Assessment of Tropical Cyclone Risk in Southwestern Western Australia using Multiple Lines of Evidence

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ABSTRACT

Stochastic cyclone models are used to evaulate risk for purposes including placing insurance and reinsurance. These models are highly sensitive to landfall frequency assumptions especially in marginal areas, which tend to be more vulnerable to damage as building code requirements are not as stringent. Considering the study area of southern Western Australia, the long-term tropical cyclone (TC) climatology is compiled and analysed to understand the potential landfall frequency. TCs were identified back to the early 19th century from a range of historical sources such as government survey records, shipping logs, in-situ and remote meteorological observations and newspaper accounts. Their characteristics in terms of location, landfall, intensity, extent, forward speed and raininess were estimated and summarised. TC annual frequencies were then calculated over a range of latitudinal wind regions and temporal eras. The results show that the study area has a long history of TC impacts that may be underappreciated from modern records. The records are dominated by strong interdecadal variability, and no long term trend in frequency was evident. The non- or low cyclonic status of these regions in the building code may be questioned. This extended climatology provide a benchmark for assessment of stochastic TC risk models and climate change trend analysis. Further, it has use cases in emergency management, prioritisation of mitigation investment, and application in building design and land use planning.

INTRODUCTION

The southwestern coastline of Western Australia (WA) contains the main concentration of the Western Australian population in the city of Perth and surrounding areas from Geraldton to Busselton. It is located on the southern margin of the Southeast Indian Ocean tropical cyclone (TC) belt and has experienced a low annual frequency of TC impact over the historical record. This paper presents a long term climatology of TC events for this region stretching back to colonisation based on the research of Aldridge and Christensen (2024 in press). It seeks to quantify the annual average occurrence of these events and discuss the probability of landfalling events that have not occurred in the historical record but require quantification to capture long return periods.

Early cyclones affecting this coastline caused significant damage to settlements, including the 1915 cyclone which caused building damage in central Perth, and the 1921 Shark Bay cyclone, estimated to be a Category (Cat) 4 to 5 event by Switzer et al. (2023) and which caused >6 m storm surge inundation. TC Alby (1979) was a Australian Category (Cat) 3 while it tracked offshore Perth and caused signficant damage to the city. Here we identify earlier events that also impacted this coastline and contribute to our knowledge of their climatology.

Past studies of the TC climatology of WA extend back to the early 20th century and include those of Hunt (1925, 1929), Lourenz (1981) and Foley and Hanstrum (1994), and for the Perth region, that of Courtney and Middelmann (2005). Courtney et al. (2021) provide an update to the Australian best tracks database, revisiting intensity estimates from 1970 to standardise the intensity estimates considering variation in wind-pressure relationships, wind speed averaging period and applications of the Dvorak technique between forecast regions. The BOM best tracks beyond 1960 are not reassessed in this study. Foley and Hanstrum (1994) distinguish two typical synoptic patterns surrounding TCs in this region: captured lows that rapidly sweep over the coastline in a southeasterly direction associated with a westerly frontal system, and cradled lows that typically track longshore in a southward direction as eastward flow is maintained n the poleward side of the cyclone. The captured systems typically have very high forward speeds that add to the destructive wind potential of the cyclone. An example of such a system is TC Seroja (2021) that impacted the town of Kalbarri and inland towns, causing $400 million of insured losses (Insurance Council of Australia 2023).

These previous studies are drawn on in the present study in addition to new historical data sources. For a full literature review, please refer to Aldridge and Christensen (2024 in press). Holmes (2021) investigates TC frequency for the northwestern coast of WA since 1970. He found that over this period, there was one landfall south of 25 ºS being TC Hazel in March 1979 over Denham. This study seeks to extend this record temporally and explicitly consider the southwestern region.

METHOD

The study area is defined as the southwestern Australian coastline southward of 25 ºS (just south of Carnarvon) to Albany. The study area covers several wind regions as shown in Table 1, corresponding to Australian Wind Regions A, B2 and C which specify the design wind speeds for the construction of residential housing in the Australian Wind Loading Standards – AS/NZS1170.2 (2021).

Table 1. Wind Regions of WA used in the Australian wind loading standard AS/NZS1170.2 (2021). The design wind speed is given for instantaneous gusts in an open terrain setting.

