

Tropical cyclogenesis: a comparative study of two depressions in the northwest of Australia

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(Received 2 November 1982; revised 24 May 1983)

SUMMARY

A comparative study of two cloud clusters in the north-west of Australia highlights synoptic influences on tropical cyclogenesis. Although both clusters developed over land in the same region, the large-scale flow was conducive to the subsequent development of one cluster into tropical cyclone *Enid* and suppressed the development of the other cluster. The non-developing low was under strong upper easterlies from an upper tropospheric ridge. An upper trough in the subtropical westerlies later split the ridge, bringing light and divergent upper winds over the low-level monsoonal trough. This facilitated the development and intensification of a low-level cyclonic circulation, tropical cyclone *Enid*.

1. INTRODUCTION

Cloud clusters and weak tropical depressions are common features of tropical regions during summer (Riehl 1979; Barrett 1974), yet only a small proportion of these intensify into tropical cyclones. Hence, a basic forecasting problem is identifying developing storms from non-developers.

In a comparison of developing and non-developing cloud clusters, McBride and Zehr (1981) and Erikson (1977), using composited data, showed that there were observational differences between the two types of cloud cluster. Clusters which later developed into tropical cyclones showed a stronger low-level circulation and generally a divergent upper circulation. This was reflected in the lower layers by the stronger tangential winds observed around developing clusters.

As well as differences in horizontal shear, McBride and Zehr, and Erikson showed that vertical wind shear differed between developing and non-developing clusters. Developing lows had small vertical shear through the centre of the clusters and stronger surrounding shears that were consistent with a lower cyclonic circulation being overlaid by anticyclonic flow. The small central vertical shear is considered essential to intensification because it minimizes upper-level ventilation and allows formation of a warm core. This point has been stressed by several authors, for example Palmen and Newton (1969), Riehl (1979), Gray (1968, 1979) and Palmen (1956). In the Western Australian region, forecasters accept the existence of a deep easterly flow with small vertical shear as being favourable for development (A. Scott, personal communication).

Vincent and Waterman (1979), in a diagnostic analysis of the development of hurricane *Carmen* in 1974, found that it intensified within a large-scale lower cyclonic flow, anticyclonic winds aloft and small easterly vertical shear. In a series of modelling experiments, Tuleya and Kurihara (1981) simulated the response of a tropical easterly wave to a variety of vertical and horizontal wind shears. Greatest intensification was achieved with easterly vertical shear between 850 and 150 mb of 15 m s^{-1} and cyclonic lower horizontal shear below anticyclonic upper shears. Intensification ensued if easterly shear was combined with cyclonic lower shear only, but not if unidirectional lower flow was combined with anticyclonic upper flow.

The experiments of Tuleya and Kurihara suggested that a tropical low can intensify given favourable surrounding low-level winds out to at least 10 latitude degrees. The work of McEwan (1976, 1982) demonstrated how vertical motion embedded in cyclonic flow interacted with the surroundings to produce an inward advection of angular momentum and intensification of a vortex. It seems from the modelling and observational studies that a cyclonic circulation will form spontaneously around a region containing strong vertical motion that is embedded within larger-scale cyclonic flow. Decay will then occur

if the depression or cyclone moves into an environment containing strong vertical wind shears or a depleted moisture supply. The influence of upper divergence enhancing mechanisms such as upper troughs (Sadler 1976; Fett 1968; Ramage 1974; Colon and Nightingale 1963) is likely to influence intensification beyond tropical depression stage or to affect the rate of deepening.

The present study compares the conditions surrounding two tropical depressions occurring within a 10-day period over north-western Australia during February 1980. They formed initially in the same region and followed similar westward tracks, one crossing the coast south of Broome, the other north of the town (see Fig. 1). The first low

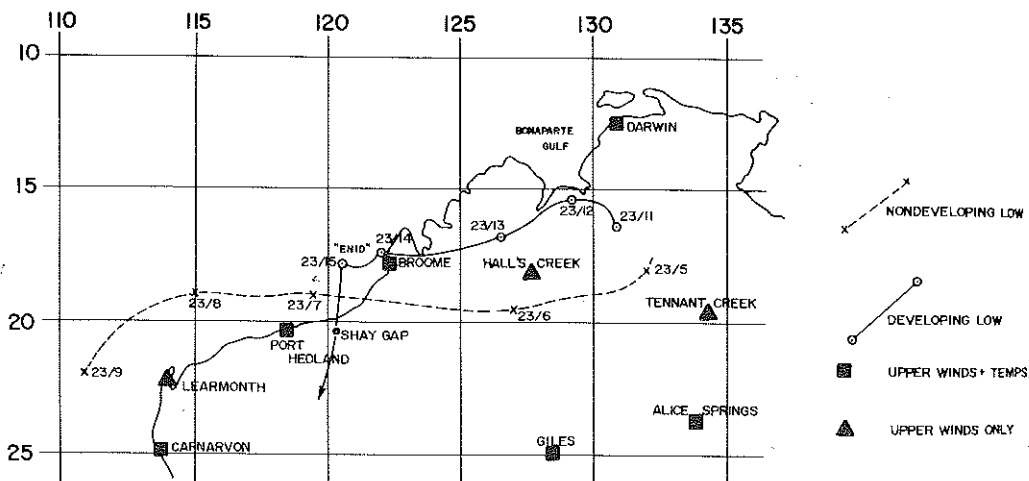


Figure 1. The location of upper wind and temperature stations and the tracks of the depressions. Positions are given at 2300 GMT for each day.

(hereafter referred to as ND) continued westward and eventually dissipated west of Carnarvon without significantly intensifying. On the other hand, the second depression (referred to as DD) became cyclone *Enid* and attained an estimated minimum central pressure of 930 mb (Crane 1981). *Enid* crossed the coast near Wallal Station and caused several million dollars damage to local cattle stations and the town of Shay Gap (Crane 1981). This period was chosen for study because it contained two tropical depressions in the same general region and affords an opportunity to identify changes in the monsoon circulation that suppressed one depression, yet allowed the second to intensify. Both depressions spent a major portion of their time over land. They moved within the Australian Commonwealth Bureau of Meteorology's upper wind and radiosonde network, and passed close to three upper wind stations.

2. OBSERVATIONS

The wind data used in this study comprised both rawinsonde and satellite cloud vector winds from GMS-1. Rawinsonde soundings were obtained from the routine upper wind network, which included stations in Indonesia as well as Australia. Observations were made at 0500, 1100, 1700 and 2300 GMT each day. Soundings at standard levels up to 100 mb were selected.

