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Assessing future projections of Intense typhoon return period and intensity over Taiwan

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Abstract

Typhoons are a leading natural cause of mass socioeconomic losses through floods, storm surges and high winds, and this is projected to worsen in a warmer climate. While the majority of literature is in agreement, there is little research into typhoon behaviour projections past the year 2100. TCWiSE – a statistical modelling tool, is used to simulate and spatially assess changes in intense (category 4+) typhoon return period and average intensity over the island of Taiwan in four different climate scenarios all with increasing intensity and frequency values. In comparison to the present-day scenario, the future scenarios recorded a +12.0%, +21.2% and +21.4% increase in average intensity, and a –10.2%, –51.4% and –45.9% median reduction in return period, indicating Taiwan will face typhoons that are more frequent and powerful relative to 2022. There is little variation observed in the intensity and return period values found between the two most extreme simulations, but a comparison between the two suggests there is a marked change in typhoon track towards Taiwan causing higher dissipation rates from more landfall events. Nevertheless, regardless of the future climate, all simulated scenarios look unfavourable for Taiwan unless rapid change is made to mitigate greenhouse gas emissions to acceptable levels.

Keywords: Typhoons, Return Period, Intensity, Taiwan, Climate Change

Introduction

Introduction to Typhoons

Typhoons are among the most devastating natural disasters to occur in East Asia. Bringing destruction through storm surges, intense sustained winds and large amounts of precipitation; typhoons cause billions of dollars in damages and large loss of life every year. Advancements in satellite technology and the advent of meteorological agencies has improved the accuracy of typhoon forecasting. Risks from typhoons can be predicted two days prior to landfall via machine learning (Chang *et al.*, 2020). However, anthropogenic climate change provides an additional dimension when predicting long term typhoon climatology and future responses.

The evolution of extreme weather events in warmer climates is a major theme of research among climate experts. Changes in recent typhoon behaviour have been monitored using historical data. Intensity (Emanuel, 2005; Li *et al.*, 2017; Ting *et al.*, 2019), frequency (Choi & Cha, 2015), translation speed (Kossin, 2018) and precipitation levels (Hall & Kossin, 2019) have all seen temporal and spatial change from as far back as 1946. For climate projections, most models use Representative Concentration Pathways (RCP) – a framework which defines four primary radiative forcing levels for different climate scenarios up to 2100CE as the metric by which to predict climate futures. As it stands, the overwhelming consensus in the literature using higher RCPs points to a future in which every typhoon characteristic is projected unfavourably for coastal communities.

Typhoons in a Changing Climate

Typhoon intensity both historically and in climate futures has been extensively researched in all ocean basins. Numerous studies have indicated that typhoon intensity has increased steadily since records began, and models suggest a continuation of this trend. Mei and Xie (2016) stated that typhoons intensified by 12-15% since 1977, while maximum potential intensity and super typhoon intensity are earmarked to increase further than current levels with increased amounts of greenhouse gas emissions (Tsuboki *et al.*, 2015; Sobel *et al.*, 2016). It is also widely accepted that increases in intensity is intrinsically linked to an increase in ocean and tropospheric temperatures (Emanuel, 2005; Mei *et al.*, 2015). From these findings, supported by evidence of increasing atmospheric CO_2 (Thoning, 1989; Beck, 2008), it's likely that future typhoon intensities are unidirectional unless reductions in greenhouse gas emissions are made.

Frequency – the regularity of typhoons in a given area has also been well researched. Studies generally agree that overall frequency will decrease, but the proportion of intense typhoons will increase (Knutson *et al.*, 2015; Bacmeister *et* al., 2018). Some are doubtful, hypothesising an increase in frequency across all categories (Emanuel, 2013). Regardless of outcome, future projections are concerning as evidence shows 85% of historical damage has been caused by category 3+ typhoons, while only accounting for 24% of overall typhoon activity (Pielke, 2008). This could be further worsened with suggestions that locations with high typhoon frequencies are at risk of compound events with further hazards such as landslides and floods arising from sequential typhoons (Zscheischler *et al.*, 2020).

Return period refers to the length of time between typhoon events. Return period can be difficult to predict for intense typhoons due to their infrequent nature (Emanuel & Jagger, 2010) but this paves the way for research to use models simulating synthetic tracks to determine change in return period. Return period has been utilised different ways. Usually defined as the length of time between typhoon events, it has also been used as a fixed timescale in which the highest intensities during that period are recorded (Elsner, 2006; Guo, 2021). In Elsner's case, the highest intensity typhoons over the past 100 years were all observed in the warmer years on record. There have been historical overviews of intense typhoon return period (Chu & Wang, 1998; Keim *et al.*, 2007), but intense typhoon return period in warmer climates is generally understudied. However, studies have determined both intensity and frequency in the same scenario, from which intense typhoon return period can be derived (Knutson *et al*., 2015; Cha *et al.*, 2020). These results lead to suggestions that return period will decrease overall in warmer climates.

Literature Gap and Research Rationale

The socioeconomic implications attached to a future with more intense and frequent typhoons is the main driver behind much research. However, while there have been numerous studies conducted with a plethora of future projections, most literature uses 2100 as a temporal limit for its climate scenarios. There is logic behind simulating scenarios and outcomes more extreme than the current projections as global warming worst case scenarios are projected to worsen as earth systems deteriorate further post 2100 (IPCC, 2013).

More importantly still, the higher end of human life expectancy passes into the 22nd century, therefore, millions of people currently alive will live to see climate impacts after 2100. Recommendations have been made to extend projections past 2100 (Lyon et al, 2021), and there are climate projections up to 2300 called Extended Concentration Pathways to do this (van Vuuren et al, 2011), but they are rarely utilised. While some papers have looked at the return period of intensity, it's uncommon to be combined with frequency to provide results for the return period of intense typhoons or for return period to be assessed over a specified country. Understanding how and where future intense typhoon behaviour will change spatially is imperative to damage limitation, given the economic cost with respect to intensity appears to be exponential (Pielke, 2008).

Typhoons affect the daily lives of Taiwanese citizens both socially and economically, both now and in the future. Understanding how intense typhoon return period and intensity will change with climate change will inform and advise the future outlook for the country. Inadequate planning for typhoon impact mitigation and preparedness can be of long-lasting detriment. Economically, damage from typhoons under climate change is expected to double by 2100, with an extra $15b of damages expected in Asia. Additionally, most damage is expected to be caused by intense typhoons (Mendelsohn, 2012) and it has been observed that typhoons can cause a 20% downturn in the local economy for the following year if >50% of buildings are destroyed (Elliott, 2015), something which is likely with current trends and future predictions. Resulting impacts such as flooding and storm surges are also directly affected by changing typhoon behaviour (Reed A.J. 2015; Garner *et al*., 2017) but predictions with confidence can help manage and mitigate these.

This paper begins to rectify these issues and add to the literature by using the Tropical Cyclone Wind Statistical Estimation Tool (TCWiSE) to model climate scenarios more extreme than current projections based on results from previous literature. TCWiSE is a statistical modelling programme that can quantify changes in typhoon intensity, frequency and return period in future climate scenarios based on historical data via the use of statistical probabilities. A more detailed description of the model is given in the methodology.

Study Area

Typhoon genesis requires ideal oceanographic and atmospheric conditions. Warm ocean waters >26°C with a deep thermocline; low vertical wind shear; and surface air convergence. The geography of the NWP fosters this, with a large expanse of ocean eastwards coupled with low frictional effects from a lack of island topography. Taiwan is located within the Northwest Pacific (NWP) basin (fig.1a & b). The NWP is the most active cyclone basin, receiving 33% of all typhoons globally. Taiwan is an island situated 200km east of the Chinese coastline. Its location in the NWP means it experiences typhoons of all intensities year round, with 167 category 1+ events coming within 150km of its shores since 1945 (NOAA, 2021). Taiwan's elevation is asymmetric. Five mountain ranges run from north to south on the eastern flank with many peaks >3000m. The mountains play a significant role in altering typhoon behaviour around the island (Brand, 1974; Wu, 2001; Wu *et al.*, 2002; Wang, 2011; Hsu *et al.*, 2018; Lin *et al.,* 2020). The steep gradient provides protection to the western side of the island via orographic blocking and diverts typhoon tracks. The same steep gradients produce large amounts of orographic precipitation leading to an abnormal amount of fluvial flooding and landslides as rivers basins fill up rapidly (Teng *et al.*, 2006). Unfortunately, as drought conditions are more frequent in months with lower typhoon activity (Hung & Shih, 2019), Taiwan's relationship with typhoons is one of convenience.

