Aust. Met. Mag. 49 (2000) 223-244

The South Pacific and southeast Indian Ocean tropical cyclone season 1998-99

Sue Oates
Queensland Regional Office, Bureau of Meteorology, Australia

(Manuscript received June 2000)

Twenty tropical cyclones formed in the South Pacific and southeast Indian Ocean region during the 1998 - 99 season. An uncharacteristic early start to the season saw the development of cyclone *Zelia* in early October followed by *Alison* in early November. But the season was most noted for the development of four category 5 systems developing off the west coast of Australia, with cyclone *Vance* making landfall as a category 5 system near the Western Australian town of Exmouth. In comparison, the Coral Sea experienced a very quiet and short-lived cyclone season with only three tropical cyclones developing in the region over a period of three weeks. Cyclone activity in the South Pacific was close to average.

The 1998-99 season was characterised by weak La Niña conditions, with the Southern Oscillation Index (SOI) remaining moderately positive throughout and cool sea-surface and in particular subsurface temperatures dominating areas across the equatorial Pacific around 140°W. The Intra Seasonal Oscillation (ISO), although demonstrating clear signals during late January to early February and again in March, lacked periodicity throughout the season.

Introduction

This paper provides a summary of tropical cyclone activity in the South Pacific (west of 120°W) and southeast Indian Ocean (east of 90°E) during the 1998-99 cyclone season. The material has been gathered from information provided by the Australian Tropical Cyclone Warning Centres (TCWCs) at Perth, Darwin and Brisbane, the Fiji Regional Specialised Meteorological Centre (RSMC), La Reunion RSMC and Wellington RSMC.

Special Sensor Microwave Imager (SSMI) data utilised in this study were accessed on the World Wide Web from the United States Navy Research Laboratory Monterey, Satellite Section Home Page. Notable features of the data used in detecting tropical cyclone positions, intensities and other significant features have been discussed in the summaries for each tropical system.

Altimeter data from TOPEX and ERS-2 satellites detailing sea-surface height anomalies, useful for detecting deep reservoirs of well-mixed cold and warm waters, has been accessed via the World Wide Web from the Colorado Center for Astrodynamics Research. Evidence of possible significant oceanic contributions to tropical cyclone development and intensification has been noted in the cyclone summaries.

Cyclone intensities provided are generally estimates based on the Dvorak (1984) technique of satel-

Corresponding authors address: Sue Oates, Bureau of Meteorology, GPO Box 413, Brisbane 4001, QLD, Australia.
Email: s.oates@bom.gov.au

lite imagery interpretation. Where not specified, mean wind speeds referred to are sustained, or ten-minute averages and maximum wind gusts are 3 second gusts. Peak intensity refers to the maximum sustained 10 minute mean wind speed.

Tropical cyclone occurrence

Twenty tropical cyclones formed in the South Pacific and southeast Indian Ocean region during the 1998-99 season, which is close to average. Twelve of these systems reached hurricane force, with four systems intensifying to category 5, on the Australian cyclone category scale. As is typical of warm episode La Niña events, the genesis area for tropical activity over the South Pacific was focused in the Coral Sea, which was a transition westward from the 1997-98 season which saw the South Pacific tropical activity centred around the Northern Cook Islands. Of the nine cyclones that developed in the South Pacific, six of these formed in the Coral Sea. An uncharacteristic early start to the season saw the development of cyclone *Zelia* in early October, with the final cyclone for the season, *Hamish* occurring in mid-April.

Details of the life cycle of these systems are given in Table 1. Cyclones developing in the south Indian Ocean west of 90°E are not discussed in this summary.

Broadscale seasonal features

The Southern Oscillation Index (SOI) is defined as ten times the normalised difference in monthly surface pressure anomaly between Tahiti and Darwin. The period from 1991 to 1997 was generally dominated by warm phase El Niño/Southern Oscillation (ENSO) conditions. However, the 1998-99 cyclone season saw a change to weak La Niña conditions, characterised by moderately positive values of the SOI and cool sea-surface and in particular subsurface temperatures across the equatorial Pacific centred on 140°W. The cool phase La Niña, though weak in the sea-surface temperature (SST) anomaly signal, was more prominent in the 150 m depth subsurface layer anomaly. These negative anomalies decreased in magnitude during the season. An off-equatorial warm band of positive SST anomalies extending from eastern Australia to South America, evident from November to April have also been observed in other cold episode La Niña events. SSTs in the tropical Australian region remained on the whole slightly positive with areas of +1°C anomalies. The SOI registered an upward trend from 11 in October to 16 in January, before decreasing to around 9 for February and March and then rising again to 18 for April, the highest value since April 1989 (Shaik and Bate 1999). The SOI was mostly greater than one standard deviation above the long-term mean for eight consecutive months from June 1998 to January 1999, the first time this has occurred since the 1988-89 La Niña. The six-month mean SOI from November 1998 to April 1999 was 13.

Typically the low-level subtropical ridge (STR) over the southern Indian Ocean was stronger than the long-term mean, though this weakened toward the later part of the season. Similarly, a stronger than normal STR persisted to the southeast of New Zealand. Negative pressure anomalies dominated the remainder of the region. Lower and upper-level wind anomaly patterns indicated an enhanced Walker Circulation (the east-west circulation over the tropical Pacific characterised by convective ascent over the tropical western Pacific, westerly winds in the upper levels, descent over the cooler waters of the eastern equatorial Pacific and easterly winds at the surface) over the western and central equatorial Pacific for the greater part of the season.

Broadscale convection is inferred from outgoing long wave radiation anomalies (OLR) from satellite imagery. Monthly mean anomalies of OLR indicate that tropical convection over the region was generally active, except for the region about the near-equatorial date-line, consistent with the significant impact of a La Niña event (Shaik and Bate 1999).

Intraseasonal variations

The most recognisable modulation of tropical convection is associated with the Intra-Seasonal or Madden Julian Oscillation (ISO) (Madden and Julian 1971). Fields of velocity potential (a measure of the divergent part of the wind) at 200 hPa provide a useful method to represent tropical convective activity and data from Fig. 10 from Shaik and Bate (1999) was used for this purpose.

The ISO although demonstrating clear signals during late January to early February and again in March, lacked periodicity throughout the tropical cyclone season. Although the 200 hPa velocity potential and mean sea-level pressure (MSLP) anomaly series indicate periods of enhanced broadscale up motion during each month, active phases were sporadic with no clear or predictable interval between one phase ceasing and the next commencing. The outgoing long wave radiation (OLR) series were even less conclusive of regular intraseasonal variation. The majority of tropical cyclone development occurred during active phases, with almost half the cyclones for the season developing during those phases that commenced in mid-January and March.

Table 1. Tropical cyclones in the South Pacific and southeast Indian Ocean 1998-99.

Cyclone name / Maximum wind	*Low first identified*	*Initial tropical cyclone phase*	*Maximum intensity*	*End tropical cyclone phase*
Zelia 21 m s^{-1}	11.3°S 93.0°E at 0600 UTC on 7 Oct	14.4°S 94.6°E at 0600 UTC on 8 Oct	14.7°S 95.0°E at 1200 UTC on 8 Oct	14.6°S 95.6°E at 0600 UTC on 9 Oct
Alison 41 m s^{-1}	10.2°S 98.2°E at 0100 UTC on 7 Nov	10.9°S 99.3°E at 0100 UTC on 8 Nov	13.8°S 95.2°E at 1000 UTC on 9 Nov	18.9°S 90.9°E at 1000 UTC on 12 Nov
Billy 36 m s^{-1}	15.0°S 121.5°E at 0700 UTC on 1 Dec	16.1°S 119.8°E at 0700 UTC on 2 Dec	18.0°S 116.9°E at 0100 UTC on 4 Dec	20.7°S 115.0°E at 2200 UTC on 5 Dec
Thelma 63 m s^{-1}	12.0°S 138.0°E at 0000 UTC on 1 Dec	9.2°S 131.3°E at 0000 UTC on 6 Dec	11.6°S 129.2°E at 1200 UTC on 8 Dec	16.5°S 125.0°E at 1500 UTC on 11 Dec
Cora 41 m s^{-1}	14.0°S 173.5°W at 0000 UTC on 21 Dec	15.2°S 178.2°W at 1800 UTC on 23 Dec	20.6°S 175.4°W at 0000 UTC on 26 Dec	29.2°S 153.7°W at 1200 UTC on 28 Dec
Cathy 28 m s^{-1}	11.1°S 100.6°E at 1900 UTC on 22 Dec	15.3°S 100.7°E at 0400 UTC on 24 Dec	16.7°S 95.5°E at 0700 UTC on 26 Dec	16.1°S 93.0°E at 1000 UTC on 27 Dec
Dani 49m s^{-1}	15.7°S 164.7°E at 2100 UTC on 14 Jan	15.9°S 164.9°E at 0000 UTC on 15 Jan	15.6°S 163.7°E at 1800 UTC on 16 Jan	27.0°S 173.5°E at 0600 UTC on 22 Jan
Olinda 28 m s^{-1}	17.2°S 158.3°E at 0900 UTC on 20 Jan	19.9°S 159.4°E at 1800 UTC on 21 Jan	25.9°S 170.3°E at 1200 UTC on 23 Jan	29.3°S 179.6°W at 0000 UTC on 26 Jan
Damien/Birenda 44 m s^{-1}	12.8°S 112.8°E at 0700 UTC on 21 Jan	12.9°S 112.1°E at 1000 UTC on 21 Jan	16.0°S 97.9°E at 2200 UTC on 24 Jan	17.5°S 84.5°E at 1200 UTC on 29 Jan [1]
Pete 26 m s^{-1}	15.0°S 149.0°E at 0000 UTC on 21 Jan	15.8°S 152.9°E at 0600 UTC on 22 Jan	20.9°S 157.6°E at 0600 UTC on 23 Jan	24.3°S 168.6°E at 0000 UTC on 26 Jan
Rona 39 m s^{-1}	15.2°S 146.8°E at 1100 UTC on 9 Feb	16.1°S 148.4°E at 1800 UTC on 10 Feb	16.2°S 145.6°E at 1200 UTC on 11 Feb	16.1°S 144.6°E at 1800 UTC on 11 Feb
Ella 23 m s^{-1}	11.2°S 160.7°E at 0000 UTC on 10 Feb	12.8°S 164.1°E at 0600 UTC on 11 Feb	15.5°S 164.8°E at 1800 UTC on 11 Feb	25.0°S 170.0°E at 0600 UTC on 13 Feb
Frank 41 m s^{-1}	21.5°S 150.1°E at 1200 UTC on 16 Feb	19.6°S 160.9°E at 1800 UTC on 18 Feb	21.5°S 165.9°E at 0600 UTC on 20 Feb	27.0°S 162.4°E at 00 UTC on 22 Feb
Gita 23 m s^{-1}	21.5°S 157.5°W at 0600 UTC on 26 Feb	25.50S 155.50W at 1200 UTC on 27 Feb	27.0°S 155.5°W at 0600 UTC on 28 Feb	30.5°S 157.0°W at 0600 UTC on 1 Mar

Table 1. Continued.

