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Projections of Typhoon Wind Speeds for Estimating the Future Typhoon Wind Hazard Due to Climate Change in the Asia Pacific Basin

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PROJECTIONS OF TYPHOON WIND SPEEDS FOR ESTIMATING THE FUTURE TYPHOON WIND HAZARD DUE TO CLIMATE CHANGE IN THE ASIA PACIFIC BASIN

A Dissertation
Presented to
the Graduate School of
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Doctor of Philosophy
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by
Sri Harshitha Polamuri
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Accepted by:
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ABSTRACT

Typhoons are among the most common and dangerous natural hazards that affect the coastal regions and islands in Asia. The typhoon activity is expected to increase in the future due to climate change. In this study, a stochastic typhoon simulation framework has been developed to simulate the typhoon tracks. An improved typhoon track simulation model is implemented which can be used to generate long-term typhoon database for Asia consisting of typhoon tracks with parameters including latitude, longitude, translational speed, heading direction, central pressure, radius of maximum winds and Holland B parameter simulated at 6h time interval. A new regression equation is introduced for modeling the radius of maximum winds (RMW) and Holland B parameter. Central pressure decay model is developed individually for mainland Asia, Japan, Philippines and Taiwan. The simulation model is used to generate long-term typhoon track database for Asia. The track database is validated by comparing the statistics of various typhoon parameters of the simulation model with past typhoon historical records. Typhoon database generated using the simulation model is validated with historical typhoon records by comparing the key parameters of simulated storms with historical observations at selected locations in the coast of China, Japan, Philippines, Taiwan and Korea. Good agreement is observed between simulated and historical tracks. The track database is used to produce a long-term typhoon wind-hazard database which can be used to generate wind hazard curves. The wind speeds calculated are validated using historical wind speed data provided by wind stations from various sources. The wind database is developed for coastal regions of Japan, China, Vietnam, Philippines and Taiwan and the database can be used for estimating the
wind speeds at several return periods, allocating wind loads in design of structures and also assessing the insurance loss to prepare the funds required to mitigate the typhoon wind damage in coastal areas.

Impact of global warming on typhoon activity is analyzed in this study. Sea surface temperature is one of the major factors in intensifying the storms. Sea surface temperature projections under multiple climate change scenarios based on global climate models (GCM) in The United Nations Inter Governmental Panel (IPCC) 5th assessment report are considered in this study. The sea surface temperature projection by three Representative Concentrated Pathways (RCP) of greenhouse gas emissions by the end of this century are incorporated in the typhoon simulation model. Scientific observations show latitude band of tropical cyclones is likely to shift poleward due to global warming. Sea surface temperature and poleward shift of storm genesis are two scenarios of climate change analyzed in this study. Twelve different climate change scenarios which consider the effect of poleward shift and RCPs are analyzed to understand the impact of these scenarios on typhoon activity in Asia. Typhoon databases are generated using the twelve climate change scenarios in 2100 and compared with the typhoon activity under current climate. Changes in annual approach rates of typhoons under multiple climate change scenarios are calculated. Wind speeds are calculated using each climate change scenario for multiple locations in the coast of Asia. Changes in the wind speeds for different return periods are analyzed for each climate change scenario by comparing with windspeeds of current climate condition.
To investigate the influence of environmental variables on genesis activity, a genesis index regression equation is considered with sea surface temperature, relative humidity, wind shear and absolute vorticity as variables. Coefficients are fitted for environmental variables to estimate storm genesis rate. Environmental variables from RCP2.6, RCP4.5 and RCP8.5 in year 2100 are substituted in the genesis index equation to estimate the change in storm frequency under three RCP scenarios. Track databases are generated using the genesis index and sea surface temperatures of three RCP scenarios. Wind speeds are calculated for selected locations in the coast of Asia to estimate the impact of climate change in occurrence rate and wind hazard in these locations.
DEDICATION

I dedicate this study to my mother, Ms. Durga Anuradha Darapureddi whose unconditional love gives me strength and make me push my boundaries.

Also, I dedicate this work to Mr. Sahith Gali who keeps me positive and gives me relentless support.

I also dedicate this work to my three best friends Ms. Naga Prathyusha Ambatipudi, Ms. Rashmi Kola and Mr. Naveen Kumar Ganji who calms me down and gives me strength.
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1. INTRODUCTION

Natural catastrophes cause the highest damage to humankind which include tropical cyclones, earthquakes, floods, draught, extreme temperatures, forest fires etc which leads to tremendous human and economic losses. Between 1980-2016, 16500 natural catastrophic events are estimated to have occurred worldwide out of which 38% of catastrophes occurred in Asia. All these catastrophes had caused nearly $4200 billion overall losses and $1100 billion insured losses worldwide (Munich Re, 2017). Among these, 41% of overall losses and 70% of insured losses are contributed by tropical cyclones. Table 1 shows the statistics of natural catastrophes occurred globally in 2017(from Swiss Re, sigma, 2018). From the table 1, clearly tropical cyclones are the most disastrous events which causes the highest insured losses globally. Nearly 35% of world’s population is expected to be living in the path of cyclones and this population is expected to increase in coming years.

The term tropical cyclone generally describes the organized system of clouds rotating over tropical or sub-tropical waters. Tropical cyclone occurs when the temperature of sea surface rises above 27°C and persist to a depth of 50m below the surface. The warm ocean water heats up the air present on the ocean surface which rises creating low air pressure below. As the surrounding air occupies this low-pressure area, more air gets heated up and rises too. As the air keeps rising up, the air temperature gets cool down. As more quantity of air rise up and cool down, the moisture in the air start forming clouds.
These clouds start growing in size and swirling which can lead to dangerous increase in speed. This Cyclones works as giant engines with the warm moist air as fuel which is fed by ocean’s heat. After making landfall, no moisture supply is done by the ocean and hence the storm eventually dissipates. The effects of tropical cyclone include extreme winds, which may cause loss of life, heavy damage of buildings and infrastructure, crops and vegetation. The terminology of tropical cyclones varies depending on its formation location and intensity. The tropical cyclone with a maximum sustained wind speed of greater than 74 mph has unique name in different regions. It is classified as “hurricane” if it is originated in Atlantic and North Pacific. It is called “typhoon” if it is in South Pacific, and “cyclone” if it is spawned in Indian Ocean. A tropical storm is classified as “tropical depression” if the peak wind speeds are between 39-73 mph, “tropical storm” when the wind speeds are less than 38 mph. These storms are categorized based on intensity and strength of wind speeds which can go more than 195mph. Saffir Simpson scale is used in United states which categorizes the hurricanes in the scale of 1-5 depending on the wind speed. Similarly, RSMC of Tokyo Japan divides the storm category from tropical depression to violent typhoon. Northwest pacific basin has the highest frequency of storms every year compared to other basins. This is because the regular rise of sea surface temperature exceeding 30°C which provides suitable conditions to spawn intense storms. Northwest pacific basin generates an average of 29 storms per year of which 20 storms reach typhoon category. This count is very high compared to Atlantic basin where only 10-
11 storms are spawned per year of which only six storms reach hurricane status. Table 2 shows the average number of tropical cyclones spawn every year in each basin.

The impacts of a typhoon when it hits the coast can be divided into three types. Firstly, their extreme winds which can destroy trees, buildings, bridges, crops etc. The heavy winds damage the properties and throws away loose debris. Secondly, the storm surges which are raising walls of sea water that can sweep through kilometers of area inland after making landfall. Third, typhoons cause heavy rainfall which results in flooding and landslides.