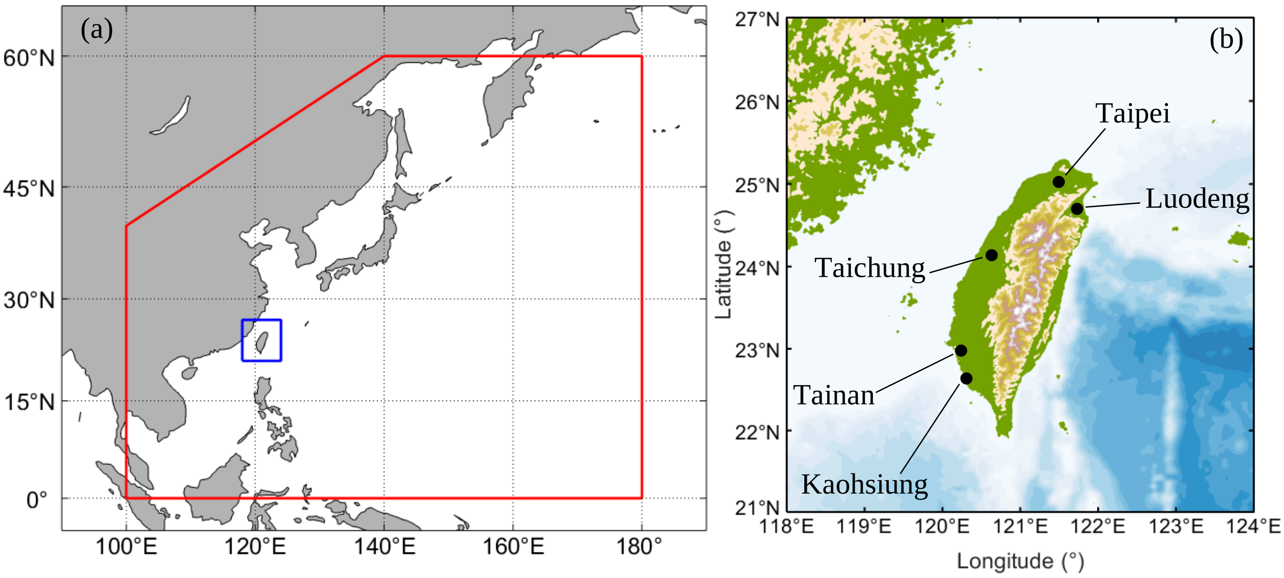

Figure 1: A map of the Northwest Pacific (NWP) typhoon basin in red, with Taiwan - the study area highlighted in the blue box (a); with a zoomed in, detailed map of Taiwan illustrating elevations and depths in the surrounding seas (b). Major cities have been annotated in black. (Base maps created using Pawlowicz, 2020).

Aims and Objectives

This paper attempts to answer questions on how two key parameters – typhoon intensity and intense typhoon return period will change from present-day, to a future climate scenario as established by a published study, and beyond. Four simulations will be run to obtain a full scope of future climate scenarios. The first simulation is one of present day as a reference point. The second scenario will be using results of future intensity and intense typhoon frequency from Cha *et al.*'s (2020) study: 'Third Assessment on Impacts of Climate Change on Tropical Cyclones in the Typhoon Committee Region – Part II: Future Projections'. This scenario outlines the predictions of a climate future in which the Earth will experience a 2°C in global temperature by 2100 – roughly equivalent to RCP 4.5. The third and fourth climate scenarios are a doubling and tripling of Cha *et al.*'s (2020) results respectively. These represent potential climate futures post 2100CE. These simulations will serve to gain a spatial understanding of where Taiwan will be affected, as well as an analysis of the intensity and return period data plotted and tabled for direct comparisons to the present-day scenario.

There are two main aims of this paper. Firstly, it is the intention of this paper to aid policy and decision makers understand where the greatest typhoon risks are across Taiwan, what potential implications can be deduced and decide what action may need to be taken to ensure the safety of citizens of Taiwan now and in the future. From this, climate change mitigation policy can be proposed, typhoon damage mitigation and coastal management strategies can be modified, and typhoon preparedness plans can be adjusted accordingly. It is expected that South-eastern Taiwan will be worst affected by changes due to their exposure to typhoons relative to the rest of Taiwan, but this could change in future climate scenarios. Secondly, this paper will critically assess how typhoon behaviour will change in a multitude of climate scenarios more extreme than current projections to understand any controls on typhoon characteristics. Given the parameters used, both intense return period to shorten and intensity to rise uniformly with each subsequent scenario is expected.

The objectives to achieve this are as follows:

- Produce four datasets to represent the four climate simulations by running TCWiSE, adjusting the climate change parameters as described in the methodology for each scenario.
- Develop a MATLAB script to plot datasets of the climate scenario simulations created in TCWiSE.
- Analyse the values of the datasets to quantify differences of intensity and intense return period between the different climate scenarios.
- Analyse the spatial variability of intense return period and intensity in each climate change simulation.
- Infer implications of the changing behaviour of typhoons under different climate change scenarios over Taiwan and discuss management strategies to combat the results from the datasets.

The paper will outline the methods with an in-depth explanation of the TCWiSE simulation process, data processing and output. It will later provide findings and then critically analyse those results considering its implications for coastal communities, potential damage mitigation options. Finally, a critical evaluation of TCWiSE as a model and recommendations for future research.

Methods

The Statistical Model

TCWiSE is an open-source statistical modelling tool programmed in MATLAB purpose built for typhoon simulation (Leijnse, 2021a). TCWiSE allows the user to plot historical typhoon data and generate new simulations comprised of synthetic typhoon tracks.

TCWiSE creates a statistically probabilistic simulation of typhoons based on historical typhoon data derived from the International Best Track Archive for Climate Stewardship (IBTrACS).

IBTrACS is a collective database accounting for all typhoon records globally from all meteorological agencies dating back to 1842. These records contain several variables that characterise a typhoons' behaviour throughout its lifespan. The data sourced chosen to compute the simulations in this research is from the Joint Typhoon Warning Center (JTWC) due to its overall completeness in comparison to other data sources from alternative meteorological agencies. JTWC commenced their documentation of typhoons in 1945. TCWiSE uses the following variables from JTWC typhoon records in the IBTrACS database for use in its programme, recorded on a three-hourly basis:

- Cyclone Basin
- Latitude
- Longitude
- Time
- Max Sustained Wind Speed
- Translation Speed
- Direction

Individual Track Initialisation and Evolution

A spatial probability density function (PDF) grid is created for each variable. Using typhoon genesis as an example; all latitude and longitude coordinates at the beginning of each historical typhoon are plotted as individual genesis points. These genesis points are assigned a grid point based on their location. This grid has a resolution of 0.1° x 0.1° (Leijnse *et al.*, 2021b). Once complete, the number of genesis points in each grid point is tallied, giving the genesis density for the whole basin. Once the simulation is complete, the same process takes place for termination density. Figure 2 is an example of the probability density function (PDF) map of historical typhoon geneses.

TCWiSE initiates a track by randomly sampling from the genesis PDF grid via the Monte Carlo method, a technique used in previous studies on typhoon characteristics (Che & Yang, 2020). Every track is also given starting values for the listed variables, once again picked based on random sampling from the probability density function grids created for each variable from the historical data.

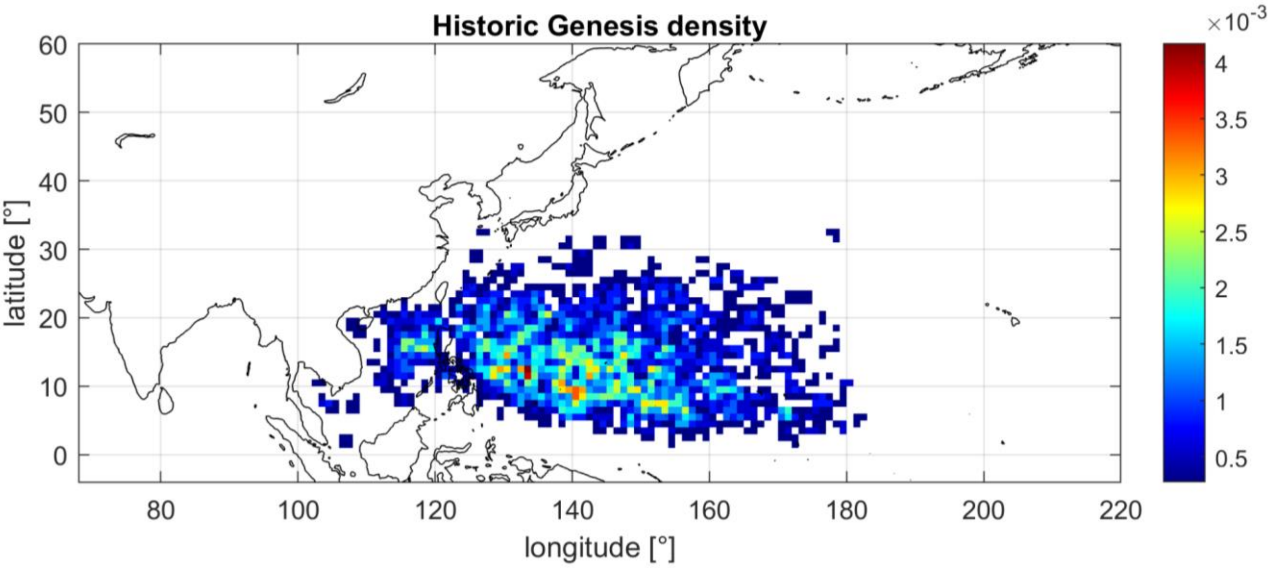

Figure 2: An example of a genesis density map created in TCWiSE, illustrating the likelihood of genesis at a given grid point (Base maps created using Pawlowicz, 2020).

