A case study of Tropical Cyclone Wilma, January 2011

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Abstract

Tropical Cyclone Wilma developed in the southwest Pacific basin during January 2011 and caused significant damage and extreme weather both in Tonga and in New Zealand. It has been suggested that Wilma was the first true tropical cyclone to reach New Zealand (without having undergone extratropical transition) but it is shown here that this is not the case. Analysis of the storm’s life cycle reveals that Wilma began extratropical transition around 1000 km north of New Zealand and was essentially extratropical in nature by the time it affected the North Island. In its early depression phase, Wilma moved slowly eastwards in the vicinity of Wallis Island and the area between Tokelau and Samoa before recurving southwards. It was named Wilma around 1800 UTC on 23 January with a central pressure of 995hPa. Wilma moved southwestward and intensified to hurricane intensity near Tongatapu, Tonga around 0600 UTC on 25 January and reached peak intensity with 10-minute average winds of 100 knots and estimated central pressure of 939hPa, early on 26 January. On 27 January, Wilma shifted onto a more southerly course and began to weaken. At 0000 UTC on 28 January, its intensity dropped to marginal hurricane, 65 knots with a central pressure of 970hPa, about 500 km north of North Island. Wilma then recurved onto a southeasterly track to pass just off the east coast of Northland, New Zealand. Wilma was an unusual storm, both since it formed well east of the usual cyclone genesis region during a strong La Niña event, and since its interaction and absorption into the mid-latitude flow did not occur until well after the extratropical transition process had begun.

1. Introduction

Wilma was the third of five tropical cyclones that developed in the southwest Pacific basin during January 2011. After reaching tropical cyclone (TC) status near Samoa at 1800 UTC on 23 January, Wilma followed a quasi-parabolic path, initially towards the southwest (Fig. 1). After being named as a tropical cyclone and during the period Wilma described a southerly path, Wilma reached hurricane intensity of 65 knots and 974 hPa by 0600 UTC 25 January. Wilma then crossed the equator and headed south towards Tonga, but did not make landfall. Wilma’s intensity was 65 knots with an estimated central pressure of 970 hPa. Continuing southeastward on a straight-line track and weakening, it passed close to the northern and northeastern extremities of the North Island of New Zealand (NZ, Fig. 1) between 1200 UTC and 2100 UTC on 28 January where associated heavy rain led to extensive flooding and landslips with damage over Tonga causing severe damage, especially in the Vava'u group of islands, estimated to cost US$3M. After becoming a major TC (defined as maximum 10-minute average winds ≥ 90 knots) between 0000 UTC on 26 January and 0600 UTC on 27 January, Wilma re-curved towards the south then after 0000 UTC 28 January, the southeast at around 30°S to the east of Norfolk Island.
estimated to cost US$17M. Record high 1-day rainfall totals for January occurred in many places in northern NZ. It was just after 1200 UTC 28 January that the Meteorological Service of New Zealand reclassified the TC as a depression formerly cyclone Wilma. During the period 1200 UTC and 2100 UTC on 28 January, Wilma’s intensity weakened further from 50 knots and 978 hPa to 45 knots and 987 hPa. Once the remains of Wilma’s vorticity centre was located just east of 180° near 40° South, it interacted with an approaching trough in the westerlies to undergo explosive cyclogenesis to produce a very deep extratropical cyclone near the Chatham Islands. Between 0000 UTC on 29 January and 0000 UTC on 30 January, as a transformed Wilma sped southeast at 30 knots, its central pressure fell 23hPa from 984 hPa to 961 hPa. This rate of deepening as defined by the Fred Sanders & John Gyakum relationship (Sanders and Gyakum 1980) exceeded one Bergeron for systems between 40° South and 50° South. Following its naming as a TC and throughout its extratropical phase, Wilma’s maximum sustained winds remained above 45 knots (83km/h).

The Main Development Region for TCs in the southwest Pacific is centred on Vanuatu. In terms of genesis, an overall greater number of storms develop during seasons with ocean-dominated La Niña events (15.3 per season). However, the greatest number of major TCs develop during seasons with ocean-dominated El Niño events (6.0 per season), with the second (4.9 per season), and third (4.1 per season) greatest number of major TCs occurring during well-coupled and atmospheric-dominated El Niño events respectively (Basher and Zheng 1995, Diamond et al 2013). Sinclair (2002) found that about one-third of all storms traversed the 35° S parallel and further noted that southwest Pacific TCs encounter baroclinic westerlies earlier in their existence than in other basins and as such begin the ETT between 25-35° S.
Sinclair (2002) further found that during La Niña conditions average storm motion was slower and more meridional in nature and ETT was confined to the area west of 170° W. During El Niño conditions, ETT occurred much faster and along a much wider range from 160° E to 130° W.