The satellite cloud vectors were obtained from the Monthly Report of the Meteorological Satellite Centre for February 1980, published by the operators of GMS-1 (Anon 1980). They comprised cumulus-level vectors, calculated from the GMS Cloud Wind Estimation System using an automatic cross-correlation procedure and cirrus-level

vectors estimated using a film loop technique. Satellite winds are commonly assigned to one representative upper level (Rodgers *et al.* 1979; Kinsky and Gan 1981; Virji 1981) despite an inevitable increase in errors. For GMS cloud winds, Hamada (1980) indicated 150 to 250 mb as being the levels of best fit for cirrus-level vectors and 1000 to 850 mb giving best agreement with conventional observations at lower levels. In the present study, assigning cirrus-level vectors to 200 mb and cumulus-level vectors to 850 mb gave a greatly increased density of data. The resulting plots may be regarded as representative of upper- and lower-level flows, rather than a specific analysis at each level. In most cases, the vectors were consistent with the synoptic situation. Gross deviations of direction or speed were few and easily edited. Streamline/isotach analyses were performed using these data at 2300 GMT for 5, 7, 9, 10, 11 and 13 February 1980.

The combined rawinsonde and cloud wind vectors were also interpolated to a Cartesian grid of 2.5 degrees interval using a distance-weighted first-degree polynomial interpolation scheme similar to that of Mancuso and Endlich (1973). Centred finite differences were used to calculate relative vorticity and divergence from

$$\xi = \partial v / \partial x - \partial u / \partial y \quad \text{and} \quad D = \partial u / \partial x + \partial v / \partial y,$$

where u and v are zonal and meridional wind components (Endlich 1967). Smoothed contours of these fields illustrated salient differences between the environments surrounding the depressions.

Time sections of winds at standard levels up to 100 mb were constructed for Broome, Port Hedland and Halls Creek. These tropical stations made one sounding per day at 2300 GMT (0700 local time). The passages of the lows close to the stations were reflected in the profiles showing the depth and strength of the vortices. Temperature deviations from the February averages are also plotted on the time sections. Visible satellite imagery from GMS-1 was available for 0300 GMT, that is four hours after the standard 2300 h observations used in the streamline/isotach analysis.

3. SYNOPTIC DESCRIPTION OF SEQUENCE

On 5 February ND consisted of a weak vortex embedded in the monsoon trough over northern Australia (Fig. 2(a)). The trough was overlaid by vigorous easterlies to the north of an upper ridge (Fig. 3(a)). Since the low was embedded in a deep easterly flow from 500 to 100 mb, it was steered westwards. Visible GMS imagery for 0300 GMT on the 6th showed a cloud cluster near 18°S 131°E, as well as extensive lower cloud over northern Australia (Fig. 5(a)).

ND continued westwards during the 6th and crossed the coast between Broome and Port Hedland on the 7th. The 850 mb streamlines for 2300 GMT on 7 February (Fig. 2(b)) show a vortex distinct from the monsoon trough. Aloft, an upper trough was beginning to intensify over eastern Australia (Fig. 3(b)). Strong upper easterlies persisted over the low. Satellite imagery for 0300 GMT on the 8th showed extensive high cloud streaming polewards from the low, as well as continuing deep convection inland.

Figure 4(a) shows a time section of winds and temperature deviations from the February average at Broome. The wind shift associated with the passage of ND may be seen up to 500 mb, with some perturbations also at 400 mb. A weak upper warm core was evident, with cold anomalies at lower levels. The depression passed within 2 latitude degrees of Port Hedland and the time section for that station (Fig. 4(b)) indicates a wind shift up to 300 mb and a warm middle and upper core.

During the 8th and 9th ND continued to track westwards and southwards. Even though it was over a region with sea surface temperatures above 26°C, it did not intensify beyond tropical depression stage. In the wake of ND, the monsoon circulation increased in strength. The time section at Halls Creek (Fig. 4(c)) shows the increase of lower easterlies at 850 and 700 mb on the 9th. Strong horizontal cyclonic shear was apparent in the region 10°S to 20°S and 125°E to 135°E (Fig. 2(c)). At higher levels, the upper trough

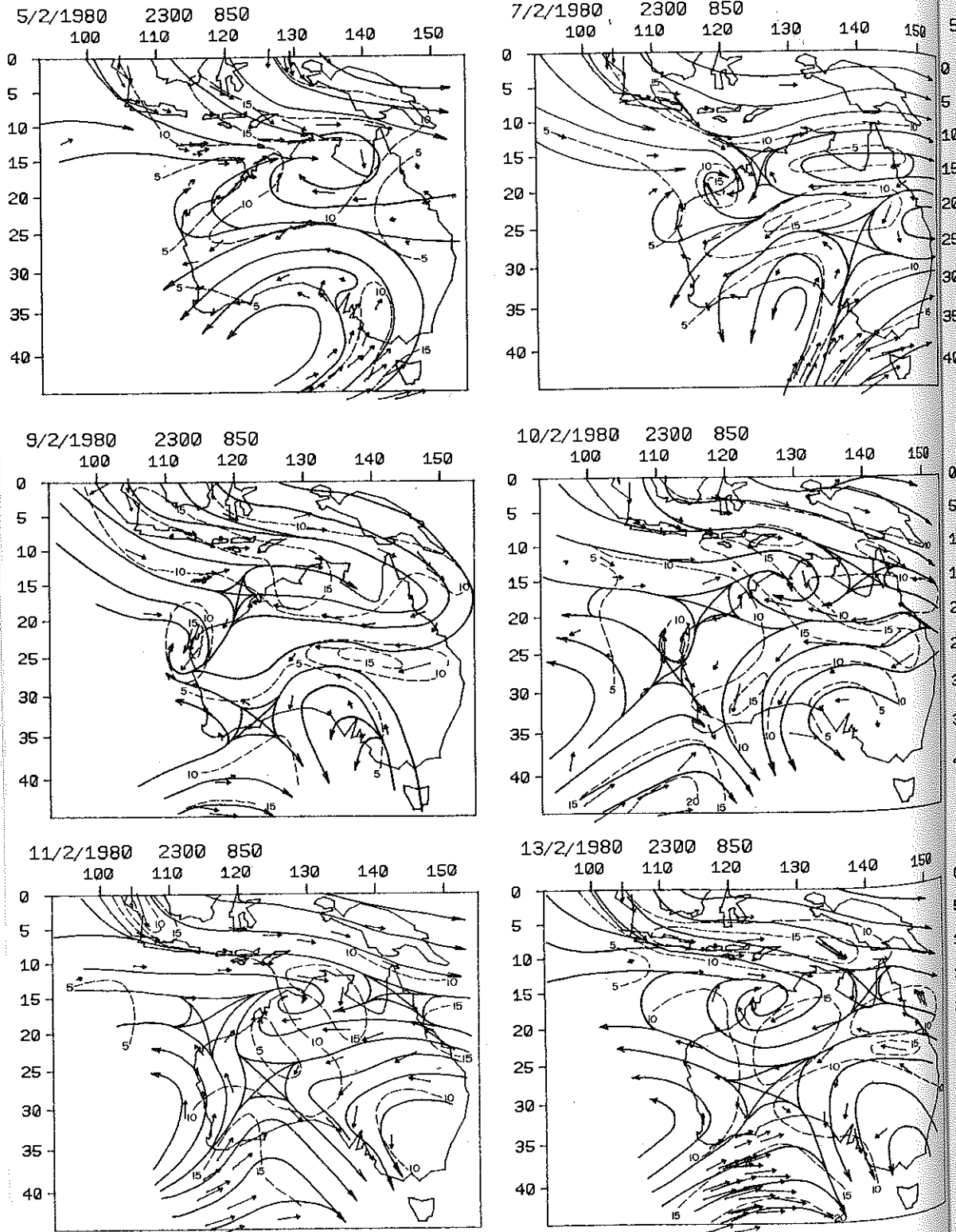


Figure 2(a-f) 850 mb streamline/isotach analysis for the dates shown.

