Climate change impact on tropical cyclone evolution and storm surge severity in the east coast of Peninsular Malaysia

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Abstract. Analysing sound information and vast amount of reliable data on tides, waves and tropical cyclone genesis require tireless effort and a great deal of research time, in an ever changing climate conditions. Here, we investigate the strong monsoon wave height in the East Coast of Peninsular Malaysia using more than 20 years of hindcasted wave and tide level data collected at selected locations. A correlation analysis performed on maximum wave heights and surge levels indicated a weak strength of dependency but shown high occurrence during Northeast Monsoon period, concurred with previous storm surge data analysis. We use historical report of West-North Pacific tropical cyclone and global sea surface temperature information to elicit historic patterns of extreme storm tracks and passing distance to understand the trends over the collective years (1986-2012) and to project a concurrent events between the cyclone and surge data. The distance of passing cyclone in closer range does not gives the expected surge height in three out of five selected tide stations, but tropical cyclones in greater distance than 500 km seems to inject a high surge in the east coast. This paper provides a case study of effective cross-sector data analysis in a natural hazard context.

1. Introduction
East Coast of Peninsular Malaysia (ECPM) encompassed four states out of 11 states in West Malaysia region. The coastal length of Kelantan, Terengganu, Pahang and east of Johor combined span more than 600 km. These states, facing the South China Sea (SCS) are indirectly expose to stronger seasonal monsoon forcing as compared to the west coastal regions. Over the years, like many other coastal areas around the globe, the ECPM has since experience and withstand mild and harsh marine climate conditions. The marine climate however revolutionizes with changes in climate. The SCS is an important marginal seas of the Western North Pacific (WNP) Ocean and subjected to winter northeasterly and summer southwesterly seasonal monsoon forcing which attracts tropical cyclones (TC) in their waters all year round. Hence, instigates a new level of catastrophe warning on coastal population resides along the ECPM.

The attraction of TC aftermath has for the last decades set off an active studies on storm surge estimation in the TC genesis regions either through theoretical or numerical works. Numerical model has been widely performed since 1950’s, in US coasts [1], North Sea [2, 3], the Gulf of Mexico [4, 5], across the continent, East China Sea [6], East coast of India [7, 8], South China Sea [9-11] studied Typhoon (Ty) Xangsane for Vietnam central coast, Ty Nesat (Pedring) in Manila Bay [12], Ty Hato in Macau [13], Cyclone Sidr in the Bay of Bengal [14] and in the Gulf of Thailand [15]. On the other part,
forecasting simulation of storm surge predictions has assisted in giving an early warnings to coastal residents, hence able to reduce TC-induced storm surge impact to the populace [16, 17]. Nonetheless, the efforts to understand the variability and impacts of TCs are kept numerously in WNP and SCS, whilst the TC environment and evolution in the south SCS is still immature.

Almost all climate models predict a rise in global sea level over the next century due to the melting arctic glaciers. Indirectly, global warming will likely generate more frequent and more severe TC. Hence, with a greater numbers of severe TC, greater storm surge and wind damage is expected. An increase in temperature about 1°C on average for Asia with projected warming is higher during northern hemispheric winter which bring harsh weather during NEM, than during summer all year round [18]. Thus the temperature rise increase the frequency of extreme precipitation and storm activities in Southeast Asia during the seasonal monsoon [19]. Even the number of category 4 and 5 storms in WNP has grown in numbers from 5.7/year (15 year period studied) to 7.7/year (second time frame) [20]. [21, 22] uncovered saturated occurrence of TCs genesis south of 18° during NEM. Storm path, storm size, storm speed, storm strength, and storm direction all can impact storm surge, where the resultant surge is considered as one of the most destructive hydrodynamic drivers in coastal regions [23, 24], especially in great losses of human lives and widespread damage to coastal infrastructure and property [25].

TC also attributes to the wind-waves growth which will further increase the potential severity of inundation through wave setup and runup. Though, to identify the exact surge level from wave setup especially during extreme storm events are more complex in nature and it is unfeasible to segregate the two [26]. Furthermore, TC-induced coastal flooding is maximised when storm surge coincides with a high astronomical tide and energetic wind waves. And the surge maxima are more likely to occur on the rising or falling tide rather than at slack water because of this dynamical coupling [27-29]. Other than the effect of temperature rise, closer distance in TC genesis gives devastated impacts in Manila Bay as compared to closer passing storms [12], similar findings is found by [30] based on TC impact on the Zhangjiang Coast.

