Potential of increasing intensity of tropical cyclones due to sea surface temperature and impact on coral reefs in the context of climate change

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Abstract
The coral reef ecosystem in Cu Lao Cham, Vietnam is part of the central zone of the Cu Lao Cham -Hoi An, a biosphere reserve and it is strictly protected. However, the impacts of natural disasters - tropical cyclones (TCs) go beyond human protection. The characteristic feature of TCs is strong winds and the consequences of strong winds are high waves. High waves caused by strong TCs (i.e. level 13 or more) cause decline in coral cover in the seas around Cu Lao Cham.

Based on the relationship between sea surface temperature (SST) and the maximum potential intensity (MPI) of TCs, this research determines the number of strong TCs in Cu Lao Cham in the future. Using results from a regional climate change model, the risk is that the number of strong TCs in the period 2021-2060 under the RCP4.5 scenario, will be 3.7 times greater than in the period 1980-2019 and under the RCP 8.5 scenario it will be 5.2 times greater than in the period 1980-2019. We conclude that increases in SST in the context of climate change risks will increase the number and intensity of TCs and so the risk of their mechanical impact on coral reefs will be higher leading to degradation of this internationally important site.

Keywords: Tropical cyclone, Sea surface temperature, Coral reef, Climate change, Intertropical convergence zone, the maximum potential intensity.

Introduction

Coral reefs represent the apex of marine biodiversity. Although they account for less than 0.1% of the seabed, tropical coral reef ecosystems provide habitats for at least 25% of known marine species[7, 21]. The natural disasters that do the greatest damage to coral reefs are tropical cyclones (TCs). A TC is characterized by strong winds and consequently high waves. Bufor devised a table to establish wind speed and wave heights caused by TCs of different levels[1,2]. Research by Harmelin-Vivien et al[11] stated that "Cyclones generate various kinds of damage by mechanical destruction, change in sedimentation, increase in turbidity, lowering of salinity and change in sea level". Strong TCs can break corals causing a huge reduction in coral cover[13].

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Waves and TC surges periodically damage coral reefs to depths of up to 20 m[3]. In addition, coral debris affects the growth of living corals. Corals below 12 m can die when buried in sand and coral debris[25].

In older research, Gray[9] showed that sea surface temperature (SST), large Coriolis force, low-level relative vorticity, weak vertical wind shear, moisture in the middle troposphere and convective instability are responsible for the formation and intensification of a cyclone. Palmen[19] and Miller[16] found that SST is one of the most important parameters in the formation and intensification of tropical cyclones. The energy released from seawater which is evaporated from the surface then condensed at higher levels, is the driving force for the activity of a TC[10].

Subsequently, SST is the main factor in storm formation and development. Two features that characterize the storm intensity are, first, the maximum wind speed near the TC center and secondly, the minimum barometric pressure at the center of the TC. Miller[16] was the first to quantify the TC and SST intensity and since then Emanuel[6] devised the concept of maximum potential intensity (MPI).

DeMaria and Kaplan[5] developed an equation for calculating the maximum intensity of Atlantic Tropical Cyclones through SST. Kotal, Kundu and Bhowmik[14] formulated an equation for determining the MPI of tropical cyclones through SST over the Bay of Bengal[5,14,26]. Research by Whitney and Hobgood[26] showed that in the Northeast Pacific, there is a linear relationship between empirical MPI and SST. Thanh et al[23] have recently determined a functional relationship between the SST at the center of the storm and the MPI of TCs along Vietnam's coastline. Thus, it is evident that many scientific studies conducted in different marine and ocean regions reveal that the maximum potential intensity of tropical cyclones can be calculated from SST.

In the context of climate change, according to data from the GCRF Blue Communities project (www.blue-communities.org), seawater temperature will rise, so the intensity of TCs will be stronger than today[22] leading to increased wave heights and the potential for greater damage to corals.

