



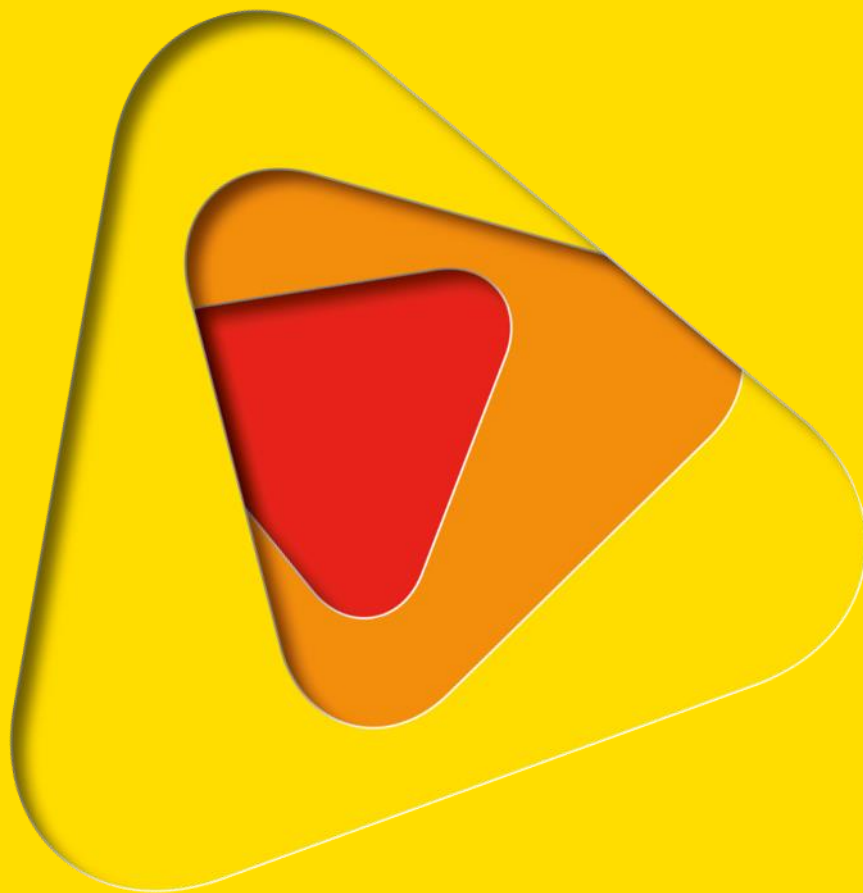
REVIEW OF TROPICAL-EXTRATROPICAL CYCLONE TRANSITIONS

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Annual Report 2014





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Review of Tropical-Extratropical Cyclone Transitions

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Summary

- As tropical cyclones move toward the poles they can interact with mid-latitude weather systems causing the storms to lose tropical characteristics and become more extra-tropical in nature, often intensifying and accelerating-- this is known as Extra-tropical Transition (ET).
- Storms that undergo ET pose a serious threat to life and property by extending tropical cyclone-like conditions over a larger area in latitudes that do not normally experience such events.
- The conditions associated with ET are favourable for the generation of large damaging waves and storm surges.
- ET occurs in nearly every ocean basin that experiences tropical cyclones and numerical model predictions of these storms are typically inaccurate.
- The Australian region remains the least studied in terms of ET with only one study specifically focusing on the threat of ET to the Australian coast.
- Cyclone track records suggest that the southwest of Western Australia is the region most at risk, late in the season, when intense tropical cyclones are most likely to interact with approaching cold fronts.
- Storms making it south of 35° S to the west of the dateline are more likely during La Niña years and late in the season (March and after).
- The general eastward component of movement of tropical cyclones in the South Pacific alleviates some of the threat of ET for the East Coast of Australia as many of the storms curve away from the coast as they move south.
- Global reanalysis models provide useful tools to study ET events. However, these models typically underestimate the intensity of tropical storms and are limited by resolution.
- Improving the accuracy of storm surge models of ET events will require careful selection of forcing data, sensitivity studies, and special parameterisations due to the complex dynamics of these rapidly changing systems.

1.1 Introduction

Highly damaging storms along coastlines can occur when tropical cyclones (TCs) collide with winter weather systems. For example, in 2012 on the east coast of the United States tropical cyclone Sandy merged with a winter weather system just prior to landfall causing widespread devastation affecting 65 million people and destroying 570,000 buildings (Halverson and Rabenhorst, 2013).

