Storms that collapse like a house of cards: a global catalog of the extremely rapid weakening of tropical cyclones

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Abstract

Extremely rapid weakening (ERW) is a form of abrupt intensity change of tropical cyclones (TCs) that has received scant scholarly attention. On the basis of worldwide TC records, this study identifies and presents 89 6-hourly periods in which a TC's maximum sustained wind speed near center diminished by 40 kt (1 kt = 0.51 m/s) or more. The vast majority of these ERW periods occurred when powerful TCs made landfall (especially in mountains), but there are also exceptions in which ERW was the result of strong vertical windshear over open oceans. Madagascar Island, Luzon Island, Taiwan Island, west Mexico, US Gulf Coast, and Yucatan Peninsula are found to experience most ERW, while the incidence of such events has so far been zero at the Baja California Peninsula, the Korean Peninsula, and the coast of the Arabian Sea.

Keywords: *hurricane, typhoon, cyclone, cyclonic storm, rapid weakening*

1.0 INTRODUCTION

A tropical cyclone (TC) is defined as a non-frontal atmospheric vortex that possesses organized deep convection and a well-defined center surrounded by closed surface wind circulation (WMO, 2017). Typically, TCs develop on warm ocean surface where vertical windshear is low and humidity in the troposphere is high, and decay when they are driven into unfavorable environments by mechanisms such as the steering flow (Ito et al., 2020; Sobel et al., 2021). Once they move inland, TCs tend to dissipate, primarily because of increased surface friction and the reduction of surface moisture fluxes (Yoo et al., 2020). TCs' ability to produce heavy wind and rain makes them tremendous menaces to human life and properties (Tang & Liang, 2006; Molua et al., 2020). A major determinant of the destructiveness of a TC is its intensity, which is measured by the maximum sustained wind speed near TC center (or wind speed for short). Intense TCs are more cataclysmic, and accordingly, a multitude of studies have been conducted on the rapid intensification of TCs (e.g., Yang, 2016; Osuri et al., 2017; Qin et al., 2019; Ng & Vecchi, 2020; Mohanty et al., 2021). Comparatively little attention has been attracted by the quick decay of TCs since weak TCs are less likely to imperil the society (Bloemendaal et al., 2021). Yet, failing to predict the rapid weakening (RW) of TCs (i.e., overestimating the intensity of a TC at a given time and place) would lead to false alarms and superfluous public expenditure on disaster mitigation (Liu et al., 2010).

Existing knowledge concerning the RW of TCs comprises a host of reports on the RW mechanisms of individual systems (e.g., Qian & Zhang, 2013; Talamo, 2020; Rajasree et al., 2021), but the effect of terrain as a contributor to the RW of TC is seldom underscored (Li & Lu, 2001; Wen et al., 2014). The basin-wide studies also focus nearly exclusively on RW that occurred over water (e.g. DeMaria et al., 2012; Liang & Wu, 2018). RW's threshold was defined by Wood & Ritchie (2015) as 30 kt in 24 h for North Atlantic and Eastern North Pacific TCs and by Ma et al. (2019) as 40 kt in 24 h for Western North Pacific TCs. In actuality, TCs may decay at a much higher rate. Principally based on the sound TC records compiled by US meteorological agencies, the present work identified and characterized TCs that underwent extremely rapid weakening (ERW) from a global perspective.

2.0 DATA AND METHODS

Best Track datasets were obtained from the Joint Typhoon Warning Center (JTWC), National Hurricane Center (NHC), and the Central Pacific Hurricane Center (CPHC), which include uniformly formatted TC information such as wind speed and center position. The range of age covered in the Best Track varies across basins. Additionally, the pre-2000 Best Track of the North Indian Ocean and the pre-1990 Best Track of the Australian Region were disregarded because of their severe errors in intensity records. The periods where Best Track datasets were examined were thus restricted (Table 1).

Table 1: *Periods where Best Track datasets of JTWC/NHC/CPHC are both available and credible*

Basin	***Period***
Atlantic Ocean (AL)	1855~2021
Australian Region (AUS)	1990~2021
Northeast Pacific Ocean (EP)	1949~2021
North Indian Ocean (NIO)	2000~2021
Southwest Indian Ocean (SWIO)	1975~2021
Southwest Pacific Ocean (SWP)	1975~2021
Northwest Pacific Ocean (WP)	1945~2021

TCs whose ERW was confirmed by the Best Track data were categorized as Class I, and their tracks were charted on geomorphic maps using Typhoon 4 (see Figures 1-5).