As warm ocean surface temperatures are integral to typhoon genesis (Gray, 1977), typhoons randomly sampled to begin where SST is <24°C are deleted from the synthetic track dataset and redone. SST data is taken from the International Research Institute of Columbia University (2017) and is used to define the monthly averages for SST at a 1° x 1° grid resolution. In the simulation, typhoons are randomly assigned a month in which they are run. This is based on the monthly distribution of typhoons (fig.3) to obtain results for the full extent of a typhoon season.

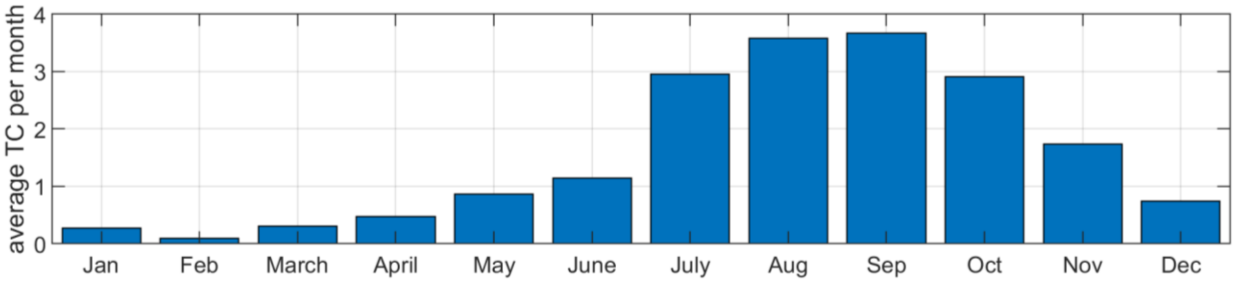

Figure 3: The monthly distributions of typhoon genesis in the NWP basin. The NWP basin is the only basin to receive typhoons year- round but is most active from July - October.

Intensity, translation speed and direction are all randomly sampled using their respective probability density function grids at each time step. Translation speed and direction are combined to determine the location of the TC at the next time step in three hours, while intensity is calculated based on the rate of change in intensity for typhoons that have historically followed a similar path from the same location. For the duration of track evolution, TCWiSE employs the Markov model, where the probabilities of a typhoons' next step are based solely on the data derived at that point and not those that preceded it, a technique used previously in modelling software (Jing, 2019). Intensity, translation speed and direction changes are partially limited for each time step, preventing unrealistic evolution through a typhoon's simulation (Nederhoff *et al*, 2020).

TCWiSE continues to sample every three hours until one of three conditions are met: sustained wind intensity is <17ms^{-1}, Sea surface temperature is <10°C, or when the historical probability of termination falls below a critical threshold. When one condition is met, track evolution ceases and TCWiSE initiates the next track. If intensity remains >17ms^{-1} however, the status of the other two conditions is overridden and TCWiSE will continue the track even if either of the two other conditions have been met.

If the typhoon has made landfall, TCWiSE applies Kaplan and DeMaria's model (1995) to decrease typhoon intensity exponentially over time. If a typhoon is over land, the intensity calculation for the next time step is disregarded and the decay coefficient is applied in its place. The decay strength parameter is set by the user. In TCWiSE, intense return period is defined as the number of occasions a typhoon's central eye comes within 100km of a grid point within any given year. Therefore, for any grid point, the number of simulation years (in this case: 100) divided by the number of instances in which this occurs gives the return period for that grid point. To compute this, the parametric wind field model created by Holland (2010) is applied to every time step of each track after the track is completed and the intensity value has been calculated. Figure 4 demonstrates the full simulation process of TCWiSE.

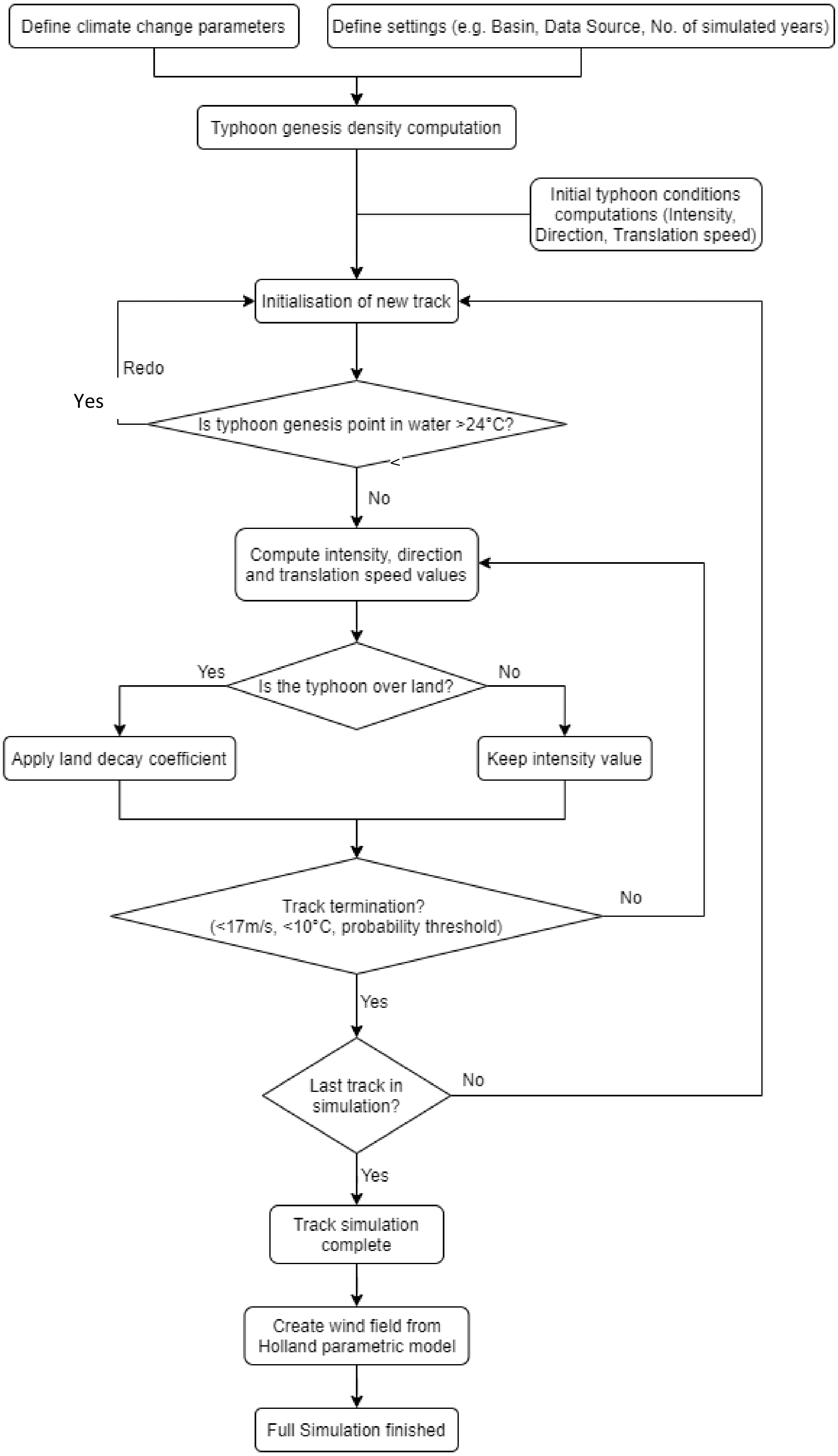

Figure 4: The TCWiSE step-by-step simulation process, including the track initialisation process.

Model Settings and Climate Change Parameter Rationale

A strength of TCWiSE is the customisation settings allowing for flexibility. Prior to running a simulation, settings were chosen on the basis for the simulation to be as realistic as possible. The main settings with their respective values are as follows:

- Land Decay coefficient: 0.0155 (Category 1 typhoons (33ms^{-1} decaying to 17ms^{-1} in 68.96 hours)
- Number of years to simulate: 100
- Basin: WP (West Pacific)
- Data source: USA (JTWC)
- Time step: 3 hours
- Start year for historical data: 1945
- End year for historical data: 2020
- Coordinate system: WGS84

To instigate a climate change effect in the model, TCWiSE contains a section named “climate change parameters” in which intensity and frequency of typhoons can be manually altered by the user prior to simulation.

While changes in intensity is based on several factors in the simulation, frequency changes are directly proportionate to the historical data. For example, if the historical data recorded 100 typhoon events in 100 years, a 20% frequency increase will cause TCWiSE to simulate 1200 tracks in 100 years. To calculate this, TCWiSE uses the average number of typhoons in the selected typhoon basin in the defined time period, divides by the number of years of historical data and applies the additional number of tracks based on the percentage increase or decrease in frequency multiplied by the number of simulated years. The equation for this is given below, and the additional percentages chosen is what the total number of typhoons in the simulation is going to be.

$$T_{sim} = \frac{T_{hist}}{Y_{hist}} \times (F + 1) \times Y_{sim}$$

Where T_{sim}= Total no. of typhoons in the simulation, T_{hist}= number of historical typhoons, Y_{hist} = years of historical data, *F* = frequency percentage change and Y_{sim}= Number of simulated years.

The first simulation was a control climate, used as a reference baseline. The control climate baseline had the climate change parameters set to +0.0% for both frequency and intensity, serving as a present-day climate scenario. This was used to set a benchmark against the three future climate scenarios, calculating to what extent typhoon behaviour will change in the future.