As tropical cyclones move toward the poles they can interact with the surrounding environment causing the tropical cyclone to lose tropical characteristics and become more extra-tropical in nature – this is known as Extra-tropical Transition, or ET. These systems are sometimes referred to as ex-tropical or post tropical cyclones. Storms that undergo ET pose a serious threat by extending tropical cyclone-like conditions over a larger area and to latitudes that do not typically experience such events (Jones et al., 2003). They often evolve into fast-moving and occasionally rapidly intensifying extra-tropical cyclones that produce intense rainfall, very large waves, and tropical cyclone intensity winds (Jones et al., 2003).

Many residents do not recognize the danger and risks that can happen when a tropical cyclone reaches colder water and undergoes extra-tropical transition (Masson, 2014). Often, predictions of ET by numerical forecast models do not accurately depict the characteristics of ET and the subsequent evolution of the resulting extra-tropical cyclone, compounding the risks to coastal communities (Jones et al., 2003).

ET occurs in nearly every ocean basin that experiences tropical cyclones. Australia experiences both tropical and extra-tropical cyclones and thus the potential threat from tropical cyclones undergoing extra-tropical transition warrants investigation (Foley and Hanstrum, 1994).

1.1.1 Characteristics and coastal risks related to extra-tropical transition

The main difference between tropical cyclones and extra-tropical cyclones (cyclones out of the tropics) is the energy source—tropical cyclones are compact storms that pull heat from warm ocean waters and release it in the storm centre (warm-cored systems) whilst extratropical storms are fueled by temperature differences in the atmosphere and cover a much larger area.

As a tropical cyclone moves poleward it experiences changes that may include increased baroclinicity (temperature/density gradients) and vertical shear, meridional humidity gradients, decreased sea surface temperature (SST) or strong SST gradients, and an increased Coriolis parameter (Jones et al., 2003). The structural changes of a that occur during ET can be seen as a transformation from a symmetric warm-core TC to an asymmetric cold-core cyclone (Evans et al., 2006).

Associated with ET is increased translation speed which contributes to the asymmetric distributions of severe weather elements including hot, dry winds, dust storms and extreme fire hazard in some areas and flooding and damaging winds elsewhere (Fig. 1) (Foley and Hanstrum, 1994).

High wind speeds and large translation speeds contribute to the generation of large ocean surface waves and swell. In the Atlantic Ocean of storm waves exceeding estimates of the 100-year return period for that region with waves as high as 30 m have been recorded a number of times (Bowyer and MacAfee, 2005).

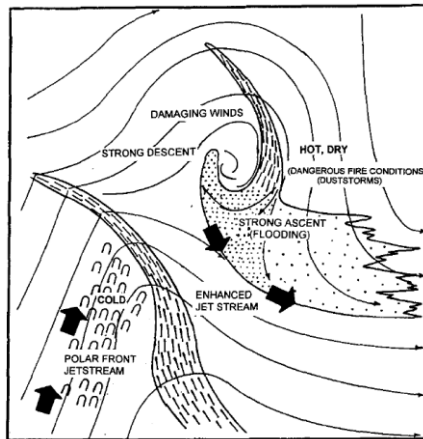


Figure 1 Diagram indicating larger scale flow and weather resulting from the interaction or ‘capture’ of a tropical cyclone in the southern hemisphere by an extra-tropical cyclone (From Foley and Hanstrum 1994).

1.1.2 Global occurrence

Extra-tropical transition occurs in nearly every ocean basin that experiences tropical cyclones (Jones et al., 2003) with examples of ET systems tracking all the way across the Atlantic or the Pacific (e.g., Thorncroft and Jones 2000). The largest number of ET events occur in the western North Pacific (Harr and Elsberry, 2000; Klein et al., 2000; Kitabatake, 2011). In the eastern North Pacific the synoptic conditions associated with the presence of a strong subtropical ridge do not favour ET, however ET still happens approximately nine percent of the time (Wood and Ritchie, 2012, 2014).

The North Atlantic basin contains the largest percentage (45%) of tropical cyclones that undergo ET (Hart and Evans, 2001) making the east coast of Canada highly susceptible with a majority of tropical storms transitioning into extra-tropical cyclones by the time they make landfall (Masson, 2014).

In the northern hemisphere tropical cyclones can retain tropical characteristics until 50°N. However, in the South Pacific on average most transitions are complete by 30°S due to the northward extent of the baroclinic westerlies in this region (Sinclair, 2002).