In general, a study on TC in the WNP specifically in SCS is by far still insufficient especially a research that is developed by locals. The shortcomings may either due to insufficient local gathered storm track data or inadequate simulation tools and models to provide the much needed information for short- and long-term risk management plan and increase people’s awareness to face future catastrophe events [31]. In the present work, Section 2 described on the data and procedures of this study. Section 3, the analysis, results and discussion on storm surge and TC evolution based on the observed tidal level, hindcasted waves and historical events of TC in the study area specifically and SCS generally and followed by a conclusion in Section 4.

2. Data and procedures

In this paper, historical records of observed and predicted data consists of tide level, hindcasted wind and waves and typhoon are acquired. The selected hourly observed records from five tide gauge stations located along the coasts of EPM (within the study domain, shown in figure 1) are acquired from Department of Survey and Mapping Malaysia (DSMM) covering data from 1983 until 2012 (table 1). The observed water level data is incomplete, but the identified gauges have less than 10% of missing values over the 25 yr hourly data period. Though, our hope is to collect more information to achieve high correlation for long term trend assessment, but previous years of observed data is not made available. Most of the standard tide stations in Malaysia were mobilised in 1980’s, not like other countries in western regions, the observed water level span more than 60 years and some even reached as far back as in 1950’s. Thus, the percentage gaps are considered acceptable for this study. The selected study domain covered a geographical boundaries from the equator, 0° to 16°N and from 99°E to 121°E which is within the SCS region and part of the WNP area, specifically covered the active TC genesis and tracks. A 6-hourly hindcasted wave records at two offshore points located more than 150 km off the coast of Kelantan (North point) and Pahang (Centre point) at roughly ± 50 m depth contours are acquired from Global Reanalysis Ocean Wave (GROW) span from 1970-2011 and from United Kingdom Meteorological Office (UKMO)(1992-2014 data). Assessment on wave data has
shown a missing gap in certain years, either due to equipment malfunction during extreme climate conditions or other uncertain reason. Nevertheless, the percentage gap is less than 15% for over 20 years of 6-hourly acquired values. Overall, both waves and observed water level data are adequate for the present work assessment. Details of the acquired data is shown in table 2. Whilst the TC data are obtained from the Hong Kong Observatory archives from year 1970 to 2017.

Figure 1. Offshore hindcasted wave and tidal stations locations (left) and study domain (right).

Table 1. Observed water level data for five standard tide stations.

| State        | Station      | Location       | ID  | Year       | Max. surge (m) | Event   |
|--------------|--------------|----------------|-----|------------|----------------|---------|
| Narathiwat   | Paknam Bangnara | 6.44°N, 101.83°E | PB  | 1986 - 2012 | 1.42            | Nov. 1988 |
| Kelantan     | Geting       | 6.23°N, 102.10°E | GT  | 1986 - 2012 | 0.93            | Nov. 1988 |
| Terengganu   | Chendering   | 5.27°N, 103.18°E | CH  | 1985 - 2011 | 0.63            | Dec. 1999 |
| Pahang       | Tg. Gelang   | 3.98°N, 103.43°E | TG  | 1983 - 2012 | 0.68            | Dec. 1999 |
| Johor (east) | Pulau Tioman | 2.80°N, 104.13°E | TIO | 1986 - 2008 | 0.71            | Dec. 1999 |

Table 2. Offshore wind and wave data and the collective period.

| Data | Source | North          | Centre          |
|------|--------|----------------|-----------------|
| Wave | GROW   | 1979 – 2011 (hourly) | 1970 – 2005 (3-hr) |
|      | UKMO   | 1992 – 2014 (6-hr)   | 1998 – 2014 (6-hr)   |
| Wind | GROW   | 1979 – 2011 (hourly) | - |
|      | UKMO   | 1992 – 2014 (6-hr)   | 1998 – 2014 (6-hr)   |
The paper consists of three parts: the first involves the analysis of trends for each variables; storm surge, hindcasted wave and typhoon parameters, respectively. The assessment of each data is focuses on extreme events during the Northeast Monsoon (NEM) where most abnormal events and TC genesis are observed and recorded. The monthly and annual maximum wave heights are screened for linear analysis to investigate the decadal trends of offshore waves within the collective years. The trend in storm surge height has already been determined in the previous research by [29], and will be presented for cross event comparison. The investigation on the collective wave data shown a distinctive stronger north-easterly and mild south-westerly forces in their respective annual and monsoonal directions (figure 2). Which is a trademark of NEM phenomena in ECPM.