Noteworthy features of TC Wilma were its formation well to the east of the normal TC genesis region during one of the strongest La Niña episodes on record and its reintensification in a higher than average latitude. Normally, tropical cyclones in the Southwest Pacific tend to form between 5° South and 20° South and west of 175° West while in strong ENSO events the formation zone can extend further east (El Nino) or retreat westwards (La Nina). However, in stronger La Nina events, there is also an anomaly of a few tropical cyclones being named south of 20° South and east of 180° (the most notable is Kim, 1999/2000). There was a suggestion that it was the first TC to reach New Zealand (without having undergone extratropical transition). This was in response to the operational strategy employed by the Meteorological Service of New Zealand in retaining Wilma’s tropical cyclone status until after the high seas warning issued at 1200 UTC on 28 January when it was located very close to northern New Zealand. Nearly all tropical cyclones have undergone transformation before crossing 30°S. There are however a few examples of storms retaining tropical cyclone status until 30-35° South although these tend to occur east of 180° (S. Ready, unpublished notes). This paper studies these features in relation to the climatology of TC occurrence and transformation in the southwest Pacific with particular emphasis on intensity and structure changes. Section 2 gives a brief survey of large-scale influences prevailing at the time and section 3 describes the extratropical transition. The paper ends with a summary and conclusions.

2. Climatological perspective

The 2010/2011 season was noted for a strong La Niña event. The Southern Oscillation Index (SOI) peaked at +2.8 in December 2010 (sourced from NIWA; Mullan 1995) and was at +2.2 from January to March 2011. In addition, the Southern Annular Mode (SAM) was positive on average through the entire TC season (November 2010 to April 2011). Diamond and Renwick (2014a) found that TC seasons during positive SOI and positive SAM conditions show a tendency for cyclones to more frequently undergo extratropical transition near New Zealand (Fig. 2, based on the South Pacific Enhanced Archive of Tropical Cyclones (SPEARTC) database, Diamond et al. 2012), consistent with the track of Wilma.

Figure 3 shows that sea surface temperatures (SSTs; taken from the NOAA Extended-Reconstructed SST dataset, Smith et al. 2008) in January 2011 were slightly cooler than normal in the formation region for TC Wilma, but were consistently warmer than normal in the sub-tropics. Also as TC Wilma moved southwards, it encountered an extensive region of favourable (weak) vertical wind shear (Fig. 3, data taken from the NCEP/NCAR reanalysis, Kalnay et al. 1996) which would have contributed to the cyclone maintaining its intensity as it moved out of the tropics.

2.1 Influence of the Madden-Julian Oscillation (MJO)

The MJO is the dominant mode of atmospheric intraseasonal variability in the tropics (Madden and Julian 1994); and was initially observed as a significant 40-50 day spectral peak in the zonal winds (U), temperature, and surface pressure fields with wave-like characteristics (Madden and Julian, 1971&1972). Over the Eastern Hemisphere, it is characterized as a large-scale convectively coupled phenomenon that propagates eastward at approximately 10 knots (5 m s⁻¹).
Meanwhile over the Western Hemisphere, the convective coupling breaks down and the eastward propagation accelerates to 20-30 knots (10-15 m s$^{-1}$). The MJO has a 30-90 day period and maximum variance at roughly 50 days (Zhang, 2005).

Zhang (2005) found that the MJO has a seasonal cycle with two peak seasons: (a) a primary peak (the one more germane to this study) which occurs when the strongest MJO signal is located directly south of the Equator during the austral summer season; and (b) a secondary peak occurring just north of the equator during austral winter (not included in this study). There is strong year-to-year variability in MJO activity, with periods of strong activity followed by long periods in which the oscillation is weak or absent (Hendon et al., 1999; Zhang, 2005; Gottschalck, et al., 2013). Kiladis et al. (2005) conducted an in-depth study of the zonal and vertical structure of the MJO that links the origins and genesis of the MJO to the physical mechanisms helping explain the 30-50 day oscillation, and notes the unique characteristics of the MJO’s behaviour in the western Pacific versus that in the Indian Ocean and Indonesia. With respect to the geographic aspect of MJO there are eight phases that are generally paired together.
(Wheeler and Hendon, 2004) as follows: (a) 8-1 (Western Hemisphere and Africa); (b) 2-3 (Indian Ocean); (c) 4-5 (Maritime Continent); and (d) 6-7 (Western Pacific or warm pool region).