The alteration of the climate change parameters in TCWiSE allows for the prediction of typhoon intensity, frequency and track in various climate change scenarios. As TCWiSE obtains climate change information based user inputs, results from a separate study which produced results based on a future climate scenario from a complex modelling system is required as a "year 2100 scenario". The study of choice was Cha *et al.* (2020). Cha stated that a 2°C increase in surface air temperature will result in a mean frequency increase of intense typhoons category 4 or above by +12.3% and a mean increase in intensity by +5.3% in the NWP Basin by the year 2100. These results form the basis of the statistics chosen as inputs for the climate change parameters in the two other climate scenario simulations. This scenario is named Cha *et al.* (2020).

Furthermore, as the purpose of this study is to ascertain changes to return period and intensity over Taiwan in scenarios that are more extreme than current projections, two further climate scenarios with double and triple the typhoon frequency and typhoon intensity results stated in Cha *et al.* (2020) were also chosen for a total of four simulations. Once the climate change parameters were decided upon, the four simulations were ran and the results were saved for data processing. These simulations are named Cha *et al.* (2020) double and Cha *et al.* (2020) treble respectively. Table 1 displays the climate change parameters used to compute the synthetic tracks for each simulation.

Table 1: A table of the climate change parameters imposed onto each simulation. There is an increase of +12.3% and +5.3% for frequency and intensity in each successive simulation, aiming to simulate climates that are progressively more extreme.

Climate Scenario	Climate Change Parameters	
	Frequency	Intensity
Present day	0.0%	0.0%
Cha *et al.* (2020)	+12.3%	+5.3%
Cha *et al.* (2020) doubled	+24.6%	+10.6%
Cha *et al.* (2020) trebled	+36.9%	+15.9%

Post Simulation

Once the simulation is complete, the dataset is organised into a MATLAB struct which houses values for latitude, longitude, average maximum intensity, the standard deviation of average maximum intensity, typhoon return period >64 knots and typhoon return period >100 knots over the NWP cyclone basin. The grid created for cyclone basin has a grid resolution of 1°x1°. Prior to the simulation, modifications to the section of code responsible for tracking the typhoon return period >100 knots. As the change in return period for category 4 typhoons (>113 knots, [58ms^{-1}]) is one of the research foci, the code was modified from 100 knots to 113 knots to reflect this.

Data Processing and Output

Track data was an automatic output as a result of running TCWiSE. For average maximum intensity and intense typhoon return period data, a MATLAB script was created to plot data over the region of Taiwan in a bounding box with coordinates 118°E-124°E, 21°N-27°N for each simulation. Boxplots were also created using the same section of the dataset. Code from M_map, a mapping software tool designed for MATLAB was incorporated into the

MATLAB script to create the maps on which simulation data was superimposed (Pawlowicz, 2020).

Results

A total of 8891 typhoons tracks were run, simulating 100 years-worth of typhoon activity in four different climate scenarios. This equated to 1877, 2107, 2338 and 2569 typhoon simulations for the Present-day (fig.5a), Cha *et al.* (2020) (fig.5b), Cha *et al.* (2020) doubled (fig.5c) and Cha *et al.* (2020) trebled (fig.5d) climate scenarios respectively. Results show little variation in terms of overall track footprint across the four simulations. Differences in track density around Taiwan are possible, but the overlay of tracks in the plot makes it difficult to observe.

Basin Intensity – Taiwan

Mean intensity values within the vicinity of Taiwan are higher than the NWP basin average across all scenarios. Average intensity in the present-day scenario is 34.3ms^{-1}, with values between 29.6 – 38.4ms^{-1} (fig.6a). Values from the Cha *et al.* (2020) scenario saw average intensities of 38.4ms^{-1}, falling between 32.6 – 43.4ms^{-1} (fig.6b). The Cha *et al.* (2020) doubled scenario saw an average intensity increase +3.1ms^{-1} to 41.5ms^{-1} (fig.6c). The maximum intensity value across all four scenarios was observed in this simulation, with values between 36.1 – 46.6ms^{-1}. The Cha *et al.* (2020) climate scenario saw the highest mean intensities by a small margin. Average intensity across Taiwan increased +0.1ms^{-1} to 41.6ms^{-1}, with a range of 36.3 – 46.5ms^{-1} (fig.6d). Increases relative to the present-day scenario show an initial steep change in intensity +12.0% to the Cha *et al.* (2020) scenario, slowing down in the additional scenarios with smaller increments of +9.2% and +0.2% thereafter (table 2).

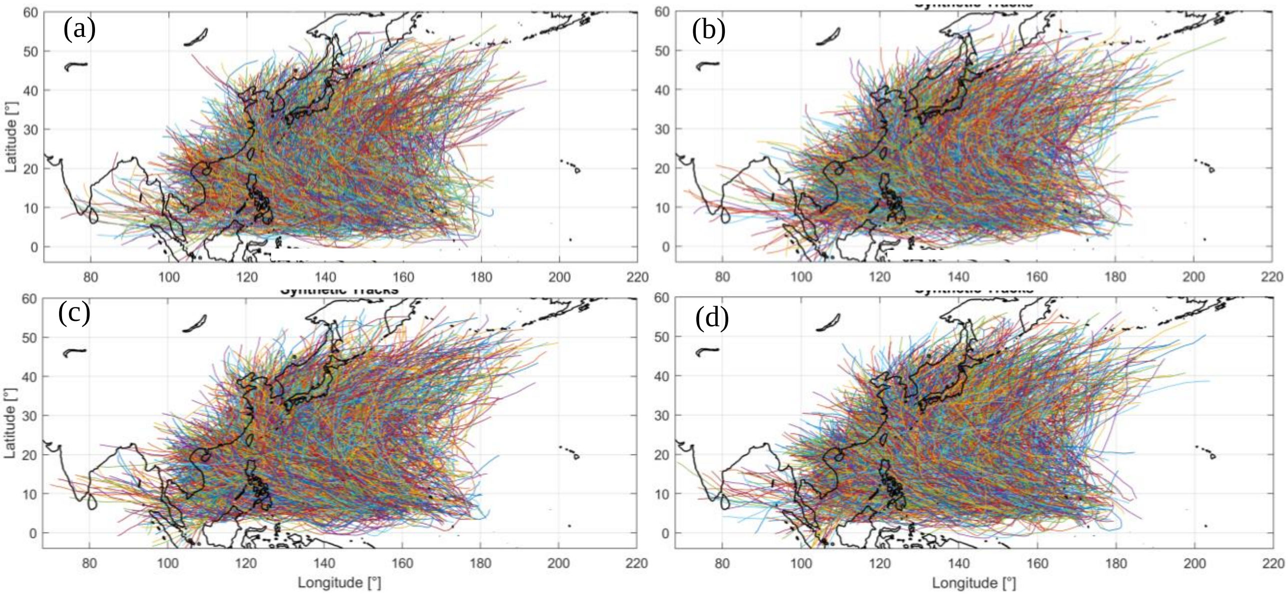

Figure 5: Map of overall track footprint in the NWP basin for each of the simulations, starting with present-day (a), Cha et al. (b), Cha et al. doubled (c) and Cha et al. trebled (d). (Base maps created using Pawlowicz, 2020).

Mean intensity values increased with each simulation, however, median intensity unexpectedly decreased from Cha *et al.* (2020) doubled to Cha *et al.* (2020) trebled values despite a +5.3% intensity increase in the model (fig.7).