Typhoons generated in Northwest Pacific basin majorly hit China, Philippines, Hong Kong, Taiwan, Japan and South Korea. Due to its location and extent of coastline more than 14,000km, China is the country that experiences the most typhoons compared to its neighbors. Provinces of China which experiences more typhoons are Guangdong, Fujian, and Zhejiang. Philippines due to its location experiences an average of six tropical cyclones every year and four storms passing close by it. A super typhoon occurs on average of once in ten years. Most of these storms occurs in eastern coast which is relatively less populated. Heavy precipitation is a very common when storms hits Philippines which makes flood the more common risk than extreme winds. Taiwan experience an average of two storms every year and three other storms passing close by it. Most of the storms hit the eastern coast of Taiwan, which is relatively unpopulated. Mountain ranges present in the east coast of Taiwan restrict the extreme winds and thus weakening the storms. Hence like Philippines, Taiwan also experiences more loss from flooding than winds. Hong Kong
experience a landfall once in two to three years. Hong Kong is sheltered by the mountain ranges in its coast which obstructs the losses from winds. Hong Kong has a sophisticated defense system to prevent flooding and hence the losses due to floods are quite low. Japan experiences an average of four storms every year. Due to its location, topography and orientation, Japan has high risk of typhoon damage in terms of both winds and precipitation. South Korea is relatively sheltered from typhoons compared to other countries in the basin, but it still experiences average of one landfall every year.

Hurricanes and typhoons recorded highest economic and insurance losses among all the disasters in the world. For example, Typhoon Haiyan struck Philippines in 2013 and was the strongest Typhoon ever recorded in modern history. Haiyan has devastated 80% of area in its path destroying homes of four million people. In 2013, Asian Development Bank estimated the losses from typhoons and earthquakes in Philippines to be approximately $1.6 billion every year. Table 3 shows top five costliest tropical storms in Asia from 1980-2014(Munich Re). Therefore, it is important to take measures to reduce the risk of severe losses caused by typhoons. Extreme typhoon winds are considered crucial in designing defense measures for typhoon prone regions. For this, a database for typhoons is necessary to assess the wind hazard in coastal regions of Asia. A typhoon database with wind speed data helps estimating the return periods of damage causing wind speeds.

Historical records are available for typhoons which affected coastal regions of Asia, but these records are confined to a very short period. For example, data sources like China Meteorological Administration (CMA) where the typhoon data is available in from 1949 to 2016, Japan Meteorological Agency (JMA) in which typhoon data is available from
1951 to 2017, International Best Track Archive for Climate Stewardship (IBTrACS) where the typhoon track data is available from 1849 to 2015. These historical records available for the past typhoon events are not sufficient for risk assessment of typhoons. This is due to the availability of data restricted to a limited period and size of the data is small in terms of the areas affected by the typhoons each year. Using this data, it is difficult to derive the key parameters of severe typhoons that affect the coast, on basis of which building codes, marine structures, loss mitigation methods need to be designed. This problem can be solved by enlarging the typhoon records for a longer period of time using numerical methods. By this, a long-term database of typhoons is produced which has typhoon tracks and their key parameters estimated for hundreds and even thousands of years. This artificially simulated catalog can be used for a more accurate quantification of the typhoon risk. Developing a long-term catalog of simulated typhoon tracks helps estimating the annual landfall rates of storms in several regions of Asia. It helps in estimating the return periods of storms with damage causing severities. The database can be used to assign design wind loads in coastal regions of Asia. Also, estimation of insurance losses caused by typhoon winds can be made.

Table 1. Statistics of global catastrophes in 2017 (Swiss Re, sigma, 2018)

<table>
<thead>
<tr>
<th>Event</th>
<th>Number of Incidents</th>
<th>Human loss</th>
<th>Insured losses ($ millions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storms</td>
<td>82</td>
<td>1,642</td>
<td>$111,475</td>
</tr>
<tr>
<td>Drought, bush fires, heat waves</td>
<td>14</td>
<td>435</td>
<td>$14,237</td>
</tr>
<tr>
<td>Hail</td>
<td>8</td>
<td>0</td>
<td>$7,549</td>
</tr>
<tr>
<td>Floods</td>
<td>55</td>
<td>3,515</td>
<td>$2,144</td>
</tr>
<tr>
<td>Earthquakes</td>
<td>12</td>
<td>1,184</td>
<td>1,615</td>
</tr>
<tr>
<td>Cold, Frost</td>
<td>5</td>
<td>153</td>
<td>1,038</td>
</tr>
<tr>
<td>Other natural catastrophes</td>
<td>7</td>
<td>1,541</td>
<td>0</td>
</tr>
<tr>
<td>Total natural catastrophes</td>
<td>183</td>
<td>8,470</td>
<td>$138,057</td>
</tr>
<tr>
<td>Man-made disasters</td>
<td>118</td>
<td>2,934</td>
<td>$6,246</td>
</tr>
</tbody>
</table>
Climate Change

Climate change is a term used to refer the long-term change in climate system of earth. Human activities such as depletion the forest cover and excess chemical release into atmosphere are some of the crucial factors for the climate change. The effects of climate change include global warming which is defined as increase in surface temperature of earth due to rising greenhouse gas (GHG) emissions. Global warming is undoubtedly a serious problem for our planet at present and in the coming future.
The Intergovernmental Panel on Climate Change (IPCC) prepares a comprehensive assessment report on climate change risk, its effects and ways to mitigate the rate at which climate change is happening. The fifth IPCC assessment report (AR5) issued in 2013 says that the global average combined land and sea surface temperature has raised from 0.65°C to 1.06°C, over the period of 27 years since 1985. IPCC report says ocean warming account for more than 90% of heat stored in the climate system over the period 1971 to 2010. The increase in ocean temperature globally is higher near the surface. The temperature of top 75m of ocean water has increased from 0.09 to 0.13 °C per decade from 1971 to 2012. Ocean warming is going to continue during 21st century. Projection of ocean warming is stronger in tropical regions, and sub-tropical regions of Northern Hemisphere (IPCC 2013). Climate change and global warming is going to impact the hurricane and tropical cyclone activity globally. IPCC recently approved The Special Report on the Ocean and Cryosphere in a Changing Climate in September 2019(SROCC 2019). The report says the annual global proportion of Category 4 and Category 5 tropical cyclones has increased in recent decades.
The projections of GHG emissions in 21st century are classified in four different Representative Concentrated Pathways (RCPs) which are used for assessment of climate change impacts. Each RCP scenario represent the possible amount of emissions throughout the 21st century. RCP2.6 represent the trajectory of lowest GHG emissions that aims to constrain the global warming below 2°C above preindustrial levels. RCP4.5 and RCP6.0 are intermediate pathways and RCP8.5 represent trajectory of highest GHG emissions.
Figure 2. Radiative Forcing of multile Representative Concentration Pathways (Van Vuuren et al (2011))

Under best case scenario of greenhouse emissions, i.e, RCP2.6, the projected increase in average global surface temperature by 2100 is approximately about 1.6°C since the preindustrial period. In the worst case RCP8.5 scenario it is about 4.3°C by 2100. Table 4 shows the estimates of total increase in average surface temperatures since preindustrial period under four RCP scenarios (in SROCC 2019). Raising ocean temperatures may lead to increase in maximum wind speeds of tropical cyclone which increase the severity of the hazard. On a global scale, the average tropical cyclone intensity and the proportion of Category 4 and 5 cyclones are expected to increase for a 2°C increase in temperature. RCP8.5 projected greater increase in average cyclone intensity than RCP2.6(SROCC 2019).
Table 4. Projections of global average SST change relative to 1850-1900 for the period 2080-2100 under the RCP scenarios. (SROCC 2019)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>By 2080-2100</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean(°C)</td>
</tr>
<tr>
<td>RCP2.6</td>
<td>1.6</td>
</tr>
<tr>
<td>RCP4.5</td>
<td>2.5</td>
</tr>
<tr>
<td>RCP6.0</td>
<td>2.9</td>
</tr>
<tr>
<td>RCP8.5</td>
<td>4.3</td>
</tr>
</tbody>
</table>

Objectives and Scope of Research

The objective of the present study is to produce a typhoon wind database which can be used to generate wind hazard curves. The results from this research can be used for estimating the wind speeds at several return periods, allocating wind loads in design of structures in the aspect of engineering and also assessment of insurance loss to prepare the funds required to mitigate the typhoon wind damage in coastal areas. This study includes assessment of change in typhoon activity in the basin due to climate change. For this purpose, the present research is divided into three parts.