Cyclone name / Maximum wind	*Low first identified*	*Initial tropical cyclone phase*	*Maximum intensity*	*End tropical cyclone phase*
Hali 33 m s^{-1}	18.0°S 154.5°W at 0000 UTC on 11 Mar	20.2°S 160.2°W at 0000 UTC on 13 Mar	21.9°S 164.2°W at 0000 UTC on 16 Mar	24.6°S 161.1°W at 1200 UTC on 18 Mar
Elaine 49 m s^{-1}	13.1°S 117.5°E at 0100 UTC on 15 Mar	14.0°S 115.8°E at 0100 UTC on 16 Mar	18.9°S 110.8°E at 0100 UTC on 18 Mar	28.2°S 114.2°E at 0100 UTC on 20 Mar
Vance 62 m s^{-1}	12.5°S 131.5°E at 1200 UTC on 14 Mar	12.6°S 126.7°E at 0000 UTC on 18 Mar	17.6°S 115.3°E at 2200 UTC on 20 Mar	33.9°S 129.9°E at 1800 UTC on 23 Mar
Frederic/Everina 54 m s^{-1}	11.5°S 119.0°E at 0300 UTC on 25 Mar	13.9°S 111.2°E at 0400 UTC on 27 Mar	17.5°S 90.3°E at 0100 UTC on 1 Apr	19.00S 71.1°E at 0600 UTC on 5 Apr
Gwenda 64 m s^{-1}	11.2°S 131.0°E at 0000 UTC on 2 Apr	12.0°S 122.6°E at 1600 UTC on 4 Apr	16.4°S 116.6°E at 1300 UTC on 6 Apr	20.5°S 119.3°E at 2000 UTC on 7 Apr
Hamish 28 m s^{-1}	10.5°S 93.6°E at 1000 UTC on 19 Apr	12.6°S 92.7°E at 0700 UTC on 20 Apr	13.9°S 91.8°E at 1900 UTC on 20 Apr	15.6°S 89.8°E at 1600 UTC on 21 Apr

Notes
1. Best track data from Perth TCWC had *Damien/Birenda* weakening below tropical cyclone strength near 16.4°S 90.0°E at 0700 UTC on 28 January 1999.

Verification statistics

Position verification statistics for each cyclone (Table 2) were derived by comparing the official warnings issued by the relevant Tropical Cyclone Warning Centres with post-analysis 'best track' positions. The 'best track' is derived from a post-event analysis of all available data and describes the most likely actual track of the system. Forecasts issued by Wellington RSMC and La Reunion RSMC have been omitted from this analysis. For comparison, verification statistics for persistence forecasts based on 12 hour 'best track' movement vectors were also calculated. Overall, forecast position errors were only slightly larger than those for the previous season. However, comparing average forecast errors over the past ten seasons, position forecast errors for the 1998-99 season were better than the mean errors for this period.

SSMI and TRMM Data

Special Sensor Microwave Imager (SSMI) data first became available in 1987 and disclosed many interesting features of weather systems including tropical cyclones. The past two years has seen this data become available in real time for forecasters in the southern hemisphere. The data can be accessed on the World Wide Web from the US Navy Research Laboratory Monterey, Satellite Section Home Page.

SSMI is focused on the retrieval of microwave energy emitted from the surface of the earth. The 85-gigahertz (GHz) microwave channel is sensitive to precipitation-sized ice particles, which scatter the upwelling radiation and reduce the brightness temperature. A low 85 GHz brightness temperature can therefore imply increased convection and precipitation. Spencer et al. (1989) defines a polarisation corrected temperature (PCT) which is made up of a contribution of brightness temperature in both the vertically polarised and the horizontally polarised channels. Spencer et al. found that the PCT range of 250 – 260° Kelvin (K) is generally a threshold below which precipitating systems are found. Mohr and Zipser (1996) used the existence of a 225°K PCT (implying a rainfall rate of about 10 millimetres per hour) to indicate the presence of cumulonimbus con-

Table 2. Position forecast verification statistics for official warnings issued by relevant tropical cyclone warning centres. Forecast positions are verified against the official best track. Persistence errors (in brackets) are included for comparison. Forecasts issued by Wellington RSMC and La Reunion RSMC have been omitted from verification statistics.

Cyclone Name	*Initial Position Error (km)*	*Number*	*12 Hour Forecast Error (km)*	*Number*	*24 Hour Forecast Error (km)*	*Number*	*48 Hour Forecast Error (km)*	*Number*
Zelia	119	9	201	7				
			(236)					
Alison	79	25	131	18	195	15		
			(154)		(244)			
Billy	24	12	47	12	96	11		
			(62)		(66)			
Thelma	20	26	64	24	113	22	203	9
			(64)		(129)		(229)	
Cora	53	23	94	11	221	9		
			(105)		(283)			
Cathy	59	15	125	14	197	13		
			(171)		(186)			
Dani	24	30	116	26	200	24		
			(108)		(267)			
Olinda	11	7	168	7	373	7		
			(158)		(433)			
Damien/Birenda	38	26	110	25	210	23		
			(108)		(240)			
Pete	43	10	151	9	325	10		
			(148)		(373)			
Rona	12	5	97	5				
			(131)					
Ella	27	16	144	9	245	7		
			(151)		(375)			
Frank	25	12	75	8	144	6		
			(115)		(330)			
Hali	18	23	99	21	157	19		
			(80)		(137)			
Elaine	40	13	117	12	185	9		
			(139)		(295)			
Vance	21	26	68	21	140	21		
			(96)		(289)			
Frederic/Everina	40	25	67	24	127	22		
			(87)		(139)			
Gwenda	41	16	116	15	248	13		
			(139)		(343)			
Hamish	109	12	179	10	237	8		
			(213)		(330)			
Total		331		278		239		9
Mean	42		114		180		203	

vection. Independently, McGaughey et al. (1996), using high resolution data from the Advanced Microwave Precipitation Radiometer, derived 225°K as a threshold for tropical oceanic convection.

The Defense Meteorological Satellite Program (DMSP) satellites carry SSMI in sun synchronous orbits which overpass near local sunrise and sunset. The swath width is approximately 1400 km which is less than the distance between orbits in the tropics, so not every location is viewed twice on a given day. Also, due to the swath width, the movement of tropical cyclones and the occasional losses of data, gaps of up to 60 hours can exist.

The Tropical Rainfall Measuring Mission (TRMM) is a joint project between the United States (under the leadership of the National Aeronautics and

Space Administration (NASA) Goddard Space Flight Centre) and Japan (under the leadership of the National Space Development Program). The TRMM satellite is the first spacecraft designed to monitor rain over the tropics. The three instruments on board include a Precipitation Radar (PR), a multi-channel microwave radiometer, designated as the TRMM Microwave Imager (TMI) and the Visible Infrared Scanner (VIRS).

- The PR measures the three-dimensional rainfall distribution over both land and ocean. The instrument will define the layer depth of the precipitation and provide information about the rainfall reaching the surface, which is the key to determining the latent heat input to the atmosphere.
- The TMI is designed to provide information on the integrated column precipitation content, its areal distribution and intensity.
- The VIRS provides very high resolution information on cloud coverage, cloud type and cloud-top temperatures.

Both TRMM and SSMI data for many of the following tropical cyclones were analysed and notable features of the data in detecting tropical cyclone positions, intensities and other significant features will be discussed in the summaries of each of the tropical systems.

Sea-surface temperatures and sea-height anomaly data

Sea-surface temperatures (SSTs) exceeding 26°C have been shown to be a necessary though insufficient condition for tropical cyclogenesis (Palmen 1938). Thin layers of warm SSTs in the paths of developing storms may be mixed with underlying cool layers and therefore not contribute to the development of the system. Deep warm oceanic mixed layers offer reservoirs of high heat content water available for the continued development and intensification of tropical cyclones (Shay 1998). These reservoirs can be identified from sea-surface positive height anomalies determined by altimeter data viewers on TOPEX and ERS-2 satellites. Data for each tropical system have been analysed and possible significant oceanic contributions to development and intensification have been noted in the individual cyclone summaries.

Tropical cyclones in the South Pacific and southeast Indian Ocean 1998-99

Zelia (Perth TCWC): 7 to 10 October 1998

Zelia (Fig. 1) was an early season, short-lived tropical cyclone, developing from a convective cloud cluster in the monsoon trough to the southwest of Sumatra. The system very slowly intensified as it moved southeast around the western side of a middle-level anticyclone. An amplifying upper-level trough to the southwest of the system provided short-term enhanced outflow in the southern quadrant and impetus for the development of deep convection on that side. SSMI imagery at 0206 UTC on 8 October showed evidence of convection in the southeast quadrant wrapping around a low-level centre. *Zelia* continued to slowly intensify over the next six to 12 hours ahead of the approaching trough to reach cyclone status around 0600 UTC on 8 October and estimated peak intensity with mean surface winds (MSW) of 21 m s^{-1} soon after. The surface reflection of the upper trough system was weak and the passage of the trough saw southeast winds develop in the low levels with opposing northwesterly winds at higher levels. Consequently the system sheared rapidly as evidenced by SSMI imagery at 0154 UTC on 9 October which reveals convection well removed to the southeast of the low-level centre. By 0600 UTC on 9 October, *Zelia* had dissipated as a tropical cyclone but maintained its identity as a tropical depression for another 36 to 48 hours.

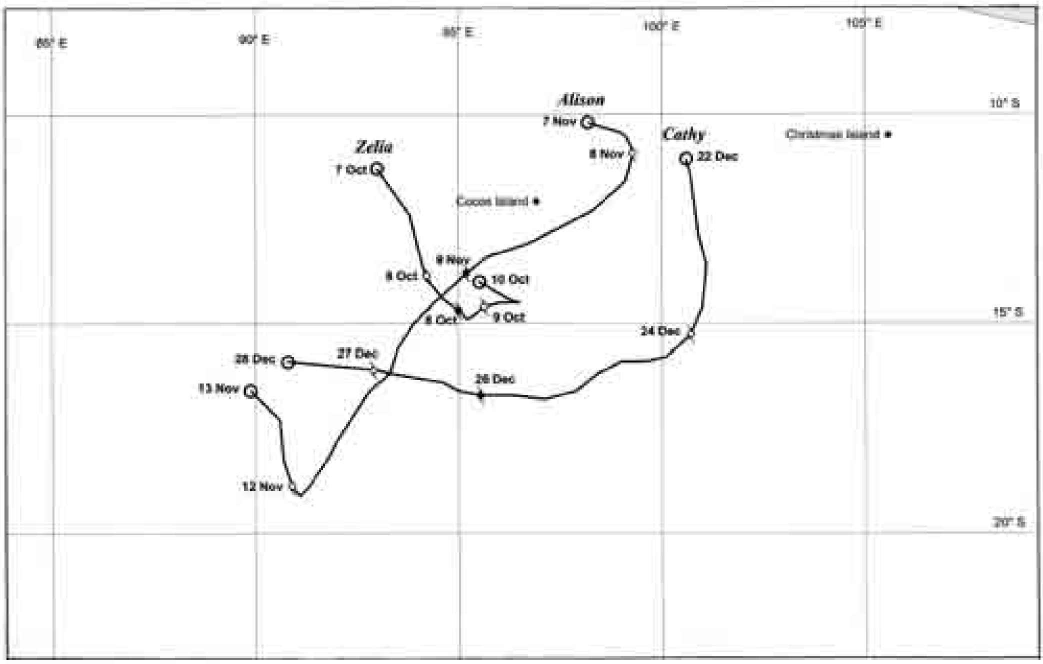
TOPEX/ERS-2 analysis indicates that *Zelia* developed and intensified over negative sea-surface height anomalies providing no strong evidence of deep oceanic influence on development. However, SSTs in the region of *Zelia*'s development and intensification were close to 1°Celsius (C) above normal.