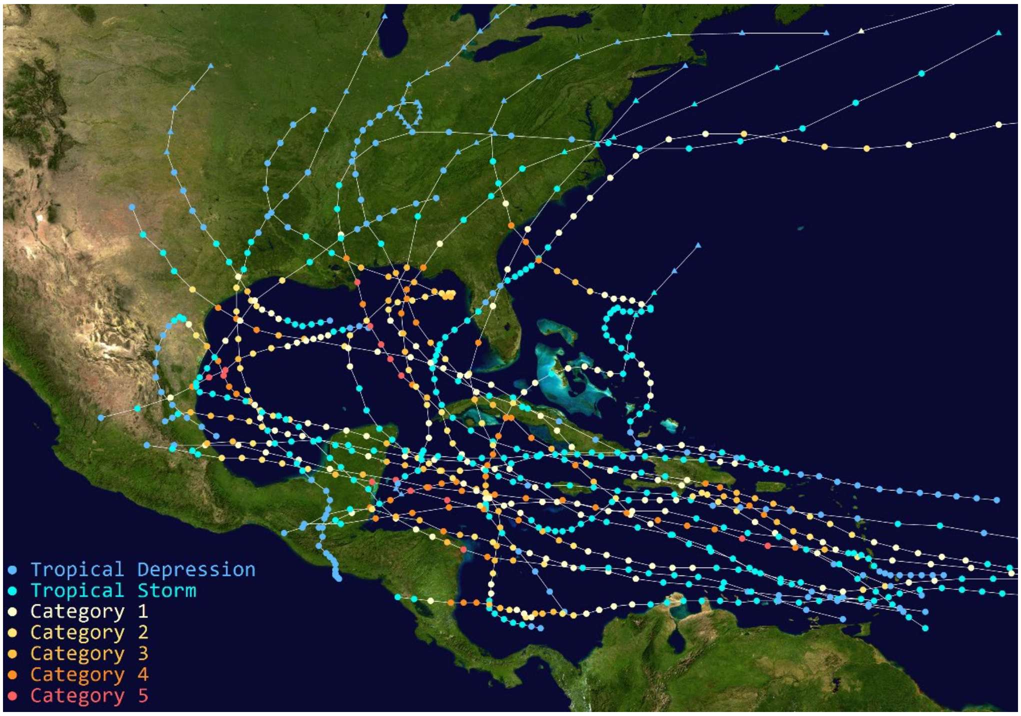

Figure 1: *Track map of Class I TCs in AL. The EP section of the paths of certain systems are not illustrated*

