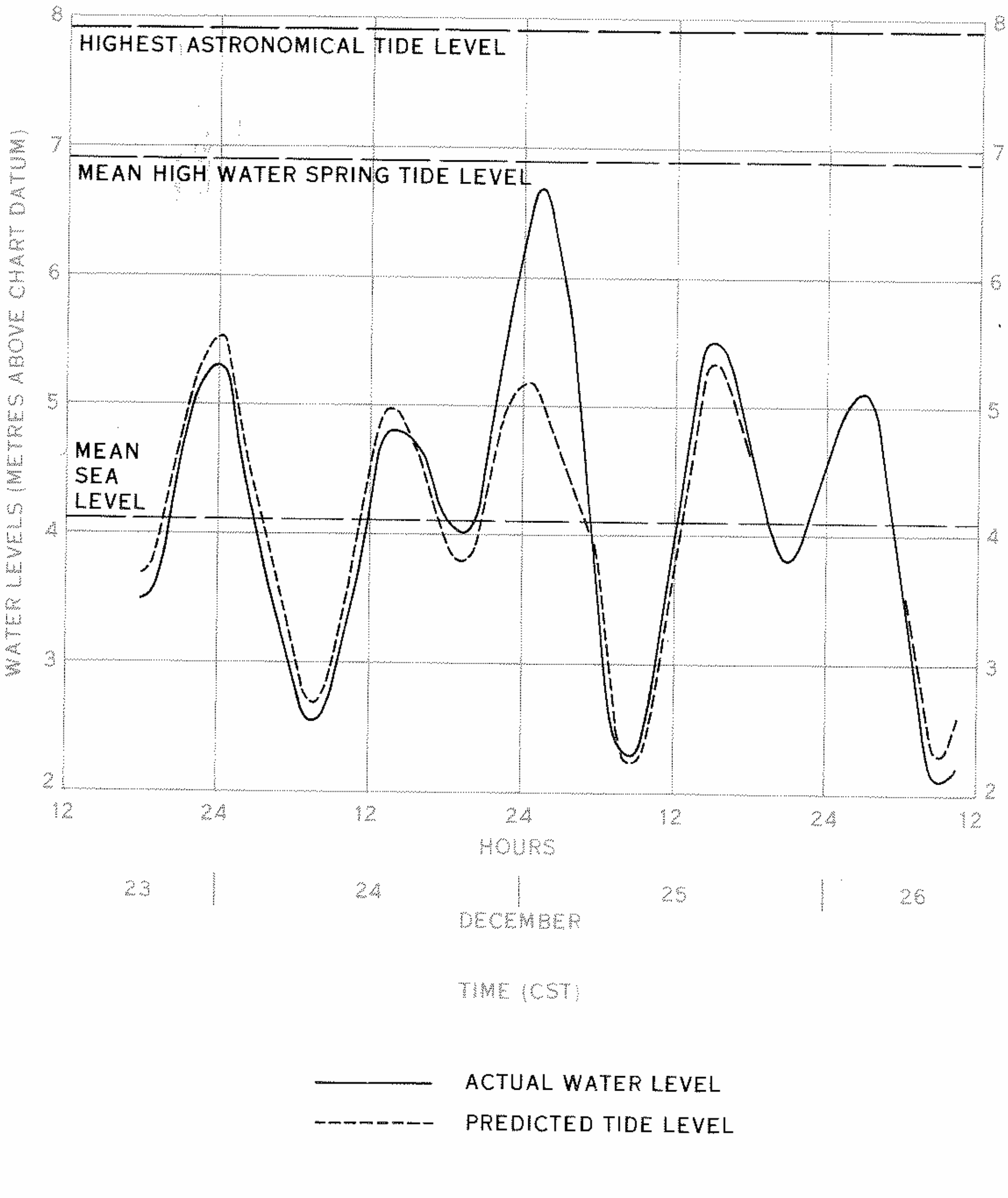

Fig 27 Storm tide of cyclone Tracy as measured by the tide gauge in Darwin Harbour. The difference between actual water level and the predicted tide is due to the storm surge.

The maximum storm surge would have occurred to the left of the cyclone's track into Darwin. Wilkinson (1975) found that this maximum surge occurred at Casuarina Beach, where there were indications that the maximum water level, including the effects of the waves breaking at the coast, was about 4 m above the predicted tide.

Electrical activity

There were a number of reliable evewitness reports of electrical activity, particularly in the eye wall of the storm.

Professor Ward, of the James Cook University of North Queensland, has reported that considerable electrical activity in the region of cyclone Tracy was detected by his equipment at Townsville. Measurements of intensity and burst rate of radio noise at HF produced by cyclone Tracy were made using the aerial array associated with the University's HF radar facility. With a design operating frequency of 21 MHz, the array was employed purely in the receive mode as a simple listening device. Noise amplitude as a function of azimuthal bearing was achieved by scanning the aerial continuously through a certain azimuth range, selected to coincide roughly with the cyclone's bearing from Townsville.

Noise burst rates associated with Tracy were at least an order of magnitude greater than those for surrounding regions at the time.

The possibility of tornadoes

There is no reliable evidence that tornadoes occurred in the immediate vicinity of the eye during Tracy's passage over Darwin. Authors such as Novlan and Gray (1974) have established environments and wind field regions that are conductive to tropical cyclone spawned tornadoes. The area of a cyclone in which tornadoes are likely to occur may be described thus:

General area:	Surface pressure between 1004 and 1012 mb.
Specific area:	Areas of vertical wind shear greater than 40 km from the surface to 850 mb. Surface winds 15 to 20 km.
Specific area:	Within the 'preferred sector': 110 to 460 km from the centre of the tropical cyclone and at an azimuthal range of 0° to 120° with respect to true north (northern hemisphere).
Specific area:	Along strong radar observed rainbands, particularly the outer rainbands.

Application of these findings to the Darwin situation suggests that tornadoes were unlikely to have occurred in the very strong wind zone surrounding the cyclone's eye.

Characteristics on leaving Darwin

There were three Woelfle anemometers operating outside Darwin at the time of Tracy. These had been installed as part of a microclimate study, so that their type and exposure were not suitable for measuring the high winds associated with a tropical cyclone. Nonetheless, they did provide accurate information on changes in wind direction and were of assistance in defining the cyclone's track. This was particularly the case for the one installed at Howard Springs.

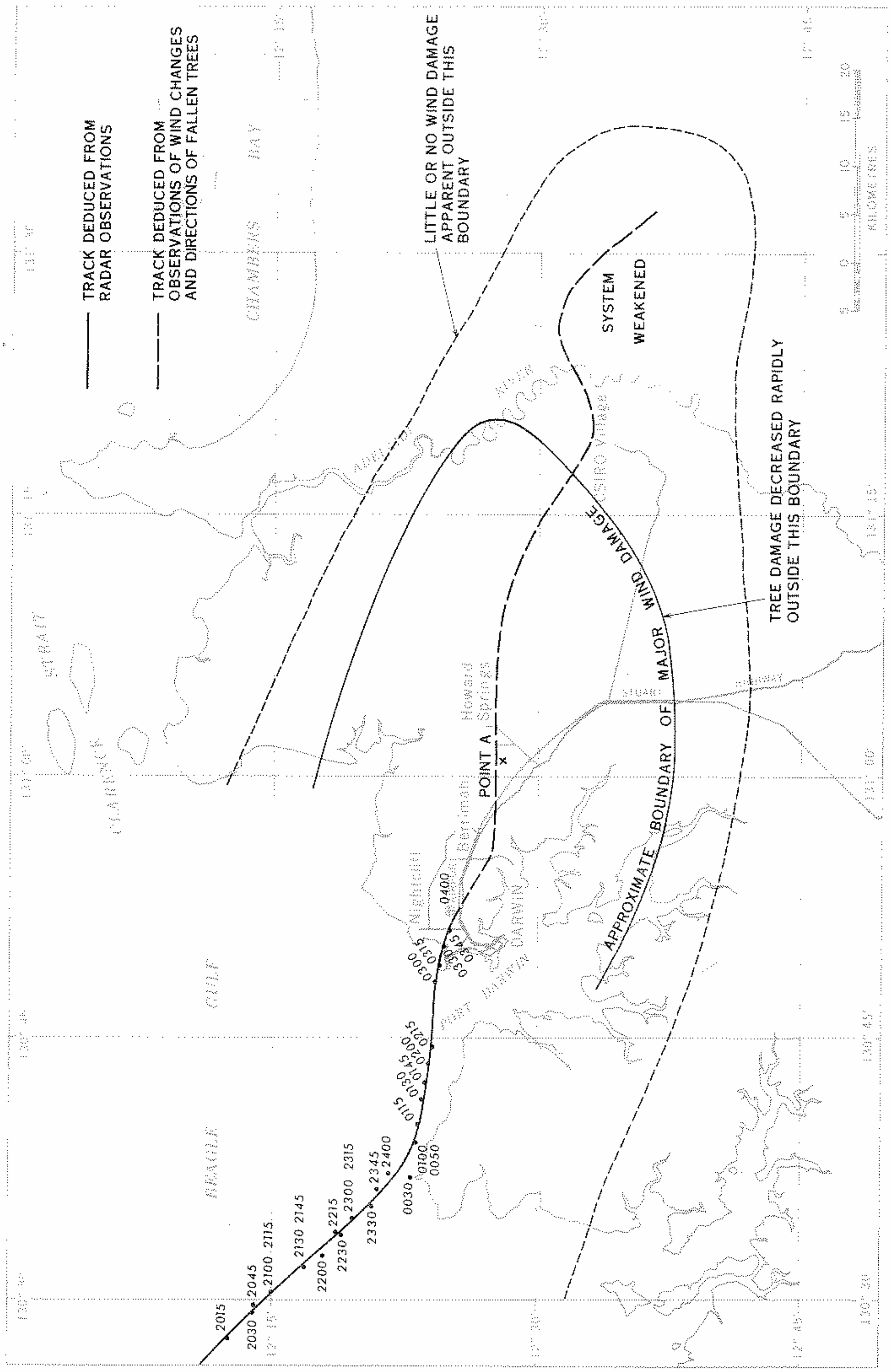

Fig 28 Final section of cyclone Tracy's track showing the pattern of wind damage determined from aerial surveys.