Alison (Perth TCWC): 7 to 13 November 1998

Severe cyclone *Alison* (Fig. 1) was the second early tropical cyclone for the season. The system developed in a well-defined near-equatorial trough and shear line, which had persisted over the southern Indian Ocean for several months. A tropical low with a distinct cloud signature was evident to the northeast of Cocos Island as early as 7 November, but the strongly sheared environment of low-level easterly flow underlying strong upper-level northwesterly flow inhibited further development at that time.

Initially the low drifted slowly east-southeast in the general northwesterly current. However, during 7 and 8 of November, a strong low-level ridge developed poleward of the system and steered the low to the southwest. At the same time the upper-level ridge extended further westwards replacing strong upper northwesterlies with diffluent upper flow. Intensification at this stage became more rapid as the upper pattern provided reasonable outflow channels on both the equatorward and poleward sides of the system. *Alison* reached cyclone status at 0100 UTC on 8 November and strengthened to its estimated peak intensity with MSW of 41 m s^{-1} by 1000 UTC on 9 November. As the cyclone passed within 240

Fig. 1 **Tracks of tropical cyclones *Zelia, Alison* and *Cathy*. Open circles denote positions at which a low was first identified and when the tropical low finally dissipated. Open cyclone symbols mark the beginning and end of the tropical cyclone phase and the solid cyclone symbol marks the position of maximum intensity.**



km of Cocos Island late on 8 November, MSW of 18 m s^{-1} with gusts to 24 m s^{-1} were recorded.

SSMI Imagery from 2243 UTC on 8 November to 1128 UTC on 9 November indicated *Alison* was becoming more vertically aligned as the low-level centre, which was on the northeast side of the convection slowly moved underneath the deep convection.

As *Alison* continued to move southwest the upper flow pattern became less favourable with strong northeast winds dominating, restricting any upper outflow on the equatorward side of the system. The environment steadily became more sheared and by 0040 UTC on 12 November TRMM imagery showed the convection well removed to the southeast of the low-level centre. *Alison* was downgraded to below tropical cyclone strength by 1000 UTC on 12 November.

TOPEX/ERS-2 sea-surface height anomaly analysis showed the original low pressure area intensified to tropical cyclone intensity over a warm anomaly, but actually reached peak intensity over a strong cold anomaly. SSTs in the region of *Alison*'s development were 1°C above normal.

Billy **(Perth TCWC): 1 to 6 December 1998**

Tropical cyclone *Billy* (Fig. 2) was the first cyclone to form off the northwest coast of Australia during the season. Weak low pressure systems persisted off the northwest Australian coast for more than a week prior to the development of *Billy*. However, on 1 December, a low formed in the monsoon trough near the tail end of a shear line associated with a decaying frontal boundary. The low was steered in a southwest direction around the ridge of a high pressure system centred to its southeast. The approach of an upper-level trough from the southwest and movement of the system into the ridge axis produced a more favourable environment for intensification with the development of weak vertical shear and a strong outflow channel on the poleward side. Consequently the low developed into cyclone *Billy* on 2 December and then rapidly intensified to reach estimated peak intensity with MSW of 36 m s^{-1} by 0100 UTC on 4 December. SSMI imagery at 2251 UTC on 2 December indicated development of deep convection on the poleward side of the system. In subsequent images, the convection increased with bands becoming more circular and completely surrounding the system centre by 0021 UTC on 4 December, indicating rapid intensification. Visible satellite imagery at this time also displayed an eye pattern, which persisted for a few hours. Radar imagery from Dampier at 0900 UTC on 4 December indicated a 25 km diameter eye.

The strength of the upper-level trough was insufficient in eroding the low-level high pressure system centred over the southeast Indian Ocean. The high intensified developing a strong easterly current south of the system centre. Strong northwesterly winds persisted at upper levels causing *Billy* to rapidly shear overnight on 4 December. By 1305 UTC on 4 December SSMI data showed deep convection displaced to the southeast of the system centre. By 0008 UTC on 5 December SSMI imagery showed the remains of the system as a vigorous low-level circulation devoid of all convection. The low ultimately weakened below gale force before crossing the coast near Onslow on 6 December 1998.

TOPEX/ERS-2 sea-surface height anomaly analysis indicated the original low pressure area developed, intensified and then weakened over a band of positive height anomalies. SSTs in this region were generally 1°C above normal.

Thelma (Darwin TCWC/Perth TCWC): 1 to 14 December 1998

Severe cyclone *Thelma* (Fig. 2) was the most intense cyclone to traverse the northern Australian region in the last 35 years and was the first Category 5 system (on the Australian scale) observed in the Timor Sea.

A tropical low was first identified in the Arafura Sea north of Arnhem Land on 1 December 1998. A deep low to middle-level ridge over central Australia steered the system steadily westward. By 0000 UTC on 6 December the low was located about 280 km north of Melville Island and had deepened into cyclone *Thelma*. The strong low to middle-level ridge which had been steering the system westward over the previous few days weakened with the approach of a strong middle to upper-level trough into the Northern Territory. The weakened ridge allowed the low to drift slowly southwards. A strong upper westerly jet stream developed over the Gulf of Carpentaria ahead of the amplifying trough system over the Northern Territory. The outflow from the cyclone into this developing westerly jet stream was coincident with the cyclogenesis and rapid intensification of *Thelma*. The system deepened to Category 5 (on the Australian scale) and estimated maximum intensity with MSW of 63 m s^{-1} by 1200 UTC on 8 December as it passed over the northwest end of the Tiwi Islands and about 185 km to the west-northwest of Darwin. A ship, positioned 50 km to the southeast of *Thelma* at 0230 UTC on 8 December reported MSW to 39 m s^{-1}. Radar imagery at 0600 UTC on 8 December indicated an eye diameter of 35 km contracting to 18.5 km by 2100 UTC on 8 December. The main impact on the Tiwi Islands was disruption to communications and power supplies. Vegetation in exposed areas suffered extensive damage and a 3 to 4 metre rise in water level, reported in Milikapiti (Snake Bay), caused minor coastal erosion. In the Darwin area, minor damage occurred to houses and power supplies which were disabled by fallen trees. A peak wind gust of 19 m s^{-1} was recorded at Darwin Airport at 0851 UTC on 8 December. Charles Point automatic weather station (AWS) recorded a peak wind gust of 29 m s^{-1} at 0550 UTC on 8 December. A record 24 hour rainfall of 425 millimetres (mm) was measured at Howard Springs and a 48 hour total of 432 mm at Darwin Airport caused local flooding in rural areas around Darwin.

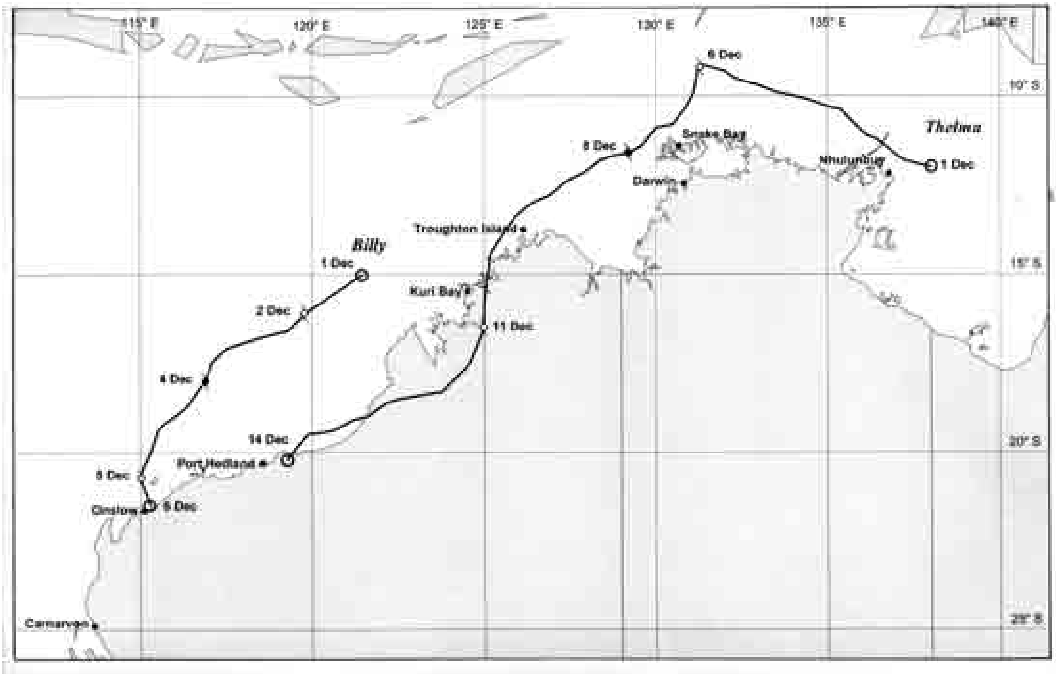
Re-establishment of the low to middle-level ridge during 8 and 9 December steered *Thelma* on a more southwestward path through the Timor Sea. SSMI data at 2318 UTC on 8 December indicated a small tight eye surrounded by deep convection enclosed in an outer more diffuse eye. By 0910 UTC on 9 December the TRMM scan showed redevelopment of deep convection and contraction of the outer eye with the inner eye wall weakening, possibly indicative of the system undergoing a concentric eye cycle. This was supported by SSMI data at 1202 UTC on 9 December which indicated further contraction of the outer eye wall as the inner eye wall weakened.

Thelma passed to the near northeast of the Troughton Island AWS on 10 December with MSW of 38 m s^{-1} and maximum gusts to 48 m s^{-1} being recorded between 0351 UTC and 0437 UTC before the AWS failed at 0500 UTC.

While continuing to move southwest, *Thelma* slowly weakened before crossing the northwest Kimberley coast about 140 km northeast of Kuri Bay around 2200 UTC on 10 December as a Category 3 system. *Thelma* continued to move in a general southwest direction overland and was finally downgraded to a tropical low at 1500 UTC on 11 December. The low-level centre moved back off the northwest Western Australia coast around 1600 UTC on 13 December but did not re-strengthen significantly. The low drifted westward for a day before making final landfall around 130 km northeast of Port Hedland at 1600 UTC on 14 December and slowly dissipating.

TOPEX/ERS-2 sea-surface height anomaly analysis showed the rapid intensification of *Thelma* between 6 and 8 December 1998 occurred over a positive height anomaly greater than 20 cm. SST anom-

Fig. 2 Tracks of tropical cyclones *Billy* and *Thelma*. Symbols as in Fig. 1.



aly data indicate *Thelma*'s development and intensification to peak intensity occurred over a region in which SSTs were up to 0.5°C below normal.

Cora (Nadi RSMC / Wellington RSMC): 21 to 30 December 1998

A tropical disturbance was first identified over the Northern Cook Islands on 18 December 1998 embedded in the South Pacific convergence zone. The disturbance drifted slowly west for several days and remained disorganised. On 23 December the system recurved and moved steadily southeast influenced by the approach of an upper-level trough over Fiji. At this time the low rapidly intensified to become tropical cyclone *Cora* (Fig. 5) at 1800 UTC on 23 December, located about 550 km east-northeast of Nadi. The system strengthened to hurricane force by 0900 UTC on 25 December, located about 280 km northwest of Tongatapa, before reaching estimated peak intensity with MSW of 41 m s^{-1} at 0000 UTC on 26 December. Satellite imagery indicated a clear eye at this time. The lowest pressure recorded at Nukualofa on the island of Tangatapa was 959.5 hPa at 0400 UTC on 26 December with a peak gust of 36 m s^{-1} recorded 54 minutes later.

