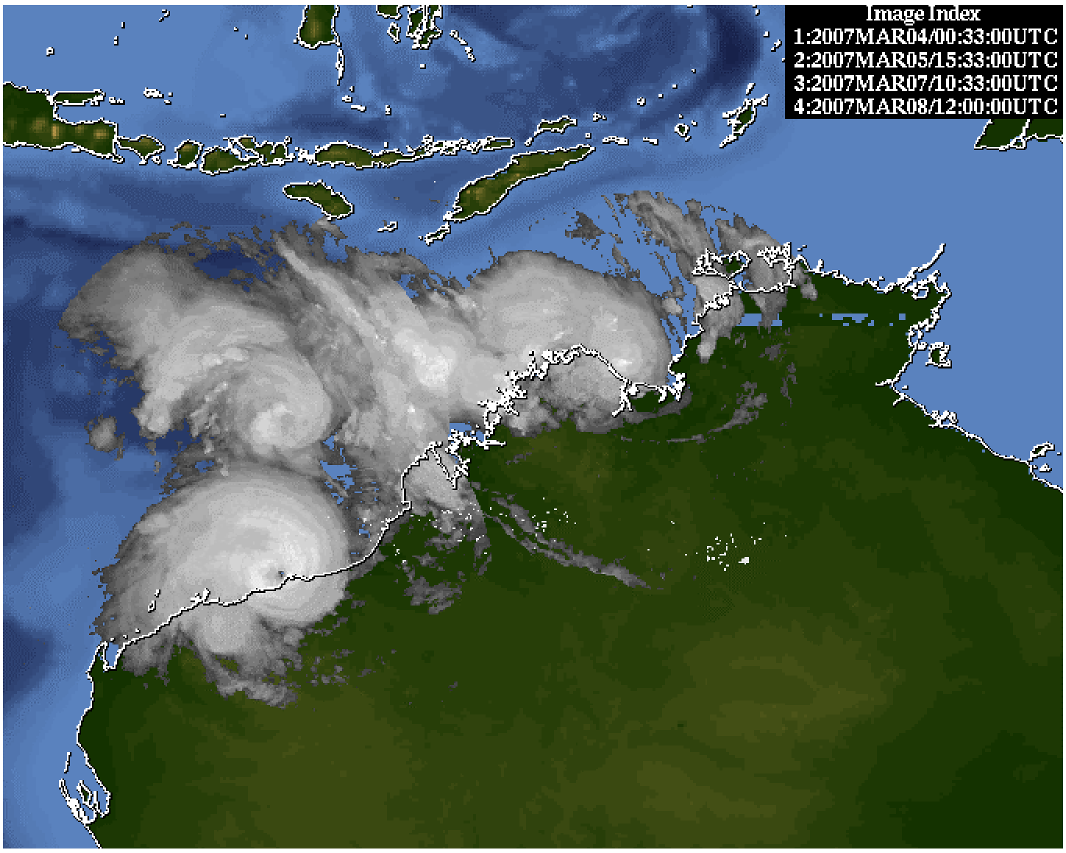
Australian Government

Bureau of Meteorology

Tropical Cyclone Season Summary
Western Australian Region
2006 – 2007



Montage of satellite images of TC *George,* March 2007.
Image provided by Chris Velden, CIMMS Uni. Wisconson

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Season Overview

There were just three tropical cyclones in the Perth TCWC area of responsibility *George, Jacob* and *Kara*, all of which occurred off the northwest coast during March. Of these only *George* had a direct wind impact to land areas crossing the coast near Port Hedland as a category 5 cyclone and causing extensive damage along its track. There were three deaths attributed to the impact of *George*. Just two days later *Jacob* crossed the coast in a similar location but as a tropical low. *George, Jacob* and *Kara* were all severe tropical cyclones, *George* reaching category 5 intensity, *Jacob* category 3, and *Kara* category 4. Although not causing a direct impact to land areas, the threat of *Jacob* and *Kara* did cause a significant economic impact by disrupting mining and offshore industry activities.

In addition in early January a tropical low was named *Isobel* operationally but was later downgraded to a tropical low during the reanalysis. It combined with a strong mid-latitude trough to cause heavy rain and flooding in the Esperance region.

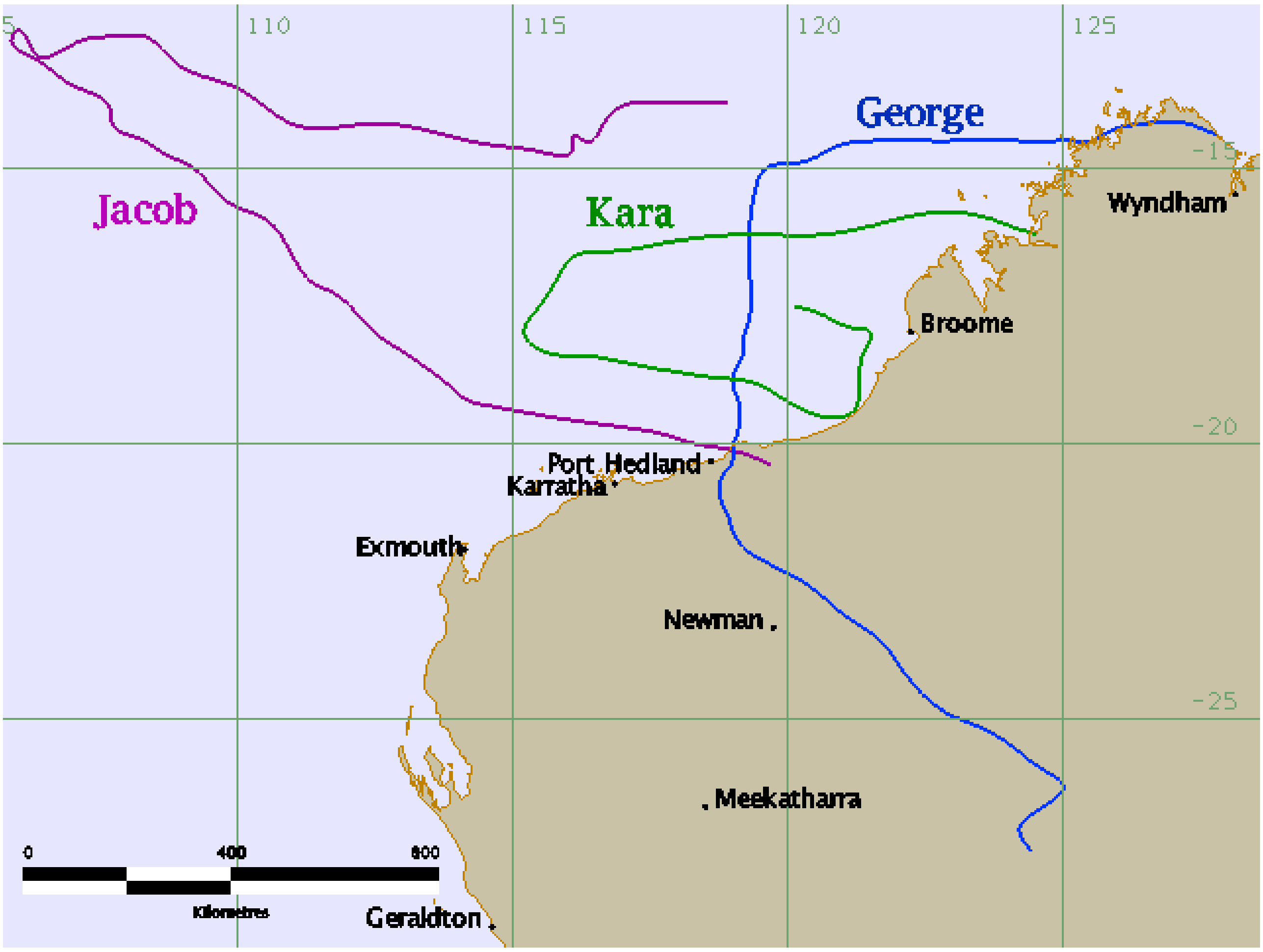

Figure 1. Tracks of tropical cyclones, 2006-07 in Perth TCWC area of responsibility.
Note: Isobel is excluded as it was reanalysed as a tropical low.

1. TROPICAL LOW 'ISOBEL' and the Esperance Rain Event
30 December 2006 - 5 January 2007

1 A. Summary
A tropical low formed south of the Indonesian archipelago on 30 December 2006 and moved initially eastwards then took a general southerly track from 2 January 2007 weakening to the north of Port Hedland on near the Northwest coast on 3 January. On the 2nd the low was upgraded to cyclone intensity operationally and named '*Isobel'* but the post-analysis indicates that the low did not reach tropical cyclone intensity. The most significant impact was economic from loss of productivity caused by the disruption to mining and offshore drilling operations and by the temporary closure of the port at Port Hedland.

Tropical moisture associated with the tropical low interacted with a remarkably deep mid-latitude trough resulting in heavy rain across the Goldfields, Eucla and South East Coastal Districts. The heaviest rainfall was near Esperance were flooding caused major damage to port facilities in particular.

1 B. The Tropical Low
A low formed in the trough at the western edge of an active phase of the Madden-Julian Oscillation (MJO) in the final days of 2006. Formation of a low somewhere between 110E and 120E was expected given the MJO signal (which had been associated with the development of systems in the southwestern Indian Ocean in previous weeks). Formation was assisted by a strengthening of the NW'ly monsoon driven by a surge from across the equator in the South China Sea. Strong monsoon winds are believed responsible for the sinking of a ferry containing 600 people in the Java Sea between Java and Borneo.

From formation to dissipation near the coast the system displayed the characteristics of a broad elliptical monsoon gyre with a generally dominant Low Level Circulation Centre (LLCC) at one end of the ellipse. Although there was evidence of other LLCCs within the gyre at various times they were not as long lived or as clearly evident in microwave imagery as the dominant LLCC. Based on its longevity, clear signature in the microwave imagery at most times and relative dominance over other LLCCs this feature was used to determine track positions, rather than tracking the centroid of the gyre. During operations there were times when the centroid of the gyre was used for fixing positions due to warning policy considerations. This is likely to result in an increase in apparent error in the operational analysis track.

As is common for monsoonal disturbances the system initially experienced easterly shear that is likely to have limited the development rate. On 1 January a well-defined LLCC (circular cloud lines indicating significant surface vorticity) became evident in the visible imagery as it separated from deep convection and was steered east in the strong low level monsoon westerlies. At 01/0600 UTC a ship (call sign DMDZ) reported 45 knot winds as this feature passed just to the south. Scatterometer winds at around 1000 UTC indicated that the synoptic scale winds in the monsoon flow on the northern side of the gyre were around 30 knots at this stage. Organisation of convective features was poor and Dvorak estimates indicated the system was below cyclone intensity. It is likely that the strongest winds in the system were associated with the northern side of the "tightly wound" and rapidly translating LLCC. It is possible that the ship experienced these winds, which scatterometry would not be expected to resolve given the scale involved.

From 01/1200 UTC the system began to take a more southerly track. During 2 January the system approached the upper ridge and at 02/0600 UTC, with gales possible in the eastern quadrant (later supported by the scatterometry pass at 0940 UTC) the system was named operationally for warning policy reasons (principally the possibility of gales over coastal areas the next morning from an unnamed system previously described as having potential to develop into a TC, and possibility of further development overnight if the shear dropped for a sufficient period before increasing due to mid-latitude trough). This decision was also supported by an increase in convection near the centre as shown on visible imagery.

Visible imagery on 3 January shows the LLCC exposed as the convection had continued to shear southward under the influence of the mid-level trough. Disconnected from the (now weakening) convection the LLCC then rapidly weakened into an insignificant feature and was indiscernible by 0600 UTC. At this time a new pressure minimum is identifiable over land near Pardoo (991 hPa) but is only associated with light winds as the remnants of the monsoon gyre continue to dissipate.

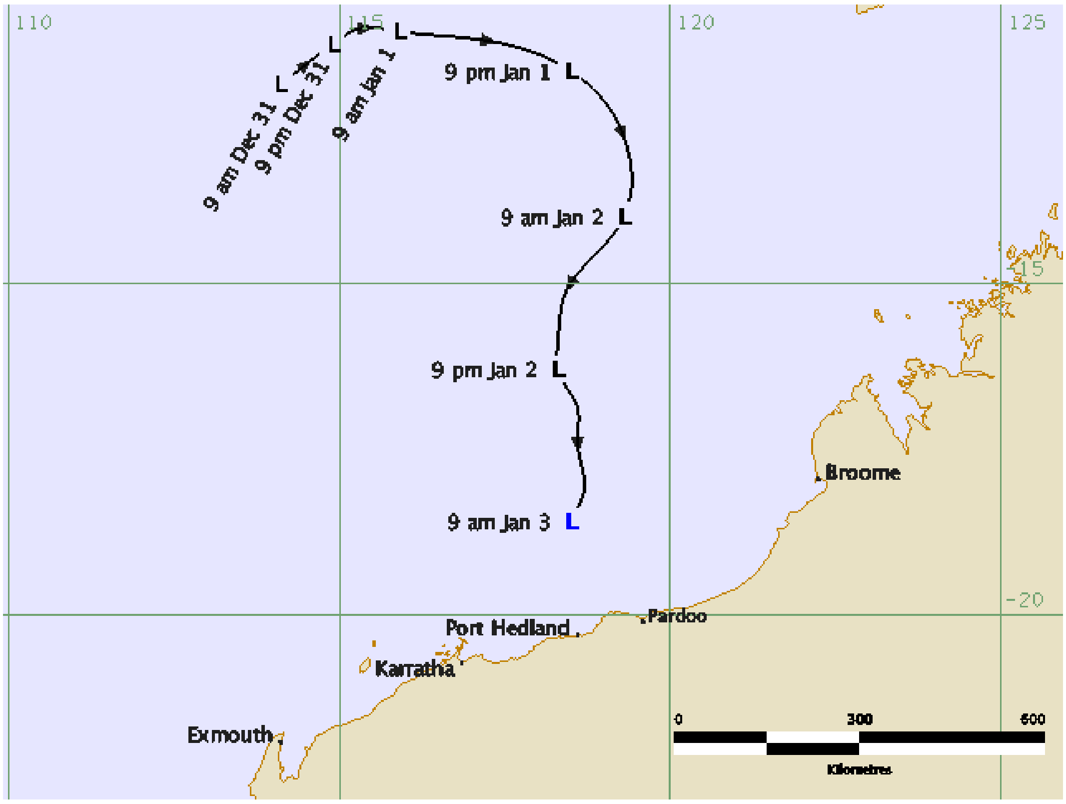

Figure 1.1. Track of the Tropical Low

1 C. The Esperance Rain Event
Tropical moisture associated with a tropical low (named *Isobel* operationally) that weakened near the coast near 80 Mile Beach on Wednesday the 3rd, interacted with a remarkably deep mid-latitude trough resulting in heavy rain across the Goldfields, Eucla and South East Coastal Districts. Many rainfall records were broken.
Notable falls included:
Esperance Aero 177mm, Cheadenup 161.4 mm, Esperance 155.0 mm, Munglinup Town 153.6 mm, Telina Downs 138.6 mm, Merivale Farm 137.8 mm, Erinair 135 mm, Ravensthorpe 112.8 mm, Salmon Gums 91.6 mm.

Cumulative 48 hour falls were: 204.2mm at Cheadenup, 186mm at Esperance and 224mm at Esperance Aero. The Esperance Aero rainfall graph shows the highest rainfall fell on the afternoon of the 4th when 88.2mm fell between 12:50 and 18:50WDT.

The weekly rainfall map ending 7 January shows an area of more than 150mm in the Esperance area and in the 80 Mile Beach area. One farmer was reported as emptying over 300 mm from his rain gauge suggesting that even higher falls occurred.
The previous highest daily rainfall at Esperance was 106.6mm on 7/1/1999. In that event 206.6 mm of rain fell in three days.

The South Coastal Highway was cut when part of the bridges across the Young and Oldfields River were washed away. Preliminary Agriculture WA reports indicate that approximately 50 000 sheep died because of hypothermia and drowning. Floodwaters also damaged fences, scoured topsoil and inundated some properties. Farmers did note that erosion soil erosion was not as bad as it would otherwise have been because of the use of seeding by direct drilling rather than conventional ploughing.