The latter part of cyclone Tracy's track is shown in Fig 28. The last radar observation was made at 0430 CST and was recorded on a manual tracing of the PPI display. This showed the centre of the eye to be located southeast of the radar, but in the absence of any actual photograph or precise readings it has not been possible to reliably determine the range. Therefore, allowing for some initial movement to the southeast after leaving the airport, the subsequent track has been deduced from aerial and ground surveys of damage patterns, eyewitness reports of wind behaviour, and the autographic wind record from Howard Springs. The dashed path in Fig 28 was considered the most likely on the basis of evidence from all sources. At point A, an eyewitness report suggested that the wind *veered* through south with the passage of Tracy's centre, while the autographic trace from Howard Springs showed that the wind there *backed* through north. Both places experienced a lull and thus the centre of the eye was fixed as passing between them. Elsewhere, the dashed path was based on the direction of fallen trees. To the north, trees had fallen under a predominantly westerly regime, whereas to the south, their direction of fall indicated a predominance of winds with an easterly component. The path constructed on this basis passed very near the former CSIRO village at Middle Point and agreed with eyewitness reports of wind behaviour at that place. From all accounts, it appears that Tracy's centre was near Howard Springs at about 0600 CST but did not reach the village until about 1100 CST, when a lull was experienced. Tracy's velocity along its track after landfall while still under radar surveillance increased to approximately 11 km/h. Its time of arrival at Howard Springs was consistent with this speed being maintained, but the timing of events at the former CSIRO village suggests the velocity reverted to about 6.5 km/h over the rest of the postulated track.

The boundary of major wind damage shown in Fig 28 was well marked from the air. It did not appear to be associated with a change in character of forestation or vegetation but rather to reflect a reduction in the strength of the cyclone's wind field across this boundary. The fact that the boundary of damage crossed the cyclone's path confirms that the system weakened quite rapidly after leaving Darwin, and the timing of events outlined above further suggests that this weakening accompanied the reduction in the cyclone's speed of movement.

It was stated earlier in this report that the last radar photographs showed indications that the cyclone was 'filling'. This observation was supported by the experience of the cyclone's eye at Howard Springs and the former CSIRO village. At both places there was a distinct lull but no calm, and it therefore appears that, although a centre of rotation still existed, an actual calm eye structure was not a featue after Tracy left Darwin.

CYCLONES IN THE DARWIN AREA

Historical résumé

Prior to Tracy and since records were kept, at least six tropical cyclones have severely affected Darwin communities. The following information comes from old newspaper accounts supplied by Mr J. Gamble, Principal Structural Engineer, Australian Department of Construction, Darwin and Australian Bureau of Meteorology records.

1839 The early settlement of Port Essington was wrecked by a 'hurricane' on 27 November. Buildings and boats were destroyed. HMS Pelorus was driven ashore.

1878 From 14 to 20 January terrific storms and hurricane squalls prevailed over an area extending from the coast to 560 km inland. During the night of 14 January every building in Darwin was damaged and several totally destroyed.

1882 On 16-17 January heavy gales did considerable damage. Many buildings were completely destroyed, and every house was more or less damaged.

1897 On 6-7 January Darwin was almost completely destroyed by a ‘disastrous hurricane’ accompanied by ‘phenomenally heavy rainfall’. It was estimated that the damage done exceeded £150 000. Twenty-eight people lost their lives – 15 on the water and 13 on shore.

1917 On 1 April Darwin was visited by a ‘hurricane’ which ‘had no equal’ since that of 1897. 110 km/h winds blew mainly from the south and southeast. Buildings were damaged and a fishing junk was wrecked and its crew of seven drowned.

1937 A severe tropical cyclone during the hours of darkness of 10-11 March caused damage estimated at £50 000 and the deaths of five people – one in Darwin and four on Melville Island. A peak of gust of 160 km/h from the north-northwest was recorded at Darwin airport just before 0130 CST on 11 March.

Comparison of Tracy with a major cyclone of the past

From all accounts, the storm of 1897 was the most intense cyclone to affect Darwin prior to Tracy. Visher and Hodge (1925) describe this storm as ‘the great hurricane’ and several interesting parallels emerge from a comparison with Tracy.

The following descriptive extract is taken from the *Northern Territory Times* and *Gazette* of 25 January 1897.

> The storm which broke over the city (Darwin) early on Wednesday the 6th inst. culminated in one of the most destructive cyclones ever recorded. From a fairly still blow about 8 p.m. the wind gradually increased to hurricane force by 11.30 or midnight, and from that on till nearly 5 o’clock it raged with terrific fury.
>
> Accompanying the wind was a downpour of rain such as even out tropical records have never equalled. . .
>
> The cyclone reached its highest pitch between 3.30 and 1.30, and in that hour it was impossible for human beings to stand erect against it. The crash of buildings and rattle of iron and timber falling about, combined with the blinding rain and roaring of the tempest, was an experience which those who underwent it will never forget to their dying day. Strongly built houses collapsed like houses of cards; roofs blew bodily away; lamp and telegraph posts were bent or torn up; immense beams of timber were hurried away like chaff; trees were

Uprooted; in many instances large houses were lifted bodily from their foundations and deposited ten and twelve feet away; and in short the night was one of terrifying destructiveness that made the stoutest heart quail. How is was that hundreds were not killed outright is one those inscrutable mysteries which will never be explained. . .

In the absence of photographs, this passage serves to illustrate the magnitude of the trauma associated with the cyclone. The following meteorological observations were made in Darwin at the time:

Midnight, 6th - Barometer 998 mb, wind E very strong, stormy heavy rain.

0300 CST, 7th - Barometer 981 mb, wind NE still blowing with hurricane force; heavy rain

0400 CST, 7th - Barometer 975 mb, wind NE still blowing with hurricane force and heavy rain.

0410 CST, 7th - Wind suddenly changed to NW, W and SW, blowing with even greater force than before.

The barometer continued to rise rapidly immediately after the wind changed. At 0410 CST the reading was 975 mb, at 0500 CST 987 mb, and at 0600 CST it was 998 mb.

Rainfall in Darwin during the passage of this cyclone was 292 mm.

At Pt Charles lighthouse the lowest barometer reading was quoted as 950 mb.

From the above readings and the previous descriptive account, it seems likely that the 1897 cyclone passed very near, but not directly over, Darwin.
A comparison with Tracy reveals that:

(a) both cyclones affected Darwin at the same time of day;

(b) the pattern of damage appears to have been similar;

(c) a similar path (as indicated by the pattern of wind changes) was followed by both cyclones near Darwin;

(d) rainfall in Darwin was almost the same in each case (292 mm in 1897 and 280 mm (est.) for Tracy);

(e) the lowest pressure measured in the 1897 cyclone (950 mb Pt Charles lighthouse) was the same as the lowest pressure measured in Darwin with Tracy.

Return period of Tracy

The probability of occurrence at a particular location of winds of the intensity, gustiness, and duration associated with Tracy is difficult to determine. Lourensz (1976) has updated previous work by Coleman (1972) of frequencies, tracks, and intensities of tropical cyclones in the Australian region. Preliminary data for Darwin show that in the 65-year period up to and including the 1974-75 tropical cyclone season there have been 21 occasions of a cyclone within 150 km, 17 occasions within 100 km, and 8 occasions within 50 km. Table 6 shows the dates and categories in which they occurred.

Table 6 Cyclones within 150 km of Darwin 1909-10 to 1974-75

Within 0-50 km	Within 50-100 km	Within 100-150 km
23 Dec 1915	6 Mar 1919	1 Dec 1948
1 Apr 1917	4 Mar 1944	2 Feb 1956
22 Dec 1920	10 Apr 1954	5 Apr 1959
11 Mar 1939	25 Dec 1959	12 Mar 1975
9 Mar 1964	3 Dec 1964	
1 Mar 1965	4 Mar 1969	
30 Dec 1965	5 Dec 1971	
25 Dec 1974	19 Mar 1974	
	3 Dec 1974	
Total 8	9	4

Many of these storms are not well documented, so their relative intensities cannot be reliably inferred.

In order to determine the relative risk of wind damage from tropical cyclones along the north Australian coast, various attempts have been made to assess the probability of the magnitude - frequency of wind gusts at particular locations. Whittingham (1964) used Gumbel extreme value distribution theory to derive such information directly from the available wind records, while Martin (1975) has adopted a more indirect approach. He has taken summaries of previous cyclones affecting particular sites and adopted a Monte Carlo system whereby a series of tropical cyclone events are simulated for each locality and subsequently subjected to statistical analysis.

In general, the usefulness of probability estimates obtained by such methods is largely dependent upon the adequacy of the available meteorological records. In the case of Darwin, the period of complete meteorological records is short and wind gust data are available for only 25 years. The return period of gusts associated with Tracy is almost certainly well beyond the length of period of the record so that its assessment requires statistical extrapolation with all its well known pitfalls. Further, since maximum wind gusts in Darwin in most years are not due to tropical cyclones, the application of a Gumbel analysis to annual extremes may lead to unreliable results. While the method used by Martin circumvents the problem of a mixed distribution it is still subject to the inadequacies of the meteorological data on which it is based. These reservations should be borne in mind when assessing results shown below. The annual extreme wind gusts recorded in Darwin for all years of record are listed in Table 7.

Table 7 Annual extreme wind gusts for Darwin

Year	Gust km/h	Year	Gust km/h	Year	Gust km/h	Year	Gust km/h	Year	Gust km/h
1935	70	1940	81	1960	106	1965	83	1970	94
1936	93	1941	104	1961	93	1966	83	1971	96
1937	158	1957	91	1962	80	1967	117	1972	87
1938	87	1958	102	1963	81	1968	80	1973	96
1939	80	1959	106	1964	91	1969	102	1974	217

Gumbel's method of analysis was applied directly to these data and the following wind gust speeds predicted for various average return periods, were obtained:

Return period (years)	10	20	50	100
Maximum wind gust (km/h)	146	167	191	211

These figures mean that in a very long period of record a gust of 146 km/h will be equalled or exceeded, on the average, once every ten years, and for 167 km/h, on the average, once every 20 years, etc. As shown by Court (1952) and quoted by Whittingham the probability of at least one occurrence in $\bar{T}$ trials is $(1-e^{-1})$, where $\bar{T}$ ($\bar{T} > 10$) is its average return and e is the base of natural logarithms. So, for example, in any selected period of 100 years, there is a 37 per cent chance (since $1/e = 0.37$) that a wind gust of 211 km/h will not be reached in Darwin. Conversely there is a 63 per cent chance that it will be equalled or exceeded on one or more occasions.