ET has a significant impact on Australia and New Zealand, being triggered by the approach of a mid-latitude trough from the west (Sinclair, 2002). However, this region remains the least studied in terms of extra-tropical transitions.

In the global database of tropical cyclones, IBTrACS (International Best Track Archive for Climate Stewardship (Knapp et al., 2010), the nature of tropical storms is recorded allowing for the plotting of cyclones recorded to have undergone ET (Figure 2). However, in the Australian region such information has not traditionally been available and a general climatology has not been developed. As a result the apparent lack of ET around Australia illustrates the lack of information about ET rather than occurrence.

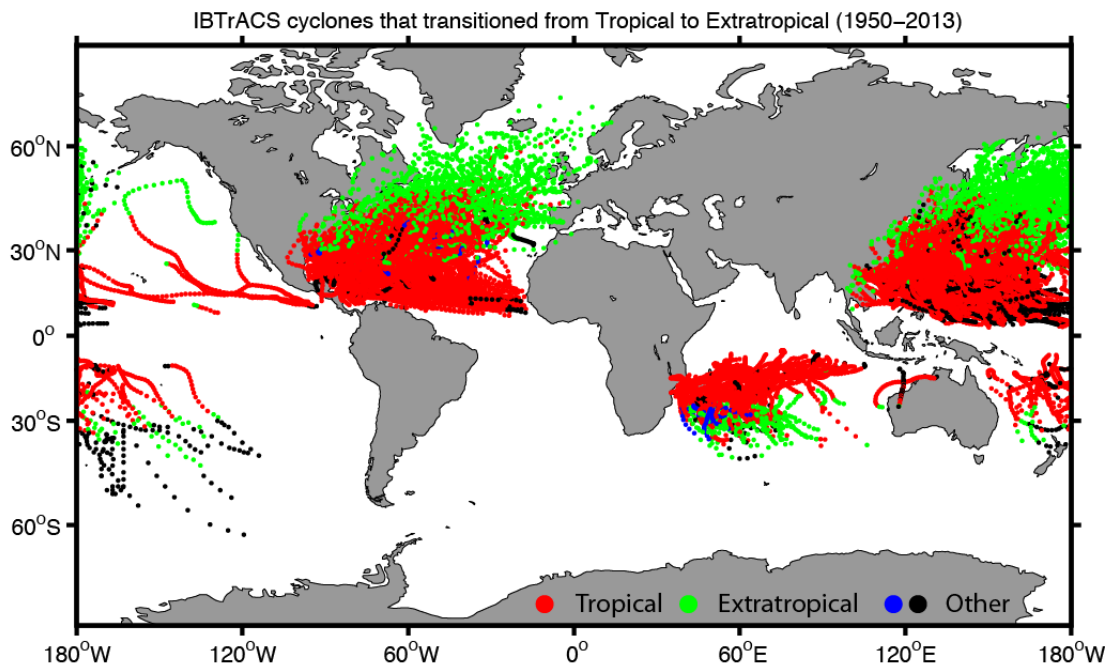


Figure 2. Map of all tropical storms recorded to have undergone ET in the IBTrACS database from 1950-2013. Red coloured tracks indicate the storm was classified as a tropical cyclone whilst green indicates the shift to an extra-tropical storm. The lack of activity around Australia illustrates the lack of information about ET rather than occurrence.

1.2 Extra-tropical transition around Australia

A preliminary review of literature and tropical cyclone tracks indicates that the southwest of Western Australia is more at risk from ET compared to the East Coast. However, few studies have investigated these events, and Australia remains the least studied region affected by ET compared to other ocean basins.

Australia is impacted by both tropical cyclones from the north (Fig. 3) and mid latitude low pressure systems (extra-tropical cyclones) originating in the southern ocean (Jones and Simmonds, 1993; Qi et al., 2006). Tropical cyclones occur along both the Pacific and Indian Ocean coasts of Australia and generally move east to west and poleward before recurving toward the east (Sinclair, 2002). Tropical cyclone activity affecting Australia is strongly modulated by the El Niño Southern Oscillation (ENSO) with more cyclones generally crossing the coast during La Niña years (Ramsay et al., 2012). On a multi-decadal timescale there is evidence for decreasing numbers of TCs, but increasing intensity around Australia (Nicholls et al., 1998).