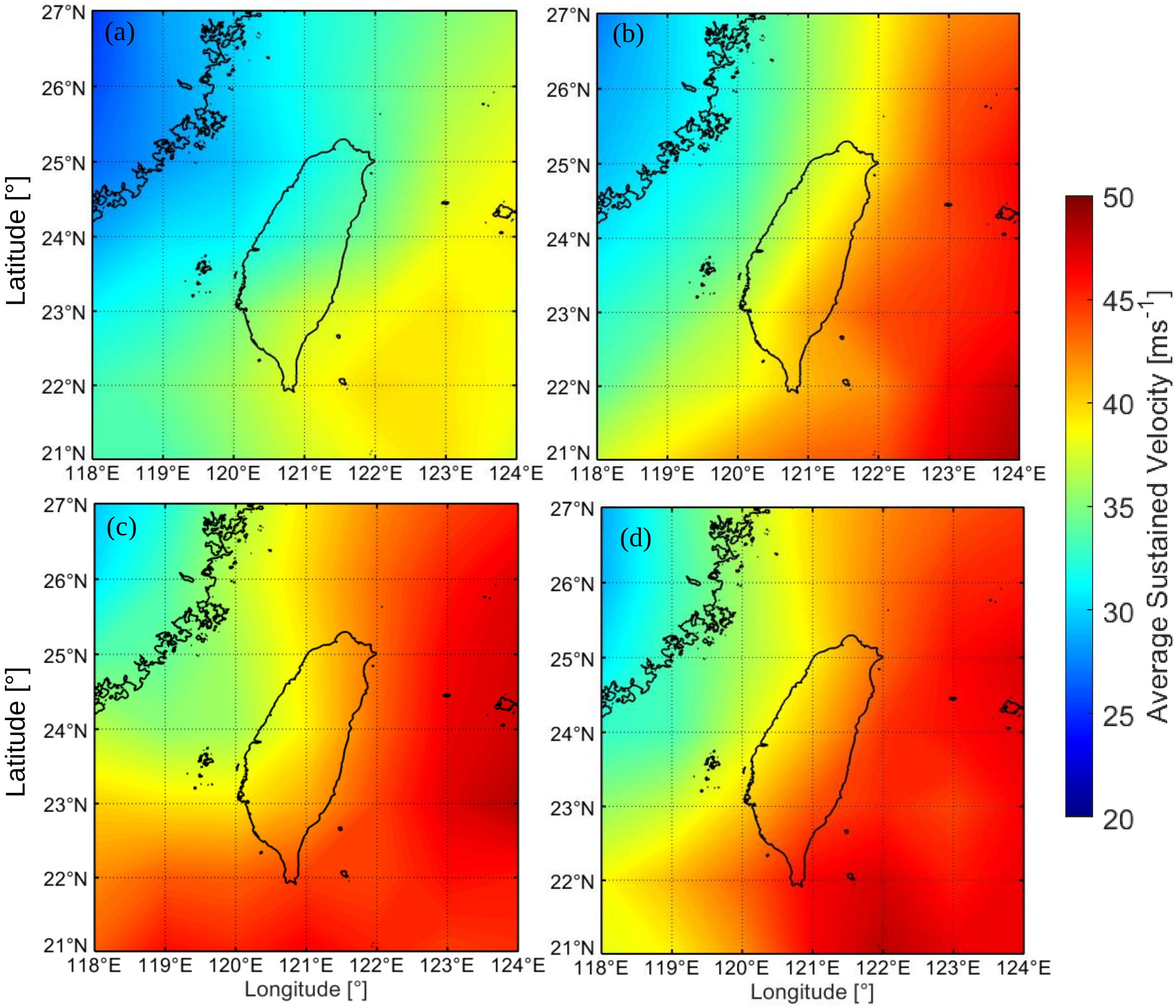

Figure 6: A visual representation of mean intensity over Taiwan for each climate scenario, from present-day (a), Cha et al. (b), Cha et al. doubled (c) to Cha et al. trebled (d). (Base maps created using Pawlowicz, 2020).

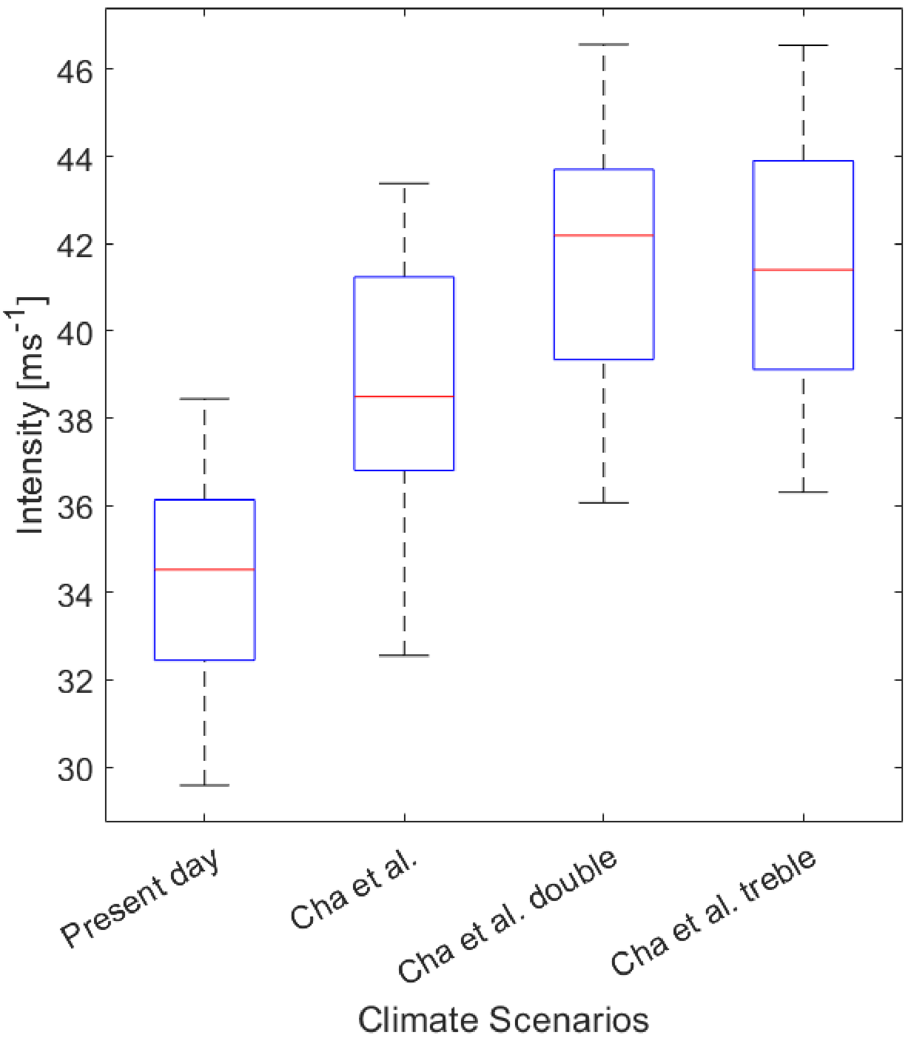

Figure 7: A boxplot of the intensity values over Taiwan. Note the higher median intensity and narrower interquartile range of the Cha et al. doubled scenario.

Table 2: Overall mean intensity of each simulation over Taiwan and their relative increase in intensity in with respect to the present-day value.

Climate Scenario	Mean Intensity [ms^{-1}]	Increase from Present Day (%)
Present day	34.3	-----
Cha *et al.* (2020)	38.4	12.0
Cha *et al.* (2020)doubled	41.5	21.2
Cha *et al.* (2020) trebled	41.6	21.4

Intense Typhoon Return Period – Taiwan

Median values for return period fluctuated with each simulation. The initial present-day simulation saw a median return period of 3.77 years, with values falling between 2.63 – 8.33 years (fig.8a). The Cha *et al.* (2020) simulation saw a further decrease in median return period to 3.39 years – a reduction of 10.2%, with values from 1.96 – 8.33 years (fig.8b). Cha *et al.* (2020) doubled saw the shortest median return period of 1.84 years, equating to a 51.4% reduction from the present-day scenario, with values between 1.23 – 2.94 years (fig.8c). The Cha *et al.* (2020) trebled climate scenario saw another small increase in average return period to 2.04 years across the island – a reduction of 45.9% relative to the present-day simulation. Despite this, the shortest return period recorded at a single grid point decreased, with values between 1.11 – 3.57 years (fig.8d).