Martin's preliminary results for Darwin using his alternative approach show that the maximum gust predicted for a 50 year average return period is 187 km/h, and for a 100 year average return period, the gust is 202 km/h.

Some confidence is engendered by the fact that these two independent approaches yield very similar answers, and as the period of reliable records is lengthened it will be possible to place increased reliance on such results. How closely Tracy approaches the extreme phenomenon for its locality cannot be determined, but it is certain that for Darwin its occurrence must be classed as a rare event.

CONCLUSION

The aim of this report has been to provide as complete and coherent an overall description of cyclone Tracy as can be achieved from a wide variety of data sources. Tracy was a very small and intense cyclone and only the broadest of its associated features could be deduced from conventional synoptic analyses. Considerable attention has therefore been devoted to the analysis of instrument and radar observations, satellite photographs, eyewitness reports, and results of aerial and ground surveys. Each of these data sources was important but none was complete in itself. The attempt has been made to draw the separate pieces of information together and to resolve any apparent inconsistencies, and by drawing heavily on the results of previous research, provide the basis on which specific conclusions have been obtained.

The determination of maximum wind has been a theme common to a number of chapters in this report. This was considered a very important aspect as considerable controversy has existed due to the lack of a complete instrumental wind record. The problem of filling this gap in knowledge has been approached in a variety of ways using satellite data, radar observations, available pressure readings, and an empirical formula. All these approaches lead to quite consistent results and engender considerable confidence in the estimated range of peak winds. There is no doubt, however, that local topography, exposure, etc., would have caused considerable variation in wind strengths over Darwin and it is quite likely that particular localities experienced winds in excess of the estimated range of speeds. This degree of uncertainty for particular localities would always exist, even with a complete instrumental recording made in the general area.

Other points of significance which emerged during the investigation were the rapid rate at which the storm developed, the short distance inside the inner eye wall to the radius of maximum winds (namely 1 km) and the magnitude of the associated peak pressure gradients (5.5 mb/km).

The overall characteristics of Tracy that have been determined may be summarised thus:

Latitude of initial development	8°S
Type of development	Rapid (Dvorak categories)
Overall mean speed of movement	6 km/h
Latitude of recurvature	11.5°S
Eye diameter	12 km (mean)
Radius of maximum winds	7 km
Radial extent of gales	50 km
Central pressure on landfall	950 mb (MSL)
Peak winds on landfall	Gusts in the range 217 to 240 km/h corresponding to mean winds of 140 To 150 km/h (estimated)
Peak pressure gradient	5.5 mb/km (approx.)
Rate of decay after landfall	Winds below gale force within 24 hours (estimated)
Lifetime as a tropical cyclone	4 days

Various aspects of Tracy have been related to the mainstream of current scientific thought; however, deeper investigation beyond the scope of this context is warranted in particular areas. Knight (1976) has already produced a compilation of cyclone Tracy rainfall from the radar PPI (position plan indicator) overlays and a preliminary analysis of his results shows a factor varying between approximately 2 and 4 between observed and composited rainfall.

Australian research using the radar data is aimed at a more quantitative assessment of the oscillations in the track and the improved use of satellite photographs as a means of forecasting movement; and in another project, the Darwin experience is being used in a review of the design and network of meteorological instruments for cyclone prone areas. The data collected during and after Tracy's occurrence has provided invaluable material and, hopefully, will assist in achieving further insights into the true nature and character of tropical cyclones.

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COMMUNICATIONS AND DISSEMINATION

Communication at the Darwin Tropical Cyclone Warning Centre failed when, shortly after 0700 CST 25 December 1974, the emergency power plant in the office failed.

Telephone and telegraph communications were operational during the cyclone, but contact with the mass media was not attempted after both radio stations failed between 0200 and 0230 CST.

Until this time the system functioned efficiently, providing adequate warnings and advice of Tracy's movement and intensity to the public. All relevant authorities were notified and kept informed of latest developments as necessary. One criticism was that on one or two occasions out of date warnings were broadcast by the media.

Telephone, telegraph, and facsimile communications to the Bureau's field offices were operational until the WSO became inoperative at about 0315 CST.

Apart from one or two short breaks due to radar failure, continuous radar plots of the intensity and position of Tracy were transmitted via Busfax facsimile to the Tropical Cyclone Warning Centre from the radio aids building at Darwin airport until after 0430 CST when the radar was damaged.

Intermittent telephone and continuous telex with interstate offices and several point to point links with Melbourne were maintained until the emergency power supply failed between 0700 and 0730 CST.

It should be noted that the emergency power supply failed due to mechanical failure and not because of Tracy.

ORGANISATION OF TROPICAL CYCLONE WATCH

Throughout the cyclone season 1 November to 30 April each Tropical Cyclone Warning Centre (TCWC) at Darwin, Brisbane, and Perth maintains a routine watch for cyclonic developments in the weather. The watch is oversighted by the Regional Director or his Senior Duty Meteorologist.

In maintaining the watch, information form all sources is used. Conventional observations of surface and sky conditions, automatic weather station reports, observations of upper level winds and temperatures, ship and aircraft reports, satellite cloud pictures, and radar observations are all considered in the analysis of meteorological conditions.

Immediately indications of the development of a tropical cyclone are confirmed, and wind speeds in excess of 60 km/h are expected, the following advices are issued as necessary:

(a) Cyclone Alert or Cyclone Warning to the public;

(b) Gale or Storm Warning to shipping and special user interests, e.g., oil rigs;

(c) Tropical Revolving Storm Advice to aviation.

Cyclone Alert

A Cyclone Alert message is issued whenever a cyclone or potential cyclone is located within 800 km of coastal communities but there is no strong indication of gales affecting those communities within 24 hours. The message is distributed to relevant broadcasting media, meteorological offices, and selected authorities. It prepares recipients to take appropriate action if a cyclone warning is issued subsequently. The Alert is reviewed every 3 hours until replaced by a Cyclone Warning or the Alert is finalised. It is re-issued at least 6-hourly intervals.

Cyclone Warning

If the cyclone is centred more than 800 km from the coast warnings are not distributed to the public, thus avoiding needless alarm. Nonetheless, the needs of island communities and offshore installations are recognised. If the centre is within 800 km of the coast and gales are expected to affect coastal communities in the next 24 hours, Cyclone Warnings are issued every 3 hours to all recipients in the threatened area. If the centre is close to the coast and posing a severe threat, warnings are issued hourly (or more frequently if practicable) to severely threatened areas. Such frequent warnings are usually possible only when the cyclone is under radar surveillance.

Flash Cyclone Warning

A Flash Cyclone Warning is issued to the public when any of the following conditions apply:

(a) first warning of conditions likely to threaten coastal communities within 24 hours;

(b) first warning to a community not previously alerted;

(c) urgent amendment of a current warning.

TEXTS OF TROPICAL CYCLONE ALERTS AND WARNINGS ISSUED BY THE DARWIN TROPICAL CYCLONE WARNING CENTRE

Priority

Tropical Cyclone Alert No 1 issued by the Darwin Tropical Cyclone Warning Centre at 4 pm CST 21/12/74.

A tropical low was centred 250 km NNE of Croker Island at 3 pm and there is a possibility of a tropical cyclone developing. Communities between Manigrida and Bathurst Island are alerted.

Ships in Arafura and Timor Seas please transmit three hourly weather and radar rain reports to Weather Darwin.

Tropical Cyclone Alert No 2 issued by the Darwin Tropical Cyclone Warning Centre at 10 pm CST 21/12/74.

Tropical cyclone Tracy was centred 200 km NNE of Cape Don at 9 pm and moving WSW at 12 km per hour. Gales are <u>not</u> expected on the coast within 24 hours but communities between Goulburn Island and Bathurst Island are alerted.

Next advice at 4 am tomorrow.

Tropical cyclone Alert No 3 issued by the Darwin Tropical Cyclone Warning Centre at 4 am CST 22/12/74.

Tropical cyclone Tracy was centred at 200 km north of Cape Don at 3 am and moving WSW at 12 km per hour. Gales are <u>not</u> expected on the coast within 24 hours but communities between Goulburn Island and Bathurst Island are alerted.

Next advice at 10 am today.

Priority

Tropical Cyclone Alert No 4 issued by the Darwin Tropical Cyclone Warning Centre at 10.30 am CST 22/12/74.

Tropical cyclone Tracy was centred 180 km NW of Cape Don at 9.00 am and moving WSW at 13 km per hour. Gales are <u>not</u> expected on the coast within 24 hours but communities between Cape Don and Bathurst Island are alerted.

Next advice at 4pm today.

Top Priority

Flash Cyclone Warning No 1 issued by the Darwin Tropical Cyclone Warning Centre at 4.15 pm CST 22/12/74.

At 3 pm CST tropical cyclone Tracy was centred 80 km north of Snake Bay and moving SSW at 9 km/h.

The centre is expected to be near Bathurst Island at 3 am CST tomorrow.

Destructive winds of 80 km/h with gusts of 120 km/h are expected on Bathurst and Melville Islands tonight and early tomorrow. Flood rains are likely over Bathurst and Melville Islands. Abnormally high tides may occur along the coast between Garden Point and Cape Don.

The next warning will be issued at 7 pm CST today.

Priority

Cyclone Warning No 2 issued by the Darwin Tropical Cyclone Warning Centre at 7 pm CST 22/12/74.

At 6 pm CST tropical cyclone Tracy was centred 95 km north of Snake Bay and is almost stationary.

The centre is expected to move only slightly and still be just north of Melville Island at 6 am tomorrow.

Destructive winds of 80 km/h with gusts to 120 km/h are expected on Bathurst and Melville Islands and Cobourg Peninsula tonight and tomorrow. Floor rains are likely over Bathurst and Melville Islands and the Cobourg Peninsula. Abnormally high tides may occur along the coast between Carden Point and Croker Island.

The next warning will be issued at 10 pm CST today.

Priority

Cyclone Warning No 3 issued by the Darwin Tropical Cyclone Warning Centre at 10 pm CST 22/12/74.

At 9 pm CST tropical cyclone Tracy was centred 75 km north of Snake Bay and drifting slowly southwest.

The centre is expected to be 40 km northwest of Snake Bay at 9 am CST tomorrow.