Elevated sea levels, large swells and heavy rainfall produced areas of flooding and salt water inundation inland. A number of houses suffered roof damage and power was disrupted due to lines being downed. The main damage was to agriculture, with root crops being the hardest hit. The total damage estimate was placed at $12 million (US).

Cora began to accelerate to the southeast during 27 December and maintained hurricane intensity until 0000 UTC on 28 December. The system was declared extratropical at 0500 UTC on 28 December but maintained storm-force winds around its southern quadrant for another 24 hours. Winds finally weakened below gale force at 1200 UTC on 30 December when the system was located around 38°S.

TOPEX/ERS-2 analysis on 22 December 1998 showed Cora developed and intensified over neutral to negative sea-height anomalies suggesting the deep oceanic layers were not a major influence on its development. SSTs in the region of development and intensification, however, were 1°C to 2°C above normal.

Cathy (Perth TCWC): 22 to 28 December 1998

Tropical cyclone *Cathy* (Fig. 1) was first identified as a weak tropical low on 16 December located about

650 km northeast of Cocos Island. The system remained near stationary for several days, commencing a southward movement late on 22 December and becoming more organised with convection developing about the system centre. The low was named *Cathy* at 0400 UTC on 24 December when it was about 500 km south of Cocos Island. Upper northeast winds over the system, turning northwest to the south restricted *Cathy*'s outflow to the southeast quadrant. Strong low-level ridging up to 700 hPa to the south of the system steered *Cathy* westward from 25 December with the cyclone reaching estimated peak intensity with MSW of 28 m s^{-1} at 0700 UTC on 26 December. However, strong westerly winds over the system at 500 hPa increased the environmental sheer and consequently *Cathy* began to weaken during 26 December. SSMI data at 0024 UTC on 26 December showed deep convection removed to the southeast of the system's low-level centre. *Cathy* weakened below tropical cyclone strength on 27 December at which time a well-organised low-level circulation devoid of deep convection was evident on visible satellite imagery.

TOPEX/ERS-2 sea-surface height anomaly analysis indicates *Cathy* developed over near-neutral height anomalies before moving over negative sea-height anomalies for the remainder of its life. SSTs in the region of development and intensification were generally 0.5°C to 1°C above normal.

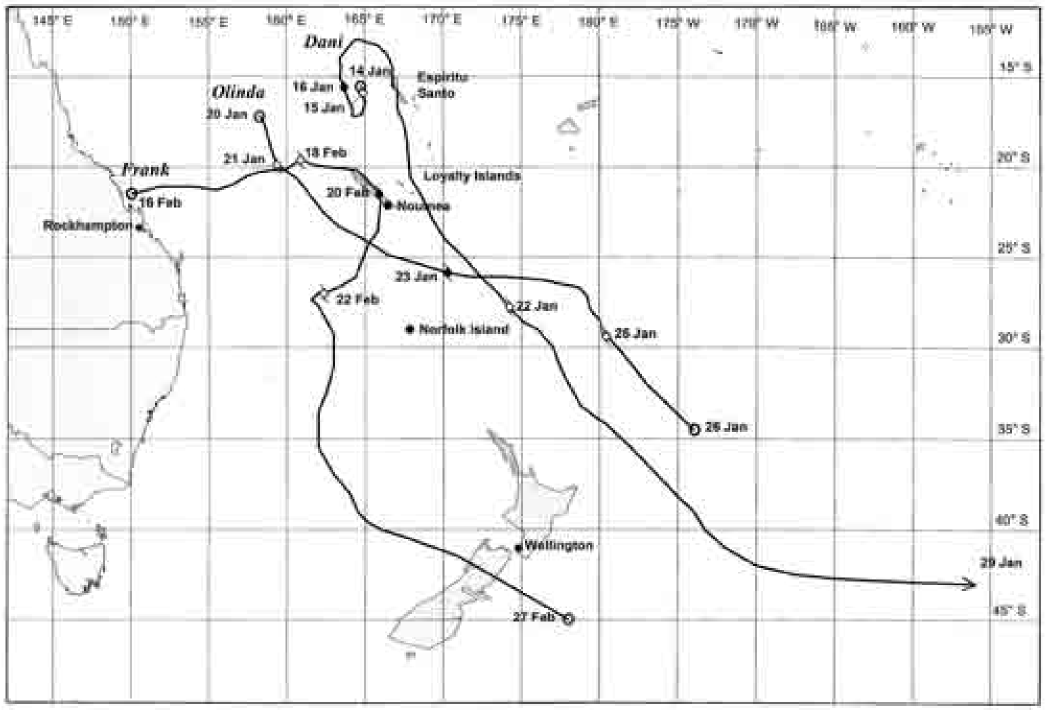
Dani (Nadi RSMC/Wellington RSMC): 14 to 29 January 1999

A weak disturbance embedded in the monsoon trough just south of the Solomon Islands was identified on 13 January. The low drifted slowly south from 13 to 16 January influenced by a deep trough extending through the Tasman and Coral Sea and a weakening high pressure system to its east. Convection improved significantly about the low during 13 and 14 January with an enhanced outflow channel developing on the southern side of the system. However, the environment remained strongly sheared at this time, inhibiting further system development. Later on 14 January the deep trough system over the Coral Sea slowly retrogressed westward over eastern Australia with middle-level ridging developing to the south of the system. This decreased the environmental shear about the low and eliminated the strong northwesterly steering flow. Geostationary Meteorological Satellite (GMS) infrared and water vapour winds indicated a more favourable upper pattern at this time with northwest winds over the system easing and strong outflow channels developing on both the poleward and equatorward sides of the low. The tropical low responded to these changes in environmental conditions, slowing its southward movement and intensifying. By 0000 UTC on 15 January the system had become significantly more organised with the low-level centre moving underneath the deep convection. It was at this time Nadi named the system cyclone *Dani* (Fig. 3), locating it about 370 km northwest of Port Vila. In response to the strengthening middle-level ridge to the south and ridging developing to the northwest, *Dani* began moving slowly southwest before recurving to the north at 0000 UTC on 16 January. During this time the system rapidly intensified as it moved into the upper-level ridge axis and upper outflow channels strengthened. *Dani* reached storm intensity (with MSW of 24 m s^{-1}) by 1200 UTC on 15 January and hurricane intensity (with MSW of 33 m s^{-1}) less than 12 hours later. Estimated peak intensity with MSW of 49 m s^{-1} was reached at 1800 UTC on 16 January when the system was located about 600 km west-northwest of Port Vila. Dvorak (1984) analysis of enhanced IR imagery between 1732 UTC and 2032 UTC on 16 January indicated a T-number of 7.0, with convective cloud-top temperatures of -76°C completely surrounding an eye temperature warmer than -30°C.

Dani continued moving in a general northerly direction until 0000 UTC on 18 January before turning more easterly in response to an amplifying upper trough over the central coast of Queensland eroding the ridge to the west of the cyclone. The system weakened during this period also as it became detached from the outflow channel on its southern side, but continued to maintain hurricane-force winds around its centre. Good system outflow continued on the equatorward side. *Dani's* response to the loss of the southern outflow channel was evident in TRMM data at 1020 UTC on 18 January which showed deep convection restricted to the northern side of the system. During this time *Dani* was located close enough to the Santa Cruz Island group to cause gale-force winds in the region between 0600 UTC on 18 January and 0000 UTC on 19 January. By early on 19 January a more divergent upper pattern redeveloped over the cyclone with southerly winds to the north and west-northwest flow to the southeast. In response, *Dani* re-intensified, and by 0057 UTC on 19 January deep convection again completely surrounded the eye, as shown in TRMM imagery. At this time, the cyclone was located over the northwest corner of Espiritu Santo with estimated maximum MSW of 41 m s^{-1}.

Dani continued to move steadily to the south-southeast under the influence of middle-level troughing over eastern Australia and a middle-level ridge to its east. Interaction with the rugged terrain of the Vanuatu Island chain weakened the system slightly but it soon re-intensified as it moved clear of the

Fig. 3 Tracks of tropical cyclones *Dani, Olinda* and *Frank*. Symbols as in Fig. 1.



islands over open ocean. A maximum MSW of 29 m s^{-1}, and minimum MSL pressure of 988 hPa were recorded at Lamap at 1500 UTC on 19 January as *Dani* passed to its east. An amplifying trough to *Dani*'s west caused the system to commence accelerating to the south and into a less favourable, strongly sheared environment. Strong westerly winds impinged on the western side of the system early on 20 January. This was evident in the 0647 UTC TRMM image which showed a significant decrease in convection on the western side. *Dani* passed the Loyalty Islands to the near east of Mare Island on its track south-southeast and continued to weaken under the influence of strong vertical shear. The system was declared extratropical by 0600 UTC on 22 January, but maintained a very well defined low-level circulation and gale-force winds about its poleward side for several more days as it tracked southeast, passing to the northeast of New Zealand.

The passage of *Dani* through the Vanuatu Islands resulted in two deaths, one on Ambae Island and the other on Malekula. In the Espiritu Santo and Malekula region, roads were badly damaged and a bridge was washed 200 to 300 m from its original location. Bauerfield Airport at Vila recorded 545 mm of rain in 24 hours including 312.4 mm between 0000 UTC and 0600 UTC on 20 January with river flooding destroying twelve homes. Agricultural crops affected included sweet potatoes, yams, tapioca, kava and coconut.

TOPEX/ERS-2 analysis for 15 January 1999 indicated *Dani* developed and intensified over a weak positive height anomaly. However, SSTs in the region of development and intensification to peak intensity were generally 1°C above average. Re-intensification of the system as it passed to the south of the Vanuatu Islands was coincident with a region of SSTs between 1°C and 2°C above normal.

Olinda (Brisbane TCWC/Nadi RSMC/Wellington RSMC): 20 to 26 January 1999

A tropical disturbance was first identified well southwest of the Solomon Islands on 19 January. The system moved southeast under the influence of a low to middle-level trough to its west and became more organised during 20 January with convection developing about a low-level centre as indicated by SSMI imagery at 0647 UTC and 1000 UTC on 20 January. The low continued to move southward during 20 and 21 January into a more favourable upper environment, ahead of an amplifying upper-level trough and improved outflow channel on the poleward side. However, the system maintained monsoon depression characteristics with maximum winds located along the outer periphery of the circulation. By late on 21 January the system began to organise more rapidly and was named *Olinda* (Fig. 3) at 1800 UTC on 21 January when it was centred 790 km west-northwest of Noumea and just inside the Eastern Australian Region of responsibility. SSMI imagery at 2014 UTC on 21 January indicated curvature in cloudbands with deep convection almost surrounding the low-level centre. The system continued to move steadily southeast steered by strong northwest winds ahead of a mobile 500 hPa trough. *Olinda* entered Fiji's region of responsibility around 0000 UTC on 22 January and continued to move towards the east-southeast in a strong westerly shear environment. However, the speed of movement of the system in the deep mean layer flow allowed *Olinda* to maintain storm-force winds about its centre for the next 24 to 48 hours as strong outflow persisted on the poleward side. The system became more extratropical during 23 January as convection dissipated leaving a tight low-level circulation. This was evident in both the SSMI and visible satellite imagery on 23 and 24 January. It was during the phase of extratropical transition that *Olinda* reached estimated peak intensity with MSW of 28 m s^{-1} at 1200 UTC on 23 January. The system continued to track southeast for several days under the strong northwest steering flow and was downgraded to below cyclone strength on 26 January. *Olinda* did not directly threaten any populated areas as it passed through the Brisbane, Nadi and Wellington regions of responsibility.