(1) Development of typhoon track simulation model

Typhoon simulation model is developed using historical typhoon data available for Asia. The simulation model is used to generate typhoon track database for 10000 years consisting typhoons with path and intensity parameters. To check the accuracy of the simulation model, the generated database is compared with past typhoon records by comparing the statistics of simulated typhoons with historical typhoons.
(2) Production of typhoon wind database

Using the simulated typhoon track database, wind hazard is estimated in coastal regions of mainland and islands in Asia. Long term typhoon wind database is generated for coastal regions of China, Hong Kong, Vietnam, South Korea, Japan, Philippines and Taiwan. Wind speeds are calculated for approximately four hundred thousand locations in Asia which can be used to generate hazard curves for desired return periods.

(3). Effect of climate change

The typhoon simulation model is coupled with different climate change scenarios to assess the impact of climate change on typhoon activity in the basin which include analyzing the changes in the average number of storms hitting the coastal regions of Asia, changes in typhoon intensities and wind speeds for selected key locations of the basin.
2. LITERATURE REVIEW

2.1. Data Sources

Japan Meteorological Agency (JMA) has typhoon track data with positions, central pressures, maximum 10-minute average sustained wind speeds, radius at 50kt and 30kt wind speeds provided for at 6-hr time interval. JMA typhoon track and central pressure data is available from 1951 whereas the wind data starts from 1977. The wind data in JMA is estimated using Dvorak Analysis which provides mean values of wind speeds corresponding the CI numbers. China Meteorological Administration (CMA) data not only provides the track and wind data, but also the cyclone-induced precipitation data. The track data in CMA is available since 1949. The data provided by CMA include positions, maximum sustained wind speeds with 2-min averaging period, minimum sea level pressures, subcenters, outrage cases over South China Sea and severe winds of landfalling cyclones. Joint Typhoon Warning Center (JTWC) provides best track data with locations, central pressure, 1-minute average sustained wind speeds at 6-hour interval. JTWC provided track data for western pacific region since 1945.

National Climatic Data Center (NCDC) by NOAA has provided a global tropical cyclone dataset called International Best Track Archive for Climate Stewardship (IBTrACS) which provides the tropical cyclone data gathered and merged from various agencies. IBTrACS data used complex merging techniques to fill the gaps between available records of historical cyclone. For Western Pacific region, IBTrACS data merged the data from Japan Meteorological Agency (JMA), Hong Kong Observatory (HKO), Joint
Typhoon Warning Center (JTWC), Shanghai typhoon Institute (STI). IBTrACS data provides locations and intensities of each storm by averaging the locations and intensities obtained from all the available data centers.

Modeling the relative intensity of typhoons require the sea surface temperature at every position of the storm eye. For this, sea surface temperature (SST) data provided by Hadely Centre Sea Ice and Sea Surface Temperature data (HadISST) is used in which monthly average sea surface temperatures are provided at 1°×1° grid resolution. HadISST takes data from Met Office Hadley Centre which provides the global sea ice and SST data since 1870.

Surface roughness length is another parameter required when calculating the wind speeds at surface level. The surface roughness length in any location depends on the type of land cover type of the location. Global Mosaics of the standard MODIS land cover type dataset provides the global land cover data organized uniformly across latitudes and longitudes. The land cover data is classified based on IGBP land cover type classification. The code values for each land cover type are shown in Table 5.

<table>
<thead>
<tr>
<th>Code Value</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Water</td>
</tr>
<tr>
<td>1</td>
<td>Evergreen Needleleaf forest</td>
</tr>
<tr>
<td>2</td>
<td>Evergreen Broadleaf forest</td>
</tr>
<tr>
<td>3</td>
<td>Deciduous Needleleaf forest</td>
</tr>
<tr>
<td>4</td>
<td>Deciduous Broadleaf forest</td>
</tr>
<tr>
<td>5</td>
<td>Mixed forest</td>
</tr>
<tr>
<td>6</td>
<td>Closed shrublands</td>
</tr>
<tr>
<td>7</td>
<td>Open shrublands</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>8</td>
<td>Woody savannas</td>
</tr>
<tr>
<td>9</td>
<td>Savannas</td>
</tr>
<tr>
<td>10</td>
<td>Grasslands</td>
</tr>
<tr>
<td>11</td>
<td>Permanent wetlands</td>
</tr>
<tr>
<td>12</td>
<td>Croplands</td>
</tr>
<tr>
<td>13</td>
<td>Urban and built-up</td>
</tr>
<tr>
<td>14</td>
<td>Cropland/Natural vegetation mosaic</td>
</tr>
<tr>
<td>15</td>
<td>Snow and Ice</td>
</tr>
<tr>
<td>16</td>
<td>Barren or sparsely vegetated</td>
</tr>
<tr>
<td>254</td>
<td>Unclassified</td>
</tr>
<tr>
<td>255</td>
<td>Fill value</td>
</tr>
</tbody>
</table>

Observations of wind speeds are needed for comparing them with modeled wind speeds. Global Surface Summary of the Day (GSOD). Global Surface Summary of the Day (GSOD) by NOAA is another source that provides daily summary data of wind speed, wind gust, pressure, temperature, snow depth and precipitation. GSOD data is available for approximately 9000 stations located globally providing the data from 1929 to present.

Environmental parameters like sea surface temperature, relative humidity, wind shear and vorticity are required for modeling the genesis index in climate change study. The historical data of SST is obtained from Modern-Era Retrospective analysis for Research and Applications (MERRA) by National Aeronautics and Space Administration(NASA). Historical relative humidity, wind shear and vorticity are obtained from National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) of The National Oceanic and Atmospheric Administration (NOAA). Future projections of SST, relative humidity and wind shear are taken from the Climate Model 3 (CM3) data from Geophysical Fluid Dynamics Laboratory (GFDL) of NOAA.
2.2. Typhoon Track and Intensity Model

Hurricane simulation technique developed by Vickery et al. (2000) is widely used methodology that simulates the hurricane tracks in Atlantic Basin. The model introduced by Vickery simulates full hurricane tracks with path and intensity parameters. Later, the model was updated by Vickery et al. (2009) by including the hurricane data updated in 10 years. The updated model has formed basis for ASCE7 hurricane wind speeds between 1998-2010.

The simulation model begins with genesis of the storm followed by modeling the track parameters like heading speeds, heading directions and the central pressure until the dissipation. The relative intensity incorporated in hurricane model by Vickery et al. (2000) is obtained from the model developed by Darling (1991). The relative intensity parameter is coupled with sea surface temperature to model central pressure. For validating the simulated tracks, site specific statistics of the simulated hurricane key parameters are compared with statistics of historical data. This model was later updated by Vickery et al. (2009) by including the significant increase in the historical hurricane data available. Vickery et al. (2009) updated hurricane simulation model by adding wind shear term and a simple 1D ocean-mixing model.