Destructive winds of 80 km/h with gusts to 120 km/h are expected hetween Bathurst and Melville Islands tonight and tomorrow. Flood rains are likely over Bathurst and Melville Islands. Abnormally high tides may occur along the coast between Garden Point and Cape Don.

The next warning will be issued at 1 am CST tomorrow.

Priority

Cyclone Warning No 4 issued by the Darwin Tropical Cyclone Warning Centre at 1 am CST 23/12/74.

At midnight tropical cyclone Tracy was centred 70 km north north west of Snake Bay and drifting slowly southwest.

The centre is expected to be 40 km west north west of Snake Bay at noon today.

Destructive winds of 80 km/h with gusts to 120 km/h are expected along the exposed coast of Bathurst and Melville Islands this morning and today. Flood rains are likely over Bathurst and Melville Islands. Abnormally high tides may occur along the north coast of Melville Island.

The next warning will be issued at 4 am CST today.

Priority

Cyclone Warning No 5 issued by the Darwin Tropical Cyclone Warning Centre at 4 am CST 23/12/74.

At 3 am CST tropical cyclone Tracy was centred 65 km NW of Snake Bay and moving slowly.

The centre is expected to be 70 km west of Snake Bay at 3 pm CST today.

Destructive winds of 90 km/h with gusts to 120 km/h are expected along the exposed coasts of Bathurst and Melville Islands today. Flood rains are likely over Bathurst and Melville Islands. Abnormally high tides may occur along the north coast of Melville Island.

The next warning will be issued at 7 am CST today.

Priority

Cyclone Warning No 6 issued by the Darwin Tropical Cyclone Warning Centre at 7 am CST 23/12/74.

At 6 am CST tropical cyclone Tracy was centred 65 km NW of Snake Bay and is almost stationary.

The centre is expected to be still near Bathurst Island at 6 pm CST today.

Destructive winds of 90 km/h with gusts to 130 km/h are expected on Bathurst and Melville Islands today. Flood rains are likely over Bathurst and Melville Islands. Abnormally high tides may occur along the north coast of Melville Island.

The next warning will be issued at 10 am CST today.

Priority

Cyclone Warning No 7 issued by the Darwin Tropical Cyclone Warning Centre at 10 am CST 23/12/74.

At 9 am CST tropical cyclone Tracy was centred 70 km WNW of Snake Bay and moving slowly WSW.

The centre is expected to be 100 km west of Snake Bay at 9 pm CST today.

Destructive winds of 90 km/h with gusts to 130km/h are expected on Bathurst and Melville Islands today. Flood rains are likely over Bathurst and Melville Islands. Abnormally high tides may occur along the north coast of Melville Island.

The next warning will be issued at 1 pm CST today.

Priority

Cyclone Warning No 8 issued by the Darwin Tropical Cyclone Warning Centre at 1pm CST 23/12/74.

At noon tropical cyclone Tracy was centred 60 km WNW of Snake Bay and moving slowly SW.

The centre is expected to be 110 km WSW of Snake Bay at 12 pm CST today.

Destructive winds of 90 km/h with gusts to 130 km/h are expected on Bathurst Island and Melville Is today and tonight. Flood rains are likely over Bathurst and Melville Islands. Abnormally high tides may occur along the coast between Garden Pt and Cape Don.

The next warning will be issued at 4 pm CST today.

Priority

Cyclone Warning No 9 issued by the Darwin Tropical Cyclone Warning Centre at 4 pm CST 23/12/74.

At 3 pm CST tropical cyclone Tracy was centred 70 km west of Snake Bay and moving SW at 5 km/h.

The centre is expected to be 150 km NW of Darwin at 3 am CST tomorrow.

Destructive winds of 90 km/h with gusts to 130 km/h are expected on Bathurst Is and western Melville Is tonight and tomorrow. Flood rains are likely over Bathurst Is and Melville Island. Abnormally high tides may occur along the coast between Cape Don and Bathurst Is.

The next warning will be issued at 6 pm CST today.

Priority

Cyclone Warning No 10 issued by the Darwin Tropical Cyclone Warning Centre at 7 pm CST 23/12/74.

At 6 pm CST tropical cyclone Tracy was centred 140 km NW of Darwin and moving SW at 4 km/h.

The centre is expected to be 160 km NW of Darwin at 6 am tomorrow.

Destructive winds of 90 km/h with gusts to 130 km/h are expected on Bathurst Is and western Melville Is tonight and tomorrow. Flood rains are likely over Bathurst Is and western Melville Is. Abnormally high tides may occur along the coast between Snake Bay and Bathurst Island.

The next warning will be issued at 9 pm CST today.

Priority

Cyclone Warning No 11 issued by the Darwin Tropical Cyclone Warning Centre at 10 pm CST 23/12/74.

At 9 pm CST tropical cyclone Tracy was centred 135 km NW of Darwin and moving SW at 4 km/h.

The centre is expected to be 150 km WNW of Darwin at 9 am CST tomorrow.

Destructive winds of 90 km/h with gusts to 130 km/h are expected on Bathurst and western Melville Islands gradually easing from the east tonight and tomorrow. Flood rains are likely over Bathurst and western Melville Islands gradually contracting westwards. Abnormally high tides may occur along the coast between Snake Bay and Bathurst Island.

The next warning will be issued at 1 am CST tomorrow.

Priority

Cyclone Warning No 12 issued by the Darwin Tropical Cyclone Warning Centre at 1 am CST 24/12/74.

At midnight tropical cyclone Tracy was centred 130 km NW of Darwin and moving SW at 4 km/h.

The centre is expected to be 140 km WNW of Darwin at midday today.

Winds of 70 km/h with gusts to 120 km/h are expected on Bathurst and western Melville Islands gradually easing from the east during today. Flood rains should gradually contract westward from western Melville and Bathurst Islands. Abnormally high tides are no longer likely along the coast between Snake Bay and Bathurst Island.

The next warning will be issued at 4 am CST today.

Priority

Cyclone Warning No 13 issued by the Darwin Tropical Cyclone Warning Centre at 4 am CST 24/12/74.

At 3 am CST tropical cyclone Tracy was centred 125 km NW of Darwin and moving south at 4 km/h.

The centre is expected to be 110 km WNW of Darwin at 3 pm CST today.

Destructive winds of 90 km/h with gusts to 130 km/h are expected to continue on Bathurst Island today.

The next warning will be issued at 7 am CST today.

Priority

Cyclone Warning No 14 issued by the Darwin Tropical Cyclone Warning Centre at 7 am CST 24/12/74.

At 6 am CST severe tropical cyclone Tracy was centred 120 km WNW of Darwin and moving south at 4 km/h.

The centre is expected to be 100 km west of Darwin at 6 pm CST today.

Very destructive winds of 120 km/h with gusts to 150 km/h are expected to continue on Bathurst Island today.

The next warning will be issued at 10 am CST today.

Priority

Cyclone Warning No 15 issued by the Darwin Tropical Cyclone Warning Centre at 10 am CST 24/12/74.

At 9 am CST severe tropical cyclone Tracy was centred 115 km WNW of Darwin and moving south at 4 km/h.

The centre is expected to be 100 km west of Darwin at 9 pm CST today.

Very destructive winds of 120 km/h with gusts to 150 km/h are expected to continue on Bathurst Island today.

The next warning will be issued at 1 pm CST today.

Top Priority

Flash Cyclone Warning No 16 issued by the Darwin Tropical Cyclone Warning Centre at 12.30 pm CST 24/12/74.

At 12 noon CST severe tropical cyclone Tracy was centred 110 km WNW of Darwin and is now moving slowly SE closer to Darwin.

The centre is expected to cross the coast between Grose Island and the Vernons tomorrow morning.

Very destructive winds of 120 km/h with gusts to 150 km/h have been reported near the centre and are expected in the Darwin area tonight and tomorrow.

The next warning will be issued at 4 pm CST today.

Priority

Cyclone Warning No 17 issued by the Darwin Tropical Cyclone Warning Centre at 4 pm CST 24/12/74.

At 3 pm CST severe tropical cyclone Tracy was centred 80 km WNW of Darwin and moving SE at 7 km/h.

The centre is expected to near Grose Is about midnight.

Very destructive winds of 120 km/h with gusts to 150 km/h are expected between Darwin and the Perron Islands tonight and tomorrow morning.

The next warning will be issued at 7 pm CST today.

Top Priority

Flash Cyclone Warning No 18 issued by Darwin Tropical Cyclone Warning Centre at 7 pm CST 24/12/74.

At 6 pm CST severe tropical cyclone Tracy was centred 60 km WNW of Darwin moving eastward closer to Darwin at about 6 km/h.

The centre is expected to be in the Shoal Bay area at 6 am CST tomorrow.

Very destructive winds of 120 km/h with gusts to 150 km/h are expected between Charles Pt and the Vernons tonight and tomorrow morning.

The next warning will be issued at 10 pm CST today.

Top Priority

Cyclone Warning No 19 issued by the Darwin Tropical Cyclone Warning Centre at 10 pm CST 24/12/74.

At 9.30 pm CST severe tropical cyclone Tracy was centred 41 km westnorthwest of Darwin and moving east south east at 6 km/h.

The centre is expected to cross the coast in the vicinity of Darwin in the early hours of tomorrow morning.

Very destructive winds of 120 km/h with gusts to 150 km/h are expected to continue between Charles Pt and the Vernon Islands tonight and tomorrow.

The next warning will be issued at 10.30 pm CST today.

Top Priority

Cyclone Warning No 20 issued by the Darwin Tropical Cyclone Warning Centre at 1 am CST 25.12.74.

At 12.50 am CST severe tropical cyclone Tracy was centred 27 km west north west of Darwin and moving east south east at 6 km/h.

The centre is expected to cross the coast in the vicinity of Darwin at about 5 am today.

Very destructive winds of 120 km/h with gusts to 150 km/h are expected to continue between Grose Island and the Vernon Islands today. Tides should not reach higher than high water mark.

The next warning will be issued at 4 am CST today

AUXILLARY TROPICAL CYCLONE WARNINGS BASED ON RADAR

Top Priority

Cyclone Warning issued by the Darwin Tropical Cyclone Warning Centre at 9 pm CST 24/12/74.

Tropical cyclone Tracy was located by radar 50 km west north west of Darwin a few minutes ago and moving east south east at 6 km/h.

Top Priority

Cyclone Warning issued by the Darwin Tropical Cyclone Warning Centre at 9.30 pm CST 24/12/74.