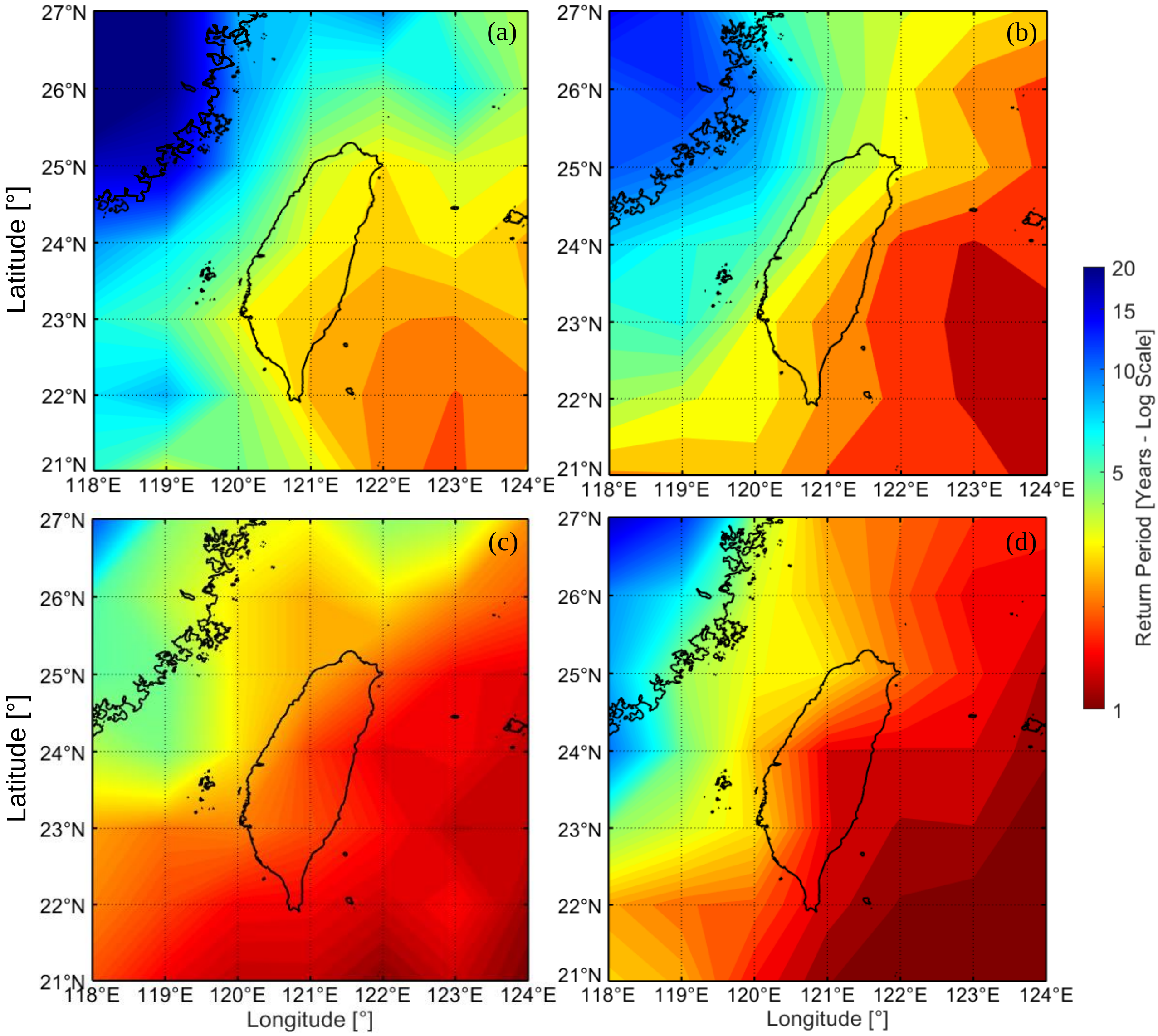

Figure 8: A visual representation of Intense (category 4+) typhoon return period over Taiwan for all simulations. Starting from top left with the present-day scenario (a), Cha et al. (b), Cha et al. doubled (c) and Cha et al. trebled (d). (Base maps created using Pawlowicz, 2020).

Cha *et al.* (2020) trebled displayed a wider range of values than Cha *et al.* (2020) doubled (fig.9). In all scenarios, the eastern fringes of Taiwan experienced the shorter return periods relative to the rest of the island. The longer intense return period in the Cha *et al.* (2020) trebled scenario is not consistent with expected results considering frequency and intensity parameters were increased from the previous simulation. Reduction in return period with respect to the present-day climate scenario values are given in table 3. The boxplot confirms that Cha *et al.* (2020) doubled and Cha *et al.* (2020) trebled produced similar results, but Cha *et al.* (2020) doubled recorded lower median values (fig.9).

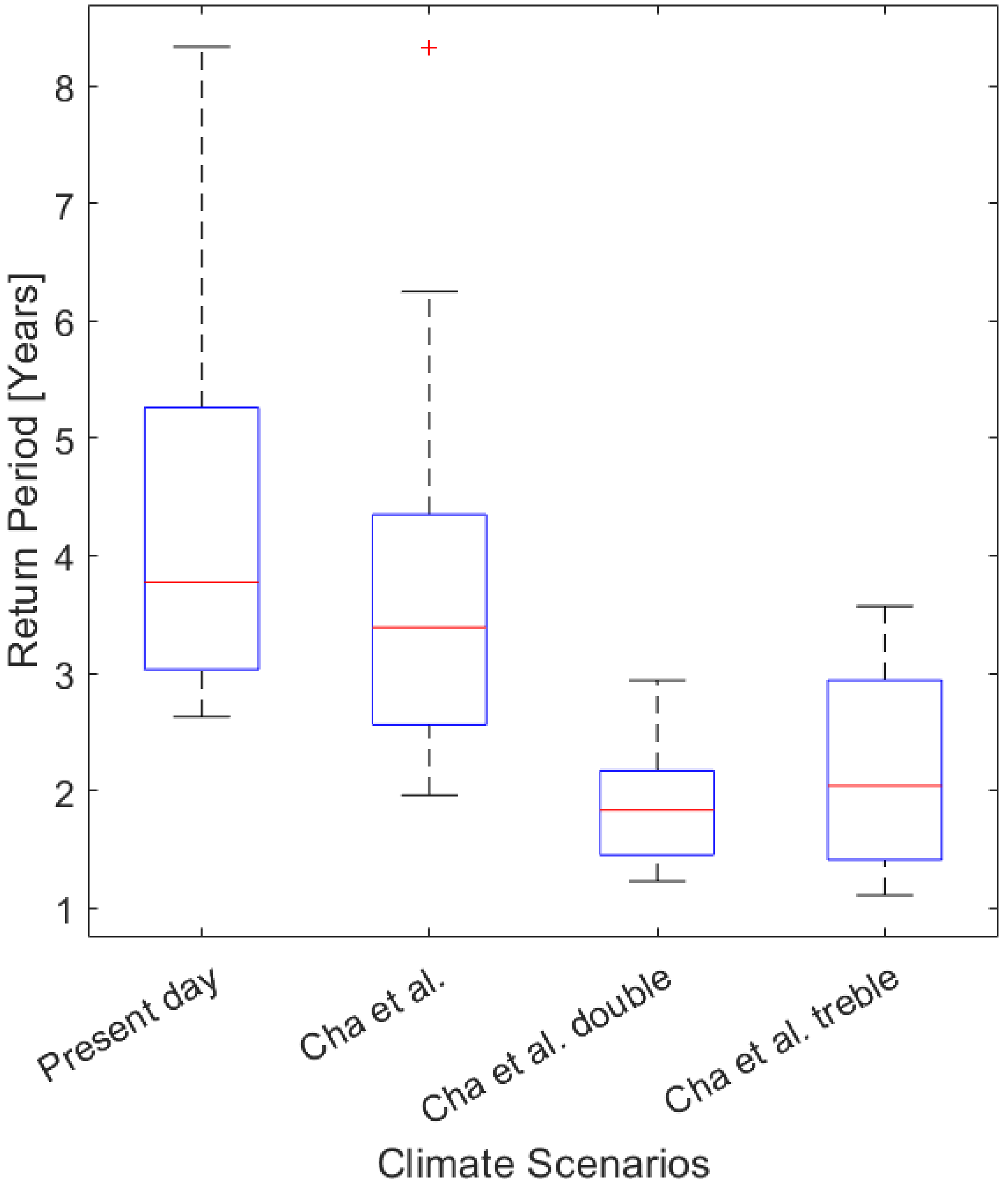

Figure 9: Boxplot illustrating the full range of return period values over Taiwan for each climate simulation. Note once again the lower median return period narrower interquartile range of the Cha *et al.* (2020) doubled scenario.

Table 3: Overall median intense return period of each simulation over Taiwan and their relative reduction with respect to the present-day value.

Scenario	Median Return Period (Years)	Reduction from Present Day (%)
Present Day	3.77	------
Cha *et al.* (2020)	3.39	-10.2
Cha *et al.* (2020) doubled	1.84	-51.4
Cha *et al.* (2020) trebled	2.04	-45.9

Return Period and Intensity Differences: Cha et al. (2020) doubled vs Cha et al. (2020) trebled.

It is beneficial to visualise spatial differences in return period and intensity between Cha *et al.* (2020) doubled and Cha *et al.* (2020) trebled. An intensity comparison of the two simulations shows Cha *et al.* (2020) trebled experienced higher intensities between +0.80 – +2.65ms across the island of Taiwan. However, there is a general decrease in mean intensity observed in the Pacific, the south China Sea and the East China Sea of -0.35ms^{-1} – -2.89ms^{-1}, -2.93ms^{-1} – -7.05ms^{-1} and -0.24ms^{-1} – -1.04ms^{-1} respectively. Intensity differences in the Taiwan Strait fluctuate between negative and positive values, ranging between -2.31ms^{-1} – +1.48ms^{-1} (fig.10a). It is evident that despite an increase in both intensity and frequency to simulate a warmer climate, shorter return periods are observed in Northern Taiwan, the south China Sea and the eastern Chinese coastline in the Cha *et al.* (2020) doubled scenario of -0.35 years, -0.27 – +1.07 years and -0.28 – -0.51 years respectively. There is a reduction in return period in the Cha *et al.* (2020) trebled scenario observed over central Taiwan and the Taiwan strait of +0.53 – +0.77 years and +0.22 years respectively, but most grid points experienced a lengthening of return period (fig.10a).