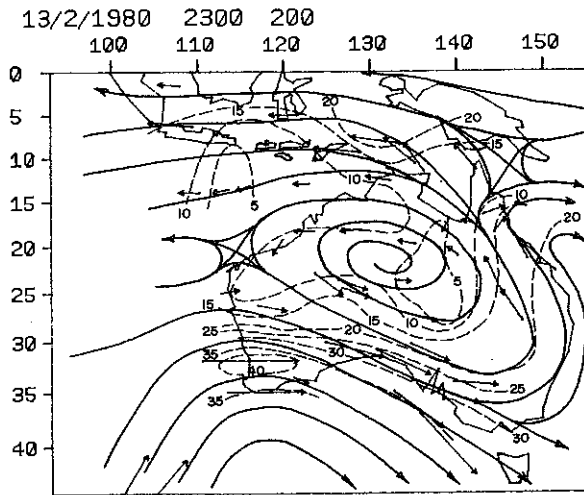
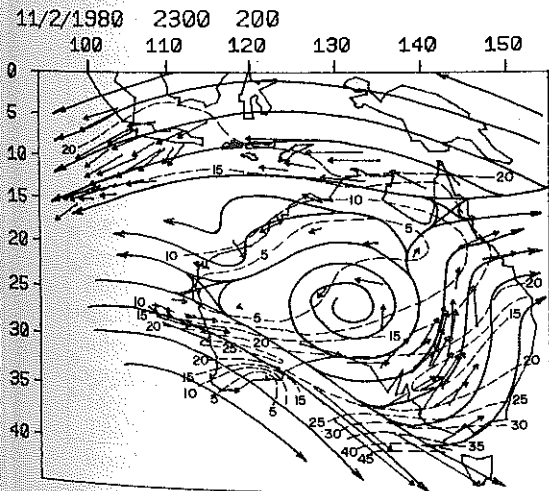
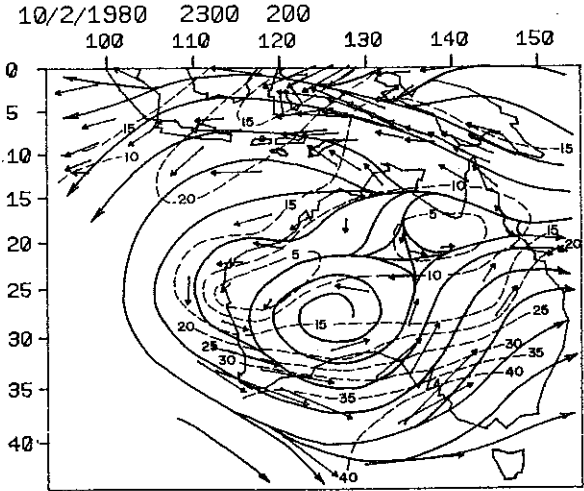
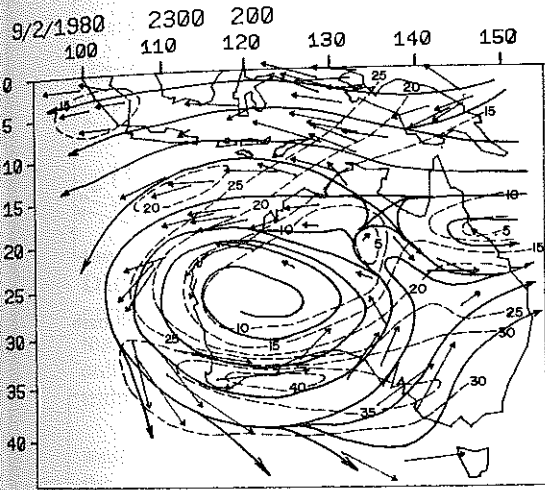
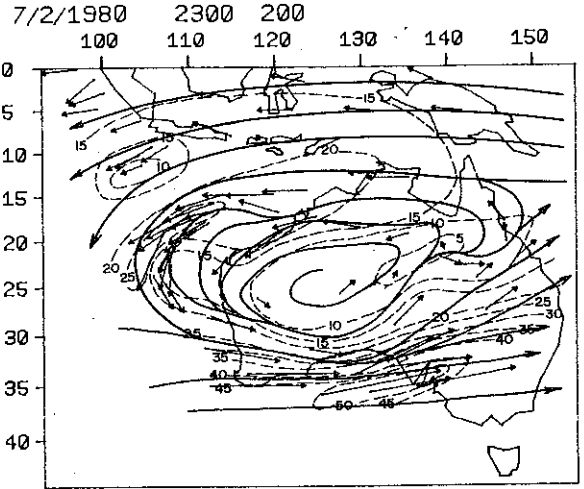
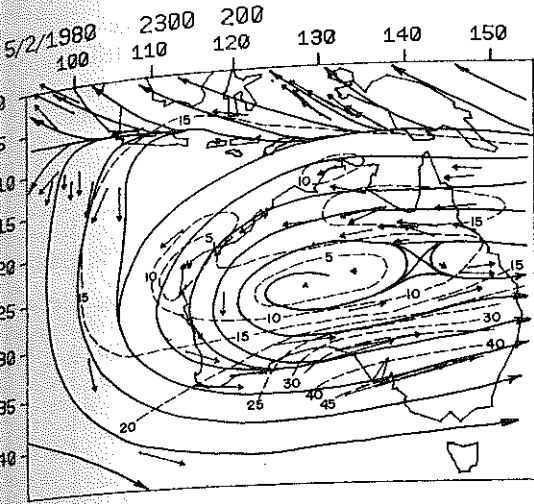


Figure 3(a-f) 200 mb streamline/isotach analysis for the dates shown.

had intensified over eastern Australia, with the previous upper ridge forming a large cell to the west. Strong upper winds prevailed over the north-west coast (Fig. 3(c)). Satellite imagery (Fig. 5(c)) for 0300 GMT on the 10th illustrates interaction with another trough south of Western Australia producing a large mass of high cloud moving polewards from ND. The cloud appears sheared westwards from the circulation centre of the low.