Li and Hong (2014) simplified track model of Vickery et al (2000) for U.S hurricanes. The track model is simplified by reducing the number of explanatory variables using Geographically weighted regression (GWR) approach suggested by Fotheringham et al (1997a; 1997b) which uses data from neighboring locations to perform regression
analysis. Thus, the location variables can be removed from existing track model. Li and Hong (2014) also presented the effect of using the product of hurricane translational speed and gradient of wind velocity relative to center in hurricane wind field modeling. Li and Hong suggested using the product of hurricane translational speed and gradient of wind velocity relative to center in hurricane wind field modeling to avoid the under estimation of wind speeds. Li and Hong (2016) used the simplified track model for simulating tracks in Western Pacific basin. Simulated track database is validated with historical data by comparing statistics of annual rates, translational speeds, heading angles, heading direction, central pressures along the coastline. Simulated tracks are coupled with wind field model to generate typhoon wind hazard maps. Li and Hong (2016) estimated annual maximum typhoon wind speed using typhoon wind hazard model which includes typhoon track and wind field models. Return periods of maximum annual typhoon wind speeds are estimated for China using circular sub-region method and best track dataset from China Meteorological Administration (CMA). Li and Hong study showed that the mean of the heading decrease from east to south west but the standard deviations of heading is relatively consistent from east to south west. The storms landfalling in north eastern China moves faster and the translational speed increases as the storm move away from the coast. The estimated wind speeds from Li and Hong are used for developing typhoon wind hazard maps for China. In this study, GWR will be applied for modeling typhoon track and relative intensity models to obtain geographically dependent model parameters. The track model is based on Vickery el al.,(2009) and intensity model is modeled by change in central pressure and sea surface temperature.
2.3. Typhoon Decay Model

To model the decay of hurricanes after making landfall, Kaplan and DeMaria (1995) developed an empirical model called Inland Wind Decay Model (IWDM). IWDM is a two-parameter model that estimated decay of wind speed is an exponential function of time after landfall. This model predicts the maximum inland distance travelled by storm winds using storm speed and intensity at landfall. Similar to this model, Kaplan and DeMaria (2000) developed a wind speed decay model after landfall for storms which make landfall in New York and Rhode Island and move across New England region. In this model, due to the faster moving storms in the upper latitudes, wind speeds are estimated at every 2 hours instead of 6 hours. Kaplan and DeMaria model has shown that modeled wind speeds in northern latitudes decays faster than those in southern latitude due to higher terrain in northern coast. Maximum inland penetration maps and hurricane induced storm surge maps are developed using the Kaplan and DeMaria models for entire coastline of US. The maps are used in the HURREVAC program developed by FEMA which is used by emergency management community. Kaplan and DeMaria study showed that the storms which made landfall in northern US can also produce substantial damage and loss due to storm surge and precipitation. Kaplan and DeMaria (2005) presented a decay model for storms moving over narrow landmasses in which the decay rate is proportional to the intensity of storm multiplies with fraction of storm over the land mass. Bhowmik et al. (2004) developed an empirical model for wind speed decay of tropical cyclones when passing across east coast of India based on Kaplan and DeMaria model. This model introduced a correction procedure for wind speed prediction for first 24-30 hours after
landfall, taking into account the trend of decay constant and use of observations. Vickery et al. (2005) developed empirical models for central pressure change after landfall of the hurricane. The central pressure difference after landfall is modeled as exponential function of time after landfall. The decay constant used in the exponential function in modeled as function of storm parameters at the time of landfall. Central pressure difference, translational speed and radius of maximum wind at landfall are used for modeling decay constant for storms in Florida peninsula and Gulf coast of US whereas only central pressure deficit at landfall is used for modeling decay constant for storms in New-England coast. The decay function is modeled for storms making landfall over Mid-Atlantic coast, Florida Peninsula and Gulf coast of the United states. Vickery et al. (2009) updated hurricane simulation model has included new hurricane data has presented a new improved model for hurricane decay after landfall. The decay rate of storms is modeled as function of central pressure, radius of maximum wind and central pressure at landfall location. In this research, the decay function will be modeled for storms making landfall over Japan, Philippines as well as main land of Asia.

2.4. Radius of Maximum Wind and Holland B Parameter Model

Statistical models for radius of maximum winds and Holland pressure profile parameter for hurricanes has been developed by Vickery and Wadhera (2008). Two empirical models were used to model the hurricane maximum wind radius for Gulf of Mexico and remaining regions. The Radius of maximum wind (RMW) model developed by Vickery and Wadhera (2008) uses latitude and central pressure of storm as predictors for the RMW. Vickery’s US model says that there is no negative correlation between radius
of maximum winds and central pressure deficit and hurricanes in Gulf of Mexico are relatively smaller than other hurricanes. A statistical model was developed by Vickery et al., for parameter B for all the storms. Holland B parameter decrease with increase in RMW and increase in latitude. The effect of latitude, RMW, central pressure deficit on Holland B parameter are accounted in one single non-dimensional parameter ‘A’. Relation between A and B is same for hurricanes in Atlantic Ocean as well as Gulf of Mexico. Vickery et al. (2009) updated hurricane simulation model has presented a new statistical model for Holland B parameter.

Vickery et al (2000) presented an improved hurricane wind field model by solving the non-linear equations of motion of hurricane. It is an improved model compared to Georgiou (1985), Vickery and Twisdale (1995a) which has used spectral model. Given good estimates of Rmax and Holland B parameter, Vickery’s model provides a good representation wind field model. The model took into account the sea-surface temperature changes and air-sea temperature difference at surface level. Jun Tanemoto and Takeshi Ishihara (2013) developed a mesoscale model for predicting cyclone induced wind speeds using JMA best track data. They developed a tropical cyclone database and proposed a new wind-field model in which wind speeds near center of storm are estimated using typhoon model and wind speeds away from the center are estimated using mesoscale mode. In this study, GWR approach will be adopted for RMW model and parameter B model. The regression equation is simplified by removing the location parameter. Also, the dependency of RMW on other variables like RMW of storm from previous time step are analyzed.

2.5. Boundary Layer Model
Surface wind speeds are calculated using boundary layer model. Kepert (2001) developed a linear analytical model for boundary layer of tropical cyclones. Vickery et al. (2009) updated hurricane simulation model which has included new hurricane data has included sea-land transition and boundary layer height. Vickery and Wadhera (2009) improved the boundary layer model by combining linear hurricane boundary layer model by Kepert (2001) with mean wind profiles calculated using dropsonde data. The change in boundary layer height from sea to land was modeled using Kepert’s approach. Kepert method uses a simple linear regression equation to calculate the boundary layer depth. This was combined with the traditional approach to model wind speed reduction due to ocean to land transition. The boundary layer model by Vickery and Wadhera (2009) will be adopted to calculate surface level wind speeds from the simulated typhoons for Asia.

Vickery et al. (2006) has presented an overview of models used in HAZUS-MZ hurricane model which predicts wind induced loads, damages, building responses and losses due to hurricanes. The model has first ever surface roughness database obtained by coupling land-use data and aerial photography. Vickery et al. (2009) has presented an evolution of hurricane hazard modeling which has discussed the state-of-the art wind-field modeling and its uncertainties. Most of the hurricane hazard modes are based on parametric track and intensity projections which provides wind speeds adjusted to site specific and gust-averaging periods. The applications of hurricane hazard modeling include prediction of hurricane damages and insurance losses, estimating design wind loads. In this study, surface wind speeds are calculated at 3-sec averaging time when storm is close to the area of interest. The model is validated by comparing the statistics of typhoon parameters with
historical data and calculated wind speeds are compared with station data provided by Japan Meteorological Agency (JMA) and GSOD.

2.6. Climate Change

It is necessary to examine poleward migration of the genesis and location of tropical cyclone Kossin (2016) examined poleward migration in tropical cyclone maximum intensities for present and future climate in Western North Pacific basin. The overall tropical cyclone exposure is observed to be decreasing in regions of Philippines, Vietnam and South China Sea and increasing in parts of East China, Japan and Korea Peninsula due to decrease in tropical cyclone frequency combined with poleward shift of lifetime maximum intensities (Kossin 2016). Analyzing the best-track data from various data sources, Kossin (2016) found the rate of poleward shift is significant on order of about 0.20 per decade. The 21st century projections using Representative Concentrated Pathway RCP8.5, Kossin (2016) identified poleward migration in lifetime maximum intensities and the migration is going to continue significantly due to warming climate effect.