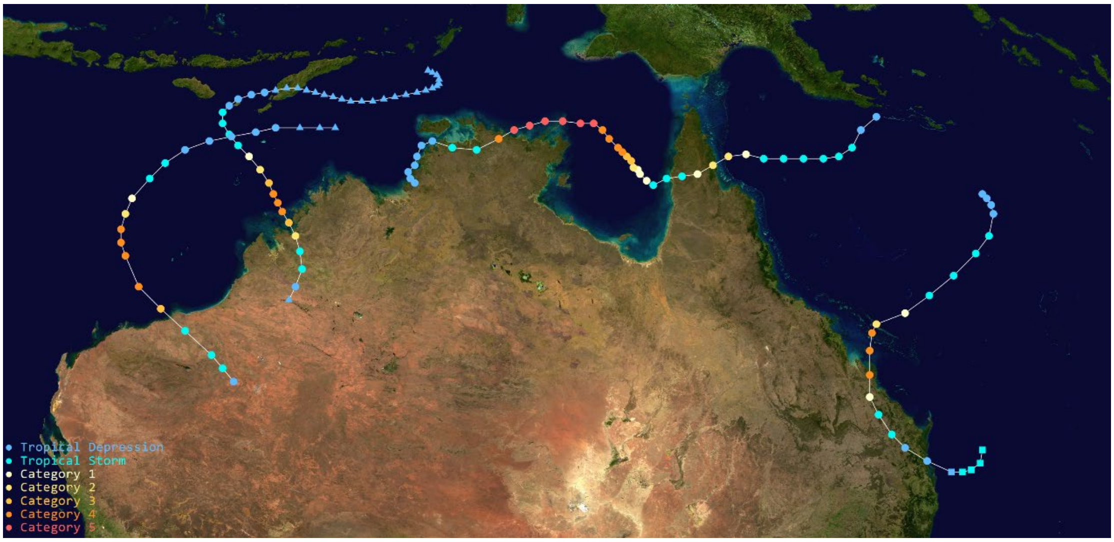

Figure 2: Track map of Class I TCs in AUS. *Interestingly, none of the systems subsequently persisted over land as* ***agukabam*** *(Emanuel et al., 2008)*

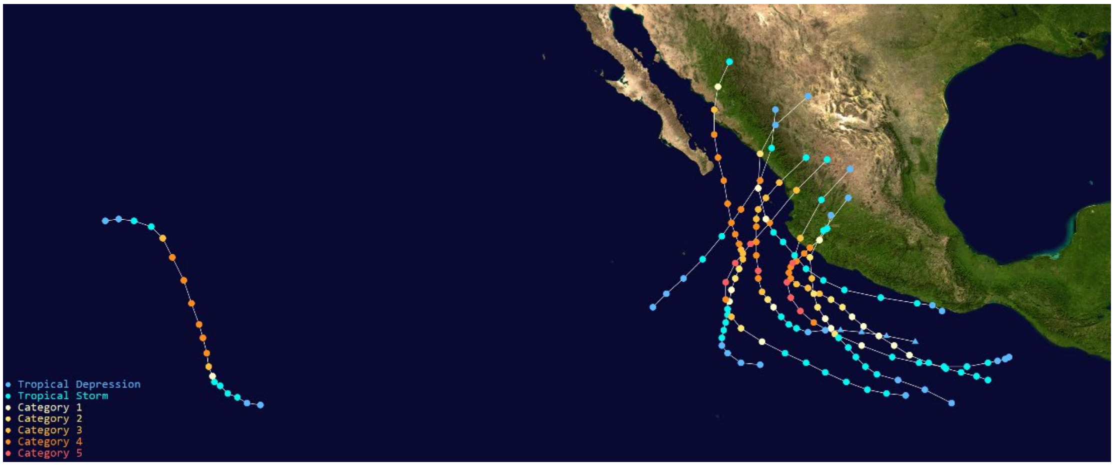

Figure 3: Track map of Class I TCs in EP. *Note the solitary track line representing hurricane Jimena (1997) in the open ocean*