Bandy Creek broke its banks at the weir at the entrance to the Boat Harbour. Sand flooded into the harbour, stranding Esperance's small commercial fishing fleet and yachts that later sat on newly created banks of sand.

Strong winds also downed power lines and high tides and heavy surf caused beach erosion. The storm surge at Esperance was measured at 60cm. Esperance recorded a wind gust of 111 km/h, eclipsing the previous highest January gust of 104 km/h that it recorded in 1975. Esperance Aero recorded 30-35 knot mean winds from 04/1750 to 05/0040 WDT as shown on the graph of Esperance Aero winds.

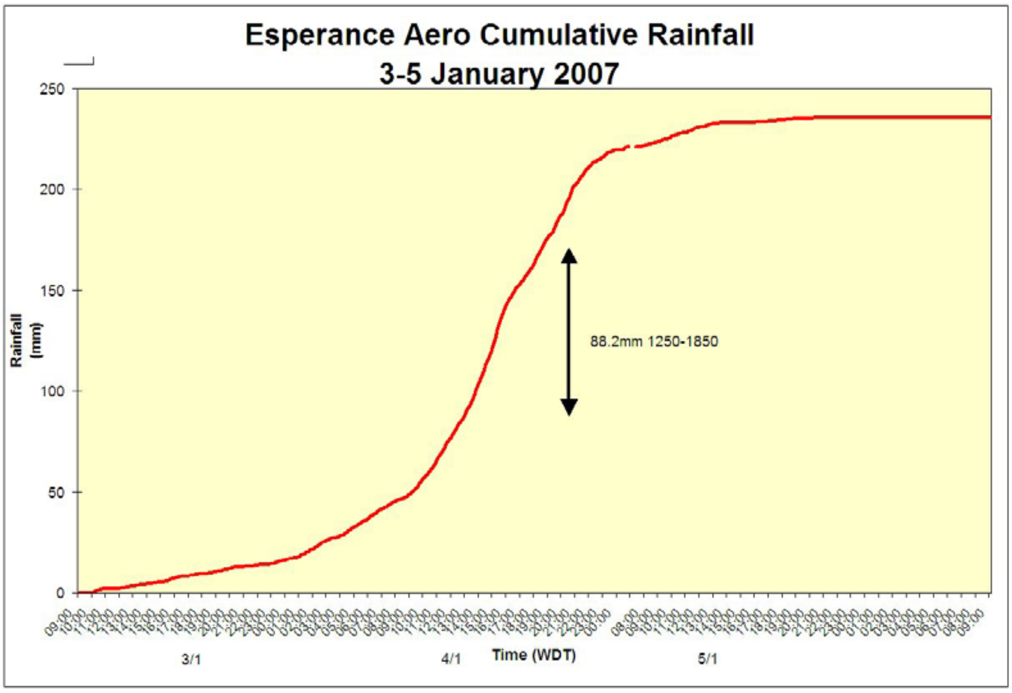

Figure 1.2. Esperance rainfall 3-5 January 2007.

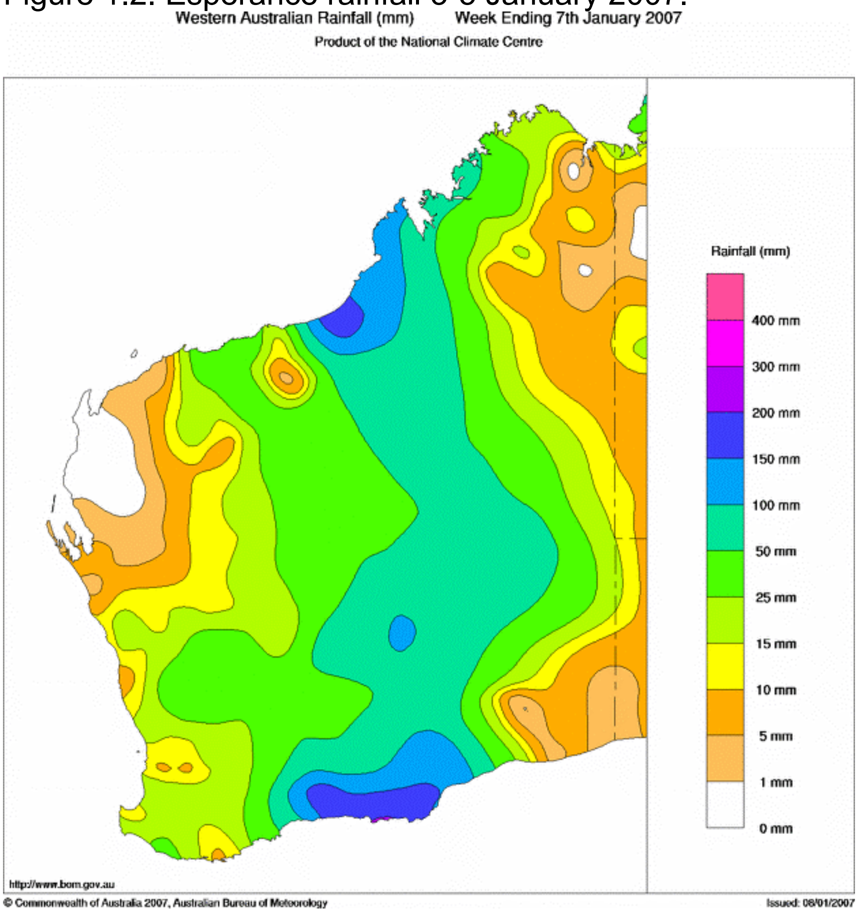

Figure 1.3. Weekly rainfall ending 7 January 2007.

2. Severe Tropical Cyclone *George*

2 A. Summary

Severe Tropical Cyclone (TC) *George* was both very intense and physically large. *George* was the most destructive cyclone to affect Port Hedland since TC *Joan* in 1975.

TC *George* formed on 3 March in the Joseph Bonaparte Gulf. It weakened back to a tropical low as it tracked westwards across the northern Kimberley and then re-intensified shortly after moving offshore into the Indian Ocean on 5 March. *George* intensified to a Severe Tropical Cyclone (Category 3) on the evening of 7 March and reached Category 5 as it approached the coast. It was still at its maximum intensity when it crossed the coast 50 km northeast of Port Hedland at 10 pm Western Daylight Savings Time (WDT) on Thursday 8 March.

The wind impact was greatest between Wallal and Whim Creek. A 10-minute mean wind of 194 km/h, equivalent to wind gusts of approximately 275 km/h, was recorded offshore at Bedout Island. At Port Hedland Airport, gusts of 154 km/h were recorded around 11 pm WDT prior to equipment failure. It is likely that stronger winds were experienced around midnight, on the outer edge of the band of maximum winds.

Winds decreased markedly as the system tracked inland overnight however *George* is estimated to have continued to produce “very destructive winds” (Category 3 or higher intensity) until just after 6 am WDT 9 March, at which time it was approximately 115 km south southeast of Port Hedland.

TC *George* produced large amounts of rain in the northern Kimberley and the Northern Territory earlier in its lifecycle. Upon approaching the Pilbara coast, substantial (but not exceptional) falls occurred. A lack of previous rainfall and the steady movement of *George* prevented significant flooding.

Reported impacts include three fatalities and numerous injuries at locations south of Port Hedland. Less than two per cent of buildings in the greater Port Hedland area (i.e. including South Hedland) sustained structural damage (Cyclone Testing Station, School of Engineering, James Cook University Queensland, (CTS) 2007a). The majority of damaged buildings were later identified as having weaknesses due to poor maintenance and it is notable that the majority of housing stock withstood the wind gusts, which were estimated to have reached around 200 km/h. The Bureau's Port Hedland radar dome sustained damage.

2 B. Meteorological Description

3-6 March: Formation

Tropical Cyclone *George* formed on 3 March when a tropical low, which had tracked across the "Top End" of the Northern Territory, moved offshore into the Joseph Bonaparte Gulf. *George* subsequently weakened back to a tropical low as it moved westwards across the northern Kimberley. The system then re-intensified into a tropical cyclone shortly after moving offshore into the Indian Ocean on 5 March. *George* then moved away from the coast tracking steadily west at 6-8 knots (11-15 km/h) – close to the climatological average. Table 2.1 summarises the track, intensity and structure of *George* and figure 2.1 provides a graphical depiction of the track.

Oceanographic conditions along *George*'s track were favourable throughout its life with broad areas of warmer than usual sea surface temperatures (SSTs) existing off the northwest coast of Australia.

George slowly intensified during 5 March and reached Category 2 intensity at 3 am 6 March before weakening back to Category 1 at 9 pm 6 March.

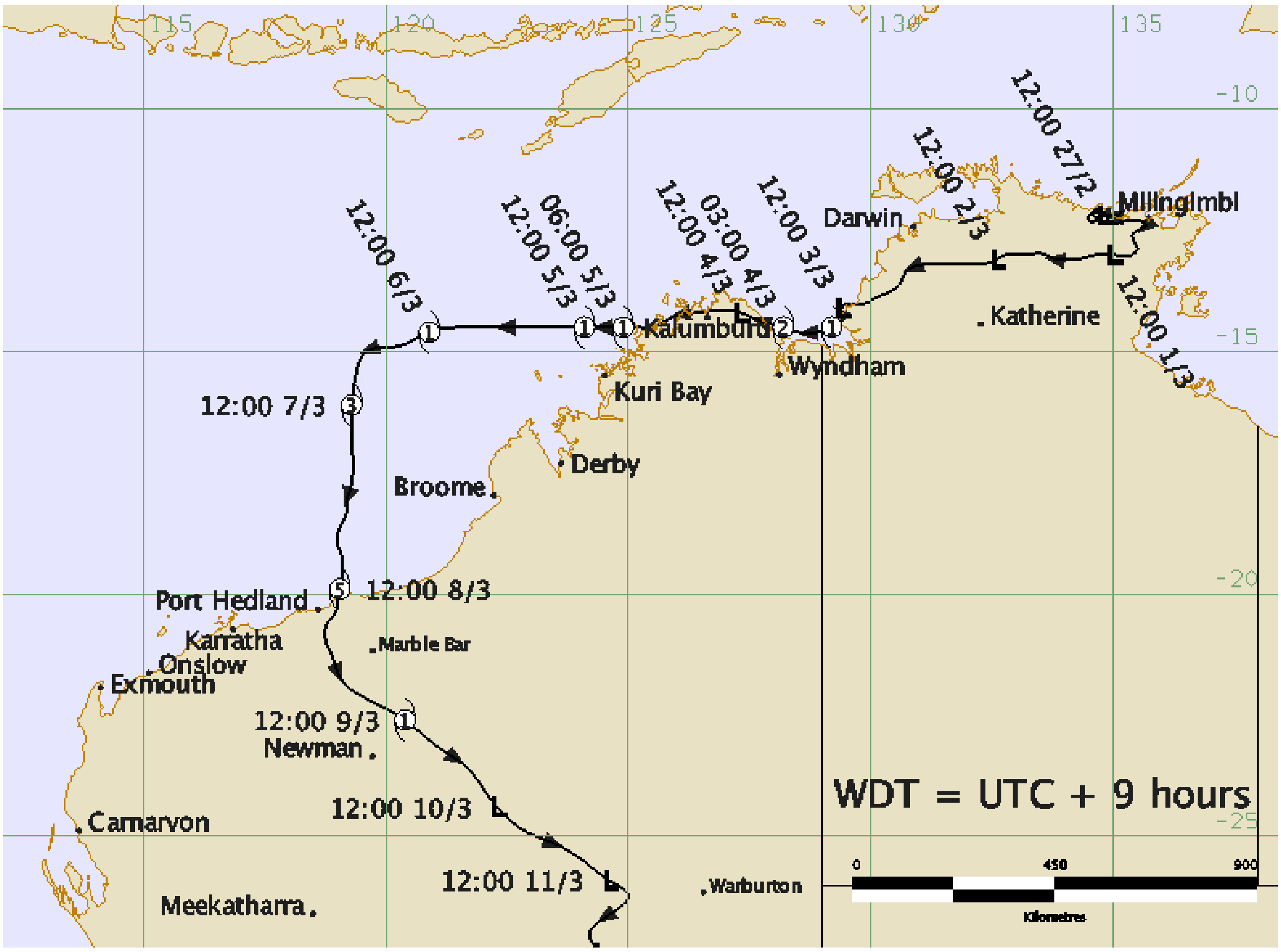

Figure 2.1 Track of Severe Tropical Cyclone *George*.

7 March: Abrupt southerly track shift
On the morning of 7 March TC *George* turned abruptly to the south, making an almost 90 degree turn to the left of its previous track, and began to rapidly intensify. It became a Severe Tropical Cyclone (Category 3) by 9 pm 7 March.

The rate of intensification during the 24-hour period to 9 am 8 March was twice that of the standard Dvorak model of tropical cyclone development (Dvorak, 1984). Its maximum sustained (10-minute) wind speed is estimated to have increased from 90 km/h to around 165 km/h during this period. It is not uncommon for intense tropical cyclones (Category 4 or 5) to undergo some period of rapid development during their life cycle (Kaplan and DeMaria 2003; Holliday and Thompson 1979).

Year	Month	Day	Hour (UTC)	Position Latitude S	Position Longitude E	Position Accuracy nm	Max wind 10min knots	Max gust knots	Central Pressure hPa	Radius of Gales nm	Radius storm force winds nm	Radius hurricane force winds nm	Radius Maximum Wind nm
2007	3	5	00	14.5	125.5	10	30	45	990				18
2007	3	5	06	14.5	124.9	15	40	55	982	43			18
2007	3	5	12	14.5	124.1	20	45	65	980	55			16
2007	3	5	18	14.5	123.2	30	50	70	976	60	15		15
2007	3	6	00	14.5	122.4	30	50	70	976	60	15		15
2007	3	6	06	14.5	121.6	30	50	70	974	65	15		15
2007	3	6	12	14.6	120.9	30	45	65	978	73			15
2007	3	6	18	14.9	120.2	15	45	65	978	78			15
2007	3	7	00	15.0	119.6	15	50	70	974	85	28		15
2007	3	7	06	15.4	119.3	15	60	85	964	93	35	25	15
2007	3	7	12	16.1	119.3	15	70	100	956	105	50	30	15
2007	3	7	18	16.8	119.3	15	75	105	952	110	50	30	14
2007	3	8	00	17.7	119.3	10	90	125	930	113	50	30	12
2007	3	8	03	18.3	119.2	5	90	125	930	108	58	30	11
2007	3	8	06	18.8	119.0	5	95	135	924	100	60	29	10
2007	3	8	09	19.3	119.1	5	105	150	910	95	59	29	9
2007	3	8	12	19.9	119.1	5	110	155	902	93	56	23	10
2007	3	8	15	20.4	119.0	5	95	135	916	93	49	23	10
2007	3	8	18	20.9	118.8	5	75	105	940	85	44	19	12
2007	3	8	21	21.3	118.9	10	65	90	950	85	34		12
2007	3	9	00	21.6	119.0	15	55	75	960	80	30		14
2007	3	9	03	21.9	119.2	15	50	70	964	75	30		14
2007	3	9	06	22.1	119.5	15	45	65	966	70			16
2007	3	9	12	22.6	120.4	25	40	55	976	35			16
2007	3	9	18	23.1	121.0	30	35	50	980	25			16
2007	3	10	00	23.6	121.7	30	30	45	982				16
2007	3	10	06	24.0	122.0	30	30	45	982				16
2007	3	10	12	24.4	122.3	40	30	45	986				16
2007	3	10	18	24.9	122.9	50	30	45	988				16
2007	3	11	00	25.2	123.6	60	25	40	990				18
2007	3	11	06	25.6	124.2	60	25	40	992				18
2007	3	11	12	25.9	124.6	60	25	40	994				18
2007	3	11	18	26.2	125.0	60	25	40	996				18
2007	3	12	00	27.0	124.2	45	20	30	1000				18
2007	3	12	06	27.4	124.4	45	20	30	1000				18

(1 nm = 1.852 km, 1 knot = 1.852 km/h)

Table 2.1. Best track summary for Severe TC *George*.