Daloz and Suzana (2017) examined the relation of poleward migration in latitude of tropical cyclone genesis to poleward migration in latitude of tropical cyclone maximum life time intensity. Daloz and Suzana (2017) study considered environmental variables from two reanalysis datasets to compare tropical cyclone genesis locations to changes in the environment. Daloz and Suzana (2017) study showed shift of favorable regions for tropical cyclone genesis towards higher latitudes in West Pacific Basin in past few decades. Hence poleward migration of tropical cyclone genesis can be significant in West Pacific Basin.
Liu (2014) examined the effect of climate change on US hurricane activity considering changes in sea surface temperatures and annual frequencies.

Some studies have used empirical indices to understand the influence of large-scale climate variables on tropical cyclone genesis. Tippet (2011) constructed an empirical index for tropical cyclone genesis as a function of climate variables. Tippet (2011) index is a Poisson regression equation estimating tropical cyclone genesis by month for a period of 40-years. Sea surface temperature, relative humidity, wind shear and absolute vorticity are used as variables to estimate the monthly tropical cyclone genesis.

Tamarin and Kasapi (2016) analyzed the storm tracks under Representative concentrated pathways (RCP) emission scenarios for the years 2080-2100 and compared the changes with historical data (1980-1999) for Atlantic, Pacific and southern hemisphere. From Tamarin and Kasapi (2016) analysis, most of the scenarios showed significant poleward shift in storm genesis locations in Pacific Basin.

Even a small change in location and intensity of typhoons can lead to significant difference in typhoon exposure of a region. Hence, it is necessary to examine and quantify the effect of poleward migration of genesis locations and climate warming on typhoon activity in the future. The focus of this study is to assess the response of typhoon activity to combination of poleward shift in genesis locations and increased sea surface temperatures considered from different Representative Concentrated Pathways (RCP).
3. TYPHOON SIMULATION MODEL DEVELOPMENT

3.1. Domain of Study

In this study, typhoon database is developed for Northwestern pacific basin where typhoons effect coastal regions of China, Vietnam, Philippines, Taiwan, Korea and Japan. Figure 3 shows the domain used in this study for developing the typhoon database.

![Figure 3. Domain used for typhon model development](image)

3.2. Typhoon Simulation Flowchart

Typhoon simulation model for the basin involves several modules beginning with genesis to model the annual count and spawn locations of the storm, tracking model for simulating the storm paths, followed by relative intensity model to generate central pressures until the storm is in ocean, central pressure decay model to simulate storm dissipation after making landfall, and wind field model. Figure 4 shows the flowchart demonstrating each module in the typhoon simulation framework.
3.3. Data sources

A variety of data sources had been used in this study which include public, private and government data. International Best Track Archive for Climate Stewardship (IBTrACS) is used for observed records for developing track and central pressures. IBTrACS provides storm event data for 174 years from 1842 to 2015 which includes storm center location and pressure at every 6-hour time interval. Sample 5-year typhoon tracks originated in western pacific basin extracted from IBTrACS data are plotted in Figure 5. Typhoon dataset from Japan Meteorological Agency (JMA) is used which provides the location, central pressure, maximum sustained wind speeds, radius at 50kt and 30kt wind
speeds. JMA started providing the last three parameters since 1977. The atmospheric parameters used in our model include the monthly average sea surface temperature which is obtained from HadiSST dataset. HadiSST provides SST data available at $1^\circ \times 1^\circ$ resolution with latitude and longitude.

![Figure 5. Five year typhoon tracks extracted from IBTrACS](image)

3.4. Genesis Model

Typhoon simulation framework begins with genesis model in which the number of storms are generated randomly for every year. Also, the spawn locations of all the storms are generated using genesis model. Figure 6 describes the annual count of typhoons in IBTrACS database from 1950 to 2015.
The number of typhoons per year are generated using a negative binomial distribution. Given the mean $\mu$ and standard deviation $\sigma$ of the observed annual storm frequencies are 36.75 storm/year and 8.18 storm/year, respectively, the negative binomial distribution parameters can be fitted using the maximum likelihood approach. The cumulative distribution function (CDF) of the storm frequency using negative binomial fit is plotted against the CDF of observed storm frequencies. From the CDFs shown in Figure 7, the fitted negative binomial distribution show reasonable agreement with the historical storm rates observed from IBTrACS.
The initial locations of typhoons are generated based on the Gaussian kernel density estimate (KDE) method by smoothing the observed typhoon spawn locations. The observed typhoon spawn locations from are plotted in Figure 8.

The Gaussian kernel density estimator is defined as in equations 3.1 and 3.2.
\[f(\hat{X}) = \frac{1}{NH} \sum_{i=1}^{N} K \left( \frac{X-X_i}{H} \right)\]  \hspace{1cm} (3.1)

Where,

\[K(X) = \frac{1}{\sqrt{2\pi}} e^{-X^2/2}\]  \hspace{1cm} (3.2)

\(N\) is the total number of spawn locations, \(H\) is the bandwidth, \(X\) is the generated spawn location, \(X_i\) is the historical spawn location, \(K(.)\) is the Gaussian probability density function kernel.

To estimate the probability density of the initial spawn locations of typhoons using the KDE method, an appropriate bandwidth is required. Choosing a large bandwidth will lead to over smoothing of the data (i.e. spawn probability is approximately the same everywhere). On the other hand, choosing a small bandwidth can create artifacts and sharp variations of probability densities for locations in close proximity. An optimal bandwidth is selected using the rule of thumb method introduced by Bowmen and Azzalini (1997). The probability density functions of spawn locations were estimated for the overall domain using the kernel density estimator. The spawning locations are generated for every year based on the estimated probability density functions. The contour plot of simulated spawn locations is compared to that of historical spawn locations in Figure 9 and Figure 10. The comparison shows the dispersion of simulated spawn locations is similar to the historical spawn locations.
Figure 9. Historical spawn locations and the KDE contours

Figure 10. Simulated spawn locations and the KDE contours.

3.5. GWR Method
Geographically weighted regression approach (GWR) is introduced by Brunsdon et al. (1996; 1997) and Fotheringham et al. (1997a; 1997b) in which parameters in an equation are estimated by weighted least square regression approach. GWR method accounts for the location of the data in a geographical space, which allows the estimation and differentiation of the local parameters from the global parameters. GWR method estimates the parameters of an equation based on weighted least squares approach. The method calculates parameters using a weighted matrix which is a diagonal matrix with each element in diagonal is a function of location of observation. If $X$ is a matrix of explanatory variables, $Y$ is a column matrix with depend variable observations, the parameter vector $\beta(i)$ is obtained based on equation 3.3.

$$
\beta(i) = [X^T W(i)X]^{-1}X^T W(i)Y
$$

(3.3)

$W(i)$ is weighted matrix at location $I$ which is shown in equation 3.4,

$$
W(i) = \text{diag}[w1(i), w2(i), \ldots, wn(i)]
$$

(3.4)

the weighted least squares GWR approach is used to model the coefficients for tracking, central pressure, radius of maximum winds and Holland B parameter models. The regression analysis for track and central pressure models are performed at every vertex of $1^0 \times 1^0$ resolution grid making total 6462 locations in Asia Pacific domain. For radius of maximum wind and Holland B parameter model, coefficients are fitted at every vertex of $2^0 \times 2^0$ grid with total 1657 locations based on the observed data that contribute to each location. Figure 11 demonstrates the grid resolution used for tracking model and relative intensity model whereas Figure 12 demonstrate grid resolution used for radius of maximum wind model and Holland B parameter model.
Figure 11. 1° by 1° resolution grids in Asia Pacific basin used for track and relative intensity models.