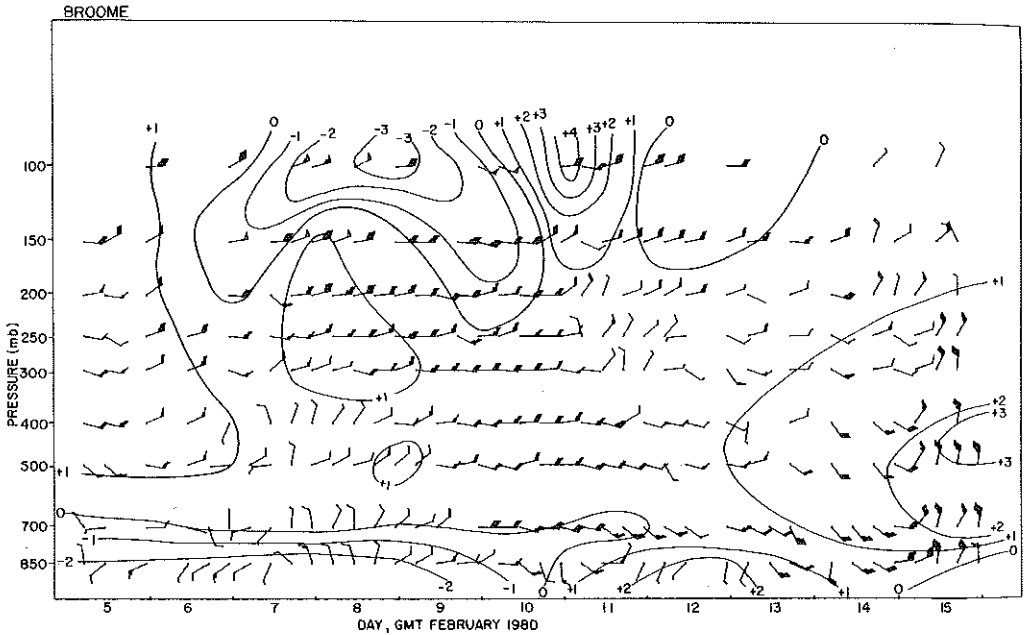


Figure 4(a) Time section of winds and temperature deviations ($^{\circ}\text{C}$) from February mean at Broome. Full barb equals 5 m s^{-1} , half barb 2.5 m s^{-1} .

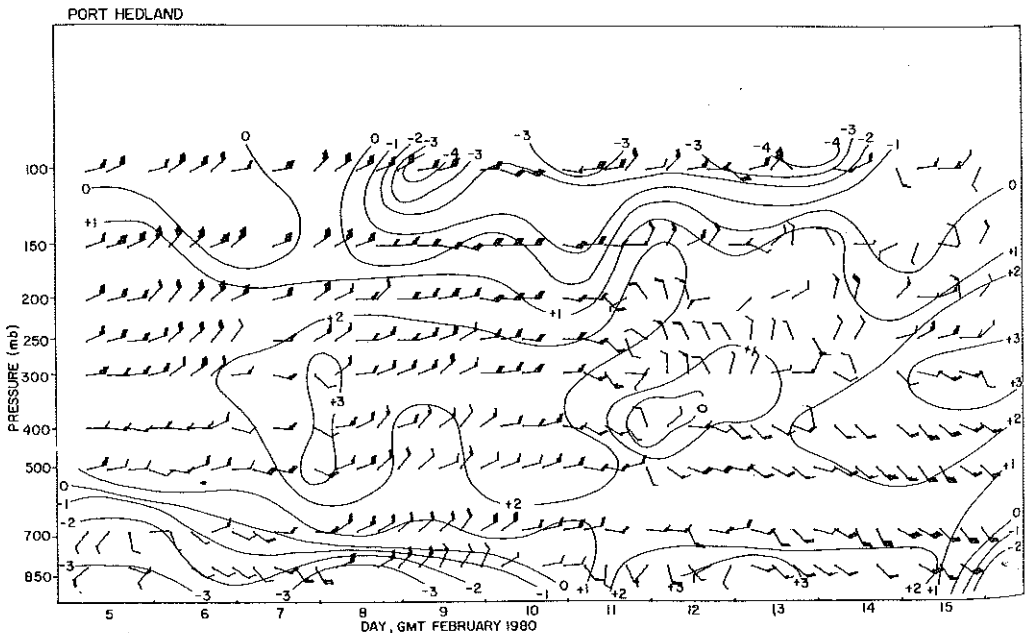


Figure 4(b) Time section of winds and temperature deviations ($^{\circ}\text{C}$) from February mean at Port Hedland. Full barb equals 5 m s^{-1} , half barb 2.5 m s^{-1} .

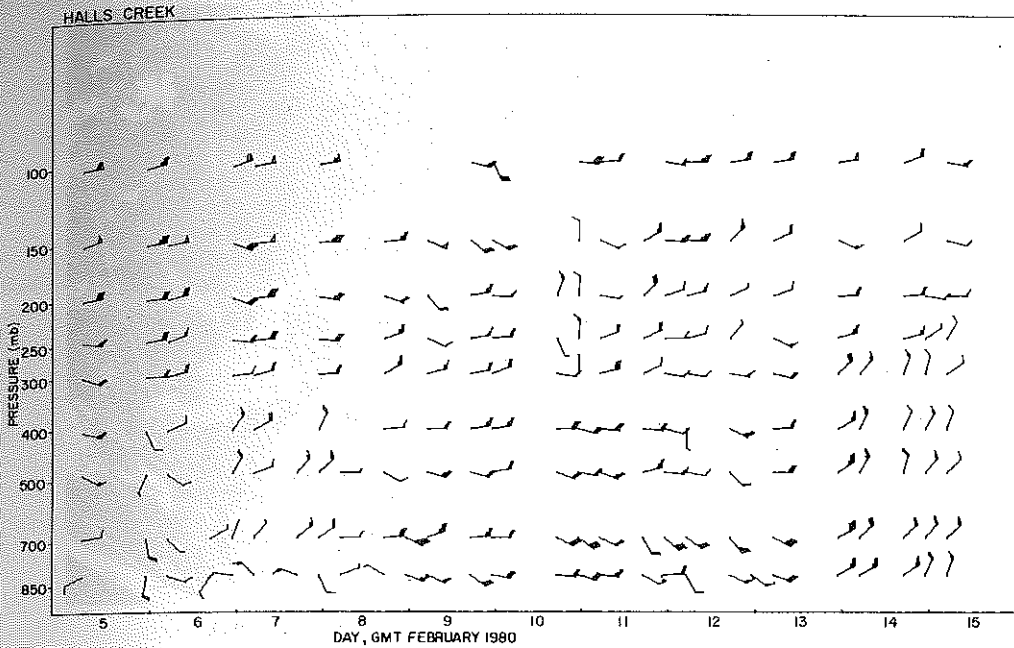


Figure 4(c) Time section of winds only at Halls Creek. Full barb equals 5 m s^{-1} , half barb 2.5 m s^{-1} .

The 850 mb streamlines for the 10th (Fig. 2(d)) show signs of a vortex forming within the region of strong horizontal shear noted the previous day. Winds at Broome and Darwin possessed a greater meridional component and 15 m s^{-1} easterlies and westerlies prevailed south and north of the region, respectively. To the south a front was approaching the south-west of Western Australia. At 200 mb (Fig. 3(d)) the upper trough had collapsed eastwards, leaving light and divergent upper winds over north-western Australia.