TOPEX/ERS-2 analysis on 24 January 1999 indicated *Olinda* developed and then strengthened to peak intensity as an extratropical system over neutral to weakly positive sea-surface height anomalies. SSTs in the region of initial genesis were 0.5°C to 1°C above average, however, intensification to peak intensity occurred over a region where SSTs were between 1°C and 2°C above normal.

Damien/Birenda (Perth TCWC/La Reunion RSMC): 21 January to 3 February 1999

An active monsoon trough south of Indonesia produced a discrete low pressure centre located about 650 km east-southeast of Christmas Island on 21 January. The system was quasi-stationary at this time. Strong middle-level ridging developed to the south of the system during 21 January steering the low south-southwest. An approaching upper-level trough from the west strengthened the upper northerly flow to the south of the system and improved the system outflow in this quadrant. In response, the low deepened and was named tropical cyclone *Damien* (Fig. 6) at 1000 UTC on 21 January, when located about 370 km southeast of Christmas Island.

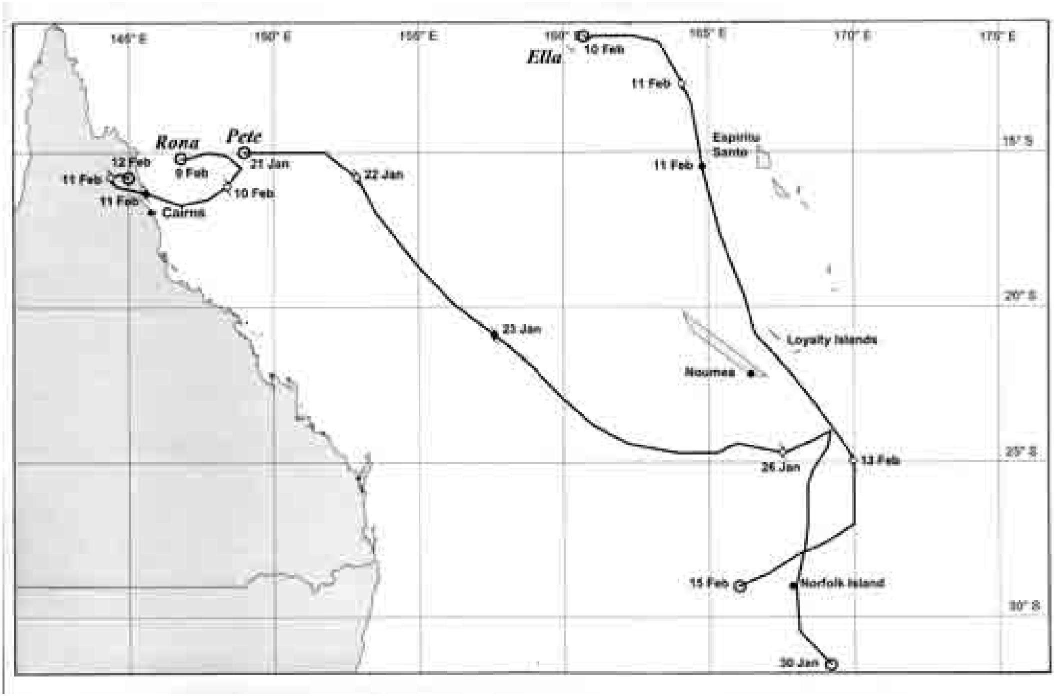
Damien continued to track west for several days as strong middle-level ridging to the south was maintained. The environment became less sheared and the upper wind pattern more favourable, with GMS upper water vapour winds at 0000 UTC on 24 January indicating good east to northeast outflow in the western and southern quadrants of the system. *Damien* slowly intensified in response to this more favourable environment, and reached estimated peak intensity with MSW of 44 m s^{-1} at 2200 UTC on 24 January. By 1200 UTC on 25 January, upper water vapour winds indicated a weakening of the diffluent pattern, with uniform easterly winds and strong vertical shear developing over the system. Consequently, *Damien* weakened rapidly and by 1400 UTC on 25 January, SSMI imagery showed convection limited to the western side of the system, sheared off by upper easterly winds. The system continued to move in a general westerly direction crossing into the Mauritius/La Reunion area of responsibility around 0600 UTC on 28 January where it was renamed tropical cyclone *Birenda*. By this time the maximum MSW were estimated at 21 m s^{-1} and the low-level centre was fully exposed with the nearest convection about 130 km southwest of the system centre. *Birenda* continued to drift westward and was finally downgraded to a tropical low by La Reunion RSMC at 1200 UTC on 29 January. Remnants of the low continued to drift west until 0000 UTC on 3 February.

TOPEX/ERS-2 analysis on 21 January 1999 indicated *Damien*'s track passed over generally negative to near-neutral sea-surface height anomalies. However, SSTs in the region of development and intensification were generally 0.5°C to 1°C above normal.

Pete (Brisbane TCWC/Nadi RSMC/Wellington RSMC): 21 to 30 January 1999

Tropical cyclone *Pete* (Fig. 4) originated from a tropical low over northeastern Queensland which moved out into the Coral Sea on 21 January. The low moved slowly southeast and strengthened to cyclone intensity by 0600 UTC on 22 January, located about 740 km east of Cairns. *Pete* moved rapidly southeast and intensified, steered in a strong west-northwest current ahead of an upper-level trough moving across eastern Australia. Good outflow developed on both the poleward and equatorward sides of the system as it continued to intensify. *Pete* reached estimated peak intensity with MSW of 26 m s^{-1} at 0600 UTC on 23 January before crossing into Nadi's region of respon-

Fig. 4 Tracks of tropical cyclones *Pete, Rona* and *Ella*. Symbols as in Fig. 1.



sibility at 0000 UTC on 24 January. The Ile de Loop (Iles Chesterfield) AWS located about 140 km northeast from the cyclone centre, reported 21 m s^{-1} MSW and a minimum station pressure of 993.3 hPa between 0500 UTC and 0600 UTC on 23 January. *Pete* continued to move steadily southeast but increasing westerly shear and cooler SSTs, influenced by the passage of *Dani* and *Olinda* in previous days saw the system gradually weaken. By 1850 UTC on 24 January SSMI imagery showed a large open eye with deep convection well removed from the centre. SSMI and visible satellite imagery during 25 January showed *Pete* developing more extratropical characteristics with a low-level centre clearly visible and deep convection well removed from the centre on the poleward side. Convection slowly decreased during 25 and 26 January and *Pete* was finally downgraded to a tropical low at 0000 UTC on 26 January. Gale-force winds about the system continued in the southern and eastern quadrant for another day or two. *Pete* did not directly threaten any populated land areas during its lifetime.

TOPEX/ERS-2 analysis shows *Pete* intensified to tropical cyclone strength over an area of weak negative height anomalies and then strengthened to Category 2 over neutral height anomalies. However, SST anomaly data indicate *Pete* developed and intensified over a region where SSTs were 0.5°C to 2°C above normal, before weakening over waters in which SSTs were close to average.

***Rona* (Brisbane TCWC): 9 to 12 February 1999**

Severe tropical cyclone *Rona* (Fig. 4) was the only cyclone to threaten and impact on the Queensland coast during the 1998-99 season. A tropical low embedded in an active monsoon trough was evident off the north Queensland coast on 9 February. Strong westerly winds persisted around the northern side of the low, however a deep low pressure system off the southern Queensland coast brought a weak pressure gradient and only light winds to the southern side of the system. A middle to upper-level trough over eastern Australia steered the low slowly eastwards, but by late on 9 February this began to weaken and within 24 hours had dissipated. This allowed strong ridging to develop south of the system, with the easterly trade winds extending northward to the monsoon trough. Coincident with ridging to the south of the system, pressures rose over New Guinea, strengthening the pressure gradient between New Guinea and the tropical low. The upper pattern in the region of the low became highly favourable for development with a strong easterly outflow channel forming on the equatorward side of the system, and strong northwest flow on the poleward side ahead of an amplifying upper trough over central Australia. In response, the low rapidly intensified and was named tropical cyclone *Rona* at 1800 UTC on 10 February, when located about 310 km east of the north Queensland coast. At this time the system had commenced moving southwest and then turned on a more westerly track as the middle-level ridge strengthened. *Rona* continued to intensify over the next 6 to 12 hours and was upgraded to storm force with estimated MSW of 26 m s^{-1} at 0400 UTC and hurricane force with estimated MSW of 33 m s^{-1} at 0700 UTC on 11 February. By this time the middle-level ridge to the south of the system strengthened further and in response *Rona* moved rapidly west-northwest towards the Queensland coast. Radar imagery (from the Cairns radar to the south of the cyclone eye) displayed a ragged, diffuse eye, however, the signal may have been attenuated somewhat by deep convection on the system's southern side. Between 1219 UTC and 1246 UTC on 11 February, Low Isles reported MSW in excess of 30 m s^{-1}, peaking at 37 m s^{-1} at 1228 UTC with a maximum gust to 44 m s^{-1}. The system eye was located about 23 km north of Low Isles at this time, however radar imagery is inconclusive in determining if the observation site experienced the radius of maximum winds. The minimum station pressure recorded at Low Isles was 983 hPa at 1216 UTC. *Rona* crossed the coast just to the north of Cow Bay near the mouth of the Daintree River around 1300 UTC on 11 February. The system continued to track west-northwest over land and maintain cyclone intensity until 1800 UTC on 11 February at which time it was downgraded to a tropical low. A definite low-level centre was difficult to track beyond this time, with several small-scale centres developing. However, the 850 hPa circulation could be traced for several days as it tracked eastward across the Coral Sea to eventually become tropical cyclone *Frank*.

Significant wind damage from *Rona* extended from Newell Beach to Cape Tribulation with the major damage occurring between Cape Kimberley and Cape Tribulation on the northern side of the coastal crossing location. Some trees in the Cape Tribulation area that survived an intense cyclone in 1934 were felled by *Rona*. As the system crossed the coast in a sparsely populated area of the north Queensland coast, structural damage to property was minimal. Heavy rainfall following the landfall of *Rona* resulted in flooding from Cairns to Townsville. Highest 24 hour rainfall totals to 2300 UTC on 12 February were 531 mm at Topaz, 474 mm at Greenhaven, and 420 mm at Kuranda. A 1 m storm surge was recorded at Port Douglas (occurring at low tide) while at the mouth of the Mossman River (near Newell and south of the radius of maximum winds) a 1.4 m storm surge was measured. Peak significant wave heights recorded at Low Isles exceeded 3.5 m with a maximum wave height in excess of 6.3 m.

TOPEX/ERS-2 analysis indicates *Rona* developed and intensified over neutral height anomalies. However, SSTs were generally 1°C above normal.