Cu Lao Cham is located in an area in the Pacific Northwest, where about one-third of the world's TC storms occur. TC Xangsane on September 25 2006 (Table 1) was the strongest one to hit the Cu Lao Cham coastline for the period 1961-

2020. A comparison of coral cover between 2004 and 2007 found a 7% reduction. In their work, Latypov et al[15] found that due to heavy rains caused by TCs, flooding from the Thu Bon River reduced the coral cover in Cu Lao Cham.

The aforementioned studies have confirmed that TCs exert a huge impact on the coral cover. The questions that need to be asked concerning the Cu Lao Cham context are: (i) what are the effects of the TC on the corals and (ii) what is the potential for greater intensity and number of TCs due to increasing SST and their impact on coral reefs given the rising concerns about climate change?

Material and Methods

Study area: Coral reefs in Cu Lao Cham are narrowly distributed, mainly concentrated on the west and southwest coast of the big island around most of the small islands (Figure 1). Almost all coral reefs in Cu Lao Cham are located in shallow water not exceeding 14 m. Cu Lao Cham island and Hon Kho have the highest number of reef-creating hard coral species (79-80 species), followed by Vung Da Bao area (64 species), then Bai Bac and Vung Da Den (53 to 57 species)[18]. The coral ecosystem in Cu Lao Cham is on the edge of serious decline due to tourism, excessive extraction of marine resources and climate change.

In the period 2004 to 2016, the coral area declined by 47%. The cover of live coral in Cu Lao Cham -Hoi An Biosphere Reserve is about 25% of the total biosphere reserve; within the reserve, coral in Vung Da Ban decreased by 91%; in Bai Bac by 78% and in Bai Huong by 70% (Figure 1).

Data collection

Daily flow data at Nong Son hydro station (Thu Bon) for the period 1981-2012 was provided by Vietnam Center of Hydro-meteorological Data[24]. Average daily SST over region 11º-21ºN, 105º-115ºE from a regional climate model. Projections of future temperature were created using the Proudman Oceanographic Laboratory Coastal Ocean Modelling System (POLCOMS)[12] which configured for South-East Asian seas driven by a regional climate model[4]. The model resolution was 0.1 × 0.1 (about 11 km) and it comprised 40 vertical levels.

About TC Xangsane

The time periods used for this study: Research shows that the intensity and duration of the TC depend on the SST. The conditions for TC development are that the surface seawater temperature is 26ºC and Gray[8] emphasizes that the 26°C isotherm extends to a depth of 60 m. Based on the daily progress of the SST, TCs in Cu Lao Cham can be identified and how they develop from the second half of February to the first half of December (Figure 2).

Based on the statistics from the Vietnam Meteorological Data Center for when the TCs arrive in the Cu Lao Cham Sea during 1961-2020, the Cu Lao Cham Sea was directly affected form September to the first half of November. According to Pham and Phan[20], 85% of the TCs were formed on the Intertropical Convergence Zone (ITCZ) directly and the ITCZ location will decide where the TC lands on the coast of Vietnam.