The following day saw an expansion of horizontal cyclonic shear along the north-west coast as southerly winds from an anticyclone in the Indian Ocean were established in the wake of the front (Fig. 2(e)). At upper levels, light easterlies prevailed over the lower cyclonic flow (Fig. 3(e)).

Extensive inland convection had been continuing and the satellite photograph for 0300 GMT on the 12th shows a ragged cloud cluster near $17^{\circ}\text{S } 130^{\circ}\text{E}$ (Fig. 5(d)). This was the earliest identification on the Commonwealth Bureau of Meteorology track for tropical cyclone *Enid* (Lourensz 1981).

DD moved steadily westward during the next two days. It passed north of Hall's Creek on the 13th and the time section (Fig. 4(c)) shows a wind shift suggestive of a cyclonic circulation up to 300 mb. At Broome, the lower south-easterlies reached up to 500 mb by 2300 GMT on the 13th (Fig. 4(a)). The 850 mb streamlines show the vortex embedded in large-scale horizontal cyclonic shear (Fig. 2(f)). Westerlies of 15 m s^{-1} continued to the north and south of DD. Aloft, the anticyclone had been pushed northwards by the upper trough advancing over south-western Australia. An outflow channel to the upper westerlies appeared to be developing (Fig. 3(f)). From its appearance on satellite imagery DD had acquired considerable organization. Figure 5(e), for 0300 GMT on the 14th, shows cyclonically curved lower cloud as well as a central mass of deep convection. The extent of overland convection confirms the continuing advection of water vapour from the oceans north of Australia.

DD crossed the coast the following day and was named tropical cyclone *Enid*. The time section for Broome (Fig. 4(a)) shows the depth and strength of the circulation that

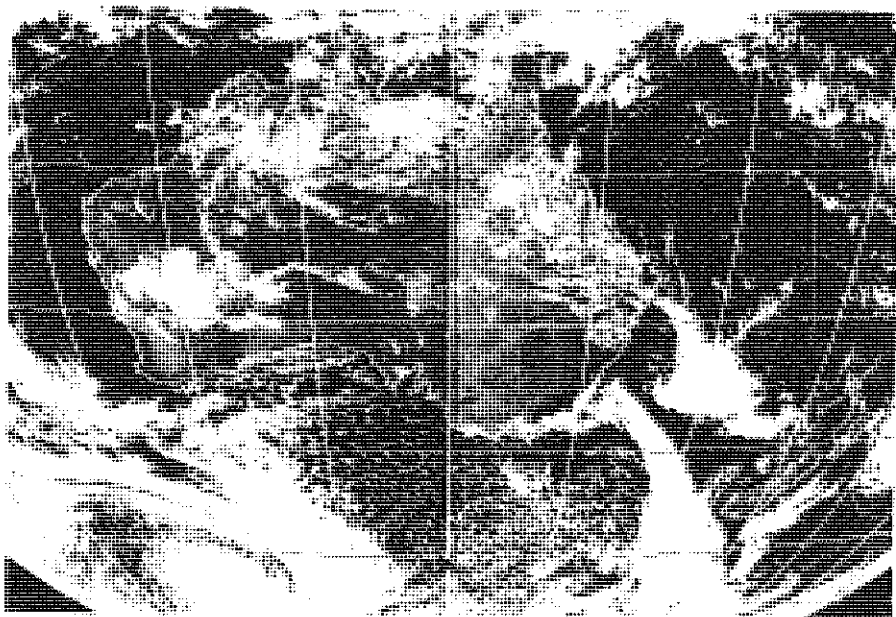


Figure 5(a) GMS visible imagery for 0300 GMT 6 February 1980.

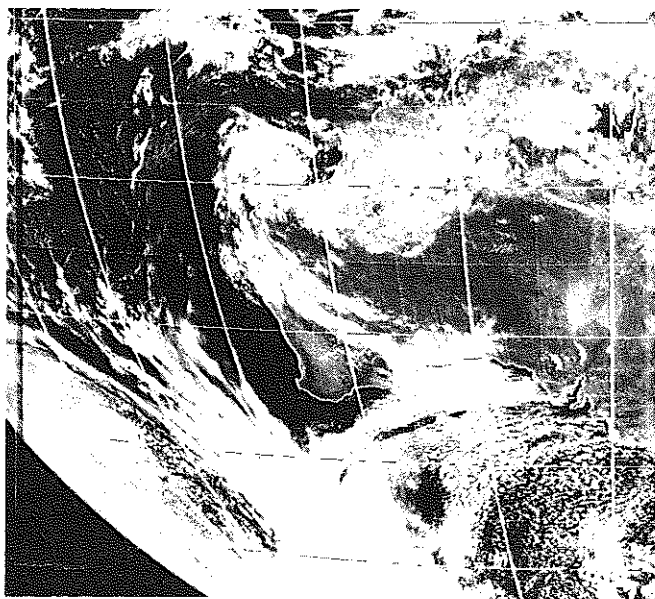


Figure 5(b) GMS visible imagery for 0300 GMT 8 February 1980.

had developed. The upper anticyclone became centred over the lower cyclone and combined with the upper trough to the south to provide strong outflow. The storm attained an estimated minimum central pressure of 930 mb on the 17th and made landfall with winds estimated at 55 m s^{-1} (Crane 1981).

Figures 6(a) and (b) show the 850 mb vorticity contours for 2300 GMT on 7 and 13 February, approximately two days after the formation of the respective depressions. For

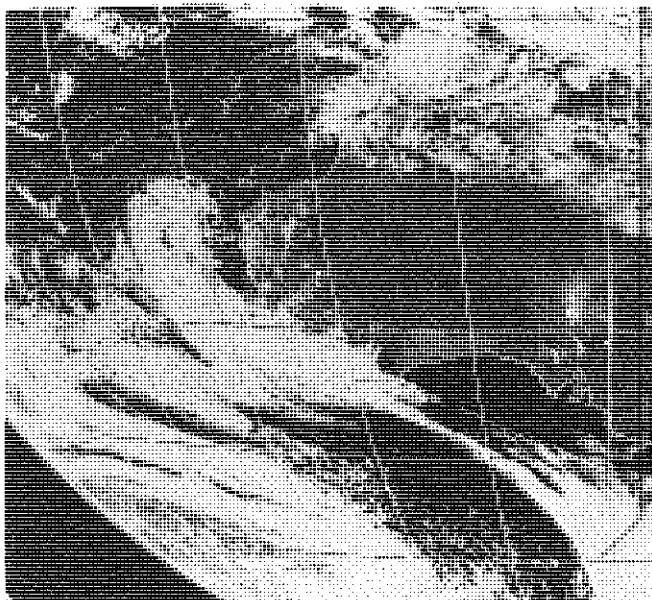


Figure 5(c) GMS visible imagery for 0300 GMT 10 February 1980.