1.2.1 Southwest Pacific (Eastern Australia)

A general climatology for the Southwest Pacific of cyclones moving into the midlatitudes was developed by (Sinclair, 1993; Sinclair, 2002, 2004) however they did not look specifically at those storms affecting the Australian coast. Jones et al. (2003) indicated that the threat of ET events for the east coast of Australia was underestimated. In the Southwest Pacific tropical cyclone season is from November to May with highest numbers of tropical cyclones in February. Nearly one-third of TC's in this region make it into the mid-latitudes (south of 35 deg. S) (Sinclair, 2002).

In the Southwest Pacific the onset of ET occurs between 20-25 deg. S which is closer to the equator than in any other basin. Most storms undergoing ET develop extra-tropical characteristics by the time they reach 25°S as compared to 40°S in the northern hemisphere. Sinclair (2004) showed that the existence of relaxed or enhanced pressure gradients south of the storms determined whether the storms would weaken or intensify. The approach of a mid-latitude trough from the west triggered extra-tropical transition in this region (Sinclair, 2002).

Storms making it south of 35°S to the west of the dateline are more likely during La Niña years and late in the season (March and after). The general eastward component of movement of tropical cyclones as they go south alleviates some of the threat of ET impacting the East Coast of Australia since few storms have historically passed near to the coast south of 24°S (Fig. 4).

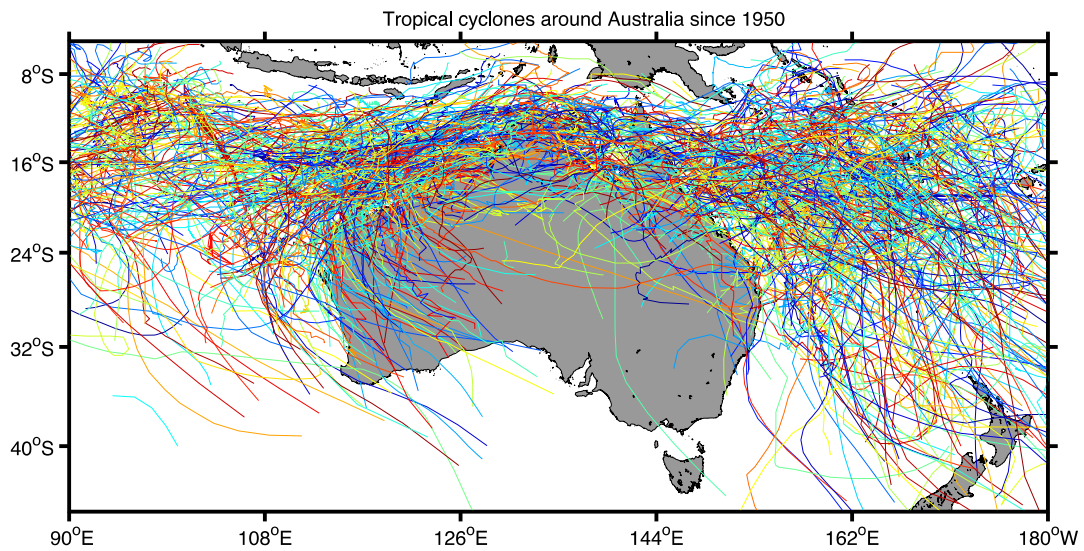


Figure 3. Plot of all tropical cyclone tracks around Australia 1950-2013 from IBTrACS.