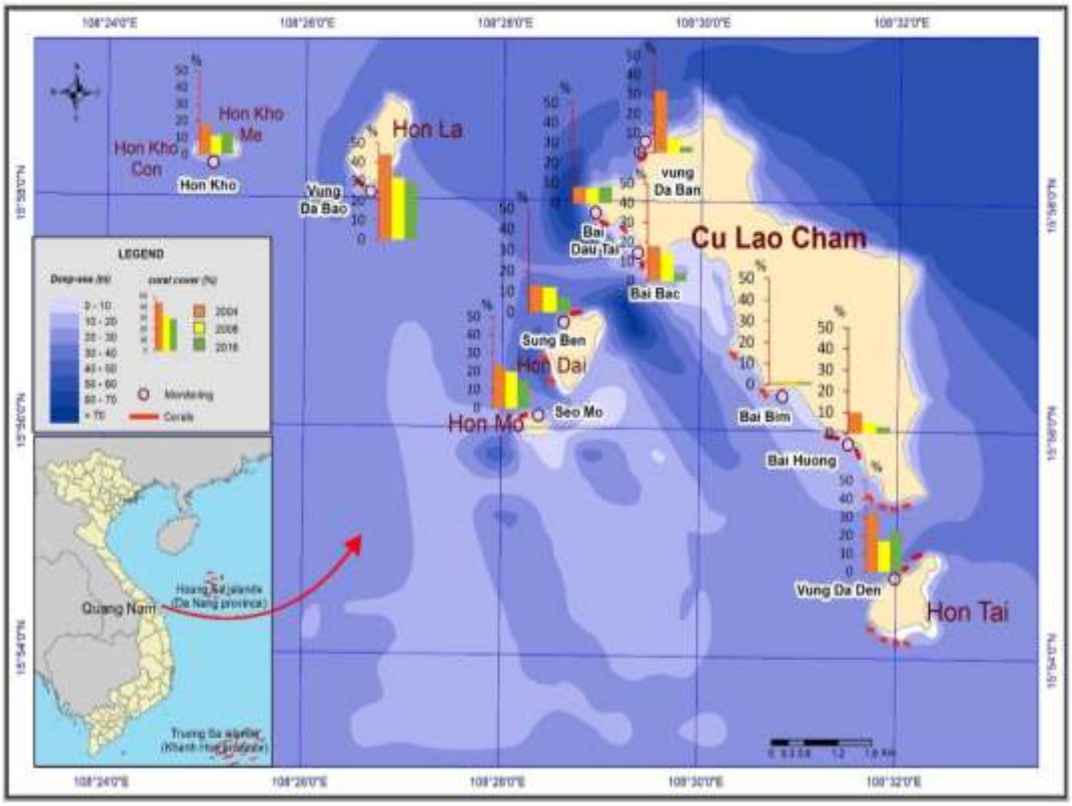

Figure 1: Fluctuation in the hard coral cover at monitoring sites over time[4]

Table 1
Some parameters regarding TC Xangsane

Parameters		Time	Values	Source
Weekly SST before TC landfall		9/25/2006	29.35ºC	GCRF
Beaufort number of TC		10/1/2016	14	Vietnam Center for Meteorology and Climatology
Highest winds (10-minute sustained)		10/1/2016	165 km/h	
Wave height derived from Beaufort number			14 m	
Rain due to TCs	Tra My Weather station	10/1/2006	258 mm	
	Tam Ky Weather station	10/1/2006	72 mm	
The highest daily flows after the storm		10/1/2006	1610 m³/s	
		10/2/2006	1230 m³/s	