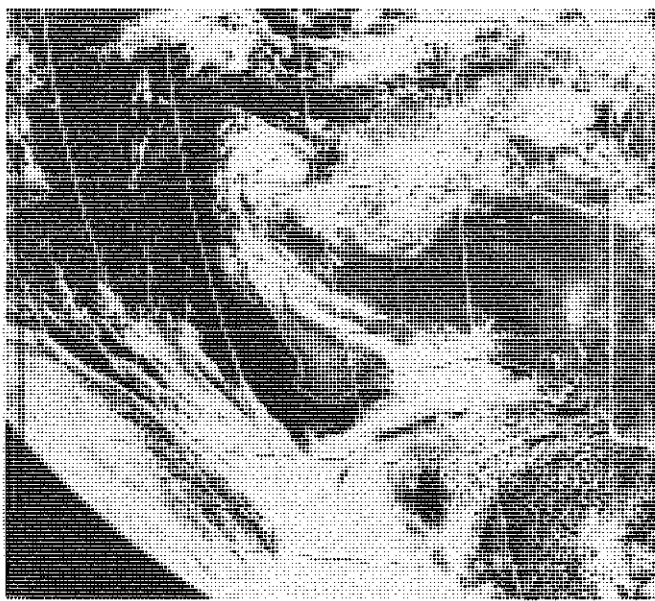


Figure 5(d) GMS visible imagery for 0300 GMT 12 February 1980.

ND there are three regions of cyclonic vorticity maxima, one associated with the low itself, the second with the surge of the monsoon following the low and the third between 135°E and 140°E . In comparison, DD was centred within a broad vorticity field that extended some 20 latitude degrees east and west of the low. From the 9th onwards cyclonic vorticity of 3.10^{-5} s^{-1} persisted over the region bounded by 120° and 130°E and centred on 15°S . Instead of two comparable vorticity maxima in the vicinity, DD was the major vorticity centre. It was consistently associated with a single vorticity maximum of 3.10^{-5} s^{-1} over northwest Australia, whereas ND's vorticity field was eroded by the resurgence of the monsoon circulation to its east.

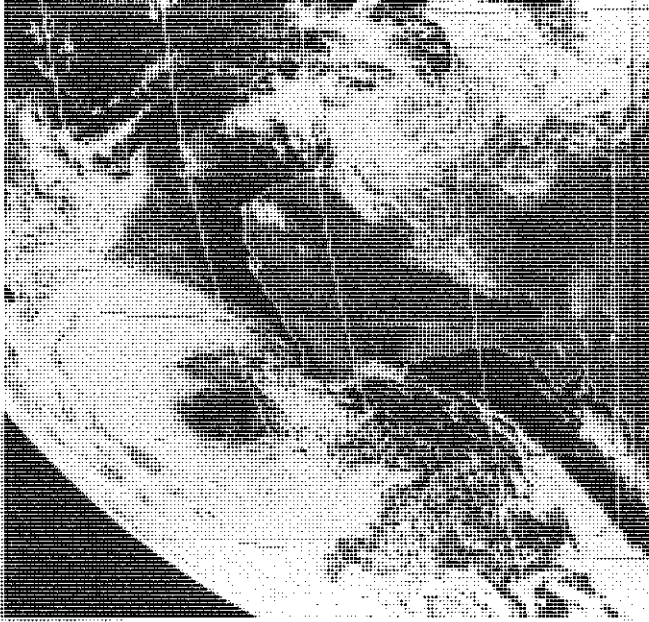


Figure 5(e) GMS visible imagery for 0300 GMT 14 February 1980.

The contours of divergence did not show large differences between the two depressions. Throughout the study period, divergence of $-1.10^{-5} \text{ s}^{-1}$ persisted north of 20°S from 110°E to 140°E . The grid point analysis, with a mesh size of 2.5 degrees, did not resolve the convergence associated with the depressions but showed large-scale convergence associated with the monsoon trough.

Upper-level vorticity calculations showed ND moving from near zero relative vorticity on the 5th to values of $-2.10^{-5} \text{ s}^{-1}$ on the 7th and 9th as it passed southwards under the upper ridge. For DD, 200 mb vorticity of greater than $-1.5.10^{-5} \text{ s}^{-1}$ persisted over northern Australia from the 9th. There was pre-existing anticyclonic vorticity over

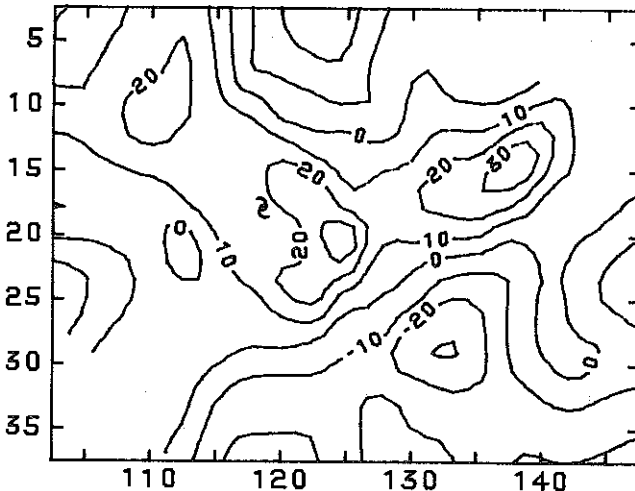


Figure 6(a) 850 mb vorticity contours for 2300 GMT 7 February 1980. Units are 10^{-6} s^{-1} . Symbol denotes location of the depression.

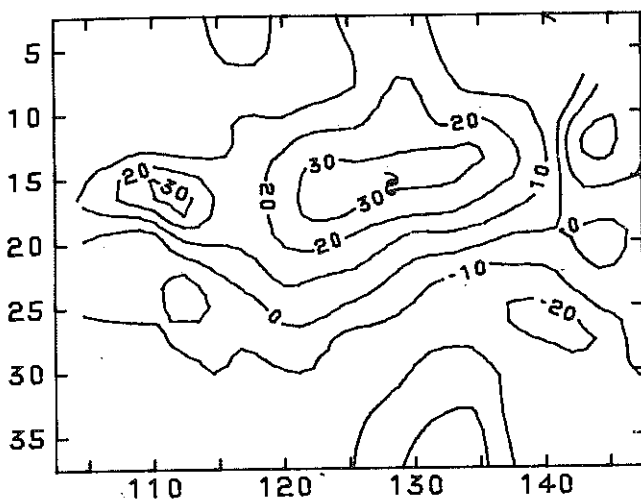


Figure 6(b) 850 mb vorticity contours for 2300 GMT 13 February 1980. Units are 10^{-6} s^{-1} . Symbol denotes location of the depression.

the region in which the low formed. Upper divergence over ND ranged from almost zero on the 5th to a maximum of 1.10^{-5} s^{-1} on the 9th. On that day the upper trough induced divergence of around 2.10^{-5} s^{-1} between 120°E and 135°E at 17°S . By the 11th, when the cloud cluster was apparent on satellite imagery, divergence at 200 mb in the vicinity was almost zero and remained low to the 13th.