Figure 3: Track plots of TC Wilma overlaid on January 2011 averaged: (left) SST anomalies (0.3°C contour interval); and (right) wind shear anomalies (10 kt contour interval). In both cases, blue contours are negative, red are positive and the zero contour has been omitted.

<table>
<thead>
<tr>
<th>Dvorak Current Intensity (CI) Number</th>
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<th>Equivalent Intensity Category number (BoM, Australia)</th>
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Table 1: Relationships between Current Intensity number, 10-minute mean wind and intensity Category number. The CI number is the same as the final T-number except when T-number shows a weakening trend or when redevelopment is indicated.

Both Leroy and Wheeler (2008) and Diamond and Renwick (2014b) have investigated the effects of the MJO on TCs in the southwest Pacific basin from the standpoint of prediction and climatology respectively. The amplitude of the MJO
based on the multivariate MJO index (Wheeler and Hendon, 2004) over the lifetime of Wilma was quite strong at an average of 1.95 and the cyclone spent 73% of its time in either MJO phase 7 or 8, the phases during which the strong convective signal of the MJO is in the southwest Pacific (Leroy and Wheeler 2008).

The average full season MJO amplitude of 1.28 (weak to moderate) found by Diamond and Renwick (2014b) is consistent with positive SST anomalies from the tropics and extending south towards NZ, as well as favourable wind shear conditions depicted in Fig. 3 which shows a region of reduced shear near northern NZ. Hence, the extratropical nature of Wilma was climatologically consistent with what would be expected given the full season SAM and MJO values. In summary, out of eight named TCs which formed east of 150°E in the 2010/2011 season, a total of six (including Wilma) became extratropical (as defined by Sinclair, 2002) in the same area near New Zealand. As noted by Lorrey et al (2013), the 2010/2011 season was climatologically one of the most active seasons for extratropical cyclones in the New Zealand region.

3. Extratropical transition (ET)

Wilma reached its peak intensity as a Category 4 (Australian Bureau of Meteorology Tropical Cyclone Category System, see Table 1) TC, with maximum sustained winds of 100 knots (185 km/h), during the first half of 26 January 2011, about 600 km south of Fiji. At the time, there was an upper tropospheric trough lying from west of Norfolk Island to near the far north of the North Island. This trough was almost stationary, resulting in a persistent frontal cloud band near the North Island (Fig. 4). Shortly after reaching peak intensity, Wilma’s cloud system started to become distorted in response to the proximity of this upper trough and by 0000 Universal Time Coordinated (UTC) on 27 January, Wilma’s eye had become very cloud-filled with its centre near 25.3°S, 173.3°E or about 1000 km north of the North Island (Fig. 5b). This resulted in the eye brightness temperatures cooling from +5°C to -52°C. However, the Dvorak TC Intensity analysis (Dvorak 1984) using the “eye” pattern still yielded a T-number of 6 with an equivalent Current Intensity (CI) number of 6. The T-number is an estimate of the intensity of a TC by taking measurements using one of these cloud patterns – “Curved Band”, “Shear”, “Eye” and “Embedded Centre” (Dvorak, V. F., 1984). The CI number which is related to the maximum wind speed of a TC is the same as the T-number except for weakening or redeveloping TCs when the CI number may be 0.5 or 1.0 above the T-number. (see Table 1).

When the eye became obscured by thick cirriform cloud, the low-level cloud centre became difficult to locate in the conventional infra-red and visible imagery so microwave imagery from the US Naval Research Laboratory (NRL) Monterey was instrumental in locating the centre amongst the cold cloud tops. (Fig. 5a). The outflow towards the poleward side of the tropical cyclone became more pronounced during 27 January UTC as upper level wind shear increased between 25°
South and 30° South, resulting in a weakening trend. At 0600 and 1200 UTC on 27 January, the Dvorak “Embedded Centre” cloud pattern was employed to analyse the intensity of Wilma, giving a T-number of 5 and a CI of 5.5 (Fig. 6).

At 1800 UTC on 27 January, Wilma was centred near 28.5°S, 172.0°E. The progressively colder seas and shearing from the northwest caused a warming of the cloud top temperatures and a shift of the low level cloud centre towards the northwestern edge of its deep convective cloud structure (Fig. 7). Because of this change in cloud configuration, application of the Dvorak “Embedded Centre” pattern proved marginal, giving a T-number of 4.5.