Wind Region	Southern Latitude	Northern Latitude (at coastline)	Design Wind Speed [m/s] -500 yr ARI	Example Towns
A	-	29 ºS	45 m/s	Perth, Bunbury
B2	29 ºS	27 ºS	57 m/s	Geraldton, Kalbarri
C	27 ºS	25 ºS	66 m/s	Shark Bay, Denham
D	25 ºS	19 ºS	80 m/s	Carnavon*, Exmouth, Port Hedland, Karratha

**Carnarvon will shift into Region C in 2025 building code update. Regions B2 to D also have a Mc factor of 1.05 for climate change. Note Region B2 and C extend further north inland of the coastline.*

A range of historical and meteorological sources were used to construct the 19th-21st century TC climatology in the study region. The location, landfall, upper, lower and most likely intensity, extent and forward speed of each event as documented or interpreted from the available records was compiled. The historical sources comprise documentary and eyewitness accounts, including ship's logs, newspaper reports, official reports of damage or fatalities, diaries and journals, and oral histories. Meteorological sources include weather station records, synoptic charts, satellite imagery, BOM best tracks, measured water levels, event damage reports and surveys.

In WA, the fragmentry spread of European settlement constrain the capture of TCs events in the historical sources. Records beacame available for Perth and Cape Leeuwin from mid-1829 then Bunbury (1840), Busselton (1842), Geraldton (1850) and Carnarvon (1883). There was no permanent settlement at Shark Bay until the 1880s and the coast between Perth and Dongara and north of Carnarvon remained largely uninhabited by the settler population prior to the 1940s. This means that the cycone record is likely incomplete in the 19th century.

Relevant information extracted from the historical data sources includes barometric pressure readings, wind speed estimates, timing of changes in wind direction, intensification and passing of the eye, rainfall, damage descriptions particularly damage to buildings and trees. From this information, the likely track and landfall location of each cyclone was constructed, and estimates made of the intensity range within a band of uncertainty. The understanding of a typical behaviour of a cyclonic wind field is used to interpret the likely position of the eye relative to observed changes in wind direction and atmospheric pressure. For the purpose of this study, concerned with design wind speeds, it is not necessary to delineate between TC and ex-TC that have or are in the process of undergoing extratropical transition. Uncertainty is present in each source of information, including observational error, inconsistencies in historical accounts, so a range of plausible parameter values given available information. This is assessed by estimating a most likely track position or value of a track parameter accompanied by estimates of the upper and lower bounds of the parameter value.

SELECTED CASE STUDIES

Aldridge and Christensen (2024 in press) present analysis of seven 19th Century events in the study area and a further 15 events between 1906 and 1960. Notable events include:

- February 1839 Shark Bay Cyclone generating storm surge and wave run up of "fifty-three yards [48.8 m] above high water mark" (Grey 1841).
- February 1872 landfall around Greenough with Category 1 impacts in Geraldton.
- March 1872 landfall between Geraldton and Perth with Cat 2 intensity observed at Fremantle.
- February 1915 landfall north of Geraldton and tracked south with rapid forward speed up to 75 kmh, with Perth and Fremantle experiencing Cat 1 intensity.
- February 1937 longshore Carnarvon to Albany with Cat 2 intensity observed off both Shark Bay and Cape Leeuwin with dramatic associated bushfires from northeasterly winds.
- March 1943 landfall near Cervantes as a Cat 2 and possibly Cat 3 with observed pressure of 978.7 hPa, and one of five or six cyclones affecting the WA coastline that year.

RESULTS: FREQUENCY ASSESSMENT

The events described in Aldridge and Christensen (2024 in press) are tabulated into likely Australian cyclone category, region of impact, landfalli or offshore and era, and a climatology of TCs is described. The eras are defined Pre-BT (1830-1906), BT_PreSat (1906-1959), PostSat (1960-2023).