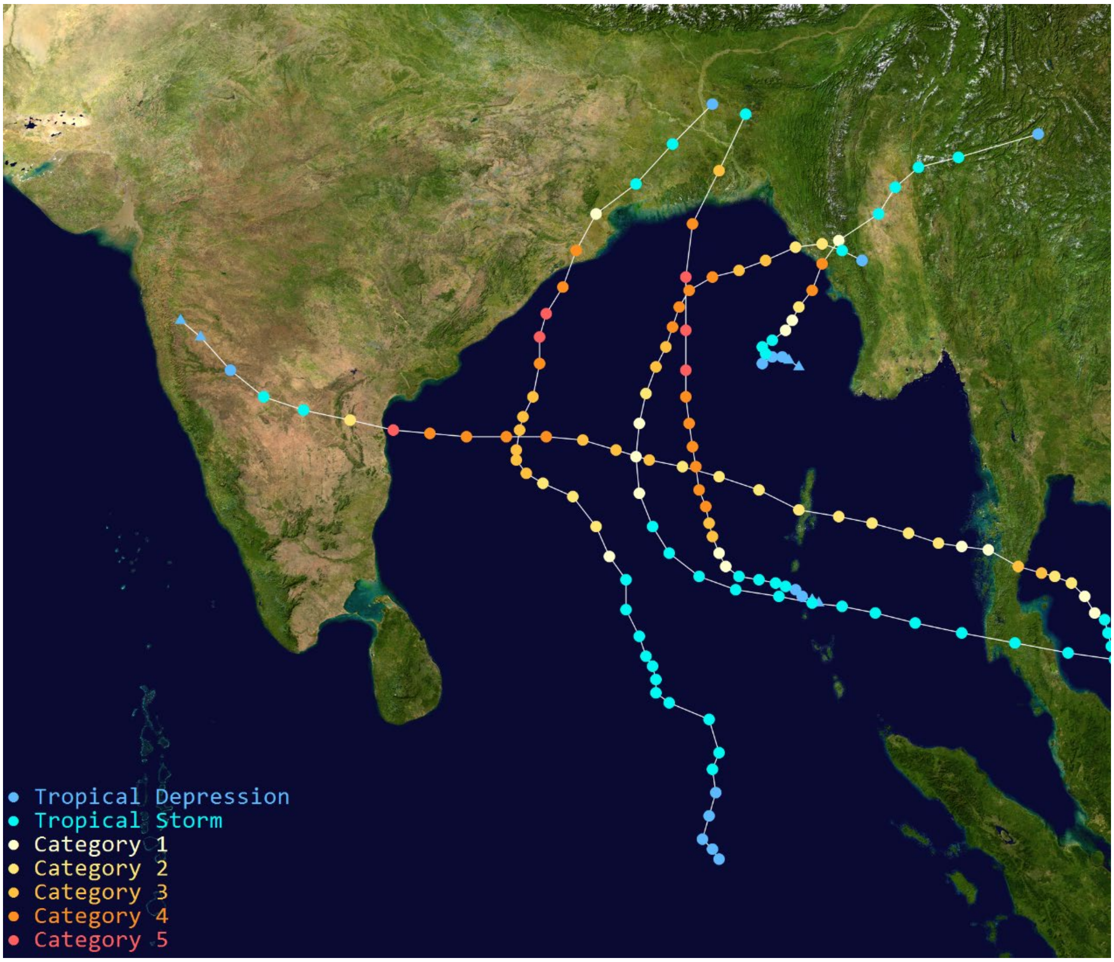

Figure 4: *Track map of Class I TCs in NIO. The WP sections of the track lines of cyclonic storms Gay (1989) and Forrest (1992) are truncated*