Ella (Nadi RSMC/Wellington RSMC): 10 to 15 February 1999

A depression was first identified by RSMC Nadi just south of Rennel Island, the southernmost island of the Solomons, on 9 February. The low, embedded in the monsoon trough, drifted slowly east ahead of a middle-level trough to its near west. Upper southerly flow into the Solomon Islands region prevented any poleward outflow, but strong diffluent southwest to southeast winds to the north of the system provided good outflow on the equatorward side. The low commenced deepening during 10 February and between 1500 UTC and 2100 UTC a ship in the area reported storm-force northwest winds around the northern periphery of the system. SSMI imagery at 1847 UTC on 9 February indicated a large monsoon rainband on the northern side of the low, however by 2148 UTC on 10 February an eye became evident. Nadi named the system cyclone *Ella* (Fig. 4) at 0600 UTC on 11 February. At this time the upper wind flow became strongly diffluent particularly on the eastern side of *Ella* between strong southwest winds to the equator and a northerly current around the eastern periphery into a deep low pressure system to the south. Consequently convection increased on the eastern side of the system, which continued to track steadily south-southeast, steered around the eastern flank of the northern Tasman Sea low. The system passed within 185 km of the western tip of Espiritu Santo in the Vanuatu Islands around 1500 UTC on 11 February before reaching its estimated peak intensity with MSW of 23 m s^{-1} at 1800 UTC on 11 February. It continued to move south-southeast through the Loyalty Islands between 1200 UTC and 1800 UTC on 12 February. By this time *Ella* was moving at a speed of 5 m s^{-1}, and although the maximum MSW were estimated at 21 m s^{-1}, the rapid translational motion augmented the winds on the left side of the system (moving with the cyclone). Lifou recorded a maximum MSW of 24 m s^{-1} with a peak gust of 33 m s^{-1} at 1314 UTC on 12 February. Some significant damage was sustained to buildings and vegetation on the northern side of Lifou. *Ella* continued tracking south-southeast on 12 February into a strongly sheared environment with strong southwest to southerly flow in the upper levels, middle-level steering to the southeast and low-level steering to the southwest. *Ella* rapidly sheared as was evident from the sequence of SSMI imagery from 2022 UTC on 11 February to 0707 UTC on 12 February which showed convection rapidly decreasing and becoming removed from the low-level centre. A small area of convection persisted about the northeast edge of the eye for the following 24 hours before Wellington RSMC declared the system extratropical at 0600 UTC on 13 February when it was located about 370 km northeast of Norfolk Island. As an extratropical system, the low tracked south then southwest around the eastern periphery of the deep northern Tasman Sea low, and was slowly absorbed by the low on 15 February.

TOPEX/ERS-2 analysis indicates *Ella* strengthened to maximum intensity of 23 m s^{-1} over moderate negative height anomalies. SSTs in the region of development and intensification were close to average.

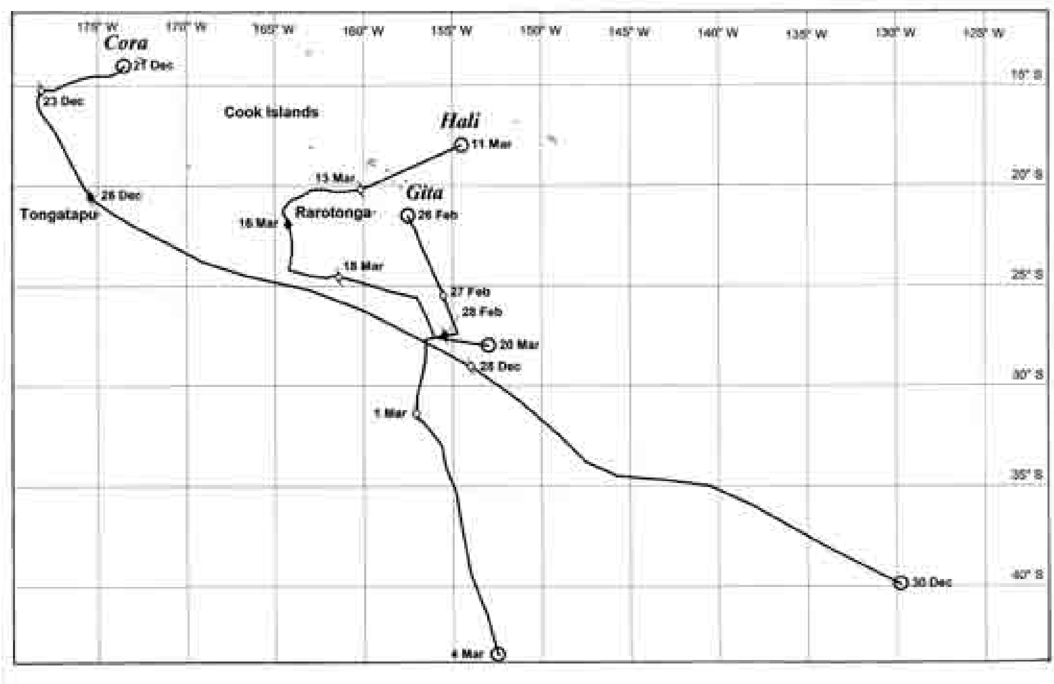
Frank (Nadi RSMC/Wellington RSMC): 16 to 27 February 1999

An 850 hPa vorticity centre, remnants of tropical cyclone *Rona*, cleared the east coast of Queensland on 16 February and tracked eastwards across the Coral Sea to the south of the subtropical ridge. By 0600 UTC on 17 February 1999 the low was located about 550 km east-northeast of Rockhampton and moving east. At 2034 UTC on 17 February, SSMI data showed deep convection developing about the eastern flank of the low-level centre. Upper outflow about the low was improving at this time with a strong southerly current to the north of the low extending to the equatorial easterly winds and strong northwest flow developing to the south ahead of an amplifying trough across eastern Australia. The sequence of SSMI imagery during 18 February showed intensification in response to this improved environment with convection developing about the system centre. At 1800 UTC on 18 February the low was named cyclone *Frank* (Fig. 3) as it moved into Nadi's region of responsibility, about 690 km west-northwest of Noumea. The system rapidly intensified over the next 12 to 24 hours as the upper trough over eastern Australia entered the Tasman Sea, further improving the outflow channel on the poleward side. *Frank* was upgraded to hurricane force, with estimated maximum MSW of 33 m s^{-1} at 1200 UTC on 19 February when the system was located at the northern tip of New Caledonia. TRMM imagery at 1524 UTC on 19 February showed a well-formed eye approximately 40 km in diameter. Koumac reported 20 m s^{-1} southerly MSW in its synoptic observations at 2100 UTC on 19 February. At this time *Frank* commenced moving southeast along the eastern edge of New Caledonia ahead of an amplifying middle-level trough to its near west and ridging to the east. The system reached estimated peak intensity with MSW of 41 m s^{-1} at 0600 UTC on 20 February as it passed over the southern end of New Caledonia about 25 km to the west of Noumea. Despite the close proximity of the centre to Noumea, relatively light winds were experienced in the capital. The rough terrain through the central region of New Caledonia appeared to weaken the system temporarily, as evident in 0706 UTC SSMI imagery on 20 February which showed *Frank* had lost its eye. However as the system moved back over water, the eye reformed as was evident from the TRMM image at 0813 UTC on 20 February. *Frank* tracked south-southwest, captured by the trough system to the west, and entered a strongly sheared environment with upper northwest flow developing over the system. TRMM imagery at 1428 UTC on 20 February showed deep convection displaced to the southeast of the low-level centre. *Frank* eventually merged with this trough system on 21 February to form a deep extratropical low. Convection redeveloped about the southern side as the system re-intensified. A secondary middle to upper trough system amplifying over eastern Australia at this time provided further impetus for intensification. The progression eastward of this trough steered the intense low south then southeast with the system finally making landfall on the southern Island of New Zealand near Westport.

Frank possessed a very small radius of destructive winds as it made landfall on a sparsely populated region of New Caledonia so as a result damage was minimal. Some townships in the northern and western parts of New Caledonia suffered power outages, disruption to water supplies and telecommunications. A number of landslides along coastal roads also resulted. Flooding caused some crop damage in the northeast portion of the island, but there were no casualties or serious damage to infrastructure. A yacht was overturned near 29°S 164°E as *Frank* passed to the near southeast. The crew took to their life raft and were eventually rescued. The long-period swell generated from *Frank*, with peak heights to 7 m reached the southern Queensland coast causing some erosion, however the event was coincident with neap tides which minimised the damage.

TOPEX/ERS-2 analysis on 17 February 1999 indicates *Frank's* path was over generally neutral sea- surface height anomalies, apart from waters to the near south of New Caledonia where positive height anomalies dominated. It was over this region that Frank re-intensified. SSTs in the region of development and intensification were generally 0.5°C to 1.5°C above normal.

Fig. 5 Tracks of tropical cyclones *Cora*, *Gita* and *Hali*. Symbols as in Fig. 1.



Gita (Nadi RSMC/Wellington RSMC): 26 February to 4 March 1999

Gita (Fig. 5) was a small, short-lived cyclone. A shallow depression was evident to the north of the Southern Cook Islands as early as 25 February. The low was embedded in the subtropical convergence zone and was drifting slowly southwards. Though convection was disorganised, low-level cloud lines were evident, suggesting a low-level circulation. The environment around the low at this time was strongly sheared ahead of an amplifying trough extending deep into the tropics. During 26 February, the middle to upper-level trough retrogressed westward and ridging developed to the near east of the low-level centre. This provided a strong outflow channel on the poleward side of the system. A deep upper-level low to the northeast of the ridge provided good outflow to the north. The surface low subsequently responded to this improved environment with deep convection developing about the system centre, particularly on the poleward side. Ridging to the east steered the low southwards as it continued to intensify. By 0000 UTC on 27 February, with deep convection wrapping around the southern side of the low-level centre, as evident in SSMI imagery, Nadi issued the first gale warning with the system located about 320 km southeast of Mangaia. By 1200 UTC on 27 February, as the low moved from Nadi's region of responsibility it was named cyclone *Gita* by Wellington RSMC. A weak middle-level ridge developed to the south of *Gita* early on 28 February which caused the system to move westwards for 12 hours reaching estimated peak intensity with MSW of 23 m s^{-1}, before recommencing its southerly movement around 1200 UTC on 28 February. By this time however, vertical shear over the system increased, evident from SSMI imagery at 0650 UTC on 28 February which showed convection removed to the southeast of the low-level centre. By 0600 UTC on 1 March, although maintaining intensity, *Gita* was declared extratropical. The low-level centre continued to drift slowly south for several days and eventually weakened below gale force by 1800 UTC on 2 March. *Gita* did not pose a threat to any landmass on its path through the southwest Pacific.

TOPEX/ERS-2 data analysis indicates *Gita* intensified to tropical cyclone strength over a moderate to strong positive height anomaly (20 cm), and then deepened to peak intensity over neutral height anomalies. SSTs in the region of development and intensification were 0.5°C to 1°C above average.

***Hali* (Nadi RSMC/Wellington RSMC): 11 to 20 March 1999**

A tropical disturbance was first identified around 0000 UTC on 11 March, embedded in an active subtropical convergence zone moving slowly southwest. The environment remained strongly sheared at this time preventing any significant development. During 12 March the upper environment became more favourable for development as the low-level centre moved under the upper level ridge. This resulted in a significant increase in convection about the system centre. The SSMI sequence of images from 1728 UTC on 11 March to 1542 UTC on 12 March showed deep convection, initially displaced to the northeast of the low-level centre, develop around the centre. By late on 12 March, the low-level centre had become vertically aligned with the deep convection as shown by the 1859 UTC SSMI image, and by 0000 UTC on 13 March, Nadi upgraded the low to tropical cyclone *Hali* (Fig. 5), located about 170 km north-northeast of Rarotonga. *Hali* continued on a westerly course for the next three days as it continued to intensify. By 1200 UTC on 15 March, when the system was centred about 310 km west of Rarotonga, *Hali* turned to the south ahead of an approaching upper-level trough from the west. The system formed an eye over the next twelve hours and reached estimated peak intensity of 33 m s^{-1} at 0000 UTC on 16 March. Continued southerly movement brought *Hali* under the influence of increased shear and cooler sea-surface temperatures and by 1200 UTC on 16 March the cyclone had weakened to below hurricane force. SSMI imagery on 16 and 17 March saw convection rapidly decrease about the system, exposing the low-level centre. A developing depression to the east also aided *Hali*'s rapid demise and by 1200 UTC on 18 March cyclone *Hali*, located about 370 km south-southwest of Rarotonga, was downgraded to a tropical low. The surface low tracked southeast for several days drifting into Wellington's region of responsibility on 19 March before finally dissipating. *Hali* was a midget cyclone in that gale-force winds surrounding the system were estimated to extend out only 90 to 100 km from the centre, and storm-force winds were confined to within about 50 km of the centre. *Hali* did not pose a threat to any landmass on its path through the Southwest Pacific.