Annual Frequency by Severity

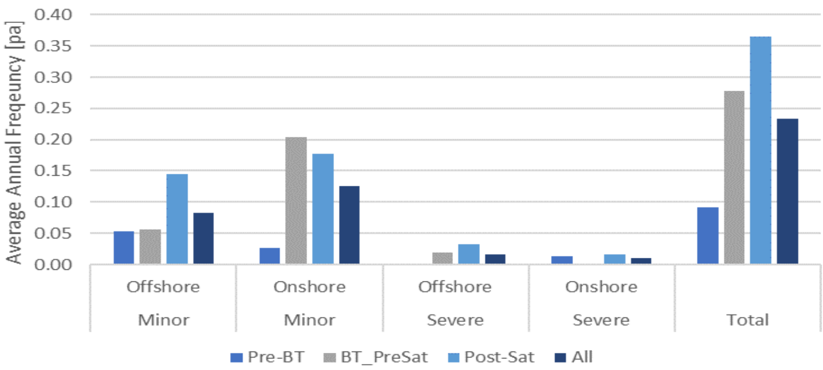

Figure 1. Average annual frequency of minor (Cat 1 and 2) and severe (Cat 3+) TCs offshore and making landfall south of -25ºS over different eras.

Figure 1 shows that the annual average frequency of TCs in the study region is not consistent between the three record eras. The Pre-Best track period from 1830 – 1906 has markedly lower annual frequency (0.09) than the subsequent best track period (0.32). This indicates that the occurrence of TCs in this study area has not been captured in full in this earlier period, and that average statistics are best considered since 1906. This accords with the understanding of the sparse nature of settlement along the WA coastline in the 19th century. It is not clear whether the frequency of TCs was underreported in the pre satellite era from 1906 to 1960 (0.28), as the frequency in the post-Satellite era (0.37) is pushed higher by the peak in events in the 1970s (see below) and the difference in annual frequency between the two time periods is not significantly different. The seasonality of TC occurrence in the study region peaks in March, and extends from November to May. The March peak in occurrence holds for each region (A, B, C), category and era of the historical record (not shown).

Annual Frequency by Region

From the records used in this study, Region A (south of 30ºS) has likely experienced 6 tropical cyclone landfalling tracks of Cat 1 and above (Figure 2): one in the pre-best tracks era (1872), 3 in the pre-satellite era and two in the post-satellite era. Three were likely Cat 1, and three likely Category 2. The most severe landfalling system was TC Marcelle in 1973, likely at Cat 2 at landfall (BoM 1973). The addition of the March 1872 and 1923 events to this record are notable. This demonstrates that Region A has experienced minor landfalling tropical cyclones in the historical record and could have the potential to experience a Cat 3 at landfall with favourable steering, noting that TC Alby (1979) was Cat 3 tracking just offshore of this region.

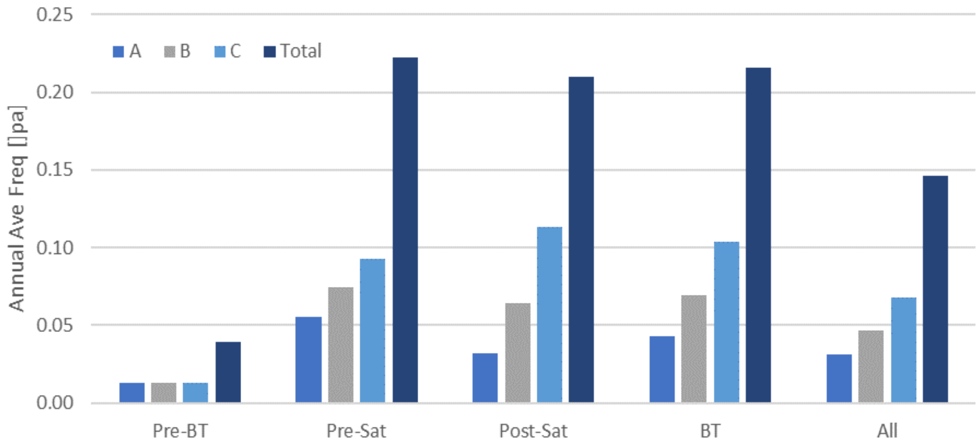

Figure 2. Frequency of landfalling TCs in Regions A, B and C in the study area by era.