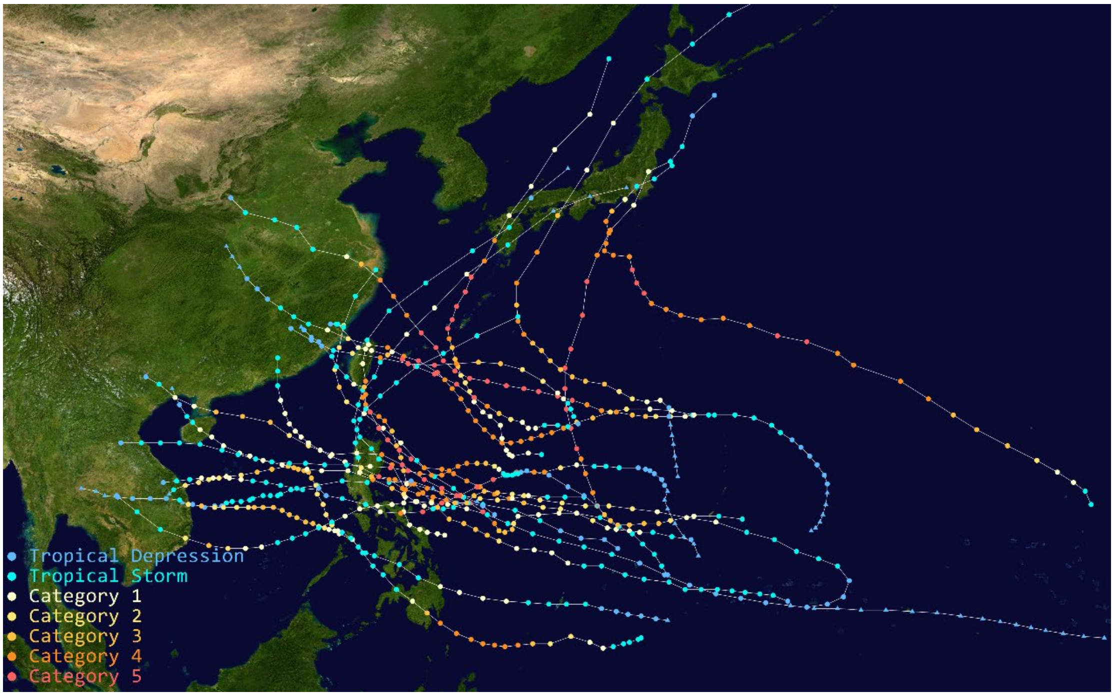

Figure 5: *Track map of Class I TCs in WP*

The Saffir-Simpson Hurricane Wind Scale (SSHWS) (Guard & Lander, 1999) was used to illustrate TC intensity. Moreover, a non-exhaustive survey was carried out looking for potential ERW in TCs that were active outside the periods described above or have been inaccurately evaluated in the Best Tracks. These TCs were categorized as Class II.

Herein, an ERW phase is defined as a 6 h period in which TCs' wind speed dropped by at least 40 kt. For instance, if a 100 kt TC undergoes an ERW phase, it would weaken from a Category 3 hurricane capable of delivering devastating damage to a mere 60 kt tropical storm in just 6 h. The intensities of Class II TCs at the start and the end of their ERW phases were subjectively assessed on the basis of satellite imagery. The major causes of all ERW phases recognized in the present paper were probed by georeferencing the paths of TCs and consulting relevant meteorological literature.

3.0 RESULTS AND DISCUSSIONS

A total of 89 ERW phases were found, involving 84 TCs (Table 2). The results further show that 86 (96.6%) of the ERW phases took place during the landfall (LF) process of TCs. Every ERW phase begins from an initial intensity of at least 75 kt. Overall, these findings are in line with the corollary of the exponential decay model developed to forecast TC intensity subsequent to landfall (DeMaria et al., 2006; Liu et al., 2021). Madagascar Island, Luzon Island, Taiwan Island, west Mexico (excluding the Baja California Peninsula), US Gulf Coast, and Yucatan Peninsula register most ERW phases. Except for US Gulf Coast and Yucatan Peninsula, the places where ERW most often occurs are characterized by tall mountains (Gillespie & Clague, 2009), which are topographic elements contributing significantly to the decay of TCs (Bender & Kurihara, 1986; Tsay, 1994). Although no TC has been observed to regenerate after landfalling accompanied by ERW in west Mexico, a number of TCs that underwent ERW as they made landfall in the other five aforementioned places were able to re-intensify when they moved over water later (*e.g.*, Boose et al., 2003).

Nine ERW TCs are known along the US Gulf Coast; by contrast, only one TC underwent ERW in the Carolinas (east US) and none in further north American shores such as New England. This agrees with the conclusion by Zhu et al. (2021) that TCs making landfall on the Gulf Coast tend to weaken faster than in other parts of the USA. Additionally, it is interesting to note the absence of ERW at the Baja California Peninsula, the Korean Peninsula, and the coast of the Arabian Sea, despite the fact that these places are at least potentially exposed to landfalls of intense TCs (Farfán & Cortez, 2005; Park et al., 2011; Soltanpour et al., 2021). Addressing this phenomenon is, however, beyond the scope of the present work.

Results presented in Table 2 indicate that three TCs experienced two consecutive ERW phases starting at super-high intensities (well over 140 kt, the threshold of Category 5 in SSHWS): The AUS cyclone Monica of year 2006 made LF in north Australia and the EP hurricane Patricia of year 2015 in west Mexico; on the contrary, the WP typhoon

Table 2: Information of TCs which underwent ERW and their ERW phases. *The acronym in the Basin column refers to the basin in which the ERW of a given TC occurred. Names of Class II TCs are marked with asterisks (*). TCs lacking official names are identified by their serial number in the Best Tracks.*

Year	*TC*	*Basin*	*Intensity pre-ERW phase (kt)*	*Intensity post-ERW phase (kt)*	*Major cause of ERW (LF: landfall)*	*Notes*
1886	Five	AL	130	85	LF US Gulf Coast	
1930	Two	AL	135	80	LF Hispaniola Island	
1949	Eleven	AL	95	55	LF US Gulf Coast	
1952	Fox	AL	125	85	LF Cuba Island	
1953	Judy	WP	120	60	LF Luzon Island	
1955	Hilda	AL	105	50	LF east Mexico	
1955	Janet	AL	150	105	LF Yucatan Peninsula	
1956	Wanda	WP	110	70	LF east China	
1956	Gilda	WP	110	70	LF Taiwan Island	
1957	Ten	EP	120	45	LF west Mexico	
1958	Seven	WP	150	90	LF Taiwan Island	
1958	Ida	WP	120	70	LF Honshu Island	
1959	Twelve	EP	120	70	LF west Mexico	