Figure 12. 2° by 2° resolution grids in Asia Pacific basin used for radius of maximum winds and Holland B parameter models.
3.6. Tracking Model

The methodology for simulating typhoon tracks is based on the empirical track modeling approach introduced by Vickery et al. (2000) for simulation of hurricane risk in the United States (U.S). The storm tracks are modeled using regression equations 3.5 and 3.6 of change in translational speed ($V_t$) and heading direction ($\theta$).

\[
\Delta \ln V_t = a_0 + a_1 \psi + a_2 \lambda + a_3 \ln V_{ti} + a_4 \theta_i + \varepsilon \tag{3.5}
\]

\[
\Delta \theta = b_0 + b_1 \psi + b_2 \lambda + b_3 V_{ti} + b_4 \theta_i + b_5 \theta_{i-1} + \varepsilon \tag{3.6}
\]

$V_{ti}$ and $\theta_i$ represent forward speed and angle at time step $i$. $\Delta \ln V_t$ is logarithmic difference between $V_{ti+1}$ and $V_{ti}$ and $\Delta \theta$ is the difference between $\theta_{i+1}$ and $\theta_i$. $a_0$ to $a_4$ represent the coefficients for the change in forward speed model. $b_0$ to $b_6$ represent the coefficients for the change in heading direction model. $\psi$ and $\lambda$ represent the latitude and longitude of the storm eye, respectively. $\varepsilon$ is the error term. This model is updated using GWR approach. As the GWR approach already considers the proximity of the data to the location of interest, the location parameters (i.e. latitude and longitude) are removed from the empirical equations 3.5 and 3.6 making the new equations 3.7 and 3.8,

\[
\Delta \ln V_t = a_0 + a_1 \ln V_{ti} + a_2 \theta_i + \varepsilon \tag{3.7}
\]

\[
\Delta \theta = b_0 + b_1 V_{ti} + b_2 \theta_i + b_3 \theta_{i-1} + \varepsilon \tag{3.8}
\]

The track coefficients, $a$ and $b$ are fitted at every $1^0 \times 1^0$ using the GWR approach. A set of track models are developed for eastward and westward moving storms. After
obtaining $a$ and $b$, the differences between the modeled values and observed values are calculated to quantify the error terms.

The scatter plots of modeled errors of translational speed and heading angles of few locations are shown. The dispersion has shown no trend indicating the randomly distributed errors and the mean of the error is closer to zero. The dispersion of the modeled and observed values of forward speed and heading angles of few locations are plotted in Figure 13 to Figure 20 which are observed to be following similar trends.

Figure 13. Dispersion of modeled and observed values of logarithmic change of forward speeds (left) changing in heading angles (right) for Eastward moving storms at $24^\circ$N and $122^\circ$E.

Figure 14. Dispersion of modeled and observed values of logarithmic change of forward speeds (left) changing in heading angles (right) for Westward moving storms at $24^\circ$N and $122^\circ$E.
Figure 15. Dispersion of modeled and observed values of logarithmic change of forward speeds (left) changing in heading angles (right) for Eastward moving storms at 35°N and 136°E.

Figure 16. Dispersion of modeled and observed values of logarithmic change of forward speeds (left) changing in heading angles (right) for Westward moving storms at 17°N and 142°E.

Figure 17 Error dispersion of logarithmic change in translational speeds (left) and change in heading angles (right) for Eastward moving storms at 24°N and 122°E.
Figure 18. Error dispersion of logarithmic change in translational speeds (left) and change in heading angles (right) for Westward moving storms at 24°N and 122°E.

Figure 19. Error dispersion of logarithmic change in translational speeds (left) and change in heading angles (right) for Eastward moving storms at 35°N and 136°E.

Figure 20. Error dispersion of logarithmic change in translational speeds (left) and change in heading angles (right) for Westward moving storms at 17°N and 142°E.
3.7. Relative Intensity model

The relative intensity is calculated from the pressure and sea surface temperature at the location of the typhoon eye. The procedure for calculating relative intensity of storm from central pressure and sea surface temperature is explained by Darling (1991). The relative intensity is modeled by the regression equation 3.9 with logarithm of relative intensity of storm eye previous time steps of storm, sea surface temperature at current stem.

\[
\ln(I_{i+1}) = c_0 + c_1 \ln(I_i) + c_2 \ln(I_{i-1}) + c_3 T_{s_{i+1}} + c_4 (T_{s_{i+1}} - T_{s_i})
\]  

(3.9)

Where, \(I_i\) represent relative intensity of storm eye at time step \(i\). \(T_s\) is the sea surface temperature at storm eye, \(c_1\) to \(c_6\) are coefficients for relative intensity model. \(\varepsilon\) is the error term. The sea surface temperature data used in the model is obtained from Hadley Centre Sea Ice and Sea Surface Temperature (HadiSST). The monthly average sea surface temperature records with resolution of \(1^0 \times 1^0\) is used for the model. Coefficients \(c_1\) to \(c_6\) are fitted using GWR method for every \(1^0 \times 1^0\).

Figure 21 shows the contours of monthly average sea surface temperature with resolution \(1^0 \times 1^0\) extracted from HadiSST data for months of January, May and October.
Figure 21. Contours of monthly average sea surface temperature from HadiSST data for months of January, May and October.

The dispersion of the modeled and observed values of relative intensities are plotted for few locations in Figure 22 - Figure 25 which are observed to be in similar trends.

Figure 22. Dispersion of modeled and observed values of Relative Intensity(left), Error dispersion of Relative Intensity (right) at 24°N and 122°E.
Figure 23. Dispersion of modeled and observed values of Relative Intensity (left), Error dispersion of Relative Intensity (right) at 30°N and 130°E.

Figure 24. Dispersion of modeled and observed values of Relative Intensity (left), Error dispersion of Relative Intensity (right) at 23°N and 135°E.
3.8. Decay model

After the storm makes landfall, the decrease of central pressure deficit need to be modeled for estimating the typhoon decay. Empirical model is developed to estimate the decay of storms making landfall in main land of Asia, islands of Japan, Philippines and Taiwan. Figure 26 shows the data points of storms after making landfall extracted from JMA. The landfall central pressure is obtained by interpolating the central pressure of storm before making landfall and central pressure after making landfall. Figure 27 shows the landfalling locations of all the historical storms.
The typhoon decay after landfall is modeled as an exponential function of time as shown in equation 3.10.

\[ \Delta P_c(t) = \Delta P_{c0} \exp(-d_0 t) \]  

(3.10)

Where \( \Delta P_c \) is the difference between central pressure and far field pressure (which is assumed to be 1013mb) at t hours after landfall. \( \Delta P_{c0} \) is the difference between central pressure and far field pressure at landfall location, \( d_0 \) is the decay constant. The ratio of
central pressure deficit calculated with $d_0$ at each location after landfall to central pressure
deficit at landfall are plotted against time for few selected storms in Figure 28 and
compared to the observed ratios.