8 March: Intensification continues up to coastal crossing

Severe Tropical Cyclone *George* came into range of the Port Hedland radar during the morning of 8 March, allowing hourly analysis of track positions. Figure 2.2 shows a satellite image of *George* close to midday on 8 March. Only minimal intensification occurred during the less favourable diurnal period from 9 am to 3 pm. However over the next three hours to 6 pm significant intensification occurred and the eye is estimated to have shrunk to around half the diameter of 24 hours earlier. At 7 pm Bedout Island recorded a 10-minute mean wind of 194 km/h as the eye wall passed over the island. This is the highest 10-minute mean wind speed ever officially recorded in Australia. However it is very unlikely to be the highest mean wind speed that has ever occurred in Australia.

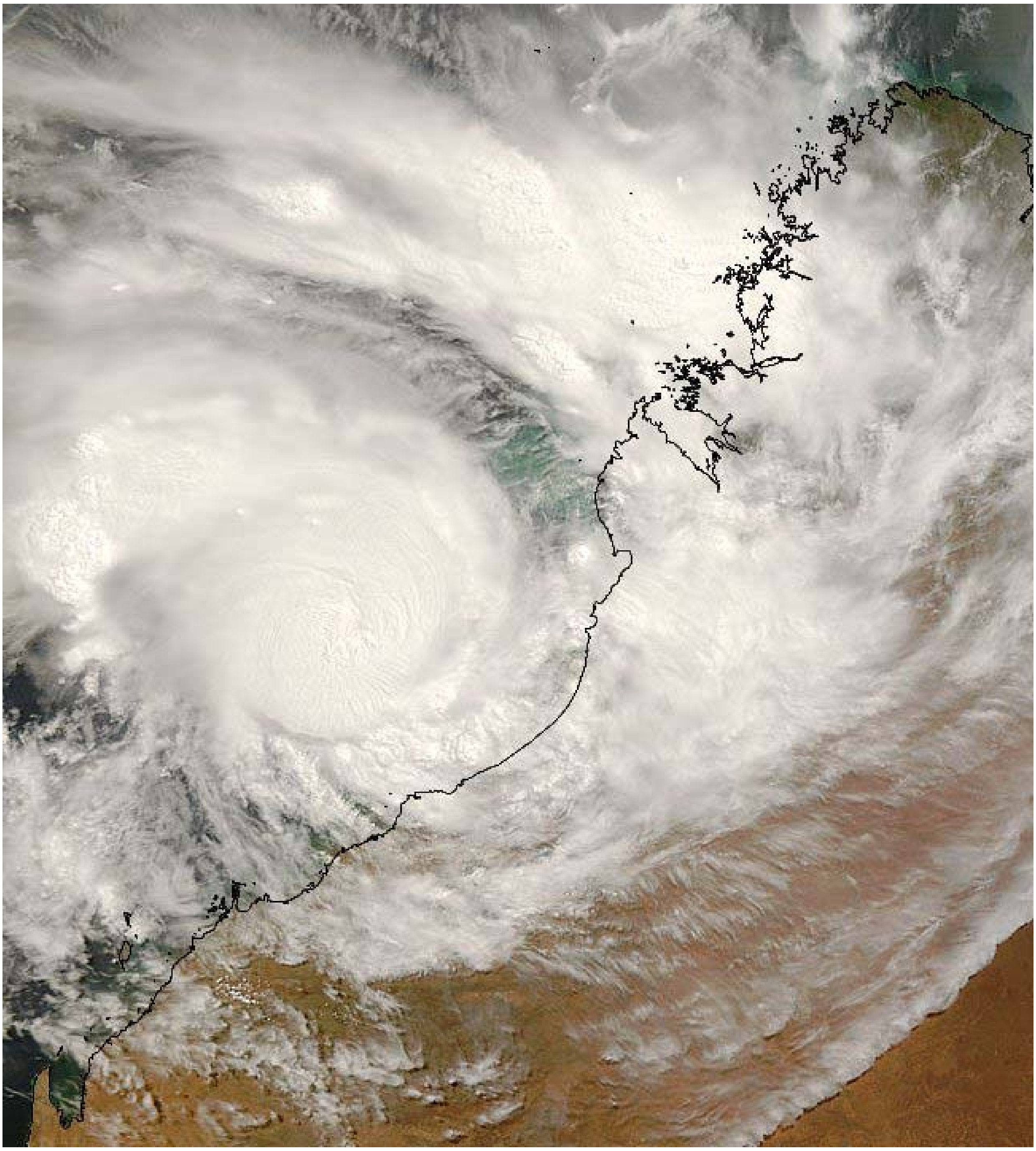

Figure 2.2. Satellite image of TC George at 10:55 am WDT 8 March (image courtesy of NASA).

Characteristics of TC George close to landfall

Peak intensity

Dvorak analysis of satellite imagery (Dvorak, 1984, 1995) indicates that peak intensity was reached just prior to landfall, with 10-minute mean winds of around 205 km/h, and wind gusts of around 285 km/h (Category 5). *George* was still at its maximum intensity when it crossed the coast 50 km northeast of Port Hedland at 10 pm. Figure 2.3 shows a panel of satellite images of TC *George* close to landfall.

Verification of Dvorak-based maximum mean wind speed estimates of tropical cyclones in the Atlantic basin against estimates based on aircraft reconnaissance indicates that 50 per cent of Dvorak estimates are within 9 km/h, 75 per cent are within 22 km/h and 90 per cent are within 33 km/h (Brown and Franklin, 2004).

The supporting observation from Bedout Island provides added confidence in the Dvorak-based “best track” estimate of peak wind gusts (285 km/h).

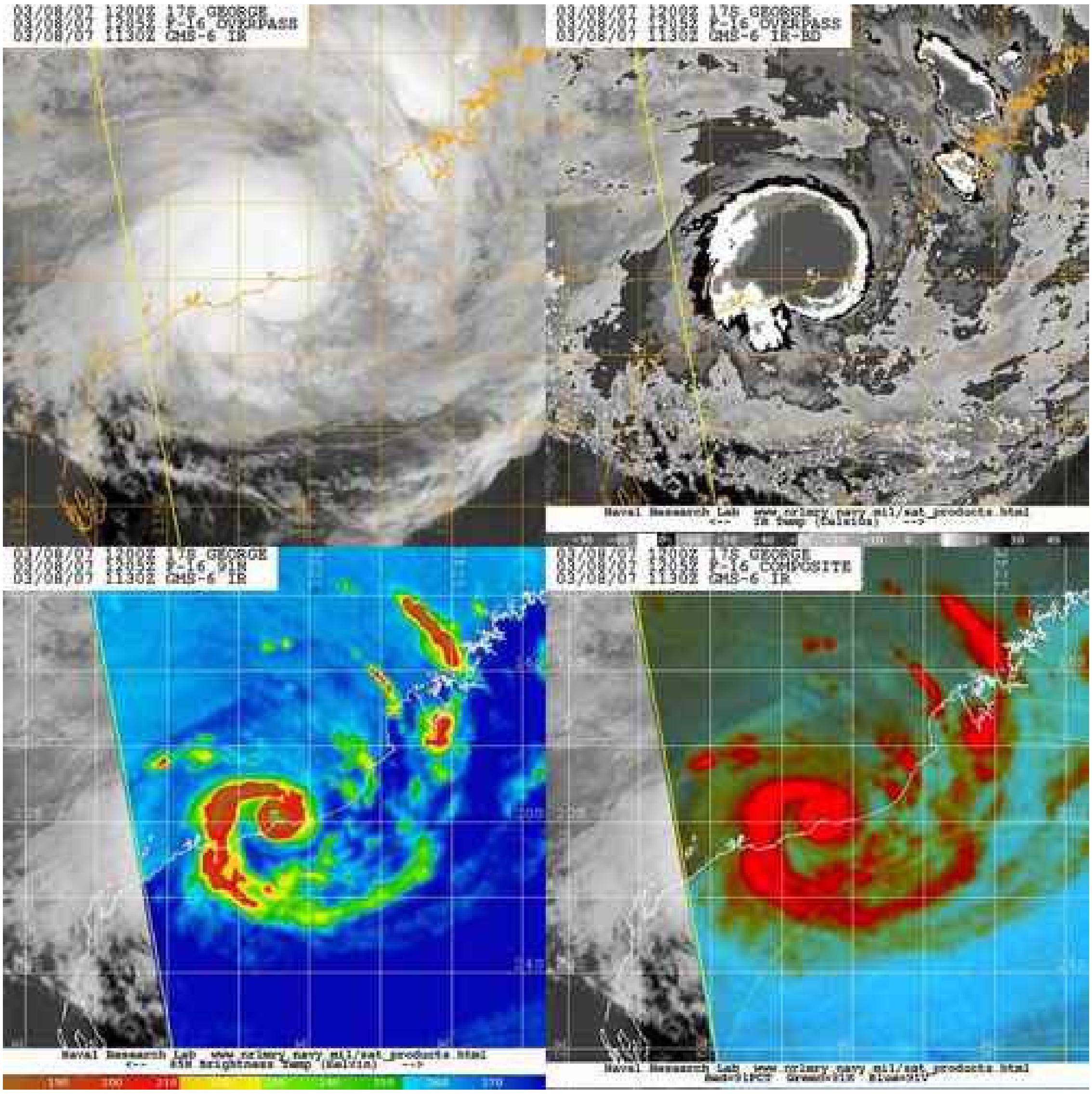

Figure 2.3. Satellite imagery of TC *George* at 9 pm WDT 8 March.
(image courtesy of United States Naval Research Laboratory: http://www.nrlmry.navy.mil/)

Radius to the maximum wind speed band

Radar imagery of *George* as it approached landfall showed a well-defined elliptical eye of up to 25 km diameter across its long axis and around 15 km across the short axis. The ellipse rotated in a clockwise direction. Elliptical eyes are common in tropical cyclones with the ellipse often observed to rotate in the same direction as the cyclone circulation (Lewis and Hawkins, 1982). Figure 2.4 is the Port Hedland radar image at 10:10WDT showing the eye at landfall.

After landfall the shape of the radar-observed eye became more variable, but generally retained marked asymmetry. As *George* tracked inland the eye diameter increased to around 30-35 km. This is consistent with a weakening in intensity.

The eye was clearly depicted in radar imagery through to 2 am 9 March after which radar imagery was not available again until the system centre was outside radar range. The eye could be identified in microwave imagery at around 3 am; however at 7 am the eye region was only weakly defined and had begun to fill with rain. By 9 am 9 March no eye could be discerned.

The radius of maximum winds (RMW) is generally observed to lie outside the inner radar-eye radius (IRR) by several to tens of km (Meighen, 1990). The relative position of the RMW to the IRR varies across different tropical cyclones and during the life cycle of a particular system. For an intense tropical cyclone with a small IRR - such as *George* at landfall - the RMW is typically found around 5 to 10 km outside the IRR. On this basis the RMW for *George* is likely to have been around 15 to 20 km at landfall, increasing to around 20 to 25 km by 3 am 9 March. The asymmetries described above should be kept in mind when interpreting the simplified depiction of the “eye swathe” in Figure 2.5.

Radius to Gales

The radius to gales is commonly used as one measure of the size of a tropical cyclone. Underlying terrain has an influence on the measurement of wind speeds. The increased roughness of the land surface compared with the ocean leads to greater frictional forces. Greater frictional forces result in lower mean wind speeds over land compared with over the ocean, but can also result in a higher ratio of wind gusts to mean wind speed - greater “gustiness”. Thus the radius to gales measured over a water surface will be greater than if the same system were over land. In the following discussion we compare figures for radius to gales only when over an ocean surface.

Scatterometer data from the QuikScat satellite provide periodic estimates of winds near the ocean surface. In the absence of in situ anemometers this data provides the best possible means of ascertaining radius to gales and has been used extensively in the “best track” analysis. (Additional information on scatterometry and the QuikScat satellite can be obtained from http://manati.orbit.nesdis.noaa.gov/quikscat/.) Anemometer data from Rowley Shoals and Bedout Island was used to validate the scatterometer data whenever possible.

Early on 8 March *George* had an average gale radius of around 200 km. This is significantly larger than the climatological average of around 150 km for cyclones of Category 3 or greater intensity in the southeast Indian Ocean. (Average calculated on post-1999 data for which gale radius estimates are more reliable due to availability of scatterometer data.) Gales extended further from the centre in the northern and southern quadrants (around 240 km) than in the eastern and western quadrants (150 and 180 km respectively).

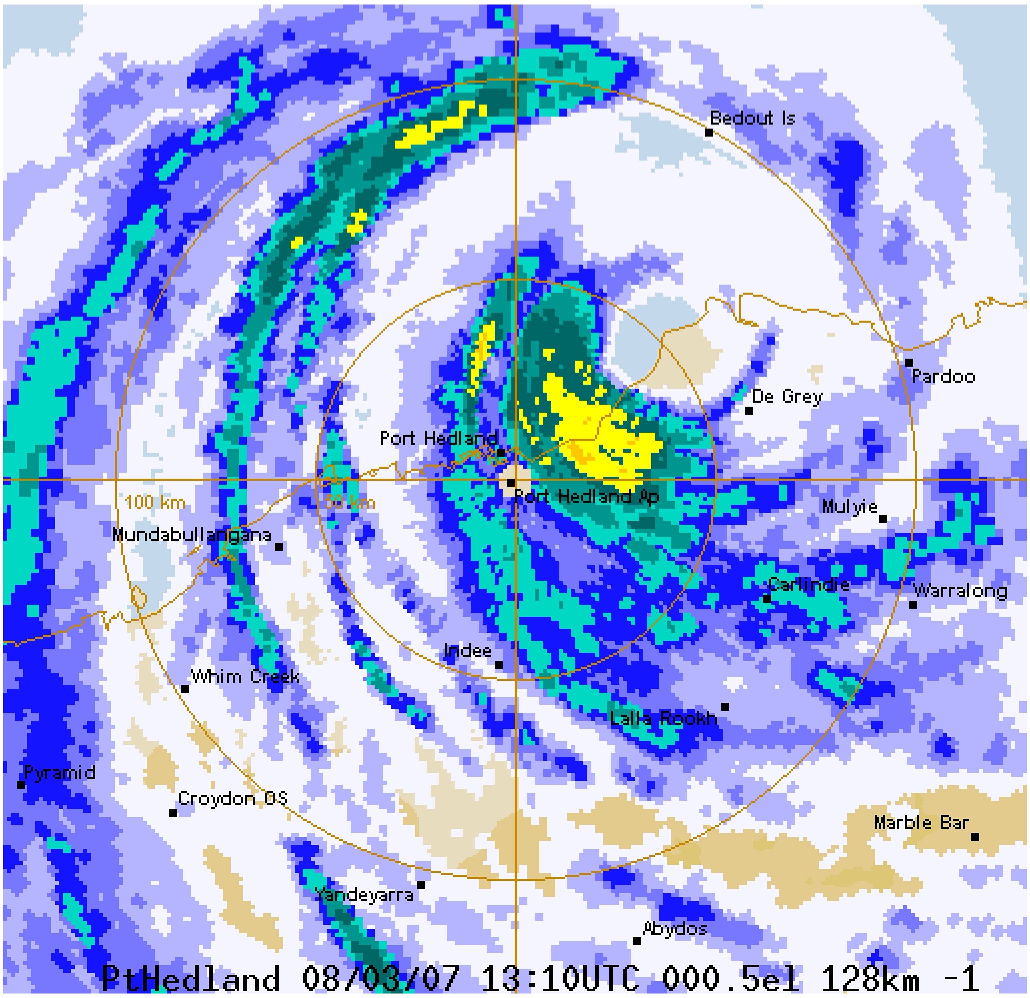

Figure 2.4. Port Hedland radar image at 10:10pm WDT, prior to radar failure.