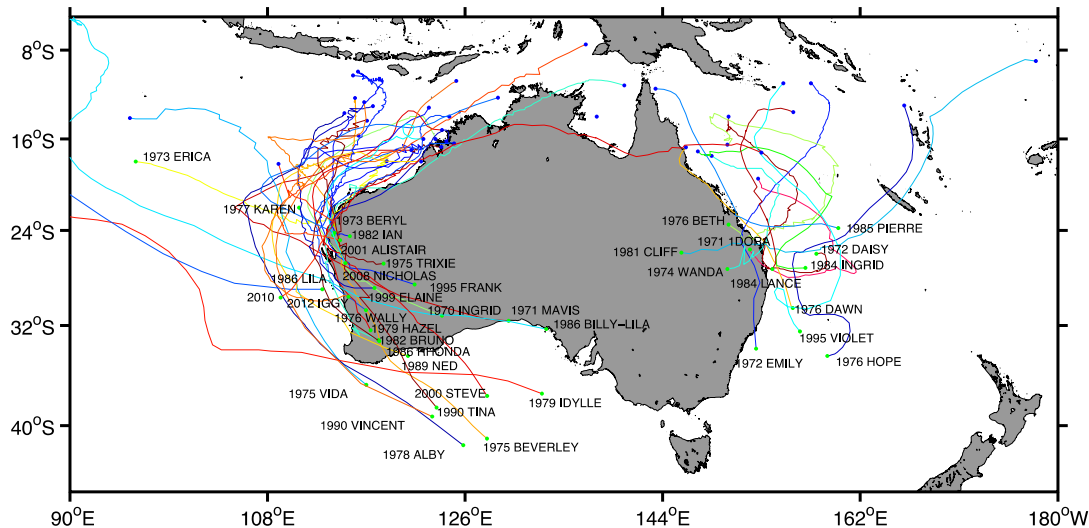


Figure 4. Cyclones with potential to impact the Australian coast while undergoing ET from 1970-2013. Potential ET cyclones were defined as storms passing within 100km of the coast below 24 degrees S (data from IBTrACS). Blue dots indicate the first recorded position and green dots mark the last recorded location of the low pressure centre.

1.2.2 Southeast Indian Ocean (Western Australia)

Over the southeast Indian Ocean relatively few tropical cyclones undergo ET (Foley and Hanstrum, 1994; Jones et al., 2003). However, these storms are perhaps more likely to impact the coast due to their tracks (Fig. 4).

Foley and Hanstrum (1994) completed the most comprehensive study of extra-tropical transition in Australia and compiled a climatology of tropical cyclones affecting the subtropical west coast of Australia. They found that twice as many cyclones affect the northern part of the state with around twenty percent moving into the mid-latitudes maintaining some intensity.

Tropical cyclones were classified into two categories based on synoptic weather patterns:

1) "Cradled" by easterly flow to the south

- All of these passed near NW Cape, moved southward parallel to coast with little acceleration and an average speed 6.5 m/s.
- Cradled cyclones were most likely to occur during January-April

2) "Captured" by prefrontal westerly flow from mid-latitudes due to an approaching low and cold front. These systems were considered to be undergoing extra-tropical transition.

- These storms accelerated and moved generally southeastward ~ 12.5 m/s (24 hours before affecting the coast).
- Acceleration occurred when fronts arrived within an average distance of 1660 km \pm 220 km.
- 100% of tropical cyclones causing damage at Perth were captured while only 20% captured damaged Carnarvon in the NW.
- These events were most likely March-April.
- Structural changes resulted in most rain poleward with dry conditions and strongest winds equatorward.

1.2.3 Historical Events around Australia

The most destructive ET event to affect Australia to date was Cyclone Alby in April 1978 (Figs 5 & 6). Alby underwent ET, merging with a cold front and accelerating, as it passed close to the southwest corner of WA on 4 April, 1978 causing strong to storm force winds over a large area of southwest Western Australia and widespread damage killing 5 people. Total damages were estimated to be around 50 million dollars, making it the most devastating storm in the region (BOM, 2014).

Hot, dry northerly winds created widespread dust storms and caused bushfires to burn out of control over much of the region as little rainfall was associated with the event. In addition large waves and storm surge caused substantial coastal erosion and flooding with water levels reaching one metre above the highest astronomical tide. Other tropical cyclones recorded to have undergone ET and affected the Australian coast are summarised in Table 1.