![Figure 28. Observed and fitted central pressure decay functions for main land Asia.](image)

The decay constant is observed to be dependent on Central pressure difference,
radius of maximum winds and translational speed at landfall location. Combinations of
these three parameters were used to calculate the uncertainty in error and best combination
with lowest uncertainty in error is opted for modeling the decay rate constant. The
following are the combinations used to model the decay rate parameter.
1. \( d_0 = m_0 + m_1 \Delta p_c + \varepsilon \)
2. \( d_0 = m_0 + m_1 \Delta p_c \cdot Vt/R\text{max} + \varepsilon \)
3. \( d_0 = m_0 + m_1 \Delta p_c \cdot Vt/\sqrt{R\text{max}} + \varepsilon \)
4. \( d_0 = m_0 + m_1 \Delta p_c / R\text{max} + \varepsilon \)
5. \( d_0 = m_0 + m_1 \Delta p_c + m_2 / R\text{max} + b4Vt + \varepsilon \)
6. \( d_0 = m_0 + m_1 \Delta p_c + m_2 / \sqrt{R\text{max}} + b4Vt + \varepsilon \)
7. \( d_0 = m_0 + m_1 \Delta p_c + m_2 / R\text{max} + \varepsilon \)
8. \( d_0 = m_0 + m_1 \Delta p_c + m_2 / \sqrt{R\text{max}} + \varepsilon \)
9. \( d_0 = m_0 + m_1 \Delta p_c / \sqrt{R\text{max}} + \varepsilon \)

However, the above nine models are compared only for those storms which made landfall in mainland Asia, combination 1 is used for other regions like Japan, Taiwan and Philippines due to insufficient radius of maximum winds data. The central pressure of track after landfall is calculated with obtained decay rate constants from each model. The calculated central pressure is subtracted from the observed central pressure values to find the error. The error found from each model are plotted against time after landfall as shown in Figure 29.
From these plots, it is observed model number 8 is predicting the decay of storms better than other models. Model 8 is used for modeling the decay rate model for main land of Asia.

3.9. Radius of Maximum Wind Model

The radius of maximum winds model (RMW) is developed by modifying the empirical model given by Vickery et al. (2009), Vickery and Wadhera (2008) for US hurricanes in which the radius of maximum winds are modeled by two equations. The radius of maximum winds are determined for gulf of Mexico hurricanes using empirical equation 3.11.

\[
\ln(R_{max}) = 3.858 - 0.000077\Delta p^2 + \varepsilon_R
\]

(3.11)
The RMW for all other hurricanes are simulated using equation 3.12

\[
\ln(R_{max}) = 3.015 - 0.00006291\Delta p^2 + 0.0337\psi + \varepsilon_R
\]  

(3.12)

Where \(\Delta p\) is the pressure difference and \(\psi\) is the latitude at the location of storm eye.

From equations 3.11 and 3.12, central pressure difference and latitude of storm are the predictor variables for RMW. Observations have shown a good correlation between RMW at current time and previous time steps. Figure 30 shows correlation between RMW to the predictor variables considered in our model.

Figure 30. Correlation between logarithmic RMW and Central pressure(left), logarithmic values of RMW at current and previous time steps(right).

So, our empirical model for RMW incorporated central pressure difference and RMW from previous time steps making the equation 3.13.

\[
\ln R_{max} = e_0 + e_1 \Delta p + e_2 \ln R_{max_{prev}} + \varepsilon
\]

(3.13)
The coefficients $e_0-e_2$ are fitted using GWR method to obtain local parameters at every $2^0 \times 2^0$. Since the location function is already taken to account by GWR approach, latitude term is not considered in the equation. The scatter plots of the modeled and observed values of RMW plotted against central pressure difference and RMW of previous time steps are observed to have similar dispersion as shown in Figure 31 - Figure 34.

Figure 31. Dispersion of modeled and observed values of log(Rmax)(left), Error dispersion of H log(Rmax) (right) at 8°N and 136°E.

Figure 32. Dispersion of modeled and observed values of log(Rmax)(left), Error dispersion of H log(Rmax) (right) at 16°N and 134°E.
Figure 33. Dispersion of modeled and observed values of log(Rmax)(left), Error dispersion of H log(Rmax) (right) at 240N and 1260E.

Figure 34. Dispersion of modeled and observed values of log(Rmax)(left), Error dispersion of H log(Rmax) (right) at 30°N and 146°E.

3.10. B Parameter Model

Parameter B determines the shape of the wind field around the storm eye. Parameter B model is developed using the statistical model developed by Vickery and Wadhera(2008) by analyzing wind field data of historical hurricanes in US with central pressure less than 980mb using equations 3.14 and 3.15.

\[ B = 1.7642 - 1.2098\sqrt{A}, \sigma_B = 0.226 \]  \hspace{1cm} (3.14)

\[ A = \frac{R_{max,f}}{\sqrt{2R_d(T_s-273)ln\left(1+\frac{\Delta p}{p_c}\right)}} \]  \hspace{1cm} (3.15)
Where, \( R_{\text{max}} \) is Radius of maximum winds, \( f \) is the Coriolis parameter, \( T_s \) is the sea surface temperature, \( R_d \) is the gas constant. \( \Delta p \) is the difference between peripheral pressure and central pressure and \( p_c \) is the pressure at storm eye. A similar approach is used to model B parameter for Asia typhoons by incorporating GWR approach to the regression equation as shown in equation 3.16.

\[
B = B_{a0} + B_{a1}\sqrt{A} + \varepsilon
\]  

(3.16)

Good correlation is observed between Holland B parameter of consecutive time steps as shown in Figure 35. Hence B-parameter of previous time step is added additionally to equation 3.16.

![Figure 35. Correlation between Holland B parameters at consecutive time steps.](image)

Hence, the modified for Holland B parameter is shown in equation 3.17.

\[
B = B_{a0} + B_{a1}\sqrt{A} + B_{a2}B_{t-1} + \varepsilon
\]  

(3.17)
$B_{t-1}$ is B parameter at time step $i$. $B_{t-1}$ is B parameter at previous time step. Modeled B parameters are calculated using these coefficients for the JMA data. The coefficients $B_{a0}$ and $B_{a1}$ are obtained at every $2^0 \times 2^0$ location using GWR method.

The is plotted against square root of A. Figure 36 shows the scatter plots of the observed and modeled values of B parameters using equation 3.16 before application of GWR method whereas Figure 37 shows the scatter plots after applying GWR method. $\sigma_{err}$ is the standard deviation of error between modeled and observed values of B parameter. From the plots, GWR method has reduced the uncertainty in the error. Figure 38 shows the scatter plots of the observed and modeled values of B parameters using equation 3.17 i.e., after adding the B parameter of previous time step. From the figure, including $B_{prev}$ has further improved the model by reducing the uncertainty in error.

![Figure 36](image-url)
Figure 37. Dispersion of modeled and observed values of Holland B parameter (without GWR method).

Figure 38. Dispersion of modeled and observed values of Holland B parameter after adding the $B_{prev}$.

The dispersion of the modeled and observed values of Holland B parameters are plotted for few locations in Figure 39 - Figure 42 which are observed to be in similar trends.
Figure 39. Dispersion of modeled and observed values of Holland B parameter (left), Error dispersion of Holland B parameter (right) at 132°E and 10°N.

Figure 40. Dispersion of modeled and observed values of Holland B parameter (left), Error dispersion of Holland B parameter (right) at 138°E and 14°N.

Figure 41. Dispersion of modeled and observed values of Holland B parameter (left), Error dispersion of Holland B parameter (right) at 132°E and 16°N.
After landfall, B parameter is modeled as an exponential function of time as shown in equation 3.18.

$$B(t) = B_0 \exp(a_B t)$$

(3.18)

Where, $B_0$ is B parameter at landfall and $a_B$ is decay rate of B parameter.

3.11. Bandwidth Selection:

In GWR approach, the extent of data from the location of interest taken to consideration depend on the value of bandwidth assumed. Bandwidth determines the weight given to the observation data depending on the distance of observation location to the point of interest. Figure 43 shows the change in weight with distance from target location for varying bandwidths.
When modeling the coefficients using GWR approach, suitable bandwidth needed to be specified for optimizing the model. For this purpose, the model is experimented by varying the bandwidths. Set of coefficients were calculated for each model by varying the bandwidths ranging from 0.35 to 0.6 with an interval of 0.01.