Region B (between 30ºS and 27ºS) has experienced 9 recorded landfalling TC events since 1830: one in the pre-best tracks era, four in the pre-satellite era and four in the post-satellite era. The annual average frequency in the best tracks era is approximately 0.05. Of these, only TC Seroja 2021 is of Cat 3 intensity, and there were three likely Cat 2 events: in 1915, 1943 and 1977 (TC Wally).

The southern coastal strip of Region C in WA (between 25ºS and 27ºS) has experienced 13 recorded TC landfalls: one in the pre-best tracks era, 5 in the pre-satellite era and 7 in the post-satellite era. The annual frequency in the best tracks era is approximately 0.07. Of these, two were Cat 4: 1921 Shark Bay (Switzer et al. 2023) and TC Hazel. This study adds the 1839 Cat 3 at Dorre Island.

Decadal Frequency

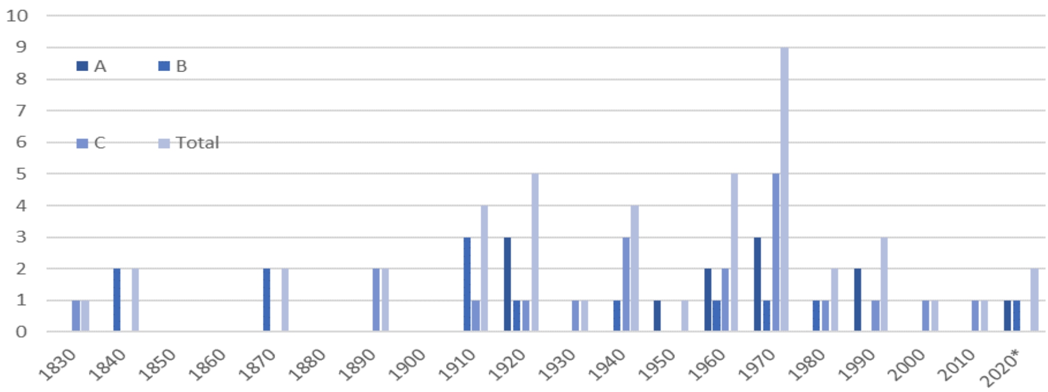

Figure 3. Decadal occurrence of TCs estimated as Cat 1 and above offshore and making landfall in Wind Regions A, B and C south of -25ºS .

The decadal occurrence of TCs recorded in the study area shows a clear step change from the inception of the BoM from 1906 (Figure 3). Gaps in the historical record exist in the 1840s, 1850s, 1880s and 1900s and no decade since. There is a clear peak in frequency in the 1970s with nine occurrences, and the 1910s, 1920s and 1960s also recording higher than the average decadal frequency of 2.9 (1900 – present). This marked decadal variability precludes consideration of a long term trend for this study area. Ramsay et al (2008) demonstrates that the trend in TC frequency is highly sensitive to the time period chosen for analysis.

Assessment of Uncertainty

The uncertainty associated with the likelihood of cyclone frequency by intensity is considered by estimating the upper, lower and most likely intensity of each event in the best-track era historical record (Figure 4). Further, the 1872 Region A event was added with a frequency in proportion to the length of that record as it has a maximum assessed intensity of Cat 3. While the intensity estimates are uncertain, using the range in intensity estimates allows consideration of the envelope of possible ARIs in each region. This method implicitly considers the quality of the data source, with a tighter range of intensity estimate for more recent events compared to earlier events with very sparse observations. It allows for the likelihood that the TC's peak intensity occurred between observation locations.