4. DISCUSSION

The composited data of McBride and Zehr (1981) show developing clusters to be characterized by stronger low-level tangential winds of greater cyclonic organization. Mean upper winds differed in that the developing clusters had divergent anticyclonic winds whereas the non-developing clusters experienced basically unidirectional flow.

Gray (1979) and McBride and Zehr (1981) specify that in the southern hemisphere a developing tropical low must have easterly zonal vertical wind shear to its north and westerly shear to its south, as well as zero or very small values through the centre of the cluster. Given that the zonal shear is the difference in u components between 200 and 850 mb, easterly shear is achieved with 850 mb westerlies overlaid by easterlies. Such shear is commonly observed on the equatorward side of the monsoonal trough. To the south of a low, westerly shear will result from lower easterlies and upper westerlies. If deep easterlies are present, westerly shear will arise from having the lower easterlies stronger than the upper easterlies. For both lows studied, easterly zonal shear was observed to their north. To the south, ND's weaker lower easterlies resulted in easterly shear whilst DD showed westerly shear. The difference in the shears reflects the observed differences in the flows surrounding the depressions.

It is well established that zero or small values of vertical wind shear are prerequisites for cyclone development (Palmen and Newton 1969; Gray 1975; Riehl 1979). This shear must be present through the centre of the cluster (McBride and Zehr 1981). In the present study no wind profiles were available within 2° radius, but profiles at stations closest to the lows indicated easterly shear greater than 15 m s^{-1} between 850 and 150 mb for ND. This shear was also apparent on satellite imagery, which showed the cloud associated with ND offset to the west of the lower circulation centre.

As ND crossed the coast, time sections of temperature anomalies (Figs. 4(a) and (b)) showed that it possessed a weak warm core at mid- to upper levels. It was most pronounced at 500 to 300 mb over Port Hedland, the closest station, and was weakly evident

at upper levels over Broome. When DD approached, several days later, a warm anomaly was apparent at 400 mb and was of a similar magnitude at Port Hedland.

The two lows therefore possessed deep cyclonic circulations and warm cores when they crossed the coast. They differed in their surrounding environments. ND formed initially within the monsoon trough and as it moved towards the coast it appeared to separate from the trough. Instead of cyclonically consistent northerlies to the east of the low, there were south-easterlies. The surge of lower easterlies at around 20°S combined with westerlies over northern Australia to provide a region of strong horizontal cyclonic shear south of the Bonaparte Gulf. This flow persisted for several days, expanding along the north-west coast in the wake of ND. It was within this region that DD formed.

The salient differences in the vorticity surrounding the depressions was not so much in the magnitude but in the horizontal organization and persistence of the vorticity. ND was initially within a broad field of cyclonic vorticity but competing maxima developed to its east as it crossed the coast. A persistent lower cyclonic vorticity maximum appeared over north-west Australia two days before DD was identified on satellite imagery.

At upper levels, ND experienced vigorous upper easterlies whereas DD was affected by easterlies of less than 10 m s^{-1} . Both depressions had 200 mb anticyclonic vorticity of similar magnitude. After the 13th, upper anticyclonic vorticity was enhanced over DD as the anticyclonic cell became centred over the lower cyclone. Upper divergence remained at low values over north-west Australia except during the 9th and 10th, when the upper trough brought strong divergence between longitudes 120°E and 130°E. This overlaid the persistent lower cyclonic centre. It did not appear to induce the initial formation of DD, which was first seen on the 11th, by which time 200 mb divergence over the region had fallen to almost zero. Intensification to a severe cyclone was aided by the superposition of an upper anticyclone over the lower circulation. Upper troughs played an important role in the development of *Enid*, firstly by splitting the upper ridge, bringing light and divergent upper winds to aid the initial formation of the vortex and later to enhance intensification. Interaction of tropical depressions with upper troughs is observed in the Pacific (Sadler 1976) and Atlantic (Colon and Nightingale 1963). In the Australian region, intensification of pre-existing disturbances is often associated with enhanced upper divergence around upper troughs and ridges (McRae 1956). McBride and Keenan (1982) indicate that equatorward extensions of troughs in the mid-latitude westerlies commonly influence upper flows during the intensification of monsoon depressions over northern Australia.

Satellite imagery suggested that ND was being provided with a water vapour supply whilst over land. Figures 5(a) and (b) show extensive low cloud with some cumulonimbus surrounding the low. On the 8th, the surge of easterlies that followed the low appeared to suppress convection south of 20°S (Fig. 5(c)) possibly causing entrainment of dry air on the eastern margin of ND. The region south of the Bonaparte Gulf, where the lower winds created strong horizontal shear from the 9th, contained persistent convection (Figs. 5(b) to (d)). The water vapour was being advected over northern Australia by the monsoon westerlies.

It is not surprising that the combination of a vigorous lower cyclonic trough, light upper winds and persistent convection should produce a tropical depression. The intensification of the lower cyclonic flow on the 9th appeared to have been externally forced. At Broome and Halls Creek (Figs. 4(a) and (c)) the low-level easterlies increased in strength after ND had passed the stations. This strengthening was observed first at Hall's Creek and then at Broome a day later and persisted for several days. Cyclonic horizontal shear was established over north-western Australia for two days before DD became apparent as a cloud cluster.

The association of tropical depressions with events at higher latitudes has been known for some years. Wilkie (1964) noted that tropical cyclogenesis was often coincident with extratropical anticyclogenesis. McBride and Keenan (1982) showed that the composite lower windfields of developing depressions over the Gulf of Carpentaria have winds of twice the climatological average from 4 to 10° radii south and east of the depressions.

Holland (1983), in constructing budgets of angular momentum for composite tropical cloud clusters, showed developing clusters to have greater eddy transports at larger radii. During the early stages of development the effect of the environment on a depression is as significant as processes at inner radii. As the depression intensifies and becomes more organized external effects become less important, though not negligible. According to Schubert and Hack (1982) an increase of low-level relative vorticity produced by stronger tangential winds acts to increase the efficiency of warming within the convective region of the low. The enhanced inertial stability reduces the radial-vertical circulation of the vortex, leading to a decrease in adiabatic cooling and a larger warming of the convective column. This mechanism could have been operating for DD, which was surrounded by a vigorous tangential circulation that was sustained throughout its development. In the present study, the large-scale environment is seen to have a major effect on the future of the depressions.

5. SUMMARY AND CONCLUSIONS

The two depressions possessed similar structures. They were both deep cyclonic circulations containing deep convection and warm mid- to upper-level cores. There were significant differences in their respective environments.

ND formed initially within the monsoon trough but separated from it as it moved westwards. Strong deep layer easterlies followed the depression, causing pronounced vertical wind shears which appeared to offset convection from the lower circulation centre. It did not intensify significantly even when it was passing over a warm ocean.