Tropical cyclone Tracy was located by radar 46 km west north west of Darwin a few minutes ago and moving east south east at 6 km/h.

Top Priority

Cyclone Warning issued by the Darwin Tropical Cyclone Warning Centre at 10.30 pm CST 24/12/74.

Tropical cyclone Tracy was located by radar 41 km west north west of Darwin a few minutes ago and moving east south east at 6 km/h.

Top Priority

Cyclone Warning issued by the Darwin Tropical Cyclone Warning Centre at 11 pm CST 24/12/74.

Tropical cyclone Tracy was located by radar at 10.30 pm 37 km west north west of Darwin moving east south east at 6 km/h.

Top Priority

Cyclone Warning issued by the Darwin Tropical Cyclone Warning Centre at 11.30 pm CST 24/12/74.

Tropical cyclone Tracy was located by radar at 11 pm 36 km west north west of Darwin moving east south east at 6 km/h.

Top Priority

Cyclone Warning issued by the Darwin Tropical Cyclone Warning Centre at midnight CST 24/12/74.

Tropical cyclone Tracy was located by radar at 11.30 pm 33 km west north west of Darwin moving east south east at 6 km/h.

Top Priority

Cyclone Warning issued by the Darwin Tropical Cyclone Warning Centre at 12.30am CST 25/12/74.

Tropical cyclone Tracy was located by radar at midnight 30 km west north west of Darwin moving east south east at 6 km/h.

Top Priority

Cyclone Warning issued by the Darwin Tropical Cyclone Warning Centre at 1.50 am CST 25/12/74.

Tropical Cyclone Tracy was located by radar at 1.30 am CST 22 km west north west of Darwin moving east south east at 6 km/h.

Top Priority

Cyclone Warning issued by the Darwin Tropical Cyclone Warning Centre at 2.30 am 25/12/74.

Tropical cyclone Tracy was located by radar at 2 am CST 18 km west north west of Darwin moving east south east at 6 km/h. The eye of the storm is expected to move over Darwin soon. Winds should become lighter to calm for a period up to 1½ hr before rapidly strengthening to its previous intensity from the opposite direction.

DISTRIBUTION LIST OF WARNINGS FOR TRACY ISSUED BY THE DARWIN TROPICAL CYCLONE WARNING CENTRE

Tropical Cyclone Alerts

Civil Defence
Police Headquarters
Darwin Navy
Harbour Master
Burns Philp & Co. Ltd (first only)
First Assistance Secretary, Department of Northern Territory (first only)
Catholic Mission Headquarters
Larrakeyah Army Barracks
Weather Service Office, Darwin Airport
Coastal Radio Stations VID and VII
PMG Outpost Radio
Officer-in-Charge, PMG Traffic
Press
ABC and commercial radio and television stations
Natural Disasters Organisation, National Emergency Operations Centre
Navy, Canberra
Interstate Bureau Offices

Tropical Cyclone Warnings

Civil Defence
Department of Northern Territory Radio
Police Headquarters
Darwin Navy
Harbour Master
Department of Northern Territory
Burns Philp & Co. Ltd (first only)
Power House
Darwin Hospital
Rural Officer, ABC
Darwin City Council
Catholic Mission Headquarters
Larrakeyah Army Barracks
Darwin RAAF
Weather Service Office, Darwin Airport
Coastal Radio Station VID
PMG Outpost Radio
Officer-in-Charge, PMG Traffic
ABC and commercial radio and television stations
Press
Natural Disasters Organisation, National Emergency Operations Centre
Interstate Bureau Offices

Prior to the issue of the Top Priority Flash Cyclone Warning No 16 at 1230 CST on 24 December 1974, the following heads of departments and local instrumentalties were telephoned by the Regional Director to advise them of the threat from Tracy to Darwin

The Administrator
The Controller, Civil Defence
The Town Clerk
The Commissioner of Police
The 2-I-C, Darwin Navy
The Officer-in-Charge, Radio Australia – Cox Peninsular
The Manager, ABC
The Mayor of Darwin

Auxilliary Tropical Cyclone Warnings Based on Radar

ABC and commercial radio and television stations
Darwin Police

Gale and Storm Warnings

Coastal Radio Stations VID, VII, and VIP
Navy, Canberra
Navy, Darwin
Maritime Operations Centre, Canberra
Interstate Bureau Offices
Radio Teletype Broadcasts AXI and AXM
Companies – ARCO, ODECO, and Atwood Oceanics

Strong Wind Warnings

Coastal Radio Stations VID and VII
ABC and commercial radio stations
Interstate Bureau Offices

Severe Storm Warnings to Aviation

A selection of interstate and overseas meteorological offices

PREDICTIVE PERFORMANCE AT DARWIN RFC

Twenty-nine of the Cyclone and Gale Warnings that were issued as Tracy approached the coast could be tested for accuracy by comparing the predicted position of the storm with the location later found by radar. All 29 were forecasts of the expected position in 12 hours time. Mean prediction position errors expressed in kilometres are given in Table (a) and the three extreme errors examined in Table (b). It is to be noted that all the poorer forecasts were made at times before the eye of the storm had been identified on radar. These instances give some idea of the way in which large unmeasurable positioning errors contribute to poorer predictive performance.

The question naturally arises as to how well forecasts of Tracy's course compared with average forecast performance. Table (c) details some recent Australian statistics. Annette's (1976) contemporaneous figures show that mean 24-hour prediction error for Northern Territory storms is about 55 per cent of the corresponding mean error for storms off the east coast of Australia. Approximately the same percentage can be presumed to apply to the difference in 12-hour prediction errors. It is to be observed that the mean prediction error for Tracy (51 km) is less than half of 55 per cent of the authoritative Curnow and Moll (1974) mean for 12-hour prediction errors for eastern Australian storms. So it can be concluded that forecasts issued by the Darwin RFC for the course of Tracy were in the mean appreciably better than is normally achievable. Corroboration of that opinion comes by noting that if the ratio of 12 to 24-hour prediction error as determinable from Gourlay's figures (112, 202) is applied to Annette's 24-hour means (135, 149) for the Northern Territory it appears that the 12-hour mean error for Northern Territory storms would be of the order of 75 or 80 km. The performance achieved by Darwin RFC for Tracy was appreciably better than this.

References

Annette, P. 1976. Some performance statistics for predictions of tropical cyclone motion. *Met. Note 89*, Bur. Met., Australia.

Curnow, R.J. and Moll, J.W. 1974. Improvement of the tropical cyclone warning service in Queensland. Department of Defence, Australia, *C.S.E. Note 33*, 5-6.

Table (a) Mean 12-hour prediction position errors made forecasting Tracy's course

	Mean error	RMSE	Number of forecasts
	km	km	
Gale and Cyclone Warnings	51*	66	29
Cyclone Warnings	42	46	16
Gale Warnings	62*	85	13
Forecasts made prior to recurvature	55*	74	20
Forecasts made during recurvature	45	48	6
Forecasts made after recurvature	40	40	3

* Data set contains the three largest errors made.

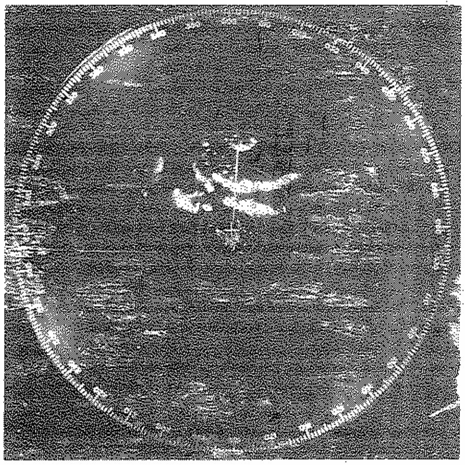
Table (b) The three worst prediction errors made in warning of Tracy's approach

Magnitude of error	Type of warning	Date/time when forecasts made	Prediction for	Reason for the magnitude of the error
km		CST	CST	
238	Gale	22/0900	22/2100	Predictions made prior to radar identification of the location of the eye
109	Gale	22/0300	22/1500	
89	Gale	21/1830	22/0630	

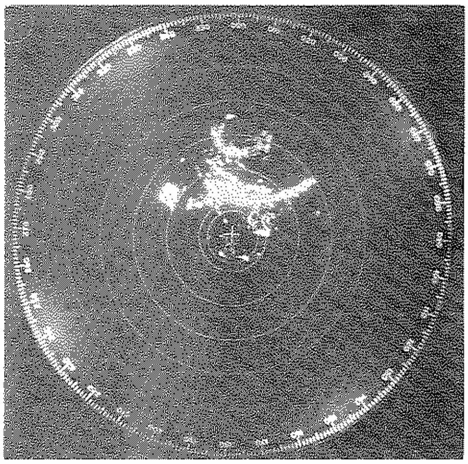
Table (c) Comparative statistics of predictive performance

Investigators	Mean prediction position error		Number of forecasts	Survey of storms
	12 hours	24 hours		
	km	km		
Annette		135	9	off Northern Territory 1973-74
		149	13	off Northern Territory 1974-75
		265	43	in SW Pacific 1973-74
		256	31	in SW Pacific 1974-75
Current	51		29	tropical cyclone Tracy
Curnow and Moll	196		240	off eastern Australia
Gourlay	112	202	63,20 resp	within 360 n mile of the Queensland coast 1967-1972

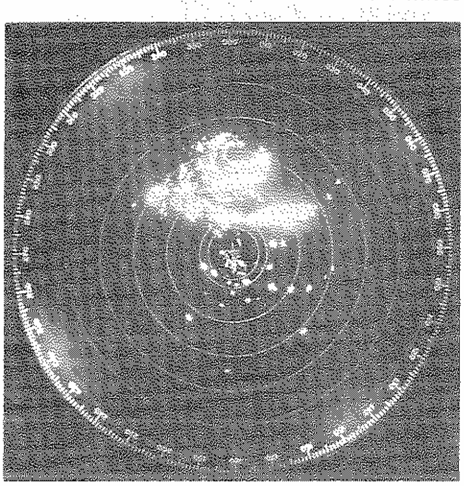
A SELECTION OF PHOTOGRAPHS OF THE DARWIN WEATHER RADAR PPI DURING THE PERIOD OF TRACY