At 0000 UTC on 28 January, Wilma was located about 450 km north of the North Island, still moving south-southwestwards at about 20kt and on the verge of recurvature, as a fast-moving short-wave trough crossed the central Tasman Sea. A remnant of Wilma’s dense convective cloud mass, associated with the central core of the cyclone, stayed in close proximity to the low level cloud centre between 0000 and 0600 UTC as the TC’s cloud system merged with the frontal cloud band that had remained slow-moving to the northeast of the North Island. At the same time, the cloud system associated with the Tasman Sea trough was advancing over the South Island (Fig. 8). At 0600 UTC on 28 January, the Dvorak “Shear” pattern could still be applied to obtain a T-number of 3 and a CI number of 3.5. This yielded estimated maximum 10-minute average winds of 50-55 knots (102 km/h). The ASCAT image that was available a few hours later supported this interpretation (Fig. 9).

The ASCAT image shows the asymmetrical wind structure of Wilma during the 1048 UTC pass on 28 January with 50-knot (93 km/h) winds on the eastern flank and lighter winds...
on the western flank, with light winds near the centre. Even though Wilma’s cloud system had merged with the frontal cloud

Figure 6 (left): MTSAT IR image at 1200UTC on 27 January. Eye not apparent as the centre of Wilma was obscured by thick cirriform cloud. Analyst was required to use the ‘Embedded centre’ cloud pattern to estimate the Dvorak TC intensity. Source: MetService.

Figure 7 (right): MTSAT image at 1800UTC on 27 January 2011. + marks the centre of Wilma and its position in relation to the colder (white) cloud tops. Source: MetService.

Figure 8 (left): MTSAT image at 0000UTC on 28 January 2011. Note the centre (+) is still closely associated with the coldest (brightest white) cloud tops so its intensity can still be estimated using the Dvorak TC Intensity technique. Source: MetService.

Figure 9 (right): ASCAT image at 1048UTC on 28 January 2011. Source: MetService
band, it managed to retain its identity for several hours more and a precipitation band seen in the radar imagery (Fig 12) stayed close to the centre until after 1500 UTC on 28 January.

This stage of Wilma's history could be termed post-tropical in the sense that it had lost most of its tropical-related characteristics but still retained a strong low-level vortex and carried a warm core extending up to the mid-troposphere, with wet-bulb potential temperatures around 23°C close to New Zealand. Hicks Bay experienced a burst of tropical air around 2100 UTC on 28 January when the dew point climbed to 23.5°C before falling sharply to 19.7°C an hour later. The SSTs had also cooled in the path of Wilma to 20-22°C.

After 1200 UTC on 28 January, the evolution of Wilma became inextricably linked to the approaching Tasman Sea trough. This interaction is described in the next section.

3.1 Synoptic aspects
In this section, ERA-Interim reanalysis fields (Dee et al. 2011) are shown at 12-hour intervals. MSLP analysis at 0000 UTC on 28 January (Fig. 10, top right) shows a well-defined trough extending to the southeast of Wilma. This feature, analysed as a warm front, was associated with the frontal cloud band discussed in the previous section. It was positioned beneath the equatorward entrance of a jet streak over the North Island and a region of ascending air at 500hPa (Fig. 10, bottom right). Rain broke out over the north of the North Island at this time. As the interaction with the approaching upper trough became established in the lead up to 1200 UTC on 28 January, the cyclone/trough combination accelerated southeastward towards the region of maximum ascent (Fig. 11, bottom right). A radar image two hours later, when the surface trough extended from Great Barrier Island to the western Bay of Plenty, showed the trough was near the eastern edge of the rain area. (Fig. 12).

At 1200UTC, the upper trough had reached its maximum amplitude and the NW jet ahead of it had intensified (Fig. 11, top left), with a large envelope of 110-knot (204 km/h) winds. This augmented the upper level divergence over the surface system as Wilma became “captured” by the westerlies (cf. bottom left, Figs.10 and 11).

3.2 Reintensification
The cyclone did not come under the influence of an upstream jet until between 1200 UTC on 28th and 0000 UTC on 29th when it lay beneath an area of enhanced upper-level divergence associated with both the equatorward entrance of the downstream jet and the poleward exit of the upstream jet (Fig. 13, top and bottom left), a favourable zone for explosive cyclogenesis. At the same time, differences in thermal advection across Wilma’s circulation peaked resulting in frontogenesis (Fig. 13, top right - 000-500hPa thickness). During this time, Wilma raced southeast at 40 knots past the north and northeastern parts of the North Island. Between 0000 UTC on 29 January and 0000 UTC on 30 January, Wilma continued to move quickly as it passed the Chatham Islands, deepening rapidly with its central pressure plummeting 23 hPa from 984 hPa to 961 hPa and the system transforming into a severe extratropical cyclone. The change in Wilma’s appearance as the TC progressed through ET and transformed into a deep extratropical cyclone is captured in a series of satellite images (Fig 14).