The monsoon trough intensified over northern Australia in the wake of ND. The resulting cyclonic wind shear coincided with persistent inland convection. An upper trough intensified over eastern Australia and brought light and diffluent upper winds that gave way to easterlies as the trough decayed. A cloud cluster formed in the cyclonic shear around two days after the strengthening of lower winds and one day after the weakening of the upper winds. The favourable surrounding flows persisted for several days as the depression intensified.

The essential differences in surrounding flows were in their organization and persistence. ND appeared to move out of large-scale cyclonic flow and was consistently influenced by strong upper winds and wind shear. DD formed within a region of pre-existing lower cyclonic flow, slight vertical wind shear and light upper winds. The upper trough did not actively promote the initial formation but nevertheless had a vital role in establishing favourable upper conditions. Even though DD was situated wholly over land, it developed in that environment to have the structure of a weak tropical cyclone.

ACKNOWLEDGMENTS

The tropical cyclone study group at Murdoch University has been funded by the Australian Research Grants Committee and the Australian Marine Science and Technology Advisory Committee. Throughout this research one of the authors (IJF) was in receipt of a Murdoch University Postgraduate Award. The paper was typed by Mrs Doreen Jones and the figures prepared by Mr Alan Rossow. All this assistance is gratefully acknowledged.

REFERENCES

- | | | |
|-------------------------------------|------|---|
| Anonymous | 1980 | <i>Monthly report of Meteorological Satellite Centre, February 1980.</i> Meteorological Satellite Centre, Tokyo, Japan |
| Barrett, E. C. | 1974 | <i>Climatology from Satellites.</i> Methuen & Co. Ltd. |
| Challa, M. and Pfeffer, R. L. | 1980 | Effects of eddy fluxes of angular momentum on model hurricane development. <i>J. Atmos. Sci.</i> , 37 , 1603-1618 |
| Colon, J. A. and Nightingale, W. R. | 1963 | Development of tropical cyclones in relation to circulation patterns at the 200-millibar level. <i>Mon. Wea. Rev.</i> , 91 , 329-336 |

- Crane, G. D. 1981 The Australian tropical cyclone season 1979–80. *Aust. Meteor. Mag.*, **29**, 41–53
- Endlich, R. M. 1967 An iterative method for altering the kinematic properties of wind fields. *J. Appl. Met.*, **6**, 837–844
- Erikson, S. L. 1977 *Comparison of developing vs non-developing tropical disturbances*. Colorado State University Atmospheric Science Paper No. 274
- Fett, R. W. 1968 Typhoon formation within the zone of the Intertropical Convergence. *Mon. Wea. Rev.*, **96**, 106–117
- Gray, W. M. 1968 Global view of the origin of tropical disturbances and storms. *Mon. Wea. Rev.*, **96**, 669–700
- 1975 *Tropical cyclone genesis*. Colorado State University Atmospheric Science Paper No. 234
- 1979 'Hurricanes: their formation, structure and likely role in the tropical circulation' in *Meteorology Over the Tropical Oceans*, D. B. Shaw (Ed.), Royal Meteorological Society
- Hamada, T. 1980 *Brief description for error estimates of satellite winds derived by CWES system*. Technical Note No. 1, Meteorological Satellite Centre, Tokyo, Japan
- Holland, G. J. 1983 Angular momentum transports in tropical cyclones. *Quart. J. Roy. Met. Soc.*, **109**, 187–210
- Konsky, V. E. and Gan, M. A. 1981 Upper tropospheric cyclonic vortices in the tropical South Atlantic. *Tellus*, **33**, 538–551
- Lourensz, R. S. 1977 *Tropical cyclones in the Australian region July 1909 to June 1980*. Meteorological Summary, Australian Bureau of Meteorology, Dept. of Science and Technology
- McBride, J. L. and Keenan, T. D. 1982 Climatology of tropical cyclone genesis in the Australian region. *Jnl. of Climatology*, **2**, 13–33
- McBride, J. L. and Zehr, R. 1981 Observational analysis of tropical cyclone formations. Part II: comparison of non-developing versus developing systems. *J. Atmos. Sci.*, **38**, 1132–1151
- McEwan, A. D. 1976 Angular momentum diffusion and the initiation of cyclones. *Nature*, **260**, 126–128
- 1982 'Convection and mixing at high Rossby numbers in rotating systems', in *Intense Atmospheric Vortices*, Proc. Joint Symp. (IUTAM/IUGG), Reading 1981. Bengtsson and Lighthill (Eds.), Springer-Verlag
- McRae, J. N. 1956 The formation and development of tropical cyclones during the 1955–56 season in Australia. *Proceedings of the Tropical Cyclone Seminar*, Brisbane, December 1956. Australian Bureau of Meteorology, 233–261
- Mancuso, R. L. and Endlich, R. M. 1973 *Wind Editing and Analysis Program—Spherical Grid (WEAP-IA)*. Users Manual, Stanford Research Institute
- Palmen, E. 1956 Formation and development of tropical cyclones. *Proceedings of the Tropical Cyclone Seminar*, Brisbane, December 1956. Australian Bureau of Meteorology, pp. 213–231
- Palmen, E. and Newton, C. W. 1969 *Atmospheric Circulation Systems: Their Structure and Physical Interpretation*. Academic Press, New York
- Ramage, C. S. 1974 The typhoons of October 1970 in the South China Sea: intensification, decay and ocean interaction. *Jnl. Appl. Meteor.*, **13**, 739–751
- Riehl, H. 1979 *Climate and Weather in the Tropics*. Academic Press, New York
- Rodgers, E., Gentry, R. C., Shenk, W. and Oliver, V. 1979 The benefits of using short-interval satellite images to derive winds for tropical cyclones. *Mon. Wea. Rev.*, **107**, 575–584
- Sadler, J. C. 1976 A role of the tropical upper tropospheric trough in early season typhoon development. *Mon. Wea. Rev.*, **104**, 1266–1278
- Schubert, W. H. and Hack, J. J. 1982 Inertial stability and tropical cyclone development. *J. Atmos. Sci.*, **39**, 1687–1697
- Tuleya, R. E. and Kurihara, Y. 1981 A numerical study of the effects of environmental flow on tropical storm genesis. *Mon. Wea. Rev.*, **109**, 2487–2506
- Vincent, D. G. and Waterman, R. G. 1979 Large scale atmospheric conditions during the intensification of Hurricane Carmen (1974). 1. Temperature, moisture and kinematics. *Mon. Wea. Rev.*, **107**, 283–294

- Virji, H. 1981 A preliminary study of summertime tropospheric circulation patterns over South America estimated from cloud wind. *Mon. Wea. Rev.*, **109**, 599-610
- Wilkie, W. R. 1964 'Evaluation of methods of forecasting development and movement of cyclones in the northeast Australia region: 1962-63 season', in *Proc. Symp. Trop. Meteor.*, Rotorua, N.Z. Nov. 1963, New Zealand Meteorological Service