Year	*TC*	*Basin*	*Intensity pre-ERW phase (kt)*	*Intensity post-ERW phase (kt)*	*Major cause of ERW (LF: landfall)*	*Notes*
1959	Gracie	AL	115	65	LF east US	
1961	Hattie	AL	130	75	LF Yucatan Peninsula	
1961	Pamela	WP	125	85	LF Taiwan Island	
1965	Dinah	WP	120	70	LF Taiwan Island	
1965	Freda	WP	130	75	LF Luzon Island	
			80	40	LF south China	
1965	Jean	WP	130	80	LF Kyushu Island	
1965	Mary	WP	140	100	LF Taiwan Island	
1965	Lucy	WP	110	70	LF Honshu Island	
1965	Shirley	WP	110	70	LF Shikoku Island and Honshu Island	
1966	Cora	WP	130	65	LF east China	
1967	Beulah	AL	110	70	LF Yucatan Peninsula	
1969	Camille	AL	115	75	LF US Gulf Coast	
1970	Georgia	WP	140	85	LF Luzon Island	
1970	Kate	WP	110	70	LF Mindanao Island	

Year	*TC*	*Basin*	*Intensity pre-ERW phase (kt)*	*Intensity post-ERW phase (kt)*	*Major cause of ERW (LF: landfall)*	*Notes*
1971	Edith	AL	140	100	LF Central America	
1972	Therese	WP	95	40	LF Vietnam	
1974	Orlene	EP	90	25	LF west Mexico	
1974	Kirsten*	EP	115	75	possibly vertical windshear	See Towry (1975); Li (2020)
1975	Eloise	AL	110	55	LF US Gulf Coast	
1976	Liza	EP	110	70	LF west Mexico	
1976	Madeline	EP	125	75	LF west Mexico	
1977	Anita	AL	120	70	LF east Mexico	
1978	Greta	AL	95	50	LF Yucatan Peninsula	
1980	Joe*	WP	120	70	LF Luzon Island	
1980	Kim*	WP	120	65	LF Luzon Island	
1980	Betty	WP	105	65	LF Luzon Island	
1983	Tico*	EP	120	75	LF west Mexico	
1983	Alicia	AL	80	40	LF US Gulf Coast	
1984	Kathy*	AUS	105	60	LF Gulf of Carpentaria	

Year	*TC*	*Basin*	*Intensity pre-ERW phase (kt)*	*Intensity post-ERW phase (kt)*	*Major cause of ERW (LF: landfall)*	*Notes*
1985	Elena	AL	100	60	LF US Gulf Coast	
1986	Honorinina*	SWIO	90	50	LF east Madagascar	
1987	Tusi*	SWP	140	85	possibly vertical windshear	see Revell (1987)
1988	Joan	AL	120	70	LF Central America	
1989	Gay	NIO	140	90	LF east India	formed and named in WP
1989	Orson*	AUS	125	80	LF west Australia	
1989	Elsie	WP	140	80	LF Luzon Island	
1992	Winifred	EP	95	45	LF west Mexico	
1992	Forrest	NIO	85	45	LF Myanmar	formed and named in WP
1993	Lola	WP	95	50	LF Vietnam	
1994	Daisy*	SWIO	90	45	LF east Madagascar	
1994	Litanne*	SWIO	110	70	LF east Madagascar	
1995	Chloe	AUS	90	50	LF northwest Australia	