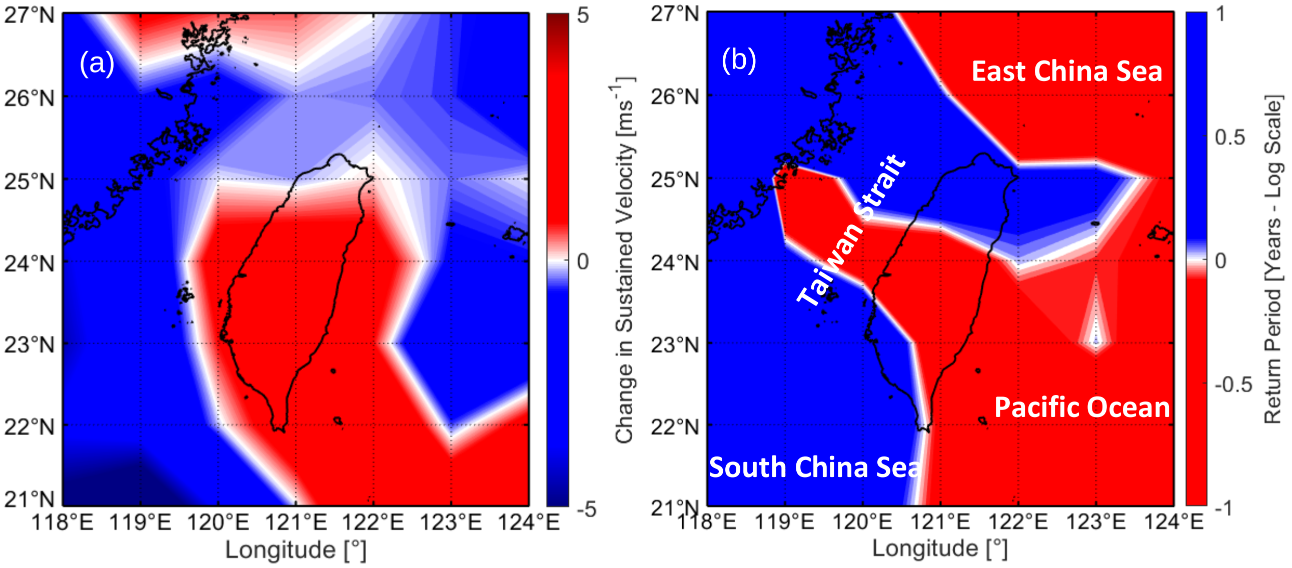

Figure 10: A comparison plot between the intensity (a) and intense return period (b) values found for the Cha et al. (2020) doubled and Cha et al. (2020) trebled scenarios. In the intensity plot (a), blue represents a higher intensity in the Cha et al. (2020) doubled scenario, while red denotes a higher intensity in the more extreme Cha et al. (2020) trebled scenario. In the annotated return period plot (b), blue represents a shorter return period in the Cha et al. doubled scenario, while red denotes a shorter return period in the more extreme Cha et al. (2020) trebled scenario (Base maps created using Pawlowicz, 2020).

Discussion

Results Interpretation

Figure 5 shows no vast differences in track evolution between the four simulations. This would imply no deviation in track path despite an increase in frequency and intensity in the later simulations, not aligning with current literature (Wang, 2011; He *et al.*, 2015). However, it is difficult to ascertain small changes due to the overlay of all tracks on the plot.

It must also be mentioned that while the overall track footprint in the basin has not changed a great deal between simulations, typhoon tracks have extended further east past the International Date Line in all Cha *et al.* (2020) simulations. This suggests a slower rate of decay for typhoons and an increase in their lifespan, particularly over open ocean waters, aligning with historical findings (Wang *et al.*, 2010). Typhoon tracks have not seen further progression further inland with warmer climate scenarios, going against recent suggestions (Li and Chakraborty, 2020). Tweaking model settings which affect typhoon decay over land could yield different results.

As expected, intensities are increased and return periods are shortened in all future climate scenarios in comparison to the present- day scenario, with southeast Taiwan worst affected. Given the climate change parameters that were introduced into the Cha et al. (2020) simulations, this was expected, and the results are consistent with current literature for intensity (Webster *et al.*, 2005; Tu & Chou, 2013; Bhatia *et al.*, 2018) and return period (Bacmeister*et al.*, 2018; Tan *et al.*, 2020). However, differences between the Cha et al. (2020) doubled and trebled scenarios in both variables are unexpectedly minor in comparison to the differences between the other simulations. A difference of 0.1ms^{-1} in the mean intensity and 0.2 years in the median return period is visible in both boxplots (fig.7 & 9) and tables 2 & 3. The boxplot also shows that while mean intensity has slightly increased from Cha *et al.* (2020) doubled to Cha *et al.* (2020) tripled, median intensity has decreased (fig.7). An analysis of spatial differences in intensity (fig.11) suggests that higher numbers of typhoons have propagated along the southern edge of Taiwan in the Cha *et al.* (2020) doubled scenario, indicating that in a climate future to the levels of Cha *et al.* (2020) trebled, typhoons have a higher propensity to make direct landfall, instead of propagating around the south as seen historically (Hsu *et al*., 2018; Hung 2020). Those propagating around Taiwan thereby retain their intensity through the continued ability to uptake moisture from the oceans. Due to the large radius of the average typhoon, those propagating around south Taiwan will still cause high winds and precipitation on the island.

This behaviour is also observed when analysing return period differences between the Cha *et al*. (2020) doubled and trebled scenarios. Shorter intense typhoon return periods are found along the Chinese Coastline to the west of Taiwan, with the exception of the Taiwan Strait in the Cha *et al*. (2020) doubled scenario (fig.10b). This behaviour can be explained once again by a higher propensity for typhoons to make direct landfall over Taiwan (fig.11). Poleward shifting typhoons has been observed previously, caused by a weakening WNPSH, and has altered expected storm surge levels in locations across the NWP (Oey & Chou, 2016; Liang *et al.*, 2017). In this case, Taiwan is directly blocking typhoon pathways. This could also explain the wider range in return period values for the Cha *et al*. (2020) trebled scenario observed in the boxplot. Chen *et al.* (2021) stated that South China will experience a higher frequency of typhoons in a warmer climate. While this is not easily observed in the Cha *et al*. (2020) or Cha *et al*. (2020) trebled scenarios, it is evident that typhoons will more frequently propagate south of Taiwan and strike the Chinese mainland in the Cha *et al.* (2020) doubled scenario, aligning with Chen *et al.*'s (2020) evaluation. The minor differences between the Cha *et al.* (2020) doubled and Cha *et al.* (2020) trebled for both intensity and return period could have been interpreted as a theoretical limit (Emanuel, 1988; Emanuel, 1995; Holland, 1997), but figure 11 shows evidence for higher rates of dissipation from more direct typhoon strikes on the island reducing mean intensities and causing longer return periods in the Taiwan Strait and over China.

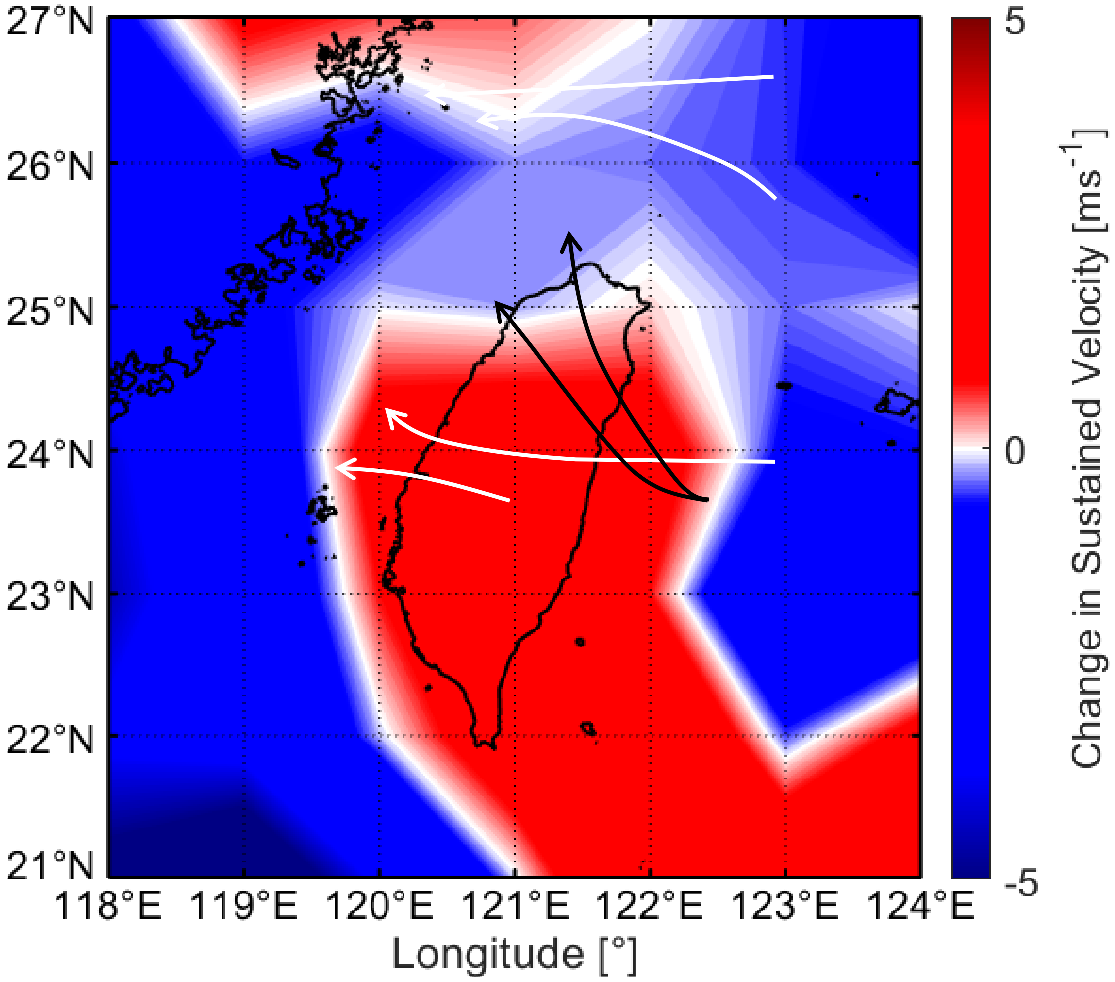

Figure 11: Intensity difference plot with arrows indicating inferred pathway by different simulations, with Cha et al. (2020) doubled in white and Cha et al. (2020) trebled in black. (Base maps created using Pawlowicz, 2020).