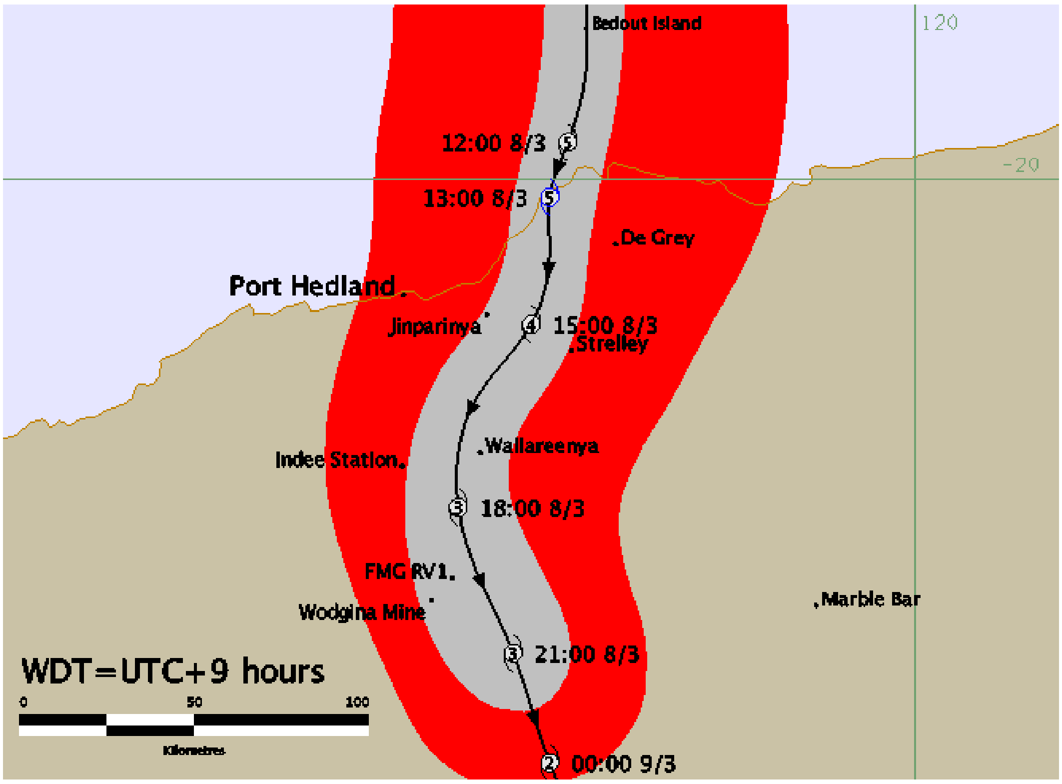

Figure 2.5. Simplified depiction of the swathe of the eye and of Very Destructive winds. Times are shown in Coordinated Universal Time (UTC). Add 9 hours to derive WDT times.

Gale periods at observation sites
Rowley Shoals experienced a period of gales of approximately 25 hours, commencing around 3 am 8 March. Bedout Island recorded a period of gales lasting approximately 40 hours. Gales had commenced by 1 am 8 March and continued through until after 5 pm 9 March. Mean winds above hurricane force (119 km/h or greater) were recorded from 5 pm 8 March through until 11 pm 8 March inclusive, excluding a lull during the passage of the eye.

The first measurement of gales (mean wind speeds of 63 to 88 km/h) by the Port Hedland anemometer occurred at 5:20 pm 8 March. By 9:00 pm WDT mean winds had increased to storm force (mean wind speed of 89 to 118 km/h). Wind gusts greater than 125 km/h, classified as “destructive” wind gusts, began to be felt in the Port Hedland area around this time. Loss of anemometer data at around 11 pm has prevented an assessment of the duration of gales in Port Hedland.

By the time the Port Hedland anemometer was returned to service (just prior to 1 pm 9 March) mean winds at Port Hedland had eased below gale force but were still above 55 km/h. Observations from Bedout Island (found to be in close agreement with the scatterometer data) indicate that gales continued over the ocean until 6 pm 9 March.

Rate of weakening after landfall
There is limited meteorological data upon which to assess the intensity and structure of *George* as it tracked inland. No wind speed measurements were obtained inland close to the centre of the system. Damage to the radar dome at Port Hedland resulted in the radar being offline from 10:10 pm 8 March until 7:20 pm 9 March. Imagery from the Dampier radar was available until 2:00 am 9 March. Satellite imagery was accessible throughout. In addition to these sources of information, useful information was obtained from interviews with people who experienced the passage of the cyclone and through the work of the Cyclone Testing Station (2007b).

The Dvorak technique for analysing the intensity of tropical cyclones (Dvorak, 1984, 1995) was not developed, nor calibrated, for use on systems weakening after landfall. However the structural changes indicated in satellite imagery remain useful indicators of the rate of weakening of the system and it is possible to make a subjective assessment of the rate of weakening based on available satellite imagery. By 2 am 9 March the eye appeared larger than it had at landfall and deep convection was waning both near the centre and in the peripheral rain bands. However the distribution and intensity of deep convection was still better than at 9 am 8 March.

Upper winds tend to be stronger in the mid-latitudes than in the tropics, particularly during winter. Hence tropical cyclones making landfall on the Pilbara coast in March or April often encounter increasingly unfavourable upper winds as they track southwards. The combination of landfall with increasing vertical wind shear leads to rapid weakening of the system despite a relatively flat terrain. In the case of *George* however it is notable that the vertical shear remained weak as the system tracked south over land and *George* was observed to retain its cloud structure longer than average. It is therefore estimated that *George* weakened more slowly than is typical for intense systems making landfall in the Pilbara.

Kaplan and DeMaria (1995) developed an empirical model of the rate of decay of tropical cyclone winds after landfall based on analysis of tropical cyclones making landfall in the

USA where aircraft reconnaissance and a dense land-based network provide better observational data as a foundation to the post-analysis. This model has been applied to *George* and forms the basis of the estimates of inland wind speed provided in the "best track". These estimates are entirely independent of the wind speeds estimated by the CTS (2007b). The close agreement between the two methods creates greater confidence in the results than could be obtained by applying either of the methods in isolation.

Figure 2.5 shows the swathe of "very destructive" winds and the area likely to have experienced the relative calm within the eye. The area experiencing the band of maximum winds will be larger than the "eye swathe". Hence the eye swathe should not be interpreted as the area experiencing the zone of maximum winds. The eye swathe matches both the available radar imagery and eyewitness reports. Although less useful due to poorer resolution, microwave imagery was also assessed for this part of the post-analysis.

The eye expanded as *George* moved inland, reaching a diameter of 30-35 km by around 3 am 9 March. A lull indicative of an eye passage was reported from Fortescue Metals Group's (FMG) Rail Village One (RV1) and the Wodgina mine site, but not from Indee Station. Radar imagery shows the eye deteriorated as it moved further inland, which is expected as a consequence of the weakening of the system after landfall.

Over the next few days *George* tracked in a generally southeasterly direction. The system is estimated to have weakened below tropical cyclone intensity by 9 am 10 March and lost identity as a discrete low pressure system around 3 pm 12 March.

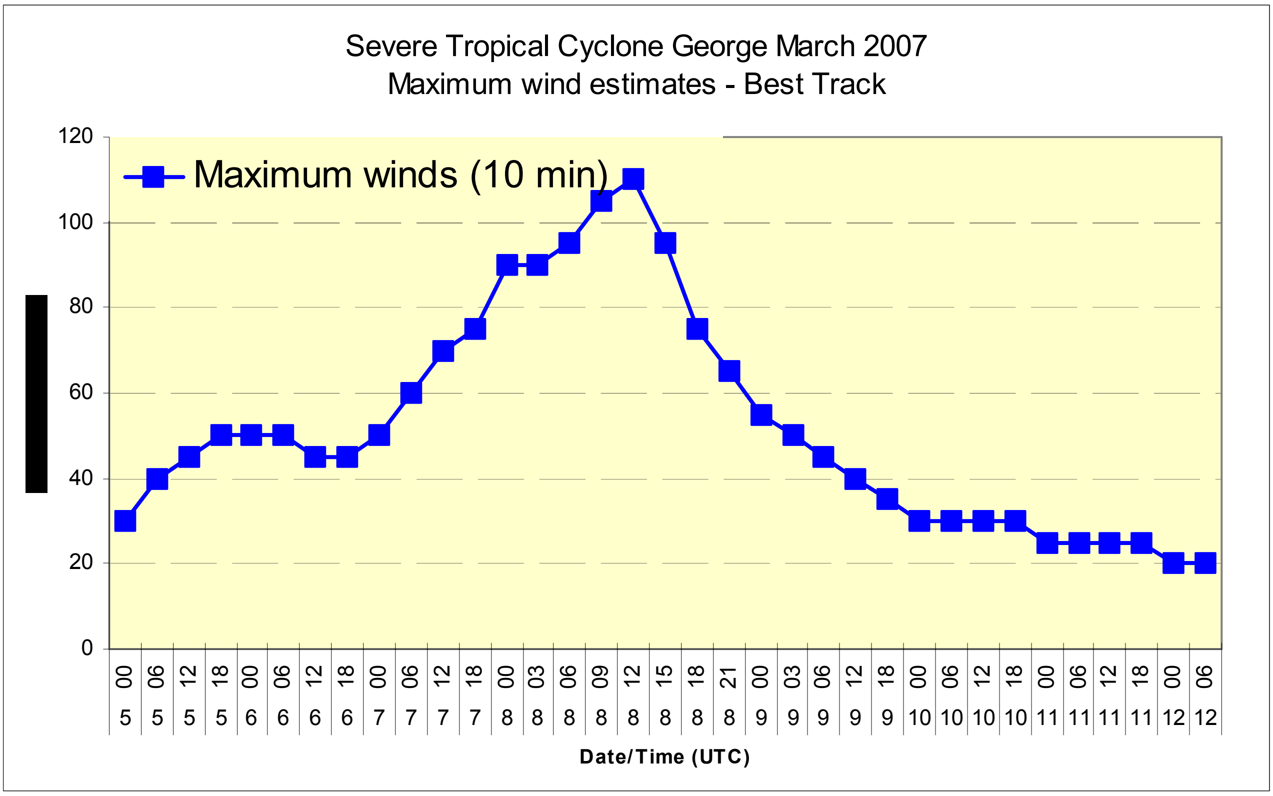

Figure 2.6. Best Track maximum mean winds (10 minute) for Tropical Cyclone *George,* 5-12 March 2007.

2 C. Impact

De Grey Pastoral Station
Tropical Cyclone *George* crossed the coast close to the mouth of the De Grey River. The De Grey pastoral station homestead sits on the banks of the De Grey River approximately 20 km inland. The closest approach of *George* to the homestead was around 20 km at 11 pm WDT. Gusts in the zone of maximum winds are estimated to have been around 275 km/h at this time, while the radius of the eye is estimated to have been around 12-14 km and the radius to the band of maximum wind about 18-20 km. This is in agreement with witness reports indicating that a lull, indicating eye passage, was not experienced. It is also consistent with the observed level of damage and the directional spread of debris.

Port Hedland
Gales commenced in Port Hedland around 5 pm 8 March and “destructive wind gusts” (gusts of 125km/h or greater) commenced at around 8:30 pm. Unfortunately the Bureau’s Automatic Weather Station at Port Hedland Airport failed prior to the period of peak winds and was not returned to service until after winds had subsided below gale force. The peak mean wind measured at the airport prior to the equipment failure was 113km/h at 10:51 pm. The highest recorded wind gust was 154km/h at around 11 pm. Although there are no reliable anemometer records of the peak winds occurring in the Greater Port Hedland area, estimates of peak gust speeds can be made based on the failure of simple structures (CTS, 2007a). The CTS estimated peak gust speeds in the Port Hedland area of 200 km/h (ibid.).

The closest approach of *George* to Port Hedland occurred around midnight when the centre came within 40 km. By this time the maximum gusts in the eyewall region are estimated to have been around 250 km/h, having dropped from around 285 km/h at the coastal crossing. Winds are estimated to have been at a maximum 20 km from the centre, dropping off markedly with increasing radial distance. The estimates provided by the CTS (2007a) are thus consistent with the estimates of peak wind gusts, given the observed structure of the system and taking account of the uncertainties involved.

Less than 2 per cent of buildings sustained structural damage (ibid.) The low damage figure relates to the fact that the estimated wind speed was 65 per cent of the current design wind speed for the area. Significant structural damage was only recorded in Port Hedland (not in South Hedland) and only in older buildings (ibid).

Storm surge
When a tropical cyclone crosses or closely approaches the coast, there is a concomitant rise in sea level above that expected from astronomical tides alone. This rise in water level is called a storm surge. It is caused principally by wind stress on the water surface and to a lesser degree by the reduction in atmospheric pressure. The sum of the storm surge and the astronomical tide produces the storm tide. Along the central Pilbara coast where tidal ranges are large, significant coastal inundation is generally averted if a tropical cyclone crosses at low astronomical tide, since the storm surge is rarely greater than the inter-tidal range.

Port Hedland escaped impact from storm surge, due to two mitigating factors. Firstly the cyclone crossed east of the town and winds in the Port Hedland area were generally blowing from the land out to sea, so in this area the wind was acting to reduce water levels. The area of maximum storm surge would have occurred just east of the mouth of the De Grey River. Secondly, the astronomical tide was relatively low at the time of coastal crossing, and, as previously discussed, this acts to minimise the storm tide thus protecting low-lying areas from inundation.

Coastal crossing occurred on a rising tide at around 1300 UTC between the low tide of 1.16m at 1123 UTC and the high tide of 6.41m at 1733 UTC. Modelling suggests that *George* would have produced a storm surge of around 4.8m, including an allowance of 0.5m for wave set-up. (The input parameters were chosen to provide an upper estimate of storm surge risk so it is unlikely that the storm surge would have exceeded this figure.) Significant inundation occurs when the storm tide (storm surge plus the astronomical tide) exceeds the highest astronomical tide. The predicted tide close to the time of coastal crossing was around 2.3m. The Highest Astronomical Tide (HAT) height for Port Hedland is 7.5m. Hence we would expect that the storm tide of around 7.1m (2.3 + 4.8) at the time of coastal crossing did not exceed the HAT of 7.5m.

There are no tide gauges installed in the area where *George* crossed the coast. When the storm tide exceeds the HAT it is possible to obtain an estimate of the storm tide from a survey of debris lines in the impact zone. In this case a survey was not attempted, as it was unlikely that any evidence would remain. This decision was supported by reports from people at De Grey Station indicating they were unable to find any evidence of storm surge at the coast.

Inland
Unfortunately no anemometer data is available inland close to George's track. The methodology used to estimate wind speeds for this part of George's track is described in Section 2B: Meteorological Description.

One fatality occurred and significant damage was sustained at Indee Station. Wind gusts of around 215 km/h are estimated to have occurred at this location.

Two fatalities and numerous injuries occurred at Fortescue Metal Group's Rail Village One (FMG RV1). The "best track" estimate of maximum wind speed indicates that gusts of around 195 km/h are likely to have been experienced at this site (see Table 2.1).

The CTS was unable to find reliable structural indicators of wind speed at the RV1 site (CTS, 2007b). However a comparison of tree damage in the area with that of the Port Hedland area (where estimates were able to be made based on failure of simple structures) produced an estimate of wind gusts of approximately 180 km/h. Given the relative uncertainties in both methods this is considered close agreement.

2 D. Observations

Wind
The maximum mean wind recorded in Tropical Cyclone *George* was a 10-minute average wind of 194 km/h at Bedout Island at 7 pm 8 March. The Bedout Island anemometer reports a 10-minute mean wind once per hour. At the Port Hedland Airport, the peak 10-minute average wind recorded was 113 km/h at 10:51 pm 8 March, and the peak gust of 154 km/h was measured around 11 pm 8 March. However, wind speed data is missing during the time of closest approach, so it is very likely the actual peak winds experienced were stronger than the values reported above. The lowest pressure recorded at Port Hedland Airport was 962.7 hPa at 00:12 am 9 March, confirming that *George* was closest to Port Hedland around midnight.

Rainfall

Substantial but not exceptional falls occurred as *George* approached and crossed the Pilbara coast, including 131mm at Pardoo in the 24 hours to 9 am 9 March (see Table 2.2). However the lack of previous rainfall and the steady movement of *George* meant that no significant flooding occurred. As can be seen in Figure 2.4 the monsoonal flow on the Kimberley coast was producing 24-hour rainfall totals comparable to that produced directly by *George*. However, the passage of TC *Jacob* within days of *George* caused additional rainfall resulting in accumulated falls over 200 mm across parts of the central and eastern Pilbara. The rain caused road closures on most roads through the area except for the Great Northern Highway.