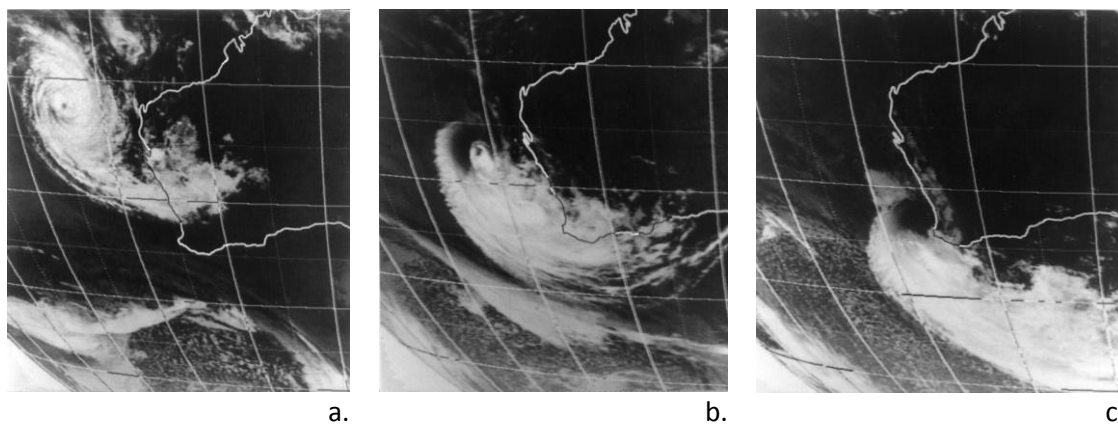


Figure 5. Infrared satellite imagery of Cyclone Alby on a) 6pm 2 April b) 2am 4 April c) 5pm 4 April 1978 showing Alby's transition from a symmetric tropical cyclone into an asymmetric extratropical system. Source: Australian Bureau of Meteorology/Japan Meteorological Agency (<http://www.bom.gov.au/cyclone/history/wa/alby.shtml>).

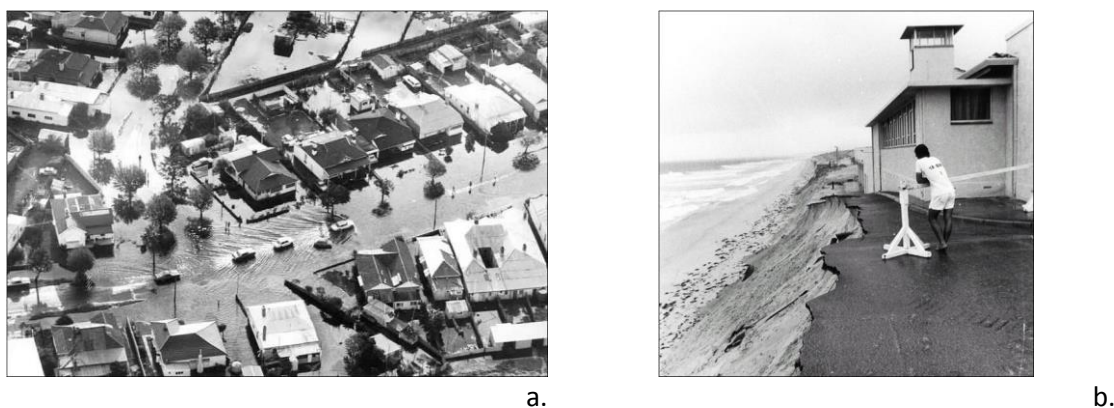


Figure 6. Storm damage from Cyclone Alby in a) Bunbury and b) City Beach, Southwest Australia. Source: Australian Bureau of Meteorology (<http://www.bom.gov.au/cyclone/history/wa/alby.shtml>).

Table 1 Tropical cyclones reported to have exhibited characteristics of extra-tropical transition by the Australian Bureau of Meteorology.

TC name	Date	Year	Region where crossed/near coast	Undertaken ET?	Damage (as reported by BOM)	Notes	Web link
Vida	16-21 mar	1975	SW WA	Maybe	Gale force winds and strong squalls caused some structural failures and severely damaged small aircraft along the lower west coast. Winds at Fremantle reached 128 km/h. It is estimated that damage approaching the value of \$1 million was caused by cyclone Vida .	Followed a similar path to Alby - Not reported to have undergone ET, but reports of strong winds and fast track and no rains suggests that ET might have occurred. In contrast with the lack of rain associated with "Vida" the strong winds had a widespread effect. Gales were reported at all coastal stations from Kalbarri southward to Bremer Bay.	http://www.bom.gov.au/cyclone/history/vida.shtml
Alby	27 Mar-4 Apr	1978	SW WA	Yes	Extensive damage Perth-Albany	Most damaging ET storm reported in Australia	http://www.bom.gov.au/cyclone/history/wa/alby.shtml
Severe TC Idylle	5-16 Apr	1979	SW WA	Yes	The only significant damage reported was some erosion at Perth metropolitan beaches.	Originated in the central Indian Ocean. The system then steadily weakened until 16 April 1979. between 16 and 18 April, however, the system became cold cored and intensified. although gale force winds were reported along the southern west coast they were not sustained except near Cape Naturaliste and Cape Leeuwin. (BOM).	http://www.bom.gov.au/cyclone/history/idylle.shtml
Ned	26 Mar- 1 Apr	1979	SWWA	Yes	Strong winds were reported at Rottnest Island and in the Rockingham area, and caused power disruptions and isolated roof damage.	A strong mid-latitude trough approaching from the southwest accelerated the remains of Ned to the southeast crossing near Perth on the morning of 1 April. Strong winds were reported at Rottnest Island and in the Rockingham area, and caused power disruptions and isolated roof damage (BOM).	http://www.bom.gov.au/cyclone/history/ned.shtml