TOPEX/ERS-2 analysis indicates *Hali* developed and intensified to peak intensity over moderately positive sea height anomalies (10 cm). The system then weakened from hurricane to storm force as it moved over a region of strong negative height anomalies. As the system neared 25°S around 18 March, strongly positive height anomalies could provide little impetus for development as the system came under the influence of strong vertical shear. SSTs in the region of development and intensification were close to normal.

***Elaine* (Perth TCWC): 15 to 20 March 1999**

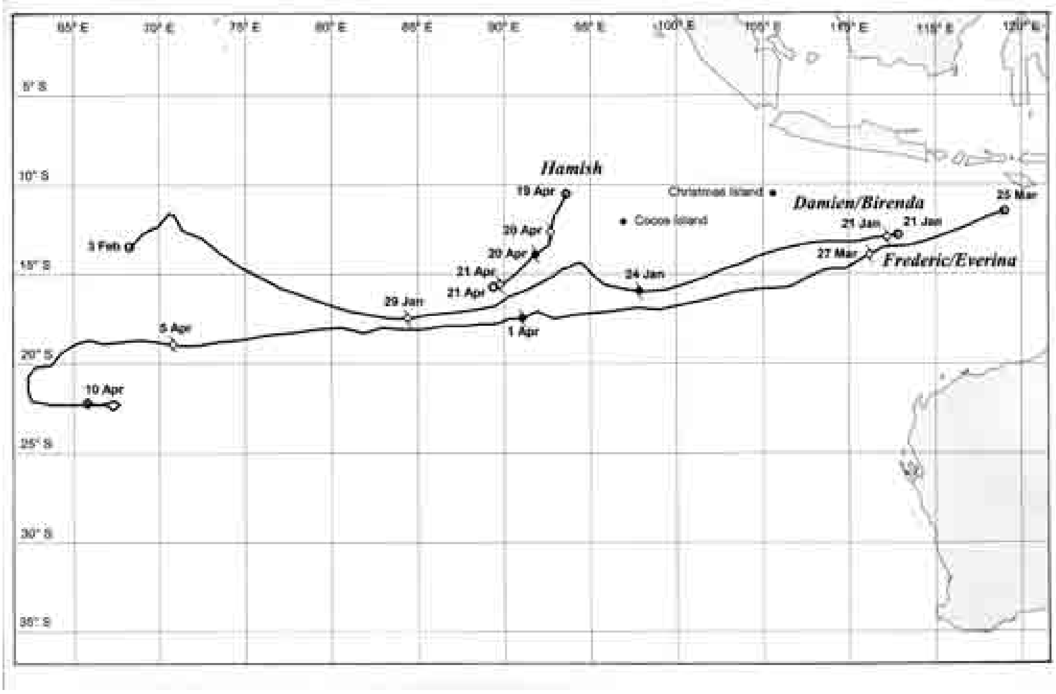
A low was evident in the monsoon trough in the Timor Sea from 0000 UTC on 12 March. This system tracked westward for several days before turning more southwest during 15 March through a weakness in the subtropical ridge to the south. By this time the low had entered a favourable environment for development with low vertical shear. The upper-level outflow pattern, dominated by a high over northeast Australia and an approaching trough over southwest Western Australia, provided good outflow channels on the southern and eastern sides of the low. Consequently the system intensified and was named cyclone *Elaine* (Fig. 7) at 0100 UTC on 16 March. Intensification continued during 17 and 18 March as a secondary upper trough approached southwest Western Australia, further improving the poleward outflow channel. *Elaine* reached estimated peak intensity with MSW of 49 m s^{-1} at 0100 UTC on 18 March. An intense system was evident from the 0420 UTC TRMM image on 18 March, which showed a well formed ring of deep convection surrounding the system eye. *Elaine* continued to move in a general southerly direction which finally led to its rapid demise late on 18 March as it entered a strongly sheared environment with upper westerly flow overlying low-level easterly flow. By 2137 UTC on 18 March TRMM imagery showed the low-level centre completely devoid of deep convection. Despite a resurgence of convection about the southern side of the system on 19 March, *Elaine* continued to weaken and was downgraded to a tropical low by 0100 UTC on 20 March. The system crossed the coast as a weakened tropical low between Geraldton and Kalbarri producing heavy rain in the region. Rainfall totals of 80 mm in six hours over the catchment areas of the Moore River on 20 March caused severe flooding in the town of Moora. Houses and commercial properties in the town were inundated by flood waters and approximately 1000 people were evacuated.

TOPEX/ERS-2 analysis indicated *Elaine* developed and intensified over neutral to negative height anomalies. SSTs in the region of development were 1°C to 2°C above average increasing to more than 2°C above average in waters over which *Elaine* reached peak intensity.

***Vance* (Darwin TCWC/Perth TCWC): 14 to 24 March 1999**

As tropical cyclone *Elaine* was developing further to the west, a tropical low was identified within the monsoon trough along the northern Australian coast,

Fig. 6 Tracks of tropical cyclones *Damien/Birenda, Frederic/Everina* and *Hamish*. Symbols as in Fig. 1.



centred about 185 km east-northeast of Darwin early on 14 March. The low steered westwards around the equatorward side of a strengthening middle-level ridge over central Australia, entered open waters of the Timor Sea during 17 March. This located the system in a favourable environment for development with weak vertical wind shear and a strengthening upper easterly jet to the near north providing a good outflow channel on the equatorward side. In response, the low developed rapidly and was named tropical cyclone *Vance* (Fig. 7) at 0000 UTC on 18 March. The rapid intensification was evident in SSMI imagery over 17 and 18 March. The large open system with eye diameter of approximately 110 km, evident from SSMI imagery at 2237 UTC on 17 March, transformed into a system with a well-formed eye (approximately 50 km diameter) surrounded by deep convection by 2034 UTC on 18 March.

Vance continued to deepen as it moved further westward during 18 and 19 March and intensified with winds increasing to hurricane force by 0000 UTC on 19 March, centred about 460 km north-northwest of Broome. Steered around the western side of the middle-level ridge, the system began to take on a more southwest track during 19 and 20 March. At this time, the favourable upper pattern improved further as an upper trough moved into the Gulf of Carpentaria, developing a southwest to southeast flow between Darwin and Broome, providing the main outflow channel for the system. In response, *Vance* continued to intensify, reaching estimated peak intensity with MSW of 62 m s^{-1} at 2200 UTC on 20 March. The system maintained category 5 intensity during 21 March and early on 22 March as it was steered southward around the western edge of the middle-level high to the east. *Vance* made landfall near the mouth of Exmouth Gulf around 0000 UTC on 22 March, passing directly through the Gulf, approximately 25 km to the east of Exmouth and 80 km to the west of Onslow. Radar imagery from Learmonth indicated an eye diameter of 40 km. A record wind gust speed for the Australian mainland of 74 m s^{-1} was recorded at the Learmonth Meteorological Office (35 km south of Exmouth) at about 0350 UTC on 22 March. A maximum wind gust of 48 m s^{-1} was recorded at Onslow. A storm surge of 3.5 to 4.0 m was recorded at Exmouth and Onslow. This combined with high tides caused severe beach erosion at Exmouth. In the town of Exmouth, about 120 houses were destroyed and a further 200 damaged. Power lines and trees were brought down and a trailer park flattened. After moving inland, *Vance* was steered to the southeast in the low-level northwest steering current and slowly weakened. By the morning of 23 March, the system was near the town of Mount Magnet and moving southeast at about 14 m s^{-1}. There was property damage in the town of Cue when winds struck at around 2000 UTC on 22 March. *Vance* was downgraded to a category 1 system around 0700 UTC on 23 March as it passed to the northeast of Kalgoorlie, and then further downgraded to a tropical low at 1800 UTC on 23 March. Heavy rainfall from the decaying cyclone caused flooding in the southern Goldfields of Western Australia and the main highway and rail links to the eastern States were cut by floodwaters. The system entered the Great Australian Bight early on 24 March and tracked east-southeast passing to the near southwest of Adelaide around 0500 UTC on 24 March and near northwestern Tasmania by 1800 UTC on 24 March after which time it merged with a frontal system. Cleve on the Eyre Peninsula in South Australia reported northerly winds averaging 21 m s^{-1} with gusts to 27 m s^{-1} at 0100 UTC on 24 March. Winds to gale force were also experienced along the coastlines of Victoria and northwest Tasmanian.

TOPEX/ERS-2 analysis provided no evidence of the influence of a deep layer of warm sea-surface temperatures on development or intensification of the system as generally neutral sea -height anomalies dominated waters over which *Vance* tracked. However, SSTs in the region of development and intensification were 1°C to 2°C above average.

Frederic/Everina (Perth TCWC/La Reunion RSMC): 25 March to 10 April 1999

Tropical cyclone *Frederic* (Fig. 6) was the third severe cyclone in a period of two weeks to affect waters off the northwest coast of Australia. A low in the monsoon trough formed well off the north Kimberley coast on 25 March. The system tracked slowly west around the equatorward side of a middle-level high over Central Australia. This placed the low in a favourable environment for development with weak vertical wind shear and good outflow on the western and southern sides of the system. In response, the low slowly deepened to cyclone intensity by 0400 UTC on 27 March when it was located about 600 km southeast of Christmas Island. The approach of an upper-level trough and the development of easterly shear over the system early on 28 March temporarily slowed the rate of intensification, but by late on 28 March the shear reduced and the environment again became favourable for further development. *Frederic* intensified to reach hurricane strength at 0100 UTC on 29 March, then deepened further to reach estimated peak intensity with MSW of 54 m s^{-1} by 0100 UTC on 1 April. SSMI imagery at 0044 UTC on 31 March showed a clear tightly coiled eye surrounded by deep convection. Dvorak (1984) analysis of enhanced infrared imagery on 31 March and early on 1 April indicated a T-number of 6.5 to 7.0. The middle-level ridge continued to steer the system westward during this period. *Frederic* maintained its intensity as it crossed westward into the Mauritius Area of Responsibility during 1 April. At this time the cyclone was renamed *Everina* by the Mauritius Tropical Cyclone Warning Centre. Increased shear as the system moved into a weakness in the subtropical ridge led to its rapid demise and *Everina* weakened to below hurricane force by 0600 UTC on 2 April.