Date	Rainfall (mm) in 24hrs to 9 am	Location
09/03/2007	140	Derby
	131	Pardoo
	124	Kuri Bay
10/03/2007	110	Warrawagine
	93	Telfer
	87	Bonney Downs

Table: 2.2 Selected rainfall figures in WA during and after landfall of Tropical Cyclone *George.*

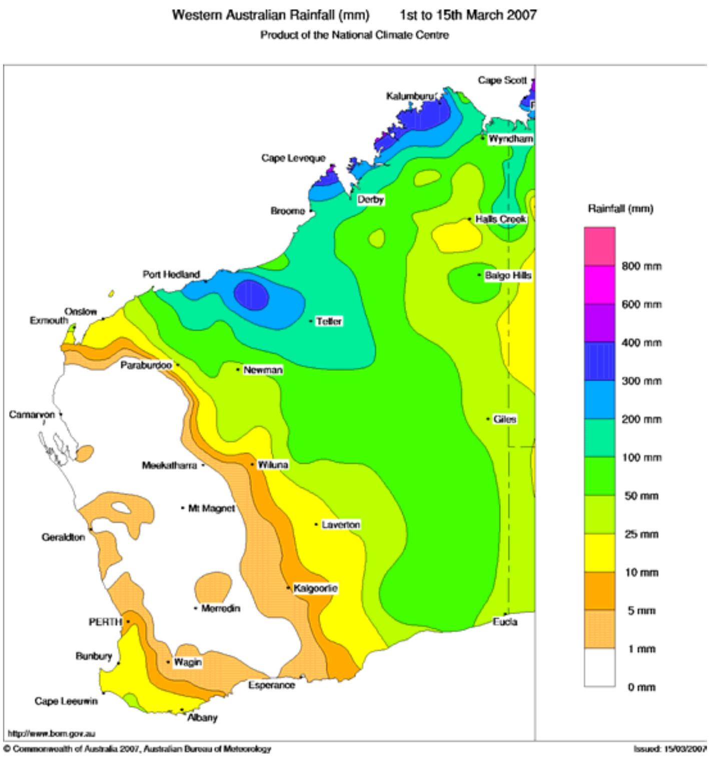

Figure 2.7 Rainfall in WA during the first half of March, including the rainfall produced by *George* and *Jacob.*

2 E. Forecast Performance

Summary of Warnings

The first mention of the discrete tropical low that was to become Tropical Cyclone *George* was made on the Northern Tropical Cyclone Outlook issued by the Northern Territory Regional Office on 25 February 2007. On 26 and 27 February the outlook was low/moderate potential for tropical cyclone development for the subsequent three days with the low expected to remain over the far northeast of the Top End. After following an erratic path for some days the system began to track westwards on 1 March.

On 2 March the Northern Tropical Cyclone Outlook indicated a high potential for development on 4 and 5 March. The first Tropical Cyclone Advice was issued at 4:30 pm (5:00 pm CST) Friday 2 March 2007. That Tropical Cyclone Advice placed the coastal and island communities between Daly River Mouth in the Northern Territory and Mitchell Plateau in Western Australia on Tropical Cyclone Watch.

The first Tropical Cyclone Warning was issued at 10:30 am (11:00 am CST) Saturday 3 March 2007 for coastal communities from Daly River Mouth in the Northern Territory to Kalumburu in Western Australia. A Tropical Cyclone Watch area extended west for coastal and island communities from Kalumburu to Kuri Bay.

The first mention of re-intensification for the transition from the Kimberley out into the Indian Ocean was made at 10:30 pm (11:00 pm CST) Sunday 4 March 2007.

After moving offshore on 5 March, Tropical Cyclone Warnings were cancelled for the Kimberley at 4 am Tuesday, 6 March 2007. The possibility that Tropical Cyclone *George* could recurve to the south was identified on 7 March and a Tropical Cyclone Watch was issued for coastal areas between Coral Bay and Roebourne at 12:55 pm 7 March 2007. Table 2.3 shows the Watch/Warning boundary changes indicated on advices issued for *George*.

Time Date (UTC)	**Time Date (WDT)**	**Advice Type**	**Boundaries**
0355 07/03/07	12:55pm 07/03/07	Watch	Coral Bay - Roebourne
1305 07/03/07	10:05pm 07/03/07	Watch **Warning**	Coral Bay - Mardie **Mardie - Pardoo**
1905 07/03/07	4:05 am 08/03/07	Watch **Warning**	Coral Bay - Mt Augustus **Onslow - Wallal - inland**
0100 08/03/07	10:00 am 08/03/07	Watch **Warning**	Coral Bay – Onslow **Onslow - Broome - inland**
0710 08/03/07	4:10 pm 08/03/07	Watch **Warning**	Coral Bay - Onslow – inland Onslow - Bidyadanga - inland
1010 08/03/07	7:10 pm 08/03/07	**Warning**	**Dampier - Sandfire Roadhouse - inland**
0345 09/03/07	12:45 pm 09/03/07	**Warning**	**Roebourne - Wallal - inland**

Table 2.3 Summary of Watch/Warning boundaries given on TC Advices for TC *George.*

The area of coast where *George* ultimately made landfall was first put under a Tropical Cyclone Warning at 10:05 pm 7 March, approximately 24 hours prior to landfall and around 22 hours prior to the onset of gales in Port Hedland. The Tropical Cyclone Warning area was extended inland to include the FMG RV1 site at 4:15 am 8 March.

The Tropical Cyclone Forecast Track Map is a graphical product that provides a track of the cyclone showing recent movement and forecast movement in the next 48 hours - with track uncertainty indicated. The Forecast Track Map “likely range of movement of the cyclone” first impinges on the coast between Exmouth and Mardie with the map issued at 10 pm 7 March. Table 2.4 shows the coastal boundaries of the uncertainty area and the changes with time.

Throughout this period the forecasts consistently indicated that *George* was expected to impact the coast as a Severe Tropical Cyclone (Category 3, 4 or 5). Furthermore the forecasts clearly indicated that the system was expected to produce “very destructive winds” (i.e. to remain a Severe Tropical Cyclone) for more than 100 km inland.

Issue Time (UTC)	**Issue Time (WDT)**	**Approximate Coastal Boundaries**
1300 07/03/2007	10 pm 07/03/2007	Exmouth - Mardie
1600 07/03/2007	1 am 08/03/2007	Exmouth - Karratha
1900 07/03/2007	4 am 08/03/2007	Exmouth – Pardoo
2200 07/03/2007	7 am 08/03/2007	Exmouth - Pardoo
0100 08/03/2007	10 am 08/03/2007	Exmouth - Pardoo
0400 08/03/2007	1 pm 08/03/2007	Onslow - Pardoo
0700 08/03/2007	4 pm 08/03/2007	Karratha - Pardoo
1000 08/03/2007	7 pm 08/03/2007	Whim Creek - Pardoo

Table 2.4 Approximate coastal boundaries of the “likely range of movement” of *George* as indicated on the Forecast Track Maps.

Track forecast performance
Track forecast accuracy for George was significantly poorer than the five-year average over the 2001/2002 to 2005/2006 seasons as indicated in Figure 2.8. It can be seen that the accuracy of the track forecasts deteriorated markedly with increasing lead-time. The 48-hour lead-time forecasts are the worst for any tropical cyclone in the Western Region in the last five years and are slightly worse than the average accuracy in the mid-eighties (477 km).

Parameter	**0 hr**	**6 hr**	**12 hr**	**18 hr**	**24 hr**	**36 hr**	**48 hr**	**72 hr**
Count	21	21	21	21	21	21	21	21
Distance (km)	27	62	107	161	214	333	504	765
Mean Wind (knots)	6	7	8	8	10	16	21	24

Table 4.3. Verification statistics for TC *George*: Track and Intensity.

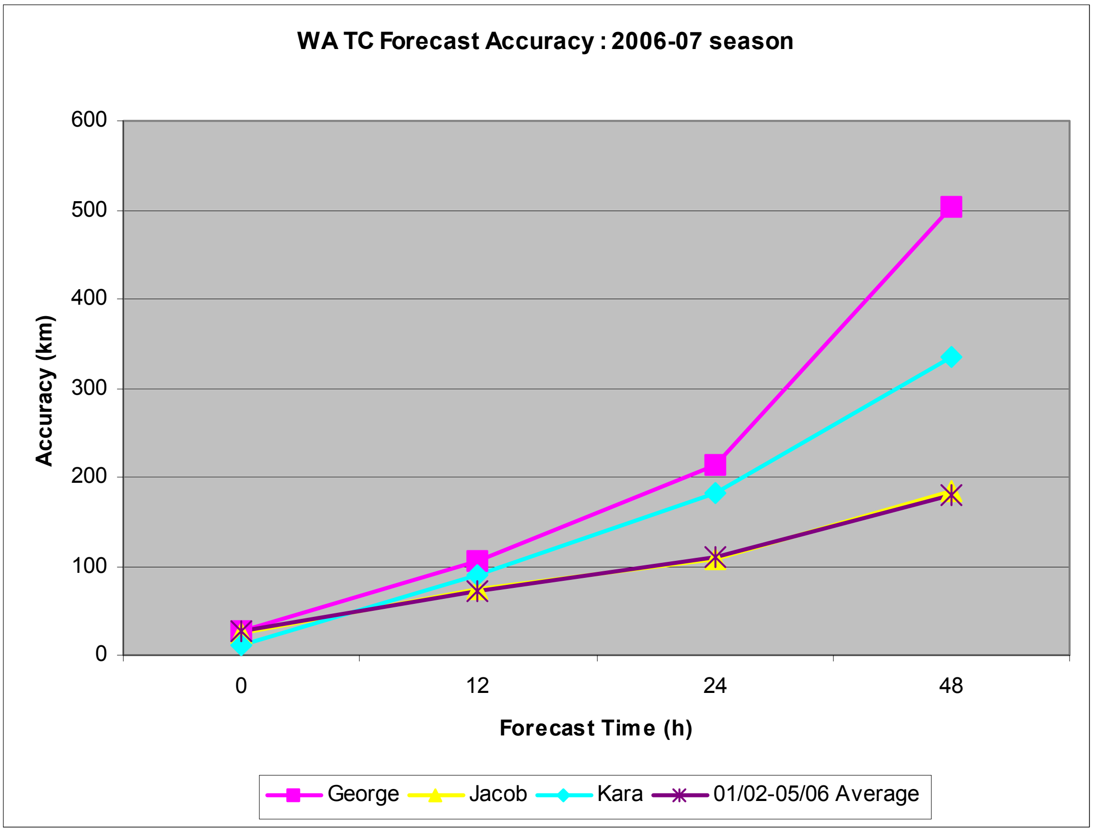

Figure 2.8. Track forecast accuracy 2006-2007 season

The Perth Tropical Cyclone Warning Centre (TCWC) did not forecast the abrupt southerly turn that occurred on 7 March and had a major impact on the overall track forecast performance. The TCWC constructs track forecasts based on a consensus approach, combining the available dynamical and statistical forecast aids in a way that has been shown to enhance forecast skill on seasonal time scales (Burton, 2006). Despite being the most skillful track forecasting methodology available – practised in all the major tropical cyclone warning centres around the world – it is still dependent on the skill of the component guidance (ibid.). The Perth TCWC has access to a wide range of dynamical and statistical guidance. The forecasts issued on 6 March drew directly upon guidance from nine independent models. Forecasters also informed their decision-making by assessing output from dynamical models run in ensemble mode (where the model is run many times under slightly varying conditions to generate a spread of likely outcomes). Remarkably, the available guidance had a "low spread" (meaning all the tracks were similar, there was very little variation in the direction or speed of the tracks – as illustrated in Figure 2.9) and *none* of the available guidance indicated the abrupt southerly shift in motion. The spread of possible outcomes depicted by the ensemble guidance failed to capture the motion that actually occurred. In the current state of tropical cyclone track forecasting this is a most remarkable outcome. While it is common for some of the available guidance to be relatively poor it is extremely rare for all the guidance to fail. The low spread in the guidance tracks would normally lend higher confidence to the track forecast. Hence this is the worst kind of situation a forecaster can face – high confidence, but ultimately low accuracy.

It is extremely difficult to diagnose why all the models failed to accurately forecast *George*'s track and it is likely that numerical modellers will use TC *George* as a test case for some years to come. Possible factors of influence will be examined further in future research.

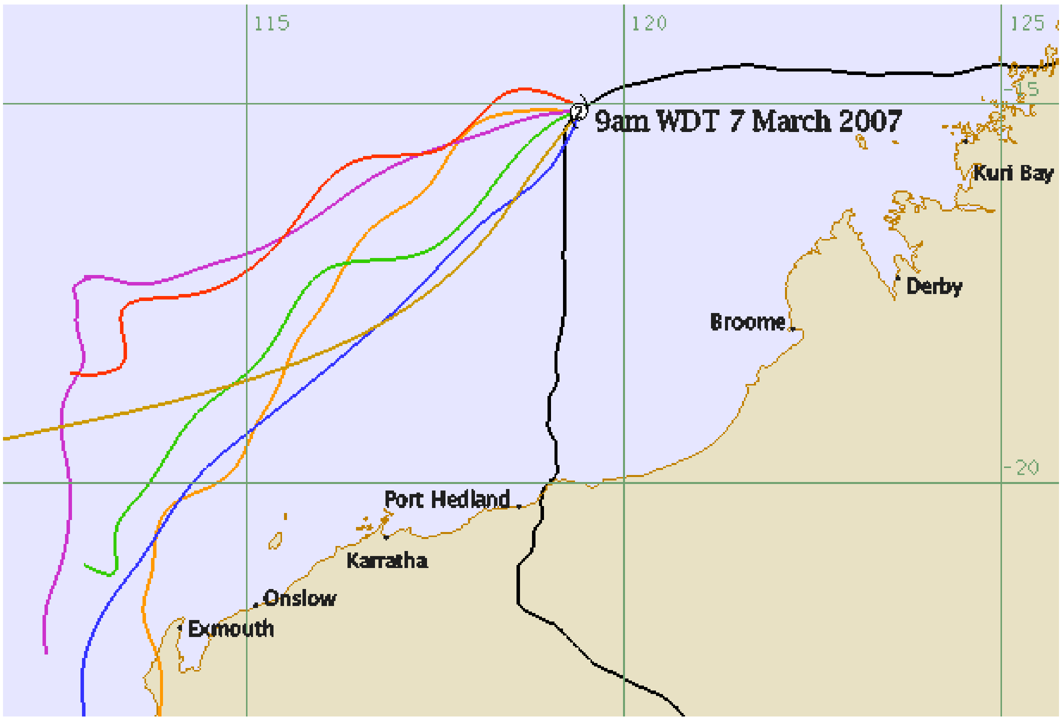

Figure 2.9. Illustration of the "low-spread" in guidance tracks. The black track represents the "best track". The coloured tracks are guidance tracks.

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3. Severe Tropical Cyclone *Jacob,* 3-12 March 2007

3 A. Summary

A low formed well northwest of the Kimberley early in March and moved steadily westwards eventually reaching cyclone intensity at 06/18UTC. Cyclone advices were issued for Christmas Island on 7 March as *Jacob* moved to the northwest but were cancelled as *Jacob* recurved to the southeast on the 8th. *Jacob* reached category three intensity late on the 9th but weakened the following day under moderate northeasterly shear. *Jacob* continued its southeast then east southeast track eventually crossing the coast just east of Port Hedland as a tropical low on the morning of the 12th. Coincidentally this was almost the exact point at which category five *George* crossed only two days before.

Although *Jacob* weakened before impacting the coast, the threat of a second cyclone put communities on high alert and hampered recovery operations following TC *George*. In addition there was an economic impact due to loss of production from oil and gas facilities and closure of port operations. Arterial roads were closed through eastern and central inland parts of the Pilbara because of heavy rain exacerbated by rainfall associated with TC *George* just a few days earlier.