An example for determining the appropriate bandwidth is explained below. Coefficients $c_1$ to $c_6$ are calculated for relative intensity model (equation 3.9) using different bandwidths ranging from 0.1 to 2 with an interval of 0.01. The change in the logarithmic relative intensity is back calculated using each set of coefficients. The change in relative intensity values obtained from each set are subtracted from the observed values of the data to calculate the error. The mean and standard deviation of errors from each set were calculated. The bandwidth that has given the lowest standard deviation of error is chosen as the optimal bandwidth for our model. Figure 44 shows the change in standard
deviation of error with bandwidth for relative intensity model. Bandwidth 0.41 is picked for our model as it showed the least error from the figure.

Figure 44. Bandwidth vs standard deviation of error for central pressure model.

3.12. Assignment of coefficients for Track, Central Pressure, RMW and Holland B model:

Figure 45 - Figure 49 shows the assignment of coefficients for track model (Figure 45 and Figure 46), central pressure model (Figure 47), RMW model (Figure 48) and Holland B parameter model (Figure 49). Simulation domain is divided to $1^\circ \times 1^\circ$ grids for track and central pressure models, $2^\circ \times 2^\circ$ for RMW and Holland B parameter models between $0^\circ$ to $70^\circ$N latitudes and $90^\circ$E to $180^\circ$E longitudes. Coefficients are fitted at vertices of each grid using GWR method. The locations with more than three number of observation data for track model are plotted in black color. In few cases, coefficient fitting is not necessary for some locations in the domain. For example, locations inside the land mass do not need the coefficients for relative intensity model as the model is only applicable until the storm is in ocean. Such locations for which coefficient fitting is not
essential are represented in red. To fill all the locations in the domain with coefficients, the cells with insufficient observation data for which coefficients are copied from nearest black location are shown in cyan. The assignment of the coefficients is different for every model.
Figure 45. Coefficients assignment of track model for storms travelling eastwards.

Figure 46. Coefficients assignment of track model for storms travelling westwards.
Figure 47. Coefficients assignment of central pressure model.

Figure 48. Coefficients assignment of Radius of Maximum Wind Model.
Each site in the study domain has its own set of coefficients which can be mapped over the domain to observe pattern of each coefficient. Figure 50 demonstrates the coefficient patterns on the domain for translational speed in track model. The mean and standard deviations of error for each model are mapped as shown in Figure 51 to demonstrate the sites where the model is over predicting and under predicting the parameters. Coefficient pattern for relative intensity, Rmax and Holland B parameter models are demonstrated in Appendix A.
Figure 50. Coefficients of track model for translational speed mapped over the study domain.

Figure 51. Error mean (µ) and standard deviations (σ) of track model for translational speed mapped over the study domain.
4. MODEL VALIDATION

4.1. Track Patterns

To assess the simulated tracks, five years of storm tracks are randomly sampled from the simulated database. For comparison, five years of real storm tracks are also plotted from IBTrACS data. Figure 52 and Figure 53 show five years of typhoon tracks selected from historical data and simulated catalog, respectively. The simulated storm tracks are observed to follow similar patterns of the real tracks, in which the storms mainly moving in westerly direction below $30^0$ latitude and start moving in easterly direction above $30^0$ latitude.

![Figure 52. Real 5-year storm tracks from IBTrACS.](image_url)
4.2. Assessment of Track Model

Each module in the typhoon simulation framework are individually examined for their performance. To inspect the performance of the track model, possible 3-day tracks are simulated using the track coefficients for storms Songda(2004), Violet(1996) and Mireille (1991). Initial latitude, longitude, translational speed and heading angle are taken as inputs to simulate the possible tracks using equations 3.7 and 3.8. The coefficients are obtained by interpolating the coefficients of four vertices of the grid in which the initial eye of storm is located. The forward speed, heading angle, latitude and longitude are simulated using the calculated coefficients. Such realizations are performed 500 times for convergence study for all storm tracks. The grey lines in Figure 54 shows all the 3-day track realizations using track model and the red line represents the original track. From the figure, the original track of Songda(2004) lies within the predicted region of the storm.
movement. More such performance assessment is done for different storms which are shown in Figure 55 and Figure 56.

Figure 54. Comparison of simulated and observed time histories of tracks of typhoon Songda 2004.

Figure 55. Comparison of simulated and observed time histories of tracks of typhoon Violet 1996.
4.3. Assessment of Central Pressure Model

Similar to track model, performance of central pressure model is tested by simulating the central pressure of historic tracks. Typhoon tracks of Songda(2004), Violet(1996), Mireille(1991) are selected to perform the assessment of central pressure model using equation 3.9. The central pressure and sea surface temperature at initial location of the storm are taken as inputs for the equation. The coefficients are obtained by interpolating the coefficients of four vertices for each grid where the storm moves. The central pressure is simulated using relative intensity model until the track is in ocean and decay model after the storm makes landfall. Figure 57 shows 500 realizations of central pressure for Songda(2004). From the figure the original central pressure mostly lies within the region of simulated central pressures. More such examples for central pressure model assessment are shown in Figure 58 and Figure 59.
Figure 57. Comparison of simulated and observed time histories of central pressure of typhoon Songda 2004.

Figure 58. Comparison of simulated and observed time histories of central pressure of typhoon Violet 1996.
4.4. Assessment of Radius of Maximum Wind Model

Performance of radius of maximum wind model is inspected by simulating the radius of maximum winds of historic tracks. Typhoon tracks of Songda(2004), Violet(1996), Bart(1999) are selected to perform the assessment of RMW model using equation 3.13. The central pressure and RMW at initial location of the storm are taken as inputs for the equation. The coefficients are obtained by interpolating the coefficients of four vertices for each grid where the storm moves. Figure 60 shows 500 realizations of central pressure for storm Songda(2004). From the figure the original radius of maximum winds mostly lies within the bound of simulated RMWs. More such examples for RMW model assessment are shown in Figure 61 and Figure 62.
Figure 60. Comparison of simulated and observed time histories of RMW of typhoon Songda 2004.

Figure 61. Comparison of simulated and observed time histories of RMW of typhoon Violet 1996.
4.5. Assessment of Holland B Parameter Model

Inspection of Holland B parameter model is performed by simulating the B-parameter for historic tracks using equation 3.17. The central pressures, sea surface temperatures, latitudes, RMW at every time step of the track and B-parameter at initial location of the storm are taken as inputs for the equation. The coefficients are obtained by interpolating the coefficients of four vertices for each grid where the storm moves. Equation 3.17 is used for simulating B-parameter till storm is in ocean and B-parameter decay model after the storm makes landfall. Figure 63 to Figure 65 show 500 realizations of Holland B parameter for the storms Songda(2004), Violet(1996) and Mireille(1991).
Figure 63. Comparison of simulated and observed time histories of B parameter of typhoon Songda 2004.

Figure 64. Comparison of simulated and observed time histories of B parameter of typhoon Violet 1996.
4.6. Distributions of Track Parameters

Simulated tracks are validated by comparing the probability density functions (PDF) of track parameters in the entire basin with observed data. Figure 66 shows PDFs of simulated translational speeds, heading angles, central pressures, radius of maximum winds, Holland B parameters for whole Asian basin compared to observed data. IBTrACS data is used for comparisons of translational speeds, heading angles and central pressures whereas JMA data is used for comparisons of radius of maximum winds and Holland B parameters. The comparisons demonstrate a good match between distributions of simulated and observed track parameters.
4.7. Track Validations

The key parameters of simulated storms are validated with historical storms at key locations selected in the coastal areas of mainland, Japan, Korea, Philippines and Taiwan. Kilometer posts are assembled at every 100 kilometers along