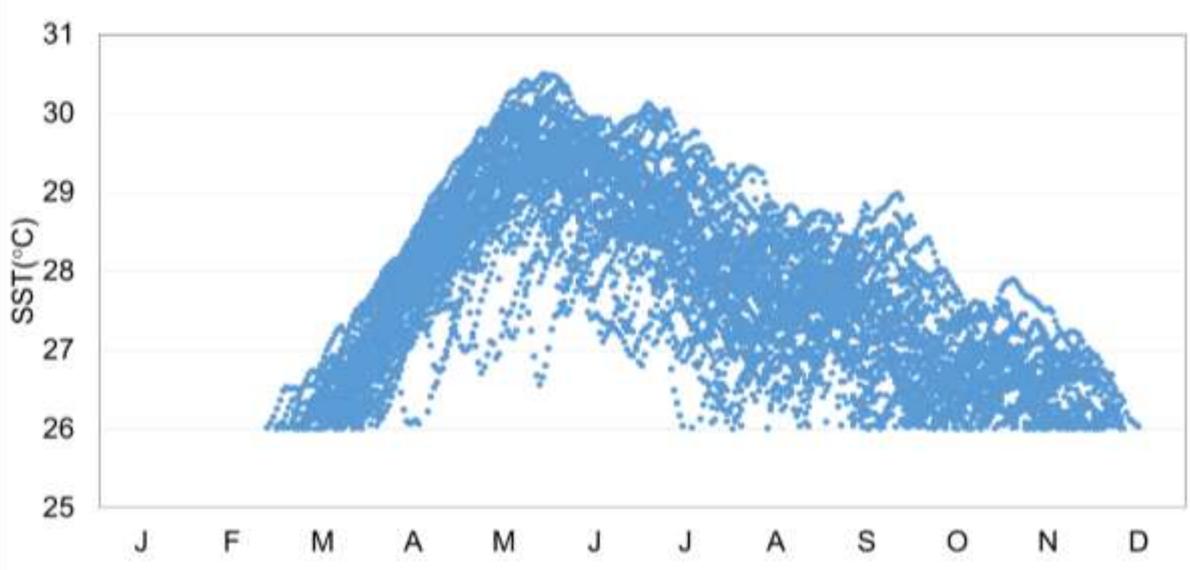

Figure 2: The area-averaged Daily SST greater than 26ºC in Cu Lao Cham Sea during 1980-2020 (11º-21ºN, 105º-115ºE)

From June, the ITCZ moved from north to south and then from September to the first half of November, the position of the ITCZ resulted in TC landing in the Cu Lao Cham Sea area.

Thus, based on the published research and the 60-year data, it is possible to determine that the TC season in Cu Lao Cham Sea is from September to the first half of November. So, in this study, only SST and the maximum potential intensity of TCs from September to the first half of November are analyzed. This research employs model historical SST data for the period 1981-2005 and scenario data for the period (2006-2060) during the TC season in Cu Lao Cham for September through the first half of November.

Analysis

We determined the maximum potential intensity of TCs based on the SST dataset:

MPI=A+Be^C(SST-T_0) (1)

where A =15.69 m/s, B=98.03 m/s, C=0.1806/°C and T_o=30.0ºC, SST is the average weekly SST and MPI is maximum potential intensity (surface sustained maximum wind speed)[27]. This study is based on weekly SST which is an average of the region located at 11º-21ºN, 105º-115ºE, over the sea areas. A time limit (September to the first half of November) has been applied for the appearance of TCs in Cu Lao Cham and the surrounding sea area to determine the potential for storms occurring in this study area.

Results

Assessing the possibility of TCs like that in 2006 occurring in the period 1981-2020: Figure 3 shows that there is a good fit between the estimated extreme wind speed and strong TCs (from level 13 upwards - equivalent to real wind speed 37 m/s) that occurred in the Cu Lao Cham Sea and nearby. In the 40-years period from 1981 to 2020, the following conclusions can be made:

- There are 38 weeks where SST conditions were suitable for the development of a strong TC (MPI>84 m/s) which is about 0.95 weeks/year in the Cu Lao Cham Sea and nearby. The sea temperature is a key condition in storm born. However, there are a number of other factors contributing to storm formation. In fact, in the Cu Lao Cham Sea and nearby areas, 5 strong TCs that landed directly were observed during the above 40-year period. Of these 5 strong TCs, only

4 strong TCs landed directly in the Cu Lao Cham Sea and nearby MPI> 84 m/s, suitable for high SST times. There were 4 strong TCs in 40 years, so the probability of conditions being suitable for a TC is approximately 4/40% = 0.1%.

The assumption adopted in this case is that the probability of this strong TC occurrence when the SST is prevailing is 0.1% and does not change in the future.

Assessing the possibility of TCs like that in 2006 occurring in the future by RCP 4.5: Referring to RCP 4.5 in the period 2021-2060 (40 years), the following statements can be made:
- There are 139 weeks of SST with enough potential to lead to the formation of TCs on an average 3.5 weeks per year.
- The period 2021-2060 has the potential for the formation of 14 strong TCs (based on the assumption of occurrence probability 0.1%) compared to 4 TCs that occurred in the years 1981-2020.
- The number of TCs in the period 2021-2060 under the RCP 4.5 scenario is 139/38 = 3.7 times greater than in the period 1981-2020.