3 B. Meteorological Description

Intensity analysis

A low was identified within the monsoon trough at 02/18UTC. Convection about the low was subject to diurnal forcing and hampered by strong easterly shear. This pattern of convective pulsing continued through the 4th, 5th and 6th with shear remaining on the order of 30-40 knots. At times satellite imagery suggested Dvorak intensity of cyclone level (DT=3.0-3.5) but given that such patterns were not sustained owing to the shear it is unlikely that cyclone intensity was reached during this phase. However, overnight on the 4-5th gales are estimated under convection in the western quadrant at 04/18 to 05/00UTC supported by rain-affected gales on the Quickscat pass. The "best track" is shown in Figure 3.1 and the maximum wind shown in Figure 3.2. The best track positions and intensities are listed in Table 3.1.

By 05/0430UTC the low level centre was well exposed although convection again developed near the centre and gales in western quadrant are likely at 05/12UTC. This pattern repeated on the 6th with continuing strong shear above 30 knots. However, overnight from the 6th to the 7th convection became more sustained as shear eased to 20-25 knots. Gales are evident in the northern quadrant only at 06/12UTC and then cyclone intensity is estimated at 06/18UTC on the basis of subsequent improved convection. Operationally the system was named *Jacob* at 07/00UTC.

Development appears to be ongoing later on the 7th as suggested by as shear finally fell below 20 knots and maximum winds were estimated at 55 knots (category 2) at 07/18UTC. Some weakening was evident during the 8th and at this point *Jacob* halted its WNW track and subsequently began its SE track towards the Australian coast. Possibly weakening was assisted by ongoing moderate shear during the diurnal minimum and also by sea surface temperatures (SST) in the area falling below 27C caused by the slow moving *Jacob* itself.

Jacob recommenced development overnight from 8-9th continuing until 09/18UTC when the maximum intensity was estimated at 70 knots (category 3) when microwave imagery showed a ragged eye pattern.

Thereafter weakening was evident assisted by movement over an area of cooler SST and on the 11th the low-level circulation centre briefly became exposed despite the estimated shear remaining below 20 knots. Brief periods of gales were observed at some offshore observing sites and on the 11th Quickscat passes indicated some areas of gales mainly in northern and western quadrants. Convection was only just sufficient to hold the system at cyclone intensity.

By landfall at 12/03UTC it is estimated that the system fell below cyclone intensity. This is despite Bedout Is registering gales at this time to the NNE and radar imagery suggesting offshore gales in the southerlies. Overall gales are estimated as extending less than halfway about the centre. As the system moved inland imagery became more unorganised.

A feature of *Jacob* was the diurnal fluctuation in intensity. Aside from the expected diurnal variations prior to cyclone intensity phase when strong shear was evident, *Jacob* showed peaks overnight on each of the nights from the 6-7 to the 9-10th culminating in maximum intensity. It is likely the relatively small size of the system contributed to this.

Motion

A strong mid-latitude ridge steered the low steadily to the west. The close proximity of TC *George* east of the low complicated the pattern, particularly as *George* was a large and dominant system. As *George* took a WSW course *Jacob*'s westerly track took a shift to the northwest.

By the 8th and 9th the ridge to the south was eroded by a mid-latitude trough. In response to this trough and also to strengthening NW winds to the northeast, *Jacob* recurved to the southeast towards the Pilbara coast. A steady SE track continued through the 10th and 11th towards the now weakening *George* over inland WA, until landfall just to the east northeast of Port Hedland on the morning of the 12th.

Jacob was tracked by Dampier radar from about 09/12UTC and then on Port Hedland radar from about 11/22UTC, although by this stage the system was poorly defined.

Structure

Being affected by moderate to strong easterly shear initially, gales were initially confined to western and northern quadrants, and even during the initial stages of *Jacob's* development the area of gales was greatest in these sectors. As *Jacob* began to track to the southeast the area of gales increased on the southern side but as *Jacob* neared the coast the only observed gales were in the western and northern parts.

Throughout its lifetime the area of gales was only on the order of 50-100 nm. The radius of maximum winds is estimated at just 10 nm during its peak intensity.

3 C. Impact

Although *Jacob* weakened before impacting the coast, the threat of a second cyclone put communities on high alert and hampered recovery operations following TC *George*. In addition there was an economic impact due to loss of production from oil and gas facilities and closure of port operations.

The combination of *George* and *Jacob* caused heavy rain over 200mm across parts of the central and eastern Pilbara. The rain caused road closures on most roads through the area except for the Great Northern Highway. The rainfall also delayed recovery efforts following TC *George* particularly about Port Hedland on the 12th. Road closures also cut access for mining and pastoral activities. Otherwise no major flooding was reported.

3 D. Observations

Wind

Gales were recorded at some privately operated offshore buoys but not at any coastal observation sites. Gales were observed at Bedout Island as the system crossed the coast at about 12/03UTC.

Rainfall

Rainfall totals on the 12 and 13 March averaged 50-100mm across much of the Pilbara. Some significant daily falls recorded on the 12th included: 114mm at Port Hedland, 86mm at Mundabullangana, 58mm at Marble Bar, 50 mm at Karratha and 49mm at Telfer; and on the 13th included: 123mm at Yarrie Station, 73mm at Telfer and 43mm at Marble Bar.

The combination of *George* and *Jacob* caused heavy rain over 200mm across parts of the central and eastern Pilbara as shown on the weekly rainfall map to 9am on the 13th in Figure 3.3. Yarrie recorded a total of 335mm of rain in the 96 hours to 9am the 13th.

3 E. Forecast Performance

A gale warning was first issued for the low that was to become *Jacob* at 11:42am WDT 5 March (05/0242UTC) for gales in western quadrants but intensification to tropical cyclone intensity (having gales extend more than halfway around the centre) was not expected while it was experiencing such strong shear.

The low was named *Jacob* operationally at 9:50 am WDT 7 March (07/0050UTC) when the first advice (TC Watch) was issued for Christmas Island. This was upgraded to a TC Warning at 4:35pm WDT (7/0735UTC). A FESA Yellow alert was included on the warning issued at 8:45am WDT 8 March (07/2345TC). The warning was cancelled at 11:00pm WDT 8 March (08/1400UTC) when *Jacob* moved away from the island.

Advices were renewed when a TC Watch was declared for areas between Coral Bay and Sandfire at 4:05pm WDT 9 March (09/0705UTC). This was upgraded to a warning for areas between Onslow and Port Hedland at 10:10am WDT 10 March (10/0110UTC). By 3:50pm WDT (10/0650UTC) the area under warning was extended from Onslow to Pardoo and the area was gradually amended until *Jacob* moved inland and advices were cancelled at 3:45pm 12 March (12/0645UTC). A summary of Tropical Cyclone Advices is given in Table 3.2.

As *Jacob* intensified into a category three system, there was concern that in an anticipated ongoing environment of low wind shear that further development was possible. This had major consequences for the highly sensitive communities of the Northwest who were in the process of bracing for severe TC *George*. Indeed the forecasts issued on the 10th were for a potential severe crossing within 48 hours. These forecasts were revised down once Jacob commenced weakening and the warning issued at 12:55pm WDT 11 March (11/0355UTC) were for a category 1 impact on the central Pilbara coast. As it turned out *Jacob* took a more east southeast track crossing east of Port Hedland.

Year	Month	Day	Hour (UTC)	Position Latitude S	Position Longitude E	Position Accuracy nm	Max wind 10min knots	Max gust knots	Central Pressure hPa	Radius of Gales nm	Radius storm force winds nm	Radius Maximum Wind nm
2007	3	2	18	13.8	118.9	25	20	45	1000			30
2007	3	3	0	13.8	118.1	25	25	45	998			40
2007	3	3	6	13.8	117.7	25	25	45	994			20
2007	3	3	12	13.8	117.3	25	25	45	994			20
2007	3	3	18	14.1	116.7	25	25	45	994			20
2007	3	4	0	14.5	116.3	15	25	45	994			20
2007	3	4	6	14.4	116.1	15	25	45	994			20
2007	3	4	12	14.6	116.1	20	25	45	994			30
2007	3	4	18	14.7	115.5	20	25	45	994			25
2007	3	5	0	14.6	114.8	15	25	45	994			30
2007	3	5	6	14.5	114.2	10	25	45	994			25
2007	3	5	12	14.3	113.4	20	30	45	992			25
2007	3	5	18	14.2	112.3	25	30	45	992			20
2007	3	6	0	14.2	111.0	20	30	45	992			20
2007	3	6	6	13.6	110.1	15	30	45	992			15
2007	3	6	12	13.4	109.8	20	30	45	990			20
2007	3	6	18	13.1	108.9	20	35	50	984	60		20
2007	3	7	0	12.6	108.3	20	40	55	982	50		20
2007	3	7	6	12.6	107.8	20	45	65	978	60		15
2007	3	7	12	12.7	107.1	25	50	70	974	70	20	15
2007	3	7	18	12.9	106.3	20	55	80	966	80	25	15
2007	3	8	0	12.5	106.0	15	55	80	966	80	25	15
2007	3	8	6	12.6	105.9	15	50	70	976	60	25	15
2007	3	8	12	13.0	106.3	20	50	70	976	55	25	15
2007	3	8	18	13.5	107.0	25	50	70	976	60	25	15
2007	3	9	0	14.0	107.7	15	50	70	978	65	25	15
2007	3	9	6	14.5	108.3	20	55	80	970	70	25	15
2007	3	9	12	15.0	109.2	20	65	90	964	75	25	10
2007	3	9	18	15.6	109.8	25	70	100	960	75	25	10
2007	3	10	0	16.0	110.6	20	65	90	964	65	25	10
2007	3	10	6	17.1	111.4	20	60	85	966	60	20	10
2007	3	10	12	17.9	112.4	20	55	80	968	55	20	15
2007	3	10	18	18.4	113.1	20	50	70	976	45	20	15
2007	3	11	0	19.0	113.9	15	50	70	978	40	20	15
2007	3	11	6	19.3	114.5	15	40	55	986	40		15
2007	3	11	12	19.5	115.6	20	35	50	988	40		15
2007	3	11	18	19.7	117.0	15	35	50	988	40		15
2007	3	12	0	20.0	118.3	15	35	50	988	40		15
2007	3	12	3	20.1	118.9	10	30	45	992			20
2007	3	12	6	20.4	119.7	15	25	45	992			20

Table 3.1. Best track summary for Severe TC *Jacob*.

Date/Time (UTC)	Action	Location
05/0242	Shipping warning issued for gales in western quadrants.	
07/0100	Named *Jacob*. Watch issued.	Christmas Island
07/0735	Warning issued.	Christmas Island
08/1400	Warning cancelled.	Christmas Island
09/0705	Watch issued.	Coral Bay to Sandfire
10/0100	Warning issued. Watch current.	Onslow to Port Hedland
10/0650	Warning current. Watch current.	Onslow to Pardoo Coral Bay to Bidyadanga, inland Pilbara.
11/0355	Warning current. No watch.	Exmouth to Pardoo, inland Pilbara
11/1847	Warning current.	Dampier to Pardoo, adj. inland Pilbara
12/0645	Advices cancelled.	

Table 3.2. Tropical Cyclone Advice summary for Severe TC *Jacob*.

Parameter	**0 hr**	**6 hr**	**12 hr**	**18 hr**	**24 hr**	**36 hr**	**48 hr**	**72 hr**
Count	19	17	17	15	15	11	8	3
Distance (km)	25	39	66	87	99	144	210	342
Mean Wind (knots)	3	4	8	13	16	23	26	18

Table 3.3. Verification statistics for Severe TC *Jacob*: Track and Intensity.

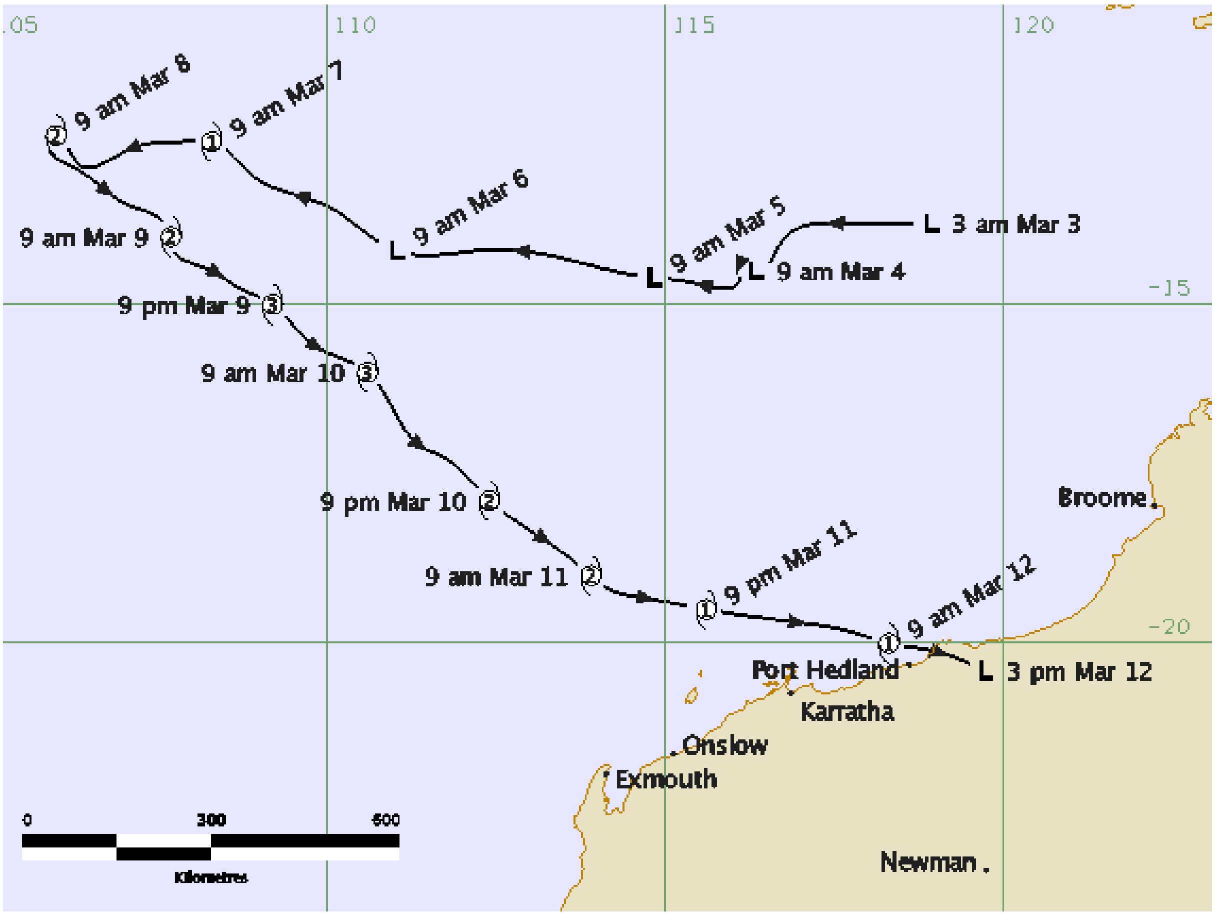

Figure 3.1. Track of Tropical Cyclone *Jacob*, 3-12 March 2007.