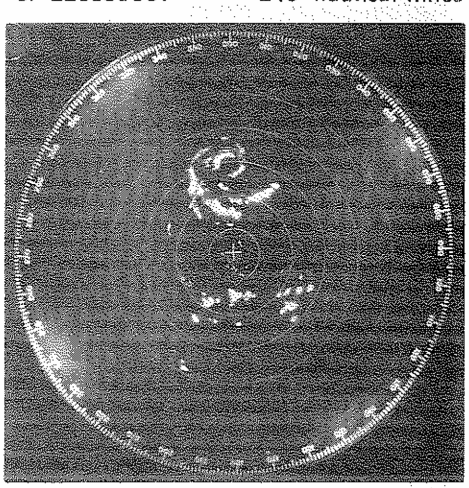
8. 221030CST 240 nautical miles



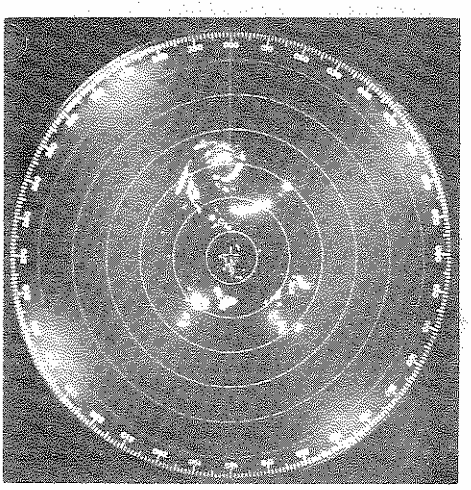
9. 221130CST 240 nautical miles



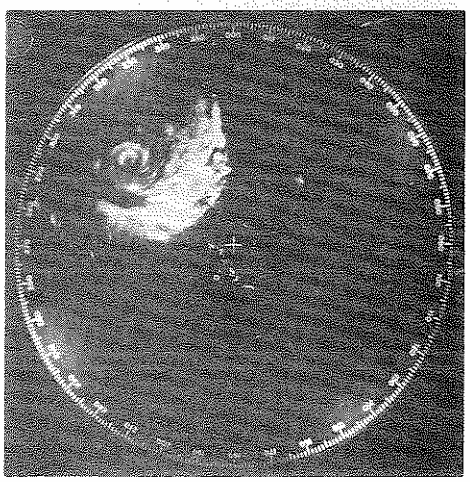
12. 221330CST 240 nautical miles



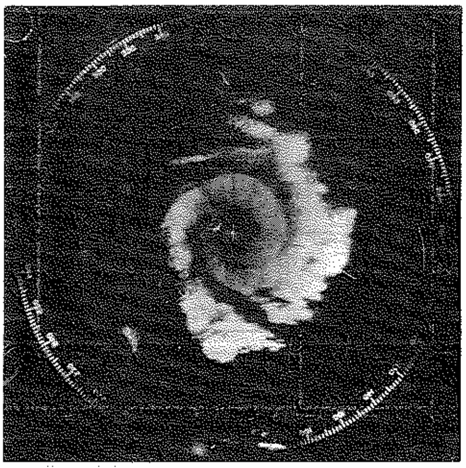
15. 221630CST 240 nautical miles



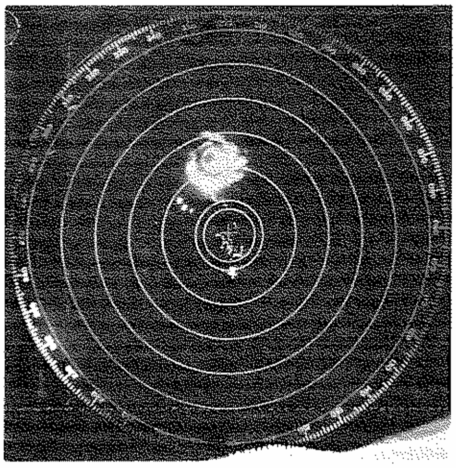
16. 221730CST 240 nautical miles



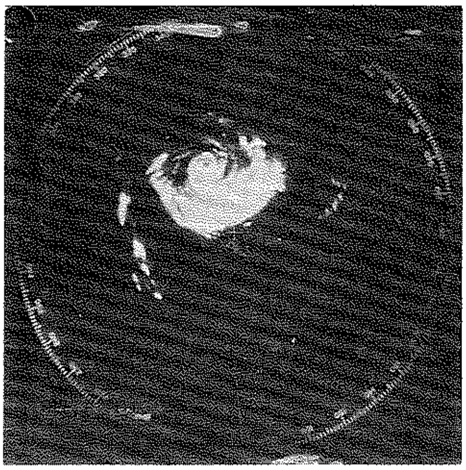
19. 222030CST 240 nautical miles



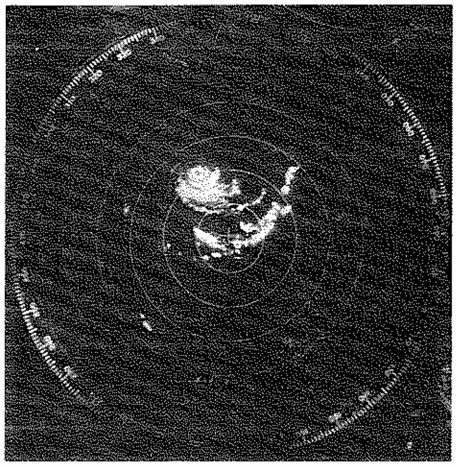
21. 222200CST 60 nautical miles



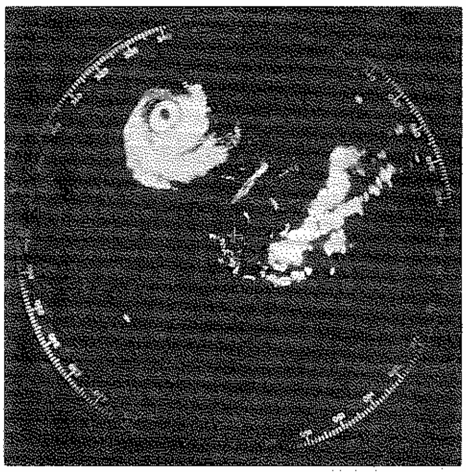
24. 230030CST 240 nautical miles



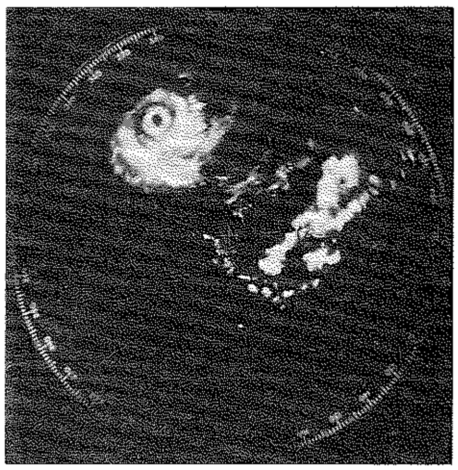
29. 230730CST 240 nautical miles



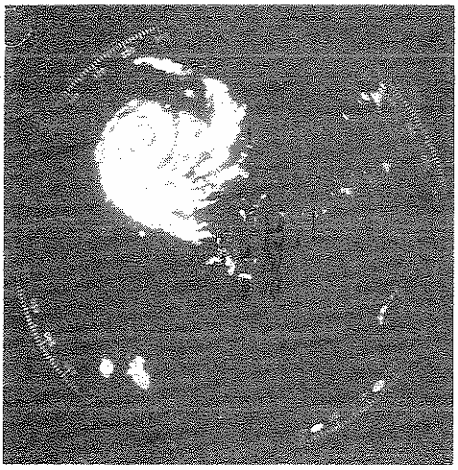
35. 231115CST 240 nautical miles



39. 231203CST 120 nautical miles

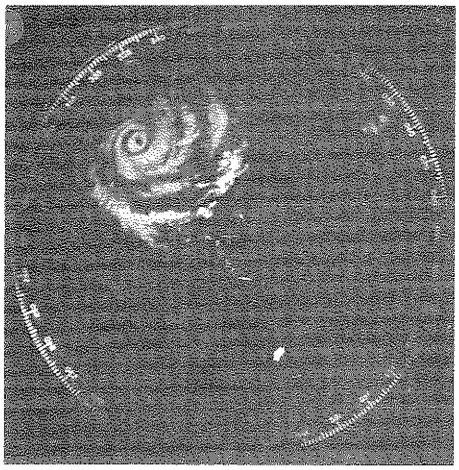


43. 231230CST 120 nautical miles

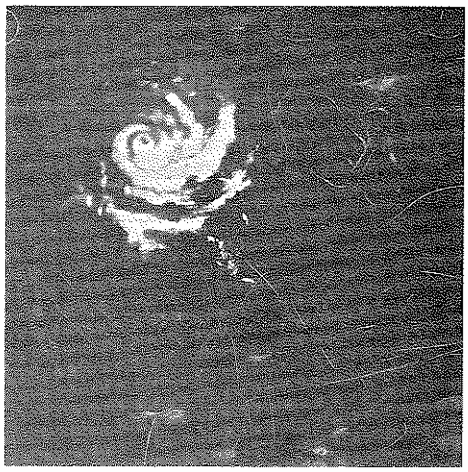


47. 231645CST 120 nautical miles

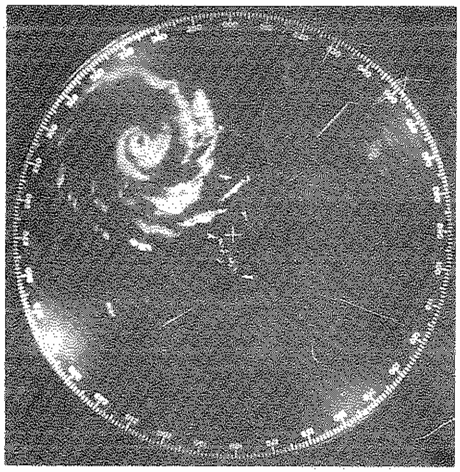
49. 231715CST 120 nautical miles



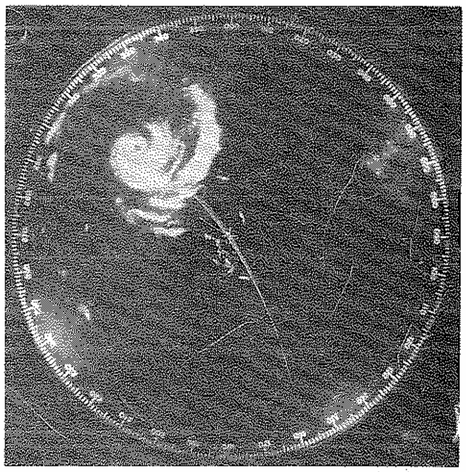
51. 231745CST 120 nautical miles