The upward trend in MPI under the RCP 4.5 scenario is clearly shown in figure 3. It is worth noting here that the maximum wind speed during a TC increases by the function $y = 0.0057x^2 - 22.793x + 22681$with a very high-reliability level (R^2=0.93). In the decade 2051 to 2060, the maximum wind speed was highest at 124 m/s (Figure 3).

Assessing the possibility of TCs like that in 2006 occurring in the future by RCP 8.5: Referring to RCP 8.5 in the period 2021-2060 (40 years), the following statements can be made:
- There are 198 weeks of SST with enough potential for strong TCs to form on an average 5 weeks per year.
- The period 2021-2060 can potentially have 20 strong TCs being formed compared to 4 TCs that occurred in the period 1981-2020.
- The number of strong TCs in the period 2021-2060 under the RCP 8.5 scenario is 198/38 = 5.2 times greater than in the period 1981-2020.

The upward trend in MPI under the RCP 8.5 scenario is clearly shown in figure 4. It is worth noting here that the maximum wind speed during a TC increases by the function $y = 0.0065x^2 - 25.742x + 25633$ with a very high-reliability level (R^2=0.89). In the decade 2051 to 2060, the maximum wind speed during was highest, at 124 m/s.

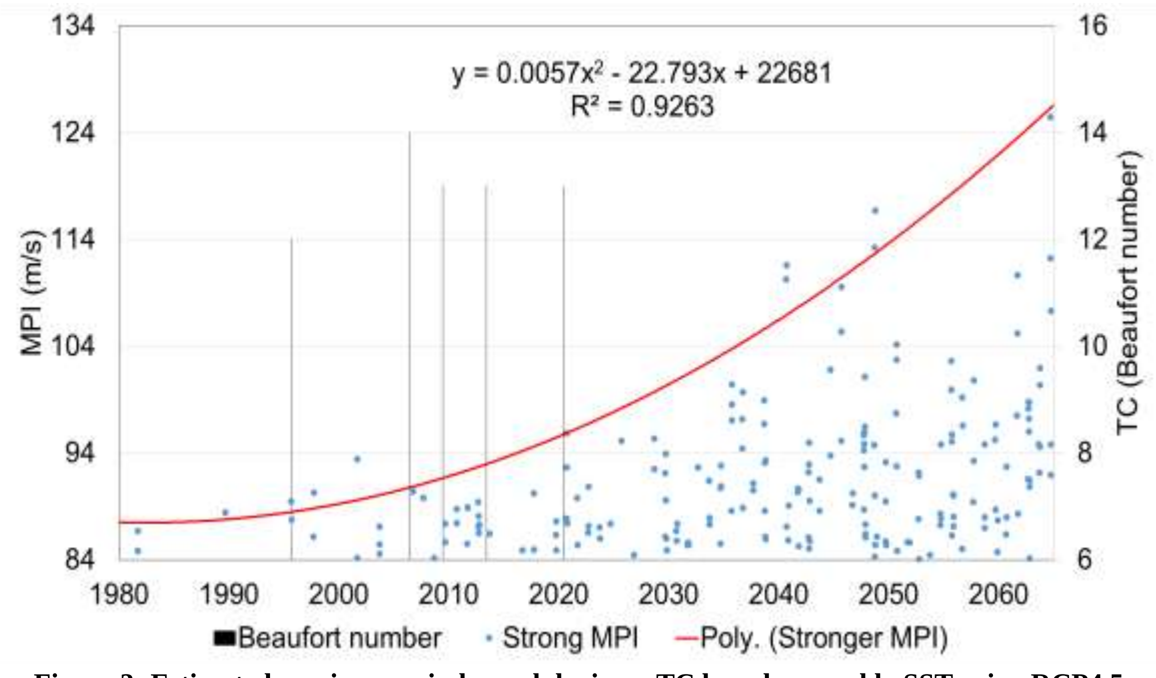

Figure 3: Estimated maximum wind speed during a TC based on weekly SST using RCP4.5 and force of strong Typhoon in the Cu Lao Cham Sea and nearby