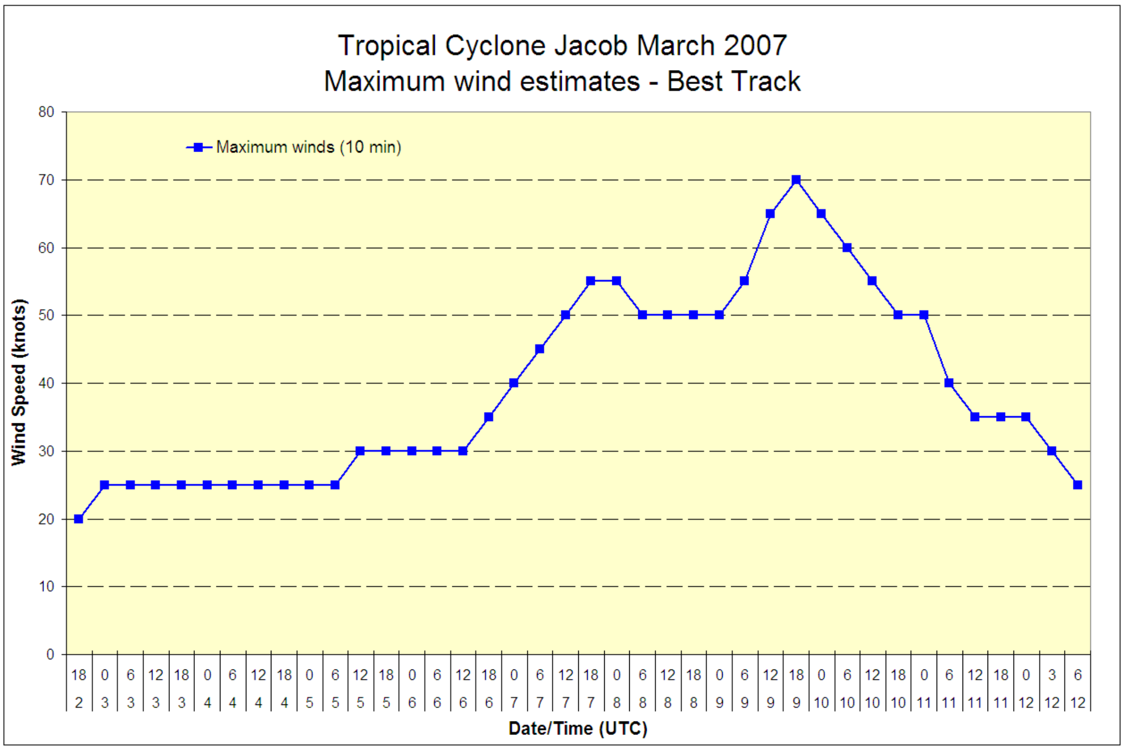

Figure 3.2. Best Track maximum mean winds (10 minute) for Tropical Cyclone *Jacob*, 3 - 12 March 2007.

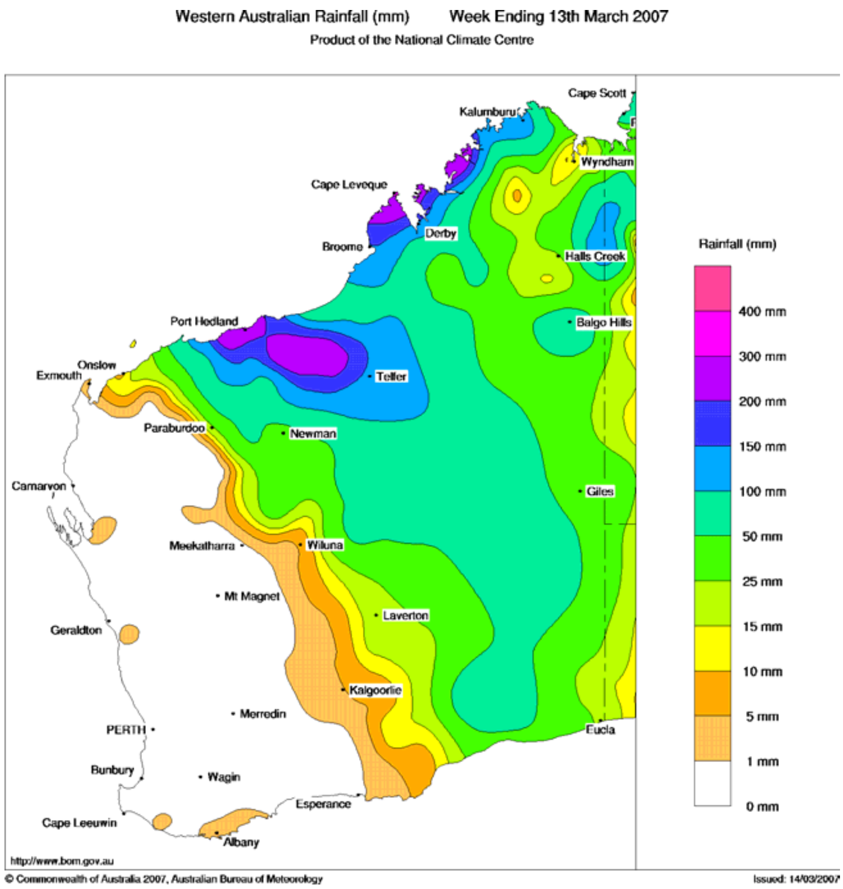

Figure 3.3. Weekly rainfall to 9am 13 March showing rainfall from *George* and *Jacob*.

(image courtesy of NASA)

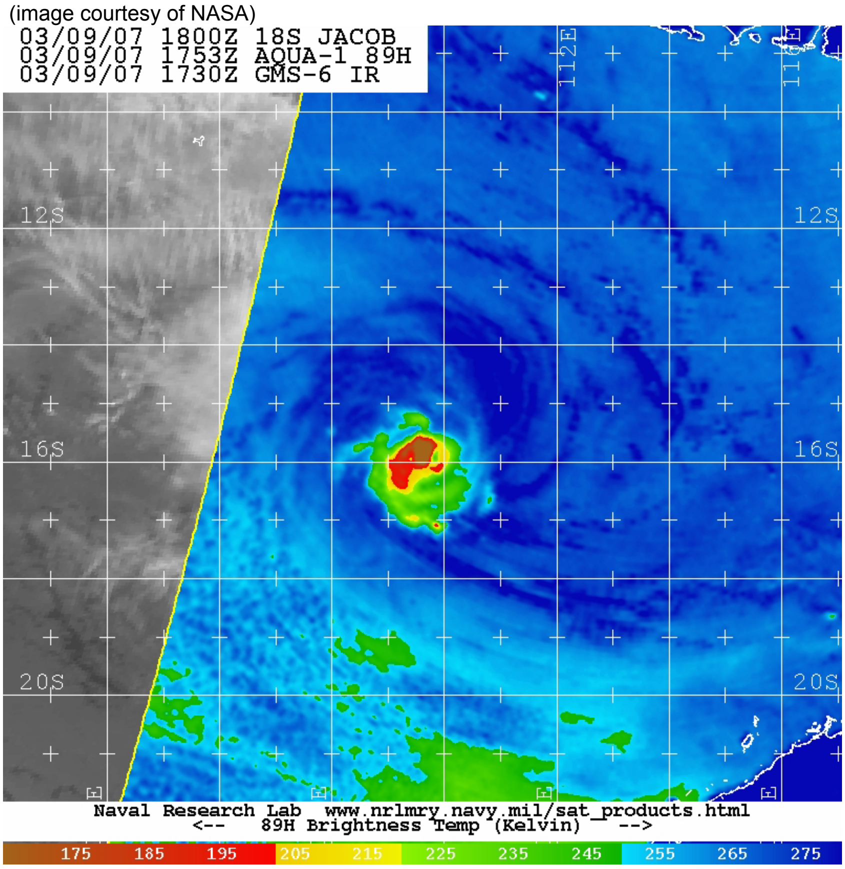

Figure 3.4. Microwave (AMSRE (Aqua) 89GHz) image at 09/1753UTC.

4. Severe Tropical Cyclone *Kara,* 23-30 March 2007

4 A. Summary

A low moved off the West Kimberley coast and developed reaching cyclone intensity about 465 km north northwest of Port Hedland at 25/06UTC as it tracked to the west. The midget system then rapidly developed to category four intensity by 26/06UTC and recurved to the east southeast. It remained at that intensity for 24 hours before rapidly weakening to a low by 28/00UTC near the east Pilbara coast at 80 Mile Beach.

Although communities were placed on alert, there was no reported wind impact or damage on the coast. Offshore oil and gas facilities were evacuated and there was likely to be considerable economic impact due to lost production.

4 B. Meteorological Description

A low moved off the west Kimberley coast on the evening of the 23rd and developed. Although convection weakened during the 24th with some easterly shear evident, conditions improved on the 25th resulting in rapid intensification. Cyclone intensity was estimated at 25/06UTC about 465 km north northwest of Port Hedland. Curvature of the convection was better indicated on microwave (TRMM) than on IR or visible imagery. During the 24 and 25 movement was a steady westerly with the mid-level ridge to the south. The “best track” is shown in Figure 4.1 and the maximum wind shown in Figure 4.2. The best track positions and intensities are listed in Table 4.1.

With favourable low shear and good upper outflow *Kara’s* development pushed the upper limits of the Dvorak development rate. By 25/18UTC an eye emerged on microwave imagery and then on IR imagery at 25/2030UTC. The small scale of *Kara* enhanced the intensification rate, gales being estimated at extending just 60 nautical miles from the centre and the eye diameter being about 10 nautical miles. This period of development peaked at 26/06UTC when maximum winds were estimated at 100 knots (10 minute mean). At this stage the system recurved to the east southeast in response to an approaching mid-level trough and steered towards the east Pilbara coastline.

The eye weakened temporarily from 26/08UTC but then redeveloped from 26/21UTC peaking at about 27/03UTC when maximum winds were estimated at 105 knots. The radius of maximum winds was estimated at just 8 nautical miles and the radius of gales just 40 nautical miles. The small scale nature of *Kara* is shown by the Quickscat pass at 26/2255UTC in Figure 4.4, the visible image at and the microwave image at Microwave (SSMIS 91GHz) at 27/0033UTC in Figure 4.5 and Modis Visible (Terra) image at 27/0225UTC in Figure 4.6.

Kara’s features then weakened dramatically on satellite imagery by strong wind shear from strong upper level winds associated with the mid-latitude trough. By 27/12UTC there was an absence of deep convection about the centre. Given the small size of the system and the rapid deterioration in the imagery the Dvorak weakening rate was broken with a reduction from 100 to 65 knots from 06 to 12UTC and then a further drop to 30 knots in the following 12 hours. It is estimated that the system fell below cyclone intensity by 28/00UTC although it is possible that there remained an area of southerly gales in the western quadrant only. The remnant low then took a northerly course and later a westerly track in response to lower level steering.

4 C. Impact
Although communities were placed on alert, *Kara* weakened before impacting the coast and there was no reported wind impact or damage. Offshore oil and gas facilities were evacuated and there was likely to be considerable economic impact due to lost production.

The heaviest rainfall fell over remote parts of the east Pilbara and no flooding was reported although local roads are likely to have been closed particularly following the previous rainfall events associated with cyclones *George* and *Jacob* earlier in the month.

4 D. Observations
Wind
There were no reports of gale force winds from coastal or island locations.

Rainfall
Kara caused high rainfall in parts of the eastern Pilbara. Rainfall totals in the 48 hours to 9am WST 28 March included 361mm at Pardoo Station (285mm on 27th), 249.4mm at Mandora (197mm on 28th), 244mm at Wallal Downs (to be confirmed) and 109mm at Telfer Airport. Rainfall totals tapered off dramatically further west, with 65.2mm being registered at Marble Bar and 35.2mm at Port Hedland in the same period. The weekly rainfall map to 9am 29 March (Figure 4.3) shows that rainfall exceeding 100mm was limited to an area from the west Kimberley south to a line from Port Hedland to Telfer.

4 E. Forecast Performance
The first indication that a potential cyclone may develop was provided on the daily Tropical Cyclone Outlook for Northwest Australia issued at 12:40pm WDT 24 March (24/0340UTC). A few hours later the first shipping warning and public advice (TC watch) for areas between Onslow and Cape Leveque were issued at 3:55pm WDT (24/1455UTC). At 2:45pm WST 25 March (25/1445UTC) *Kara* was named operationally and at 5:50pm WST (25/0950UTC) a warning was issued for areas between Exmouth and Wallal with a Watch continuing from Wallal to Broome. As *Kara* began its sharp turn to the east southeast overnight on the 26/27th, the coastal threat zone shifted to the east eg 26/18UTC although the timing of the forecast movement was a little slower than the actual track. By 11:55am 27 March (27/0355UTC) the warning zone was between Roebourne and Bidyadanga contracting to Pardoo to Bidyadanga at 9pm WST (27/13UTC). At 8:45am WST 28 March (28/0045UTC the warning was finally cancelled.

It is very significant that a category 4 system was within 190 km (103nm) north northwest of Port Hedland and there was sufficient confidence in the forecast to not put Port Hedland and other major towns on yellow alert thus saving the communities and in particular industry in costly preparation measures. Only the sparsely populated region between Pardoo and Sandfire were placed on Yellow alert.

Despite the difficulty in getting accurate numerical weather guidance information the official forecasts were reasonably successful in providing the basic messages of:

1. The system will develop as it moves to the west southwest.

2. It is likely to recurve to the southeast.

3. The system should weaken prior to reaching the coast.

Aside from that there were inaccuracies in the details specifically not picking the rapid intensification to category four level and not getting the sharp recurvature to the east southeast accurately.

The early track forecasts eg 24/18UTC were quite accurate. As *Kara* developed and moved to the southwest it seemed a coastal impact was possible in the particularly sensitive region of Port Hedland where category five TC *George* had passed just weeks before. Although weakening was expected a cyclone impact remained a possibility at Port Hedland until 9pm 27 March (27/21UTC) when the warning zone contracted to Pardoo to Bidyadanga.

Year	Month	Day	Hour (UTC)	Position Latitude S	Position Longitude E	Position Accuracy nm	Max wind 10min knots	Max gust knots	Central Pressure hPa	Rad. of Gales nm	Rad. of storm force winds	Radius of Hurricane force winds	Radius Max. Wind (RMW)
2007	3	23	6	16.2	124.5	25	15	35	1005				
2007	3	23	12	16.0	123.9	35	20	45	1004				
2007	3	23	18	15.8	123.1	35	25	45	1002				
2007	3	24	0	16.0	121.7	25	25	45	1000				
2007	3	24	6	16.2	120.7	25	25	45	998				
2007	3	24	12	16.2	119.3	20	25	45	998				
2007	3	24	18	16.3	118.1	15	25	45	998				
2007	3	25	0	16.4	117.5	15	30	45	996				
2007	3	25	6	16.5	116.8	15	40	55	990	50			25
2007	3	25	12	16.6	116.1	20	50	70	982	60	15		25
2007	3	25	18	17.0	115.8	15	60	85	972	60	20		10
2007	3	26	0	17.6	115.4	10	80	115	952	70	25	15	10
2007	3	26	6	18.0	115.2	10	100	135	926	60	25	15	8
2007	3	26	12	18.3	115.5	15	90	125	940	60	25	15	10
2007	3	26	18	18.4	116.1	10	90	125	940	50	25	15	10
2007	3	26	21	18.4	116.3	10	95	135	934	45	25	15	8
2007	3	27	0	18.5	116.9	10	100	140	926	40	25	15	8
2007	3	27	3	18.6	117.4	10	105	150	920	40	25	15	8
2007	3	27	6	18.7	118.0	15	100	140	926	40	25	15	8
2007	3	27	9	18.8	118.7	20	80	115	952	40	25	15	8
2007	3	27	12	18.9	119.6	25	65	90	968	40	25	10	10
2007	3	27	18	19.4	120.3	25	50	70	982	30			10
2007	3	28	0	19.4	121.2	15	30	45	996				
2007	3	28	6	18.8	121.3	20	25	45	998				
2007	3	28	12	18.3	121.4	20	25	45	1000				
2007	3	28	18	18.0	121.5	20	25	45	1000				
2007	3	29	0	17.9	121.4	15	25	45	1000				
2007	3	29	6	17.9	121.3	10	25	45	1000				
2007	3	29	12	17.8	120.9	20	25	45	1000				
2007	3	29	18	17.6	120.5	20	25	45	1000				
2007	3	30	0	17.5	120.1	10	25	45	1000				

Table 4.1. Best track summary for *Kara,* 23-30 March 2007.

Date/Time (UTC)	Action	Location
24/1455	TC Watch and Shipping warning issued.	Onslow to Cape Leveque
25/1445	Named *Kara*. Watch issued.	Onslow to Broome
25/1750	Warning issued. Watch continues	Exmouth to Wallal. Wallal to Broome.
27/0355	Warning continues. Watch cancelled.	Roebourne to Bidyadanga.
27/2100	Warning continues.	Pardoo to Bidyadanga
28/0045	Warning cancelled	

Table 4.2. Tropical Cyclone Advice summary for TC *Kara*.