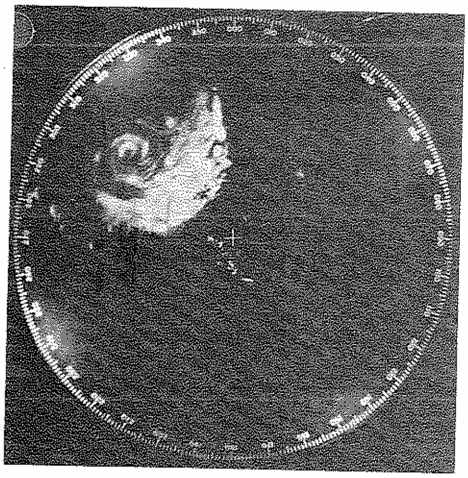
53. 231815CST 120 nautical miles



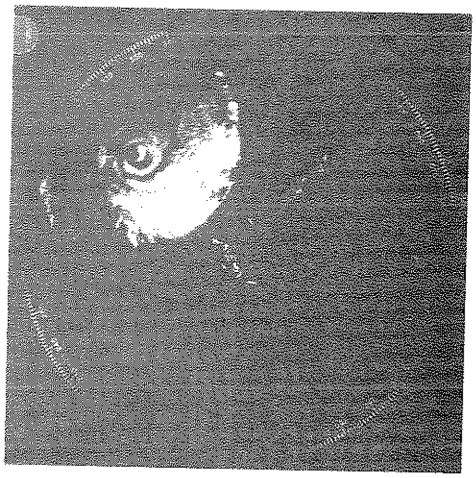
55. 231915CST 120 nautical miles



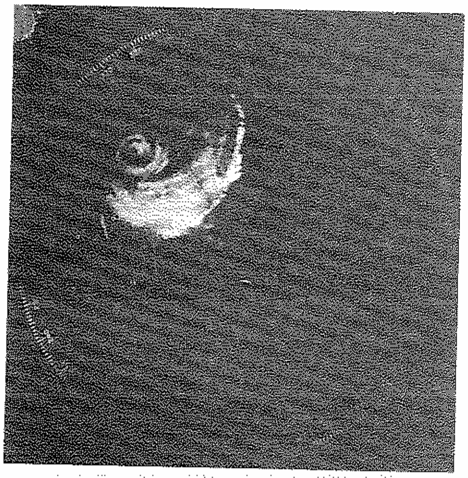
57. 231945CST 120 nautical miles



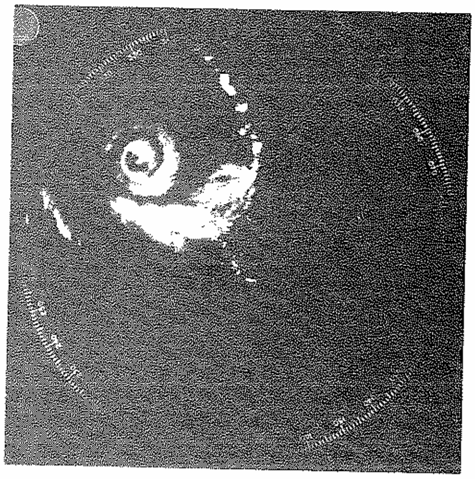
61. 232215CST 120 nautical miles



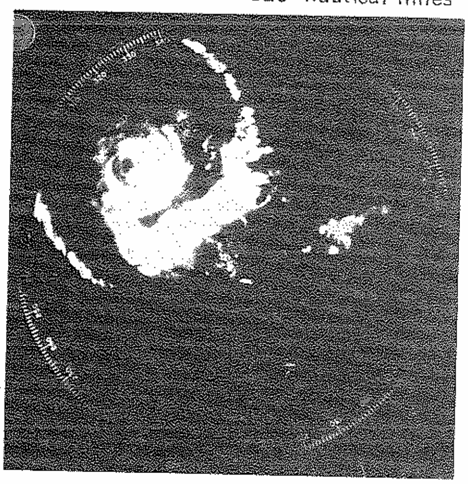
63. 232245CST 120 nautical miles



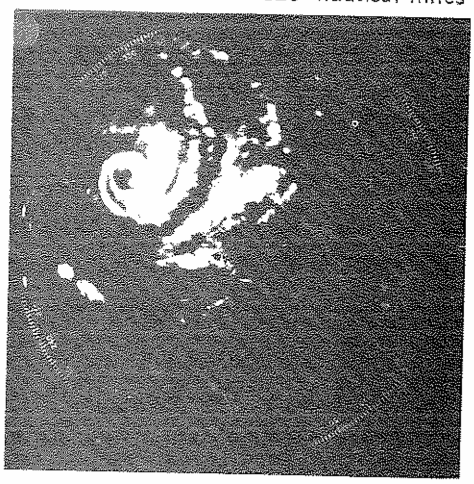
65. 232315CST 120 nautical miles



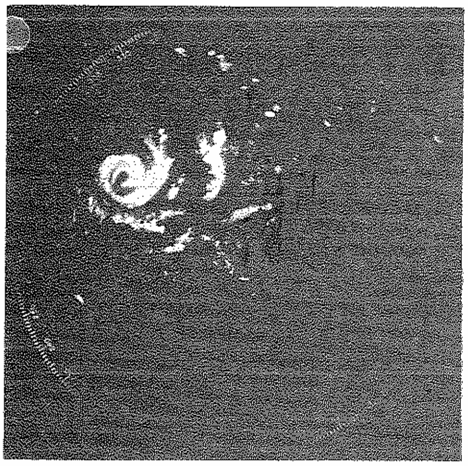
69. 240015CST 120 nautical miles



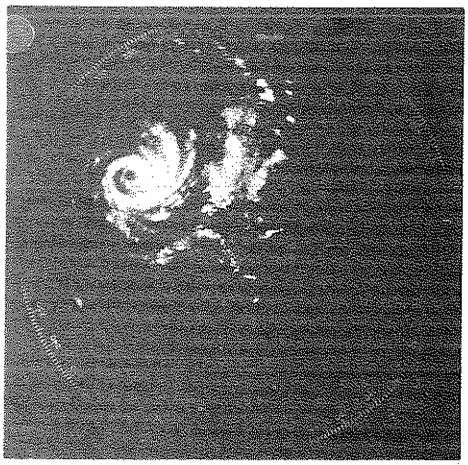
73. 240115CST 120 nautical miles



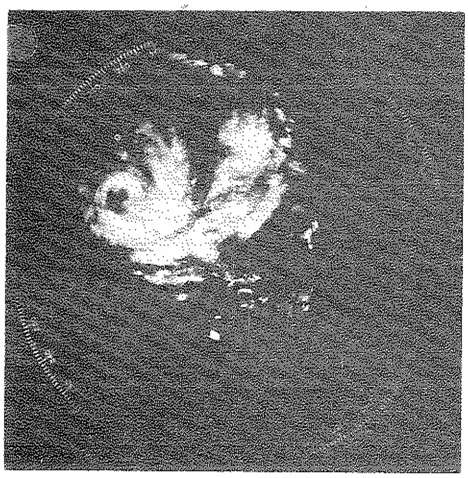
77. 240315CST 120 nautical miles



81. 240415CST 120 nautical miles

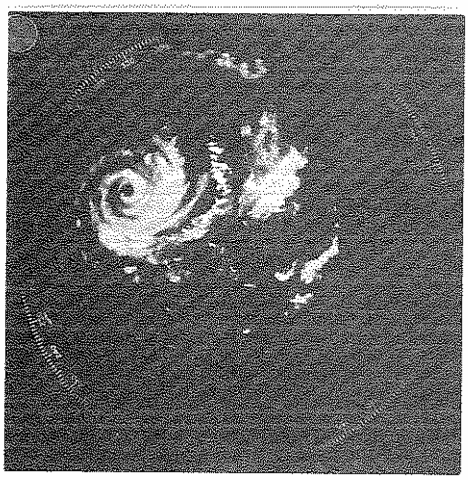


83. 240445CST 120 nautical miles

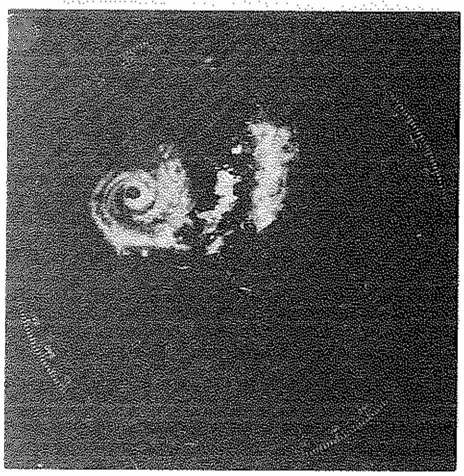


87. 240545CST 120 nautical miles

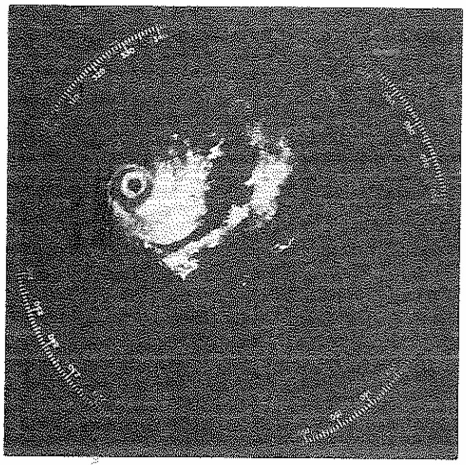
91. 240645CST 120 nautical miles



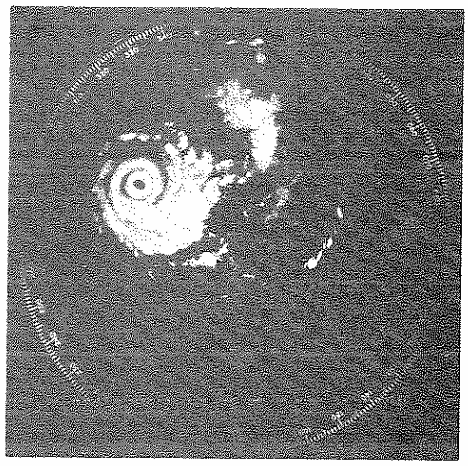
93. 240715CST 120 nautical miles



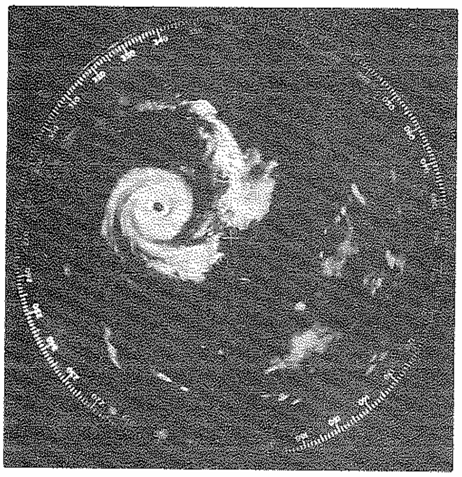
95. 240915CST 120 nautical miles