3. Results and discussion

An analysis of historical data was performed to assess the trends and its strength of dependency between each variables (surge and waves). The monthly maximum wave height for the north point shown a similarity in pattern as in the southern point, where a distinctive pattern of high waves over 2.0 m during the NEM and less than 2.0 m wave height during SWM with occasional spike in August are identified (figure 3). The maximum recorded wave height in north is less than the wave height recorded at centre point which may be influenced by direct strong wind blowing from WNP straight towards the centre of ECPM area. Whilst coastal areas in the north ECPM is mildly obstruct from strong north-easterly wind from WNP by the land mass of Vietnam. The wind force is further reduced as it propagates further into the Gulf of Thailand, which resulted in mild surge impact.
Assessment on the annual maximum wave height in northern region shown a decreasing trends in the first 20 years and increase in later years, parallel with the increased in storm surge level due to climate change investigated by [29] (see figure 4). Year 2002 and 2003 mark the turning point of the trends in the northern region, and year 1994 in the centre region, which largely from the contribution of warmer El Niño event [32]. The highest wave height recorded in north and centre regions identified in 2001 may likely due to strong La Niña event [48]. Indeed, similar case was found in the storm surge events [29], [33] have confirmed that ENSO has a large impact on the inter-annual variability of tropical cyclones in the Western North Pacific basin thus will likely influence surge and wave intensity.

An investigation on dependency strength between the the storm surge and wave heights using correlation analysis shown that there is no linearity between the two parameters for both points (figure 5). The reason being is that waves are most commonly caused by wind, whilst, storm surge can be considered as the sum of three primary components; i) meteorological effects caused by low atmospheric pressure at the center of the storm, ii) wind effects caused by wind stresses on the water surface, and iii) wave effects caused by wave breaking in the surf zones (known as wave setup).

Nevertheless, joint force of high tide-surge and waves are becoming a common traits during NEM season; as in extreme flood events experienced in Kelantan, Terengganu and Pahang at the end of year 2014. Storm surge magnitude also governed by the TC strength and distance to the storm centre. While storm speed and intensity are ruled by warmer ocean surface and lower atmospheric pressure in SCS. Though, the effect of global sea surface temperature (SST) on TC intensity is not covered in this work. Analyzing the TCs tracks data gathered from HKO annual report gives a phenomenal understanding on the probable impact of the TC genesis on storm surge level based on a selected TC-induced surge events (table 3). Several significant TC tracks were shown passing closer and at a distance to ECPM waters (figure 6). From the observation, most of the storm passed just outside the passage (south of SCS) going into the Malaysian waters but then divert northwest-wards and landed or crossing the Gulf of Thailand into the landmass of Thailand or Vietnam. Along the way, TC intensity decreased gradually as it crossed Thailand land mass, but later gathered in strength as it crossed the Andaman Sea and hit the coast of southeast of India.

Close encounter with TC along the Malaysian coast has recorded both significant surge height and the reverse (figure 7). For instance, from the data assessment, maximum surge has been identified occurs during tropical depression (TD) with sustained wind speed less than 20 m/s, weaker than during severe tropical storm (STS Tess) with more than 35 m/s storm speed. Which later confirmed by a correlation test between surge height and TC strength where no linearity is found between the two variables (figure 8). To top it all, both storms are located more than 1000 km from the ECPM coast, but the impact has generated a contra surge height. These contradiction in surge height has led to a possibility that the passing distance regardless of the storm strength is not the sole influence of surge severity but may likely from other marine climate drivers. Despite the low correlation, the interconnection between the two variables should not be taken less seriously.
**Figure 4.** Annual maxima wave heights for North (dot) and Centre (line) points and annual maximum storm surge (below).