Table 2
TC made a direct landing and there is a high risk of TC making a direct landing due to high SST

	1981-2020	2021-2060	2021-2060
		RCP 4.5	RCP 8.5
TC Direct landing or Potential TC direct landing by high SST	4	14	20
	100%	366 %	521 %

From the above analysis, a table was developed to document the strong TCs that have occurred and the risks that the number of strong TCs will occur in the future.

Discussion

Tropical cyclones result in high coastal waves, heavy rain and heavy floods. Issues discussed herein are the impacts of strong TCs on corals due to high waves or floods. According to a previous study[17], heavy rains in the Quang Nam region were not only due to TCs but also due to a combination of ITCZ and cold air, troughs and turbulence in wind zones. As a result of heavy rains, floods were high and the discharge flow increased. Average daily flows above 8000 m^3/s were measured on October 14, 1981; November 22, 1998; December 4, 1999; November 27, 2004 and November 12, 2007. Hence, large flows of over 8000 m^3/s in Cu Lao Cham usually occur at the end of November and into December (Table 3). These events did not occur at the same time as the TC season in Cu Lao Cham (from September to the first half of November). The river flows cause flooding in downstream parts of the catchment and convey a huge volume of sediment to the coastal area.

However, there is no confirmation about how these events impact the coral at Cu Lao Cham (which is located 15 km from the river mouth). In fact, the largest average daily discharge flow due to TC Xangsane, as recorded at Nong Son station on September 25 2006, was 590 m^3/s. This discharge flow is insignificant compared to the observed high discharge flow at Nong Son hydrographic station (over 8000m^3/s). According to Latypov et al[15], the decline in coral in 2006 was due to flooding from Thu Bon River as a consequence of the TC Xangsane storm that occurred on 25th September 2006. According to our research, a decline in coral in 2006 was due to high waves as a consequence of the TC Xangsane storm that occurred on 25th September 2006.

Our findings highlight that under the RCP 4.5 and RCP 8.5 scenarios, there is a risk of increased damage to the coral reefs in Cu Lao Cham, particularly for the 2040 and 2050 decades. While our findings specifically refer to the coral reefs of Cu Lao Cham Biosphere Reserve, they are applicable to corals worldwide because they look at two global phenomena: climate change and TC.

Conclusion

The high temperature of seawater is what causes violent tropical TCs that can mechanically erode coral reefs. Based on climate change projections from the 'Blue Communities' regional model, this study strongly suggests that TCs will be more frequent and stronger in the future. With the risk of the increasing number and intensity of TCs, the risks of their mechanical impact on coral reefs will be higher leading to the destruction of corals and loss of coverage compared to the current state.

The findings of the research will have beneficial practical implications, helping environmental management agencies by providing them with valid data for the conservation of the biosphere reserve. Research on additional coral species adapted to higher temperatures is needed to preserve the Cu Lao Cham -Hoi An, a biosphere reserve. Finally, decisive action is locally required to cope with climate change.