Year	*TC*	*Basin*	*Intensity pre-ERW phase (kt)*	*Intensity post-ERW phase (kt)*	*Major cause of ERW (LF: landfall)*	*Notes*
1996	Herb	WP	130	75	LF Taiwan Island	
1997	Jimena	EP	100	60	vertical windshear	see Lawrence (1999)
1999	Gwenda	AUS	100	60	LF west Australia	
2001	Chebi	WP	85	45	LF east China	
2001	Iris	AL	125	60	LF Central America	
2002	Kenna	EP	100	35	LF west Mexico	
2004	Charley	AL	125	75	LF US Gulf Coast	
2005	Dennis	AL	110	45	LF US Gulf Coast	
2006	Monica	AUS	155	115	LF north Australia	successive ERW
			115	55		
2007	Dean	AL	150	110	LF Yucatan Peninsula	
			75	30	LF east Mexico	
2007	Sidr	NIO	100	60	LF Ganges Delta	
2009	Fanele	SWIO	80	30	LF west Madagascar	
2009	Ketsana	WP	90	50	LF Vietnam	

Year	*TC*	*Basin*	*Intensity pre-ERW phase (kt)*	*Intensity post-ERW phase (kt)*	*Major cause of ERW (LF: landfall)*	*Notes*
2010	Giri	NIO	135	80	LF Myanmar	
2012	Giovanna	SWIO	95	45	LF east Madagascar	
2015	Marcia	AUS	115	75	LF east Australia	
2015	Patricia	EP	180	110	LF west Mexico	successive ERW
			110	50		
2016	Sarika	WP	115	75	LF Luzon Island	
2018	Willa	EP	100	45	LF Mexico west coast	
2018	Michael	AL	140	80	LF US Gulf Coast	
2019	Fani	NIO	115	75	LF east India	
2019	Kenneth	SWIO	120	75	LF southeast Africa	
2020	Goni	WP	170	130	LF Luzon Island	successive ERW
			130	75		
2021	Grace	AL	100	60	LF east Mexico	

Goni of year 2020 traversed the Bicol Peninsula at the southeastern tip of Luzon Island. It can be inferred from Rogers et al. (2017) and Santos (2021) that Goni, Monica, and Patricia are each the strongest TC to make landfall in their respective area. With regard to Patricia, the present study notes that this hurricane not only sets the record for the most rapid over-water weakening rate in EP and AL (Rogers et al., 2017) but is also the fastest of all TCs in terms of ERW in the modern meteorological history, its 165 kt decrease in intensity in 24 h eclipsing all other systems. The EP Hurricane Ten of year

1957 is the sole TC whose 6-hourly ERW is greater than that of Patricia (75 kt versus 70 kt), but the accuracy of the former's Best Track is less believable in view of its age.

Three entirely over-water ERW phases are recognized as well, each involving a single TC and occurring immediately after these TCs attained their peak intensities. The EP hurricane Jimena of year 1997 is the most thoroughly studied of the three. Lawrence (1999) identified vertical windshear, which was known to substantially interrupt the structure of TCs (Frank & Ritchie, 2001), as the main reason for the ERW of hurricane Jimena. Unfortunately, however, the peak intensities of the other two TCs, viz. the EP hurricane Kirsten of year 1974 and the SWP cyclone Tusi of year 1987, were evidently underestimated significantly in the Best Tracks, which thereby masked the two TCs' ERW. Vertical windshear was the most likely factor that caused the ERW of hurricane Kirsten (Towry, 1975; Li, 2020) and cyclone Tusi (Revell, 1987). Besides, two WP TCs that ostensibly underwent ERW while over water, namely Thelma (1951) and Carla (1965), are excluded from the statistics because their JTWC Best Tracks appear to be questionable in comparison with the Best Tracks published by China Meteorological Administration (CMA, 2023) and Japan Meteorological Agency (JMA, 2023).

4.0 CONCLUSION

The quickest decay of TCs, termed extremely rapid weakening (ERW), usually takes place when certain high-intensity TCs make landfall, particularly in mountainous regions. The present work sets the threshold of ERW as 40 kt per 6 hours; nevertheless, in most astounding cases, TC intensity could decline by up to 70 kt in several hours. ERW of TCs is frequent in Madagascar Island, Luzon Island, Taiwan Island, west Mexico, US Gulf Coast, and Yucatan Peninsula, whereas no ERW has been recorded among TCs landfalling at the Baja California Peninsula, the Korean Peninsula, and the coast of the Arabian Sea. In rare instances, strong vertical windshear may also dramatically weaken TCs while they remain over water. However, the occurrence of ERW does not necessarily indicate a TC would continue to fill rapidly until dissipation.

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