Parameter	**0 hr**	**6 hr**	**12 hr**	**18 hr**	**24 hr**	**36 hr**	**48 hr**	**72 hr**
Count	16	15	14	15	16	14	12	10
Distance (km)	12	50	91	135	181	255	334	416
Mean Wind (knots)	9	10	12	12	15	19	21	6

Table 4.3. Verification statistics for TC *Kara*: Track and Intensity.

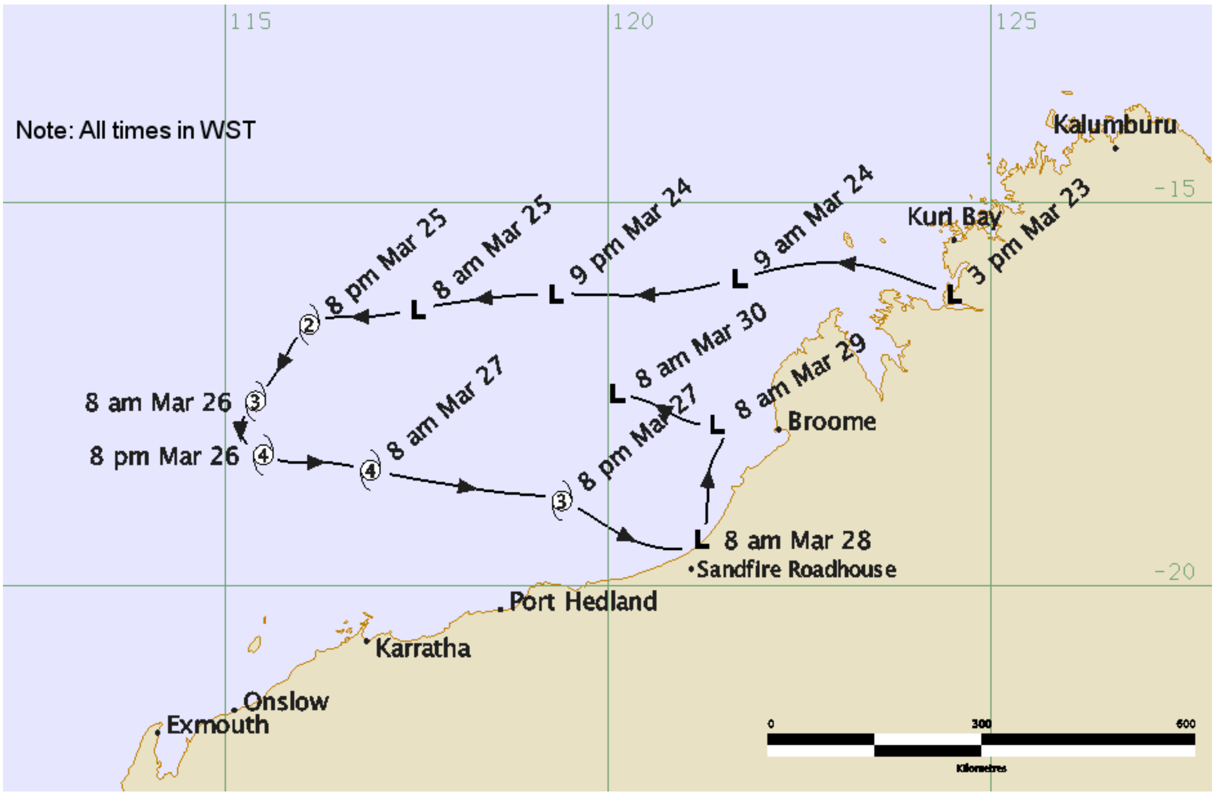

Figure 4.1. Track of Tropical Cyclone *Kara*, 23-30 March 2007.

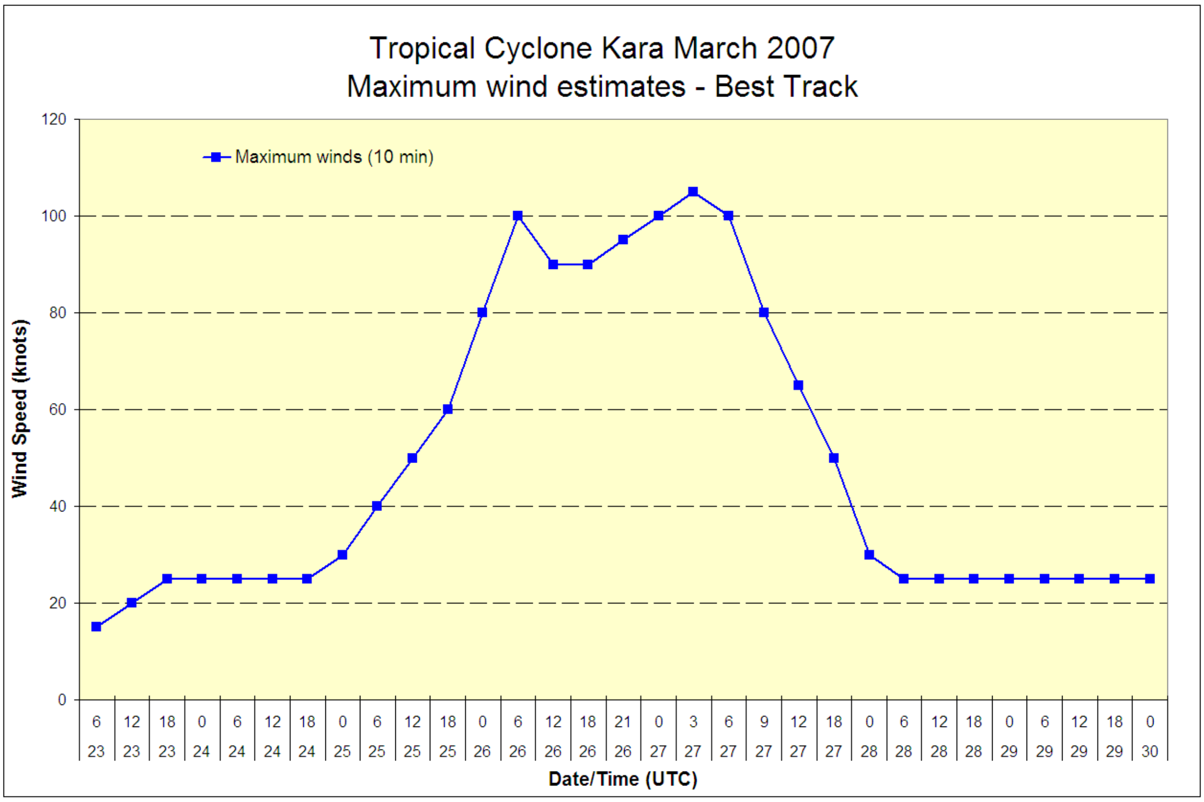

Figure 4.2. Best Track maximum mean winds (10 minute) for Tropical Cyclone *Kara*, 23 - 30 March 2007.

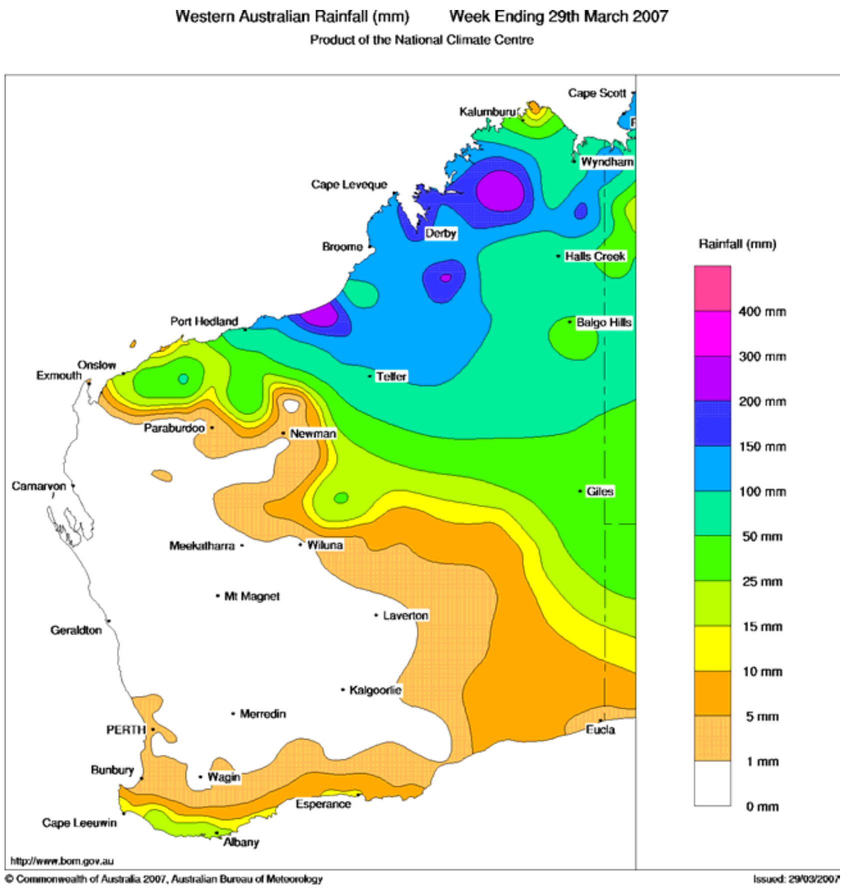

Figure 4.3. Weekly rainfall to 9am 29 March showing rainfall associated with *Kara*.

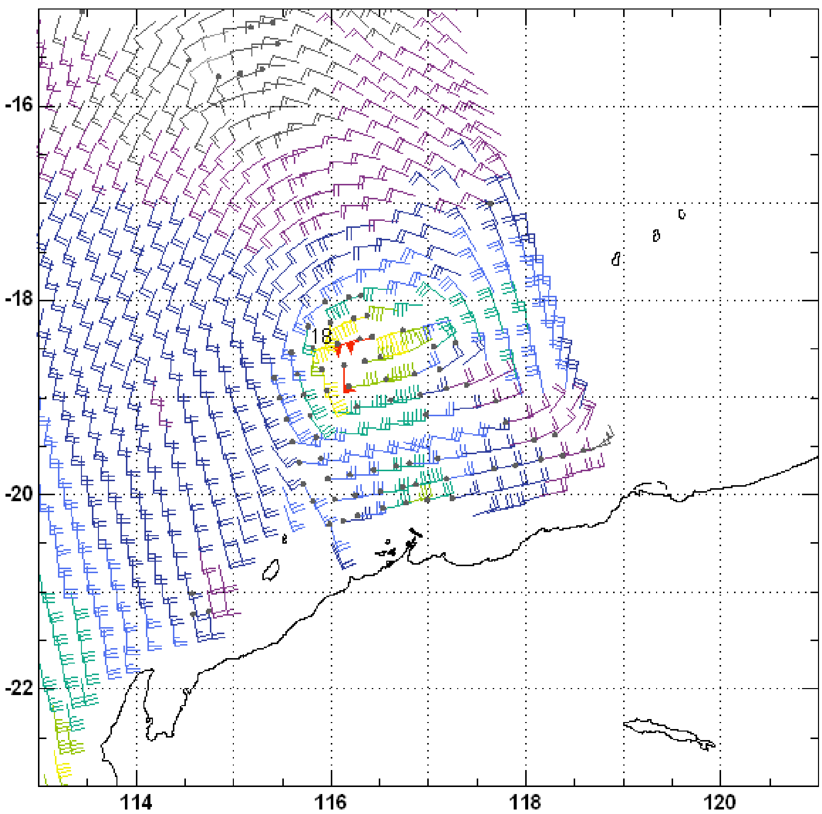

Figure 4.4. Quickscat at 22:55UTC 26 March 2007.
(image courtesy of RSS: http://www.ssmi.com/)

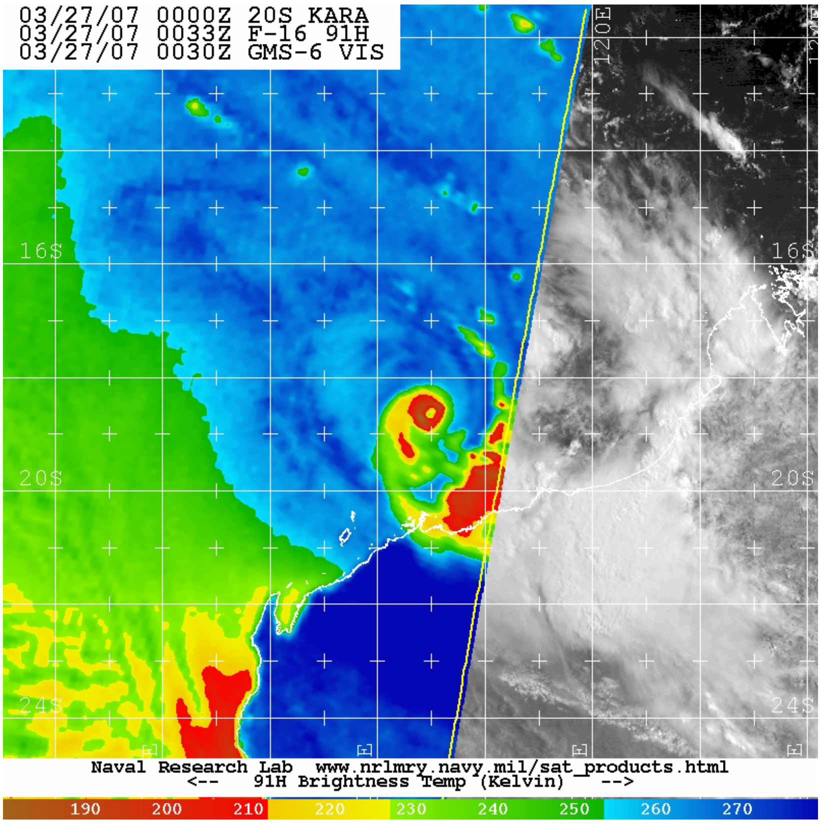

Figure 4.5. Microwave (SSMIS 91GHz) image at 27/0033UTC.
(image courtesy of US NRL: http://www.nrlmry.navy.mil/)

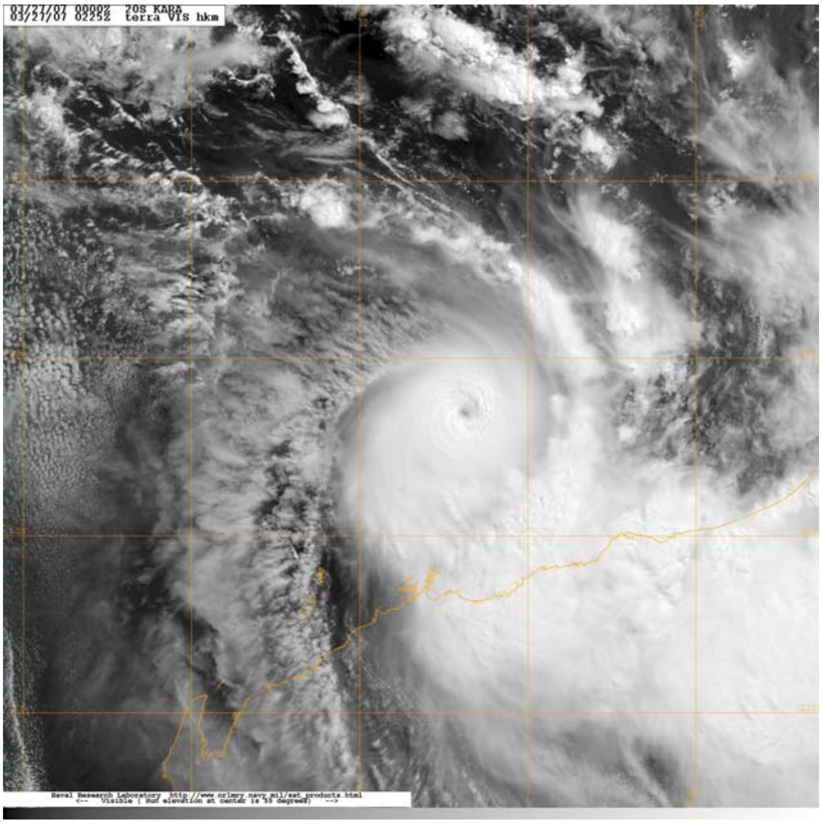

Figure 4.6. Modis (Terra) Visible image at 27/0225UTC.
(image courtesy of NASA)