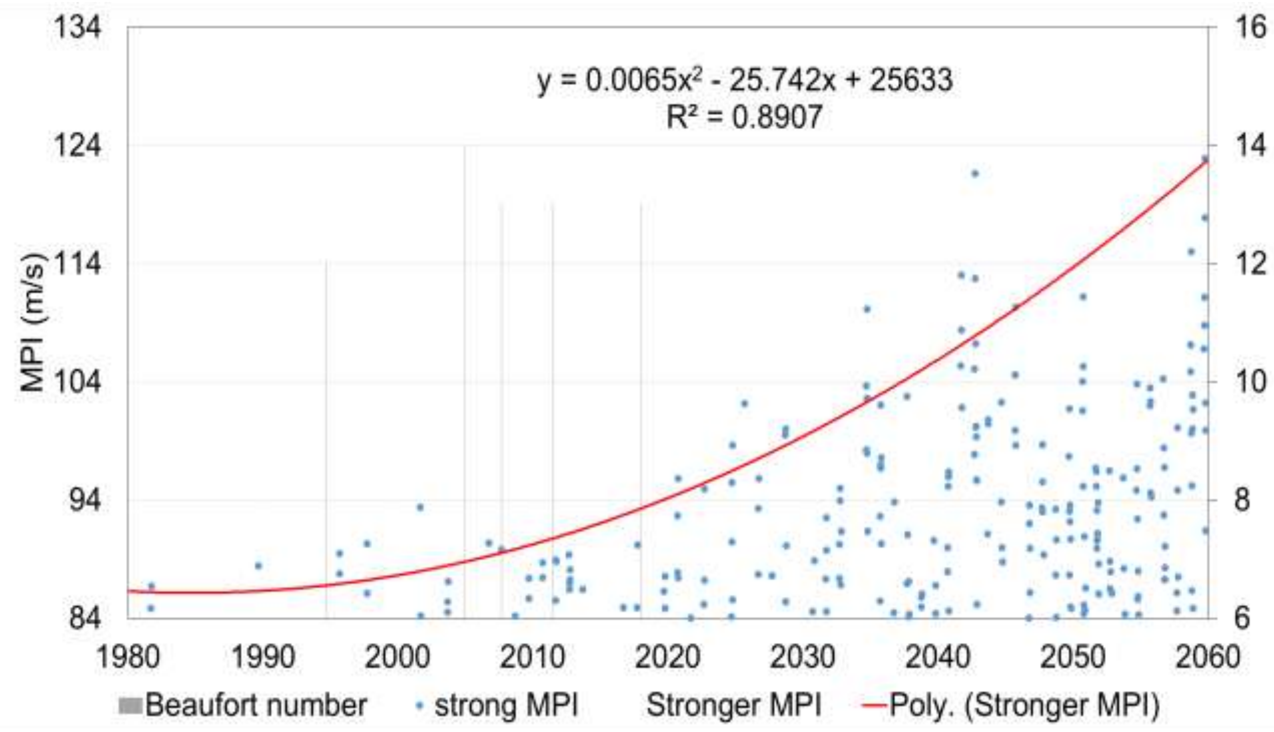

Figure 4: Estimated maximum wind speed during a TC is based on weekly SST using RCP8.5 and force of strong Typhoon in the Cu Lao Cham Sea and nearby

Table 3
Days with the maximum discharge flow according to a year in the Nong Son hydro station and day with a strong TC landing in Quang Nam province and nearby area.

Year	Month	Day	Flow (m^3/s)	Month, Day	SST (ºC)	Storm name	Force
1981	11	17	6270				
1981	10	14	9620				
1982	10	7	1760				
1983	10	30	6270				
1984	10	13	5030				
1985	11	30	4020				
1986	12	3	7920				
1987	11	20	2070				
1988	10	10	3520				
1989	5	25	2160				
1990	11	13	6570				
1991	10	24	3490				
1992	10	24	5360				
1993	11	29	3360				
1994	10	21	3650				
1995	11	10	5130	26/10	29.3	Zack	12
1996	10	29	6790				
1997	9	22	5890				
1998	11	22	8920				
1999	12	4	8560				
2000	11	17	5620				
2001	10	22	4760				
2002	10	25	2200				
2003	10	17	5630				
2004	11	27	8260				
2005	10	26	4810				
2006	25	9	590	25/9	29.3	Xangsane	13
2006	12	6	4600				
2007	11	12	8410				
2008	10	17	5620				
2009	9	30	7030	29/9	27.8	Ketsana	13
2010	11	16	6570				
2011	11	7	6730				
2012	10	7	1750				

Source: Vietnam Center of Hydro-Meteorological data

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