Severe TC Vincent	2-4 Mar	1990	SW WA	Maybe	No, it stayed offshore	By 0000UTC 5 March, an approaching cold front over the eastern Indian Ocean caused Vincent to accelerate first in a southerly and later in a south-easterly direction. Satellite imagery revealed a rapidly decaying cyclone structure with the upper and middle-level cloud being sheared away from the low-level centre. By 0001 6 March, Vincent was 200 km west-southwest of Cape Leeuwin and moving southeast at 60 km/h. The 991 hPa low-level centre was devoid of cloud but gales were still being reported along the coastal strip (BOM).	http://www.bom.gov.au/cyclone/history/vincent90.shtml
Mavis	2-29 mar	1971	NW WA/ Shark Bay	Yes	Some flooding in Denham	Crossed near Denham, no BOM report and very little info available.	N/A
Hazel	7-14 mar	1979	NWWA/ Shark Bay	Yes	Sea action damaged the jetties at Exmouth, Cape Cuvier, Carnarvon and Denham. Buildings were inundated with sea water between Carnarvon and Shark Bay. In all damage and losses due to <i>Hazel</i> amounted to some \$20 million.	Hazel accelerated and averaged about 33 km/h during the sixteen hours before landfall. Thereafter the speed of the weakening system increased to more than 70 km/h before it dissipated (Foley & Hanstrum 1994).	http://www.bom.gov.au/cyclone/history/hazel.shtml
Herbie	18-21 may	1988	NW WA/ Shark Bay	Yes	<i>Extensive - Herbie</i> caused wind damage between Carnarvon and Denham, produced a storm surge at Denham that left fishing vessels stranded along the main street, grounded a large freighter at Cape Cuvier and caused flooding along the Irwin and Greenough Rivers inundating the streets of Dongara.	<i>Herbie</i> moved some 1500 km in the 24 hours prior to crossing the coast at Shark Bay reaching speeds of over 70 km/h. The central pressure was measured at 980 hPa at landfall. Carnarvon recorded a wind gust of 120 km/h and similar speeds were estimated at Denham. <i>Herbie</i> continued its southeastward track through inland parts of the state and gradually weakened (BOM).	http://www.bom.gov.au/cyclone/history/wa/herbie.shtml
Lance	3-7 april	1984	East Coast	Maybe (not reported)	Unknown	A new low developed around 2100 UTC 7 April near the northern tip of Fraser Island ahead of a marked upper-level trough that was moving northeast over New South Wales. This low moved south-southeast and deepened to about 980 hPa by 1500 UTC 8 April when it was centred approximately 200 km east-northeast of Brisbane. During 8 and 9 April heavy rain and storm-force winds were experienced along the Moreton coast and nearby islands. After 0900 UTC 9 April the low moved away	http://www.bom.gov.au/cyclone/history/lance.shtml

to the east and gradually weakened. The low was not classified as a tropical cyclone.

1.3 Challenges to understanding and prediction

Accurately predicting weather and ocean conditions and the associated hazards such as formation of destructive waves and storm surges requires knowledge of the intensity as well as structure of the storm. Transitioning tropical cyclones are inherently difficult to accurately simulate in numerical model forecasts (Evans et al., 2006).

Storm surge and wave models are highly sensitive to the wind fields used to force them. As a result predicting the storm surge created by a cyclone that is accelerating, intensifying, and not well represented in tropical cyclone models (e.g. Holland et al., 1987) or mesoscale atmospheric models is particularly challenging.

However, recent advances in numerical models have increased our ability to understand how cyclones undergoing ET behave and potentially can improve the simulation of ET related storm surges.

1.3.1 Global reanalysis models

Global reanalyses have been derived at major numerical model weather prediction centers and have improved dramatically in recent years. A majority of climatologies for occurrence of ET in the various ocean basins have been developed using such reanalysis data sets (e.g. Harr and Elsberry, 2000; Klein et al., 2000; Hart and Evans, 2001; Sinclair, 2002; Qi et al., 2006; Wood and Ritchie, 2014)

A common method for analysing changes that occur when a tropical cyclone undergoes ET is to derive a Cyclone Phase Space diagram (Hart, 2003) from the thermal wind and asymmetry extracted from the reanalyses. Schenkel and Hart (2012) and Murakami (2014) evaluated the ability of the reanalysis models to capture the dynamics of tropical cyclones and found the models did reasonable job of reproducing position and structure but consistently underestimated intensity.