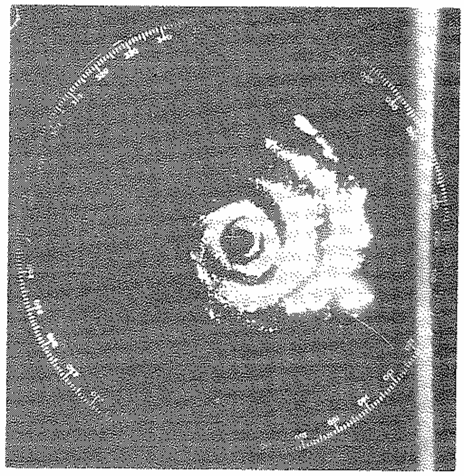
99. 241015CST 120 nautical miles



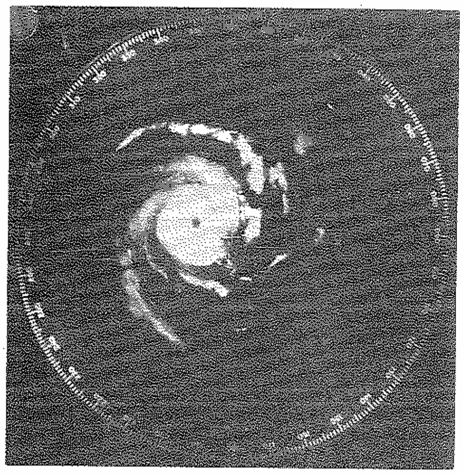
101. 241045CST 120 nautical miles



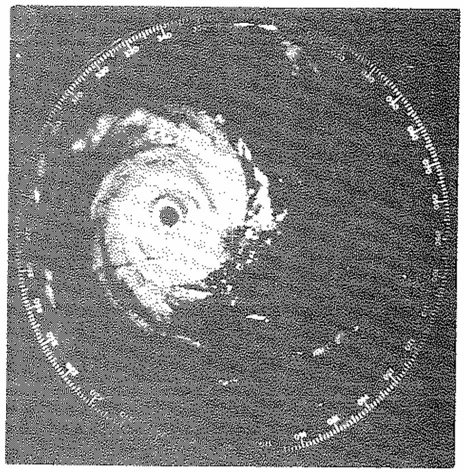
109. 241445CST 120 nautical miles



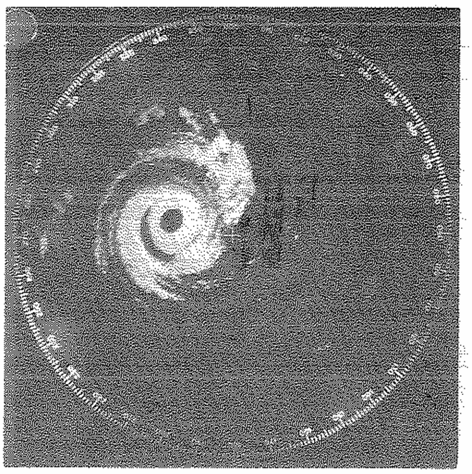
117. 241825CST 60 nautical miles



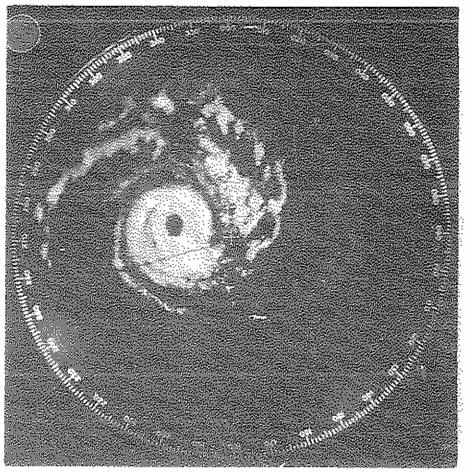
122. 242115CST 120 nautical miles



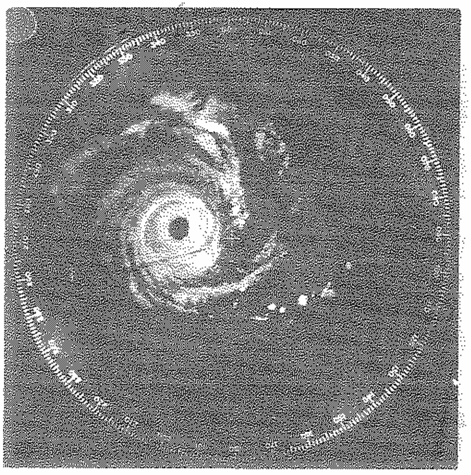
125. 242245CST 60 nautical miles



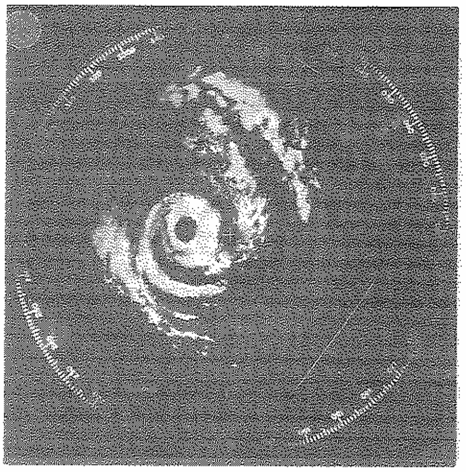
126. 242315CST 60 nautical miles



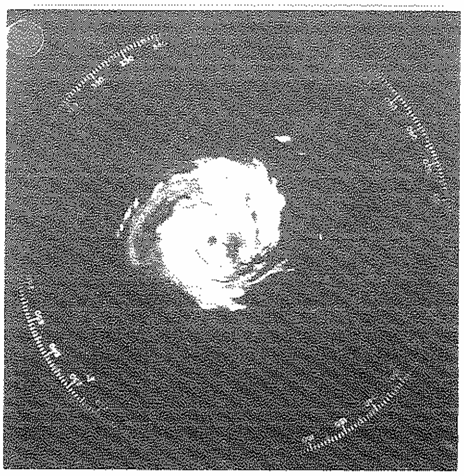
129. 242345CST 60 nautical miles



132. 250015CST 60 nautical miles

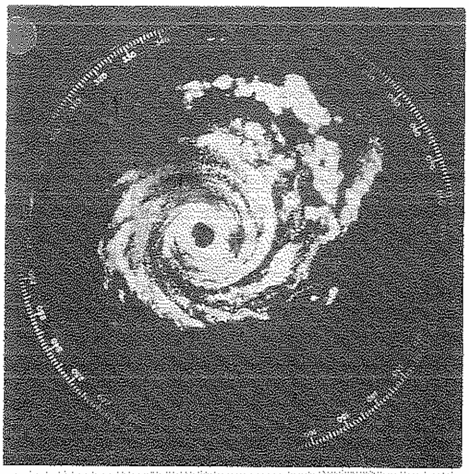


133. 250115CST 60 nautical miles

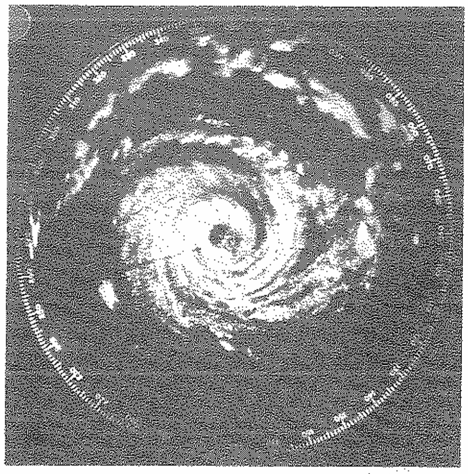


134. 250115CST 120 nautical miles

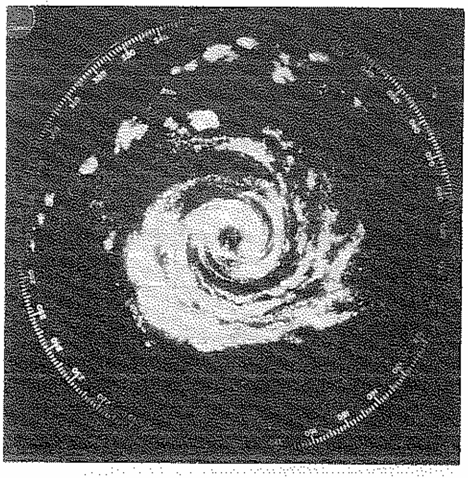
136. 250145CST 60 nautical miles



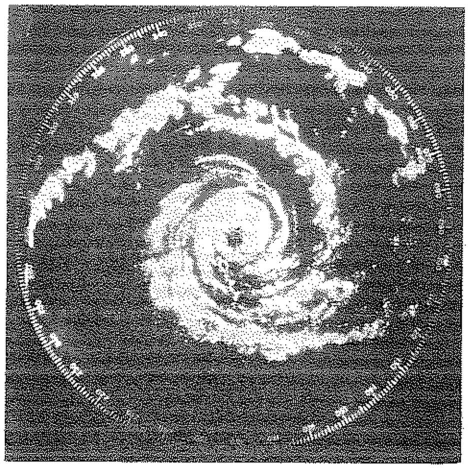
138. 250215CST 60 nautical miles



140. 250315CST 60 nautical miles



142. 250345CST 60 nautical miles



144. 250415CST 60 nautical miles

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