**Figure 5.** Regression analysis on storm surge level and wave height.
Table 3. Selected Storm Surge and Tropical Cyclone events from 1986 to 2012.

| Name   | Month-Yr | SS (m) | TC speed (m/s) | Distance (km) | TC air pressure (hPa) |
|--------|----------|--------|----------------|---------------|-----------------------|
|        |          | PB     | GT  | CH  | TG  | TIO  |               |               |
| TD<sup>a</sup> | Nov86    | 1.30   | 0.96 | 0.39 | 0.27 | 0.20 | 16             | 844            | 1002           |
| TD<sup>a</sup> Ogden<sup>e</sup> | Nov87    | 1.19   | 0.90 | 0.67 | 0.63 | 0.62 | 13             | 1260           | 1003           |
| STS<sup>b</sup> Tess | Nov88    | 1.42   | 0.93 | 0.43 | 0.44 | 0.48 | 36             | 1110           | 970            |
| TS<sup>c</sup> Gay | Nov89    | 0.54   | 0.52 | 0.45 | 0.42 | 0.42 | 18             | 159            | 1000           |
| TD<sup>a</sup> Forrest | Nov92    | 0.75   | 0.51 | 0.42 | 0.41 | 0.39 | 16             | 230            | 995            |
| TS<sup>c</sup> Manny | Dec93    | 0.74   | 0.57 | 0.45 | 0.38 | 0.39 | 18             | 1285           | 995            |
| TS<sup>c</sup> Owen<sup>e</sup> | Apr94    | 0.16   | 0.20 | 0.19 | 0.20 | 0.17 | 23             | 1700           | 996            |
| STS<sup>b</sup> Linda<sup>e</sup> | Nov97    | 0.35   | 0.44 | 0.31 | 0.32 | 0.27 | 25             | 330            | 985            |
| TD<sup>a</sup> | Dec99    | 0.47   | 0.62 | 0.63 | 0.68 | 0.71 | 16             | 1045           | 1000           |
| TD<sup>a</sup> Durian | Dec06    | 0.52   | 0.50 | 0.54 | 0.58 | 0.52 | 23             | 680            | 985            |
| STS<sup>b</sup> Hagibis<sup>e</sup> | Nov07    | 0.26   | 0.25 | 0.29 | 0.26 | 0.27 | 31             | 1215           | 975            |
| ST<sup>d</sup> Megi | Oct10    | 0.72   | 0.74 | 0.37 | 0.34 | -    | 49             | 2140           | 940            |
| TD<sup>a</sup> | Nov12    | 0.66   | 0.65 | -   | 0.52 | -    | 16             | 660            | 1002           |

<sup>a</sup>Tropical Depression  
<sup>b</sup>Severe Tropical Storm  
<sup>c</sup>Tropical Storm  
<sup>d</sup>Severe Typhoon  
<sup>e</sup>TC strength not in linearity with storm surge height

Figure 6. Various TC tracks in close proximity and away from Malaysian waters [34].
Conclusion
The wave heights in the ECPM is driven mainly from the strong seasonal monsoon climate with higher waves produced during NEM. Over 20 years of hindcasted offshore wave data, the waves shown an increasing trends concurrent with the rise in storm surge heights recorded from the selected five tide gauge stations along the ECPM. The correlation test of wave-surge however, shown a low results of dependency, but the combined force could lead to an exaggerating coastal flood impact to coastal population resides along the coastal area.

The assessment of TC data however, shown various combination of storm speed, sea surface pressure and the distance between point source of TC genesis and study area. The storm intensity is found to be not so parallel with the high sure level, though in overall, level of surges remain high (> 0.3 m) in each TC events. In the assessment of TC track distance with respect to storm surge height, a closer passing storms but less in intensity is found to inject higher surge height as compared to a far distance but more intense storm. And in other cases, a very severe storm has resulted in high storm surge although originated more than 1000 km from the site of study. This has led to a conclusion that the severity of storm surge is not solely depends on the near storm events and strength but may be influenced by other marine climate driven factors such as the coriolis effect, coincide event of high astronomical tides, temperature changes etc., which has yet to be further analysed. Overall, the findings of this study can be seen as a turning point for further analysis and cross event investigations to understand the degree of TC impacts on the Malaysian coasts in the near future and in the ever changing climate conditions.
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