The Japanese 55-year Reanalysis (JRA-55) appeared to be the best for a number of metrics related to its use of wind retrievals surrounding the tropical cyclone data (TCR) in their assimilation systems (Murakami, 2014). While other datasets, such as CFSR and ERA-I, do not appear to be as accurate for climatologies they perform well in other areas due to their higher resolution.

A preliminary look at the simulated wind fields for Cyclone Alby in 1978 from the JRA-55 reanalysis (Fig. 7) showed the model did a reasonable job of reproducing the asymmetric structure and acceleration of Alby as the storm passed by the southwest of Western Australia. However, for the purpose of forcing ocean storm surge models it will likely be necessary to undertake sensitivity studies to determine the most appropriate atmospheric model and/or to develop parameterisations to account for inadequacies in the wind fields.

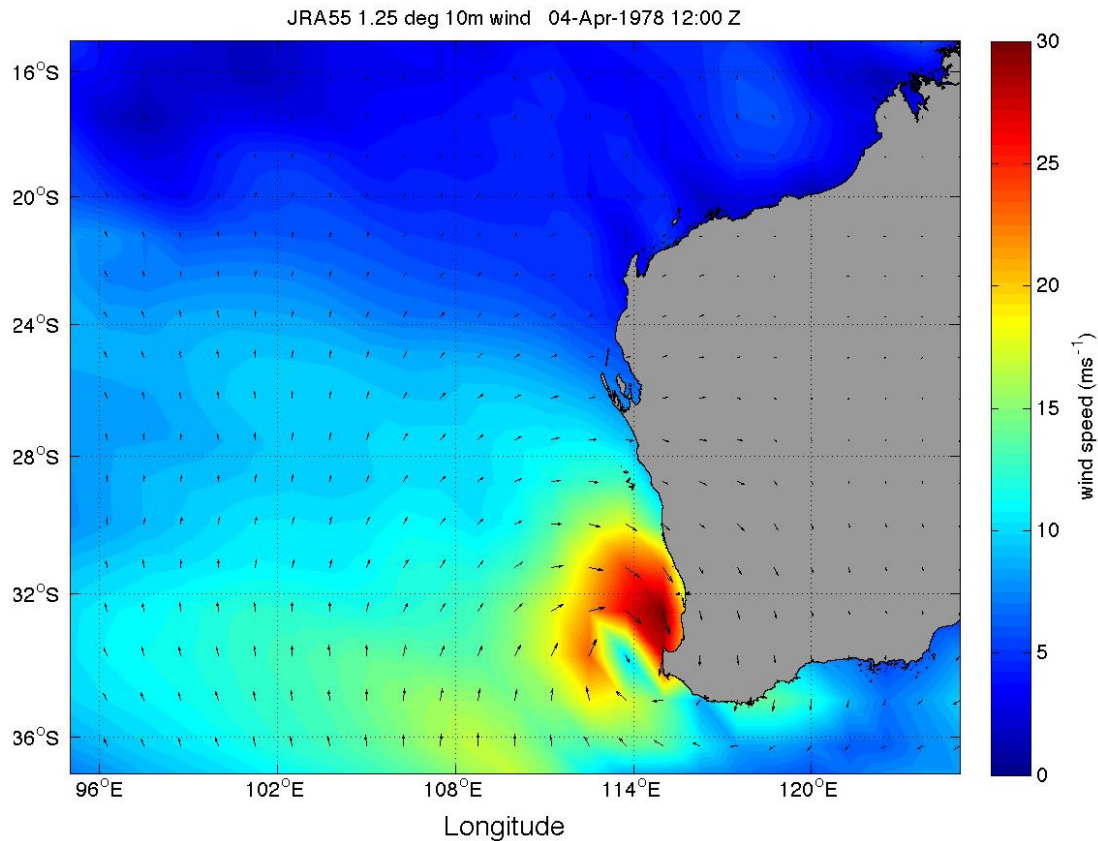


Figure 7. Wind field for Cyclone Alby on 04 April 1978 from the Japanese 55-year Reanalysis (JRA-55). The simulation captured the asymmetry and strong northerly winds to the east of the storm track that were associated with the spread of bushfires, erosion, storm surge and flooding and substantial damage in the southwest of WA.

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