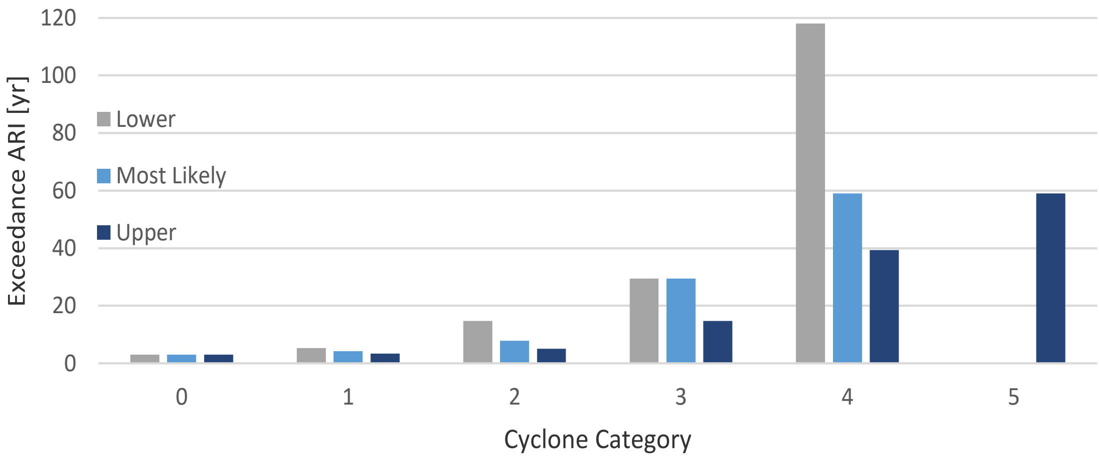

Figure 4. Range of ARIs for landfalling TCs by Cat for the study region and each of Wind Region A, B and C south of -25^{0}S . Note: Region A Cat 3 ARI max ~>200 years.

The analysis shows that a TC of Cat 1 or above occurs in the study region with an ARI of 4 years with a range of 3 to 5 years. This increases to approximately 60 years for Cat 4 TCs with a range of 40 to 120 years, and this is concentrated in Region C in the north of the study area. In Region B, a Cat 3 TC may occur with a 60 to 120 year ARI. Cat 2 TCs in Region B has an average ARI of 30 years and this may be as frequent as 17 years if considering the maximum estimated intensity of each cyclone. In Region A, a Cat 2 TC has an ARI of ~60 years with a range of 40 to 120 years, while a Cat 3 may be possible with an ARI in the range of 200 years, considering the 1872 cyclone may have been Cat 3 at its peak, which seems reasonable given that TC Alby 1978 was of Cat 3 intensity just offshore.

Interannual Variability

There is a tendency towards clustering of events within years and in adjacent years with a coincidence with La Nina occurrence in the Pacific. For landfalling cyclones of Cat 1 and above, four seasons have experienced two events (1871-1872, 1942-1943, and 2020- 2021), all of which were La Nina events. When considering all events including tropical lows and offshore events, 1943 experienced three events within six weeks from late January to mid March, perhaps associated with favourable SSTs, onshore steering flow and a blocking high over central Australia preventing landfall further north. Clusters of years with more frequent occurrence of cyclones and lows (both on and offshore) include the period 1915-1917 (4, La Nina 1916 - 1917), 1943 – 1945 (5, La Nina in 1943), 1960 – 1963 (4), 1966 – 1971 (6, La Nina in 1970 - 1971), 1975 – 1979 (6, La Nina in 1975 and 1976) and 1988 – 1991 (5, La Nina in 1988 - 1989), with no such clusters in consecutive years for the past 30 years. It is also possible that earlier clusters occurred in 1872 (2 events) and from 1843 to 1845 (2 events), both of which were associated with La Nina periods.

DISCUSSION AND CONCLUSION

The value of using historical sources to augment the TC climatology in marginal regions has been demonstrated in this study, which has shown that the southwestern WA study area has a long history of TC impacts that may be underappreciated from modern records. Specifically, the occurrence of impactful events in the 19th century such as the 1872 cyclones has been identified, as well as addtioanl events in the early 20th century with an improved understanding of their location and intensity from a range of sources.The records are dominated by strong interdecadal variability, and no long term trend in frequency was determined. This analysis does not directly allow us to answer the important question of what the frequency of cyclones beyond the observed intensity or what is the ARI of the most severe cyclone within the region, but provides a useful empirical climatology from which risk assessment stochastic cyclone modelling can be based. The analysis of the frequency of Category 2 and 3 events in Regions A and B showing return period for a Category 3 landfall in Region B is in the range of 60 – 120 years and in Region A is possibly in the vicinity of 200 years. This suggests that the non- or low cyclonic status of these regions in the building code should be reconsidered. These new extended climatologies provide benchmarks for assessment of stochastic TC risk models and climate change trend analysis. Further, it has use cases across emergency management, prioritisation of mitigation investment, hazard assessment and application in building design and land use planning.

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