There is similarity across all scenarios, with highest intensities seen in the southeast corner and lowest intensities in the northwest corner. This confirms that Taiwan will continue to provide additional blocking and dissipate typhoon energy. As the scenarios progress into more extreme climes, dissipation of typhoon intensity is still observed, but overall intensity levels remain high post landfall. An investigation into the dataset shows that typhoon decay occurs at similar rates for each simulation (19.5% – 25.0%) which is inconsistent with Brand's findings of a 41% rate of decay (1974). As intensities are very high prior to landfall, the mountain ranges struggle to dissipate typhoon energy to a point where their destructiveness is manageable given the positive correlation between typhoon intensity and rate of decay (Zhu, 2021). The location of Taiwan also favours typhoon conditions which can conversely induce a slower rate of decay (Kaplan & DeMaria, 2000).

The overarching results are one of alignment with the current predictions. The simulations of every future climate scenario suggests that unless anthropogenic emissions can be curbed to regulate global temperature, typhoons around Taiwan will get stronger and the likelihood of typhoons of category 4 intensity occurring will increase, and this looks to worsen in climates more extreme than current projections post 2100 (Lyon *et al.*, 2021). An apparent change in the typhoon track between Cha *et al.* (2020) doubled and Cha *et al.* (2020) trebled also warrants further investigation. Regardless, each future scenario holds worrying consequences for Taiwan, a country already experiencing several typhoons each year.

Implications

Progression into any of the future climate scenarios would have profound implications for Taiwan and its citizens. The largest danger from rising intensities will be the effect on storm surge levels. Although storm surge height depends on several factors, it is linked closely to typhoon intensity (Li *et al.*, 2019; Camelo, 2020; Wang *et al.*, 2022) Increases in storm surge height will not only be exacerbated by typhoon intensity, but in combination with sea level rise (SLR), where the rate of SLR is double that of the global average. The frequency of flooding events from SLR alone is predicted to double by 2050 (Vitousek et al. 2017) and urban areas are most at risk from flooding events (Lin *et al.*, 2022). Both impacts working in tandem will exacerbate the effects, overtopping coastal defences, eroding beaches and inundating settlements. The findings from this study underline the importance of understanding the response of the Taiwan coastline from additional inundation due to larger storm surges and higher intensities. Research is underway in this topic (Mori & Takemi, 2016; Almar *et al.*, 2017), but studies specifically in Taiwan would be advantageous.

While storm surges are the principal cause of loss during a typhoon event, Taiwan’s topography makes flooding from fluvial sources and landslides equally as dangerous (Chang, 2014). Typhoon Morakot in 2013, one of Taiwan’s deadliest typhoons in recent history, decimated a village through mudflows and flooding (Tsou, 2011; Wu, 2014). More frequent storms of a higher intensity will heighten overall levels of precipitation causing more flooding and landslide events that could exceed typhoon Morakot, marking danger even for those not residing by a coastline. This will be a pressing concern if the typhoon behaviour progressed to the levels of Cha *et al.* (2020) trebled, where high intensities and shorter return periods were observed over the middle of the island. Combined with higher surface runoff from increasing urbanisation, Taipei – Taiwan’s capital and largest population centre is at high risk of persistent fluvial flooding (Hsu *et al.*, 2015, pp. 97-112)

Indirect impacts will be also felt by Taiwanese citizens if intense typhoons are more frequent and intensity levels increase. Higher levels of crime and unemployment are predicted after typhoons in a warmer climate (Pao, 2014; Yu *et al.*, 2017; Yu, 2019) and there’s evidence for typhoons causing an increase in mortality by up to 33.4% in the subsequent months following a typhoon (Parks *et al.,* 2022).

Typhoons with high destructive potentials can disrupt fragile ecosystems. Coral reefs around Taiwan are of economic importance to the country, estimated to be worth up to $520m per year in South Taiwan (Maynard, 2017). Unfortunately, most coral reefs around Taiwan are located on the east coast, in direct line with a typical Taiwan landfalling typhoon. Coral Reefs require stable environments to survive, but powerful typhoons occurring on a more frequent basis will create persistent unfavourable conditions, making coral reef growth untenable even without taking other climatic factors into account (Kashavmurthy *et al.*, 2019).

Although research into spatial variation of intense typhoon return period and intensity with climate change is understudied, the threat of climate change to Taiwan and its effects on typhoons is well documented. There have been investigations into the creation of coastal buffer zones around Taiwan to prevent overdevelopment and reduce typhoon impacts (Lan & Hsu, 2021). This research can be used to provide spatial context to future typhoon risk, allowing policy makers to understand where to focus coastline management efforts.

Model Improvements

TCWiSE serves a gap in the typhoon climatology toolbox. Simulation runs all took place on a simple desktop computer with a fraction of the processing power of supercomputers traditionally used in weather forecasting or climate projections. As TCWiSE is a new tool (Nederhoff *et al.*, 2020) the development curve is still sharp and improvements can be made with the intention of creating simulations with a higher degree of accuracy.

As mentioned in the methodology, all typhoons are allocated a month in which a track is simulated. Given that typhoon frequency and intensity is highly dependent on sea surface temperature (Emanuel, 1987), allocating a month provides a realistic simulation of the full typhoon season. To simulate the monthly fluctuations in sea surface temperature, TCWiSE uses monthly averaged sea surface temperature data from the data library of International Research Institute of Columbia University (2017) developed by Reynolds and Smith (1998) at a grid resolution of 1° x 1°. This determines the extent of ocean water at an ideal temperature for typhoon genesis. This monthly averaged data is based on recordings from 1971-2000. However, in view of the close connection between rising sea surface temperature and climate change reported in numerous studies (Khalil, 2015; Sakalli and Başusta, 2018; Seager *et al.,* 2019; Ruela *et al.,* 2020) TCWiSE would benefit from allowing the user to incorporate a theoretical increase in sea surface temperature into its model. This would in turn affect the genesis and termination locations of typhoons, providing a more accurate outlook of what the typhoon season may resemble in the future. This inclusion would improve the models' interpretation of typhoon track evolution and the annual frequency distribution of typhoons, as there is evidence pointing towards the duration of the typhoon season increasing as a result of climate change (Kossin, 2008; Dwyer *et al*., 2015).

Translation speed is also another variable that is predicted to change in a warmer climate (Wu, 2005; Kossin, 2018; Hall & Kossin, 2019; Knutson et al 2020). This could be an additional climate change in the same way frequency and intensity can be altered. This addition could allow users to combine data from TCWiSE simulations with precipitation models to ascertain changes in rainfall. While TCWiSE cannot replace complex climate models, its ease of use and possible combinations with other tools such as Delft3D to calculate storm surge risk (Leijnse et al., 2021b), TCWiSE is a great tool to use for policy makers to ascertain and advise on the spatially varying risk from typhoons in any location.

Conclusion

With every future climate scenario, intense typhoon return period and intensity is predicted to become more unfavourable for Taiwan, potentially triggering many side effects both direct and indirect, incurring heavy socioeconomic losses. The changes will affect the whole island, but the southeast in particular will see the highest increases and bear the brunt of more extreme and frequent intense typhoons. While the extent of loss increase was not quantified, previous literature findings assumes that future losses will be much more than previously observed.

Future typhoon behaviour around Taiwan does not appear to increase linearly with more extreme climate scenarios. Despite the typhoon intensity and frequency differences between Cha *et al.* (2020) doubled and Cha *et al.* (2020) trebled, it's unclear which simulation had the more extreme climate change parameters imposed on it. From the data analysis, it appears that the Cha *et al.* (2020) trebled scenario observed more typhoons directly hitting from the southeast, which aligns with the prior expectation, but the Cha *et al.* (2020) doubled scenario witnessed more tracks deviating around the South of Taiwan and shorter return periods for intense typhoons in the north in Taipei and southwest in Kaohsiung/Tainan – both regions with high population densities.

Understanding these spatial changes in future climates are good indicators of typhoon behaviour that can drive policy making decisions not just in the upcoming years, but for future generations in the long-term. TCWiSE provides great context for future scenarios. However, Taiwan's unique geography and location means rainfall intensity and translation speed must be considered when attempting to fully assess future impacts.

Further research and recommendations

The simulations in this study are easily replicable not only in the NWP, but for all areas globally where typhoons occur. One further step would be to see if these results are relevant only to Taiwan, or if the values found are different. This would indicate that climate change will have varying impacts dependent on location.

The difficulty of deriving meaningful data concerning typhoon tracks around Taiwan can also be solved. A deeper investigation into the data and isolating the typhoons that entered a bounding box surrounding Taiwan would be useful to establish if there are any trends in typhoon track with an increase in the climate change parameters. Another recommendation would be to combine TCWiSE simulations with storm surge models to accurately predict coastline risk from storm surge. This has already been done in the Bay of Bengal with good results (Leijnse *et al.*, 2021b).

Impacts from typhoons are projected to escalate, but the changes are not restricted solely to intensity and return period. Other factors such as precipitation levels and translation speed are also evolving. Mean translation speed for the entire NWP basin was calculated, but the differences were negligible, ranging from 6.76-6.93ms and was therefore not considered further in this study. However, typhoon translation speed specifically over Taiwan can be analysed from the datasets in a further step to obtain a better picture of future typhoon activity in each simulation as translation speed can affect forecasts for storm surge levels (Rego & Li, 2009).

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