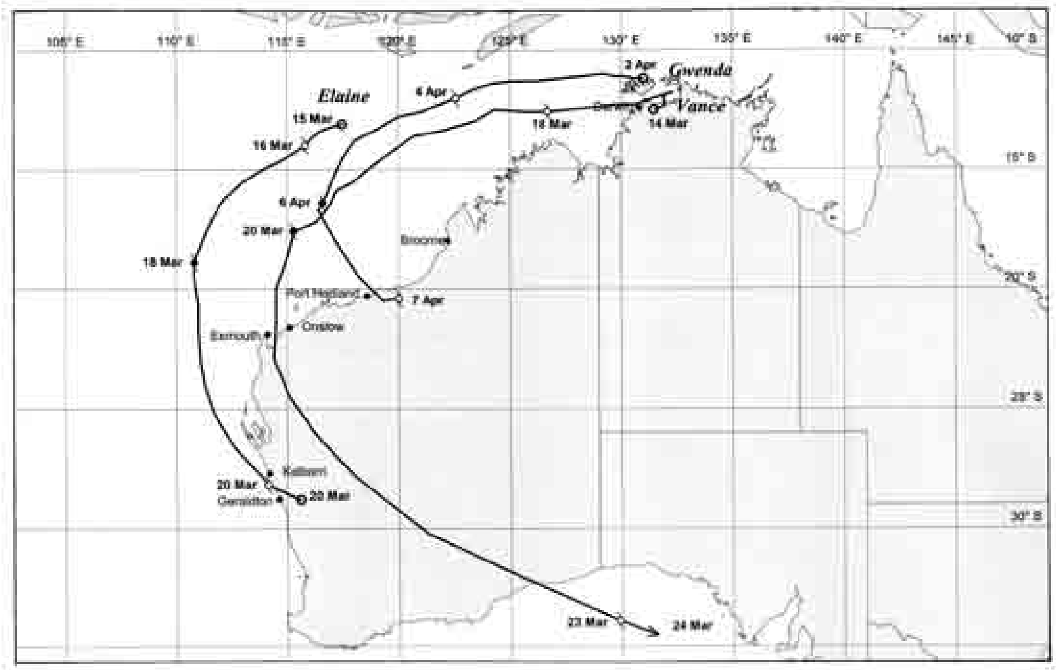
The system was finally downgraded to a tropical depression (by La Reunion) at 0600 UTC on 5 April. This weakening transition was evident in the sequence of SSMI and TRMM imagery from 1550 UTC on 31 March to 0255 UTC on 2 April. The clear eye pattern with deep convection surrounding the system centre, evident on 31 March, had reduced to a small area of convection in the southeast quadrant by 2 April.

The rapid development of cyclone *Frederic* to hurricane strength on 29 March took place over an area of weak positive sea surface height anomalies as evident in the TOPEX/ERS-2 analysis on 28 March. A strong gradient in the sea-level elevation near 18°S 93°E was coincident with the intensification of Frederic to estimated peak intensity with MSW of 54 m s^{-1}. SSTs in the region of development and intensification were generally 0.5°C above average.

Gwenda (Perth TCWC): 2 to 7 April 1999

Severe tropical cyclone *Gwenda* (Fig. 7) was the most intense system to develop in the Australian region during the 1998-99 tropical cyclone season and the fourth system off the Western Australia coast to reach category 5 intensity (on the Australian scale). The estimated minimum central pressure of 900 hPa, associated with *Gwenda* was also the lowest on record for systems developing in the Perth TCWC region of responsibility. A low was first identified in the weak monsoon trough to the north of Darwin on 2 April. The system tracked steadily east for several days under the influence of a strengthening low to middle-level high over northeast Australia. By 4 April, the low was located well out in the Timor Sea, but strong environmental shear prevented any further development. Despite the strong shear over the system, an approaching upper-level trough from the west provided a strong outflow channel on the poleward side of the low centre. This was sufficient for slow development and by 1600 UTC on 4 April the system was upgraded to tropical cyclone *Gwenda*. Over the following 36 hours, Gwenda explosively intensified as it moved underneath the upper ridge axis, relaxing the environmental shear that was inhibiting its development over the previous few days. Strong outflow

Fig. 7 Tracks of tropical cyclones *Elaine, Vance* and *Gwenda*. Symbols as in Fig. 1.



channels persisted to the south of the system ahead of the approaching middle to upper-level trough. This steered *Gwenda* southward and then southeast with the system reaching estimated peak intensity with MSW of 64 m s^{-1} at 1300 UTC on 6 April. Dvorak (1984) analysis of enhanced infrared imagery at this time indicated a clear eye pattern (eye diameter approximately 30 km) and a T-number of 7.0. Cloud-top temperatures of deep convection surrounding the cyclone eye were -80°C. However, the trough, which provided the initial impetus for development was also responsible for the rapid weakening of the system. Upper northwesterly winds overlying low-level easterly flow led to rapid shearing. This was evident from the SSMI image at 1152 UTC on 7 April which showed convection streaming off to the southeast of the low-level centre. Within 24 hours from 1200 UTC on 6 April, *Gwenda* weakened from its maximum intensity of 64 m s^{-1} to about 39 m s^{-1}. A further 12 hours saw the system weaken further to below tropical cyclone strength. By this time, *Gwenda* had crossed the coast 50 km to the east of Port Hedland (around 1600 UTC on 7 April) with gale-force winds. The strongest MSW recorded at Port Hedland was 21 m s^{-1}, with maximum gust to 28 m s^{-1}, occurring around 1530 UTC on 7 April. Following landfall, the system weakened further before finally dissipating.

TOPEX/ERS-2 analysis on 3 April 1999 indicates Gwenda spent its lifetime over generally neutral sea-surface height anomalies. SSTs over the area of development and intensification were generally 0.5°C to 1.5°C above average.

Hamish (Perth TCWC): 19 to 21 April 1999

Tropical cyclone *Hamish* (Fig. 6) was the final cyclone for the 1998-99 season. A tropical low embedded in the monsoon trough was analysed southwest of Sumatra on 16 April. Located in the upper-level ridge axis with a favourable poleward outflow channel, the low slowly deepened. The major steering influence was a 500 hPa high to the east of the low, directing the system southwest. The low was upgraded to tropical cyclone *Hamish* just after 0700 UTC on 20 April when the centre was located about 300 nm west of Cocos Island. *Hamish* continued to intensify during the 20 April reaching estimated peak intensity with MSW of 28 m s^{-1} by 1900 UTC. The continued movement poleward finally led to the demise of the system as it encountered increasing vertical shear with strong upper westerly winds ahead of an approaching trough, overlying low-level easterly flow. The system weakened rapidly as convection was sheared off to the southeast of the low-level centre and by 1600 UTC on 21 April, *Hamish* was downgraded to a tropical low. The subtropical ridge to the south of the system became the predominant steering influence on the remaining low-level centre, directing the system westward.

TOPEX/ERS-2 analysis on 21 April indicates *Hamish* developed and intensified to peak intensity over an area of marginally positive sea-surface height anomalies. Typically SSTs over the region were close to average.

Discussion on influences on tropical cyclone genesis and structure change

The above SST and TOPEX/ERS-2 analyses are inconclusive in providing evidence that deep warm oceanic mixed layers, offering reservoirs of high heat content water, had a strong influence on tropical cyclone development and intensification. Systems developed and intensified over negative, neutral and positive sea-surface height anomalies. Severe cyclone *Gwenda*, the most intense system to develop in the region during the 1998-99 season, developed and intensified over neutral height anomalies. In comparison, SSTs in the region of development and intensification of most systems were generally above average. The major exception was severe cyclone *Thelma*, which developed and intensified to peak intensity over an area of below average SSTs. However, sea-surface height anomalies in the area were strongly positive, particularly over waters in which *Thelma* reached peak intensity, suggesting that the mixed layer may have provided some contribution to the system's intensification. *Ella, Hali* and *Hamish* developed over areas where SSTs were close to normal. In comparison, sea-surface height anomalies were typically neutral to moderately positive.

Typically, a stronger signal for system intensification and decay could be seen in the environmental wind field. System intensification was generally coincident with weakened environmental wind shear and the development of an upper outflow channel, whereas rapid system decay was in most instances closely linked with increased environmental shear.

Tropical disturbances

Tropical low (Nadi RSMC): 18 to 20 January 1999

A trough extending from cyclone *Dani* linked to a tropical low located just southwest of Fiji, brought north to northwest flow across the Island Group. In the six hours to 1200 UTC on 18 January, Nadi recorded 48 mm of rain. In the following six hours Nadi recorded another 237 mm of rain following the development of strong low-level confluent northeast to northwest flow over the region. Further rain and thunderstorms continued over the next 12 hours and in the 24 hour period from 0600 UTC on 18 January to 0600 UTC on 19 January, Nadi recorded 451 mm of rain. Widespread flooding in the western parts of Vitu Levu caused loss of life and widespread damage to infrastructure, livestock and crops. Six people were killed and damage was estimated at $4 million (Fijian dollars).

Tropical Low (Brisbane TCWC): 8 to 10 February 1999

A mean sea-level low pressure system over waters to the east of Brisbane, in combination with a middle to upper-level low pressure system over inland Queensland produced a strong backing with height vertical wind structure over southeast Queensland, conducive to extreme rainfall events. A strengthening mean sea-level ridge to the south of the low further enhanced low-level convergence.

Heavy rainfall over southeast Queensland, resulting from this system, produced widespread flooding in the region. The highest rainfall recordings over the 24 hour period to 2300 UTC on 8 February included 404 mm at Maleny, 370 mm at Mary Cairncross and 322 mm at Nambour, all located in the Sunshine Coast hinterland region. Flooding of local rivers and creeks claimed the lives of 7 people. The Mary River at Gympie peaked at 21.95 m, the highest flood level recorded since January 1898. More than 30 houses and 60 businesses were inundated by flood waters. Many roads were cut or severely damaged by land slips and strong winds along the coastal belt brought down power lines and caused some roof damage.

The middle to upper-level low continued to move westward during 8 April and became decoupled from the mean sea level low, still located to the northeast of Brisbane. By 2300 UTC on 9 April, the surface low had dissipated and the middle to upper level low had moved into central Australia and weakened. This allowed the mean sea level ridge to extend along the east coast of Queensland to the monsoon trough where tropical cyclone *Rona* was beginning to form.

Acknowledgments

Descriptions and 'best track' data for each cyclone were kindly provided by the Australian Bureau of Meteorology, the Fiji Meteorological Service, Met Service New Zealand and RSMC La Reunion.

References

Dvorak, V.F. 1984. Tropical Cyclone Intensity Analysis Using Satellite Data. *NOAA Technical Report NESDIS 11*, 45pp.

Madden, R.A. and Julian, P.R. 1971. Detection of a 40-50 day oscillation in the zonal wind in the tropical Pacific. , 702-7.

McGaughey, G., Zipser, E.J., Spencer, R.W. and Hood, R.E. 1996. High-resolution passive microwave observations of convective systems over the tropical Pacific Ocean. *Jnl appl. Met., 35,* 1921-47.

Mohr, K.I. and Zipser, E.J. 1996. Defining mesoscale convective systems by their 85-GHz ice scattering signature. *Bull. Am. Met. Soc., 77,* 1179-89.

Palmen, E. 1948. On the formation and structure of tropical cyclones. *Geophysics, 3,* 26-38.

Shaik, H.A. and Bate, P.W. 1999. The tropical circulation in the Australia/Asian region - November 1998 to April 1999. *Aust. Met. Mag., 48*, 211 - 22.

Shay, L.K. 1998. Ocean Processes excited by tropical cyclones. *Rapporteur reports of the Fourth WMO International Workshop on Tropical Cyclones (IWTC-IV)*, Haikou, China.

Spencer, R.W., Goodman, H.M. and Hood, R.E. 1989. Precipitation retrieval over land and ocean with the SSMI: Identification and characteristics of the scattering signal. *J. Atmos. Oceanic Technol., 6,* 254-273.