3.3 Comparison with climatology
When a TC enters middle latitudes the onset of the process of extratropical transition (ET) can be identified by the degree of thermal asymmetry in the 600-925hPa thickness field as given by the B-parameter which is a measure of warm minus cold asymmetry (see Sinclair 2004 for details). Onset of ET is defined as the start of the period when the B-parameter exceeds 10 in three or more successive 12-hourly analyses (five or more successive 6-hourly analyses).
Figure 10: ERA-Interim reanalysis fields for 0000UTC 28 Jan 2011.
Top left – 250hPa height (blue contours, 100 geopotential metre [gpm] interval) and isotachs (knots, shading starts at 50kt and changes in 20kt steps to 110kt);
Top right – mean sea-level pressure (blue contours, 5hPa interval) and 1000-500hPa thickness (black contours, 50gpm interval);
Bottom left – 250hPa divergence (sec\(^{-1}\), 10\(^{-5}\) sec\(^{-1}\) interval, blue contours negative, red contours positive, zero contour omitted);
Bottom right – 500hPa vertical motion (hPa sec\(^{-1}\), 0.15hPa sec\(^{-1}\) interval, blue contours negative, red contours positive, zero contour omitted).
The cross in each panel denotes the centre of TC Wilma. The dashed line indicates the MSLP trough southeast of the TC centre.
Figure 11: As in Fig. 10, but for 1200UTC 28 Jan 2011

Figure 12: Auckland radar image for 1358UTC 28 January 2011.
Figure 13: As in Fig. 10, but for 0000UTC 29 Jan 2011

This criterion suggested the onset of ET in Wilma’s case occurred at about 0000 UTC on 27 January (Fig. 15) between 25-30°S but its cyclone structure did not conform to any climatological model (Sinclair 2004). In the satellite imagery at 0000 UTC on 27 January (Fig. 5), Wilma still sports an eye but it is becoming rapidly cloud filled. There is also a clear separation between the cyclone’s cloud system and the frontal cloud band.

Wilma’s behaviour bore some similarity to the low composite ("low south" and “low southwest”) categories identified by Sinclair (2004) but the principal trough in the westerlies lay well to the southwest over the Tasman Sea and the background gradient was very weak. The situation was complicated by the presence of the weak upper trough to the west when Wilma was at 30°S around 0000 UTC on 28 January (Fig 10, top left), a feature that was decaying steadily.

Unlike the climatological composites, Wilma had not been absorbed into a mid-latitude trough system at the time of ET onset. Climatologically, rapid cyclogenesis (reintensification) events occur in the southwest Pacific at an average latitude of 33°South (Sinclair 2004) but Wilma reintensified at a much higher latitude. The double-jet configuration associated with maximum surface development did not appear until the cyclone was at latitude 40°S (Fig.13, top left).
Figure 14: MTSAT IR images during ET process and transformation into a deep extratropical cyclone (Source: MetService). **Top left** – 0000 UTC 28 Jan 2011: Still a TC but ET has commenced. **Top right** – 1200 UTC 28 Jan 2011: Transition to post-TC completed. **Bottom left** – 0000 UTC 29 Jan 2011: Transforming into an extratropical cyclone. **Bottom right** – 1200 UTC 29 Jan 2011: Transformation into a deep extratropical cyclone completed.
4. Summary and Conclusions

TC Wilma was associated with extreme weather and significant damage both in the tropics (Tonga) and the extratropics (New Zealand). Wilma occurred during a strong La Niña event, well east of the normal TC genesis region under La Niña conditions. The 2010/11 cyclone season also experienced the positive phase of the SAM (on average), a situation associated with increased likelihood of extratropical transition near New Zealand.

Analysis of the thermal structure of the cyclone suggests that extratropical transition began around 0000 UTC on 27 January 2011 when Wilma was at around 25°S, well north of New Zealand. Hence, Wilma was extratropical in nature by the time it affected New Zealand, although it retained a strong low-level vortex and a warm core up to the mid-troposphere. During 28 January UTC, Wilma interacted strongly with an upper-level trough in the westerlies and reintensified into a vigorous mid-latitude cyclone east of the South Island during 29 January 2011.

Wilma’s extratropical transition was unusual in that it did not involve interaction with a significant mid-latitude trough until well after extratropical transition had begun. However, Wilma had taken on predominantly extratropical structure by the time it passed close to the northern coast of New Zealand. This was evident in the asymmetric wind structure shown in Fig. 9 with the tight core of winds close to the centre no longer evident. Mid-latitude reintensification did not occur until the remnants of Wilma were east of New Zealand and poleward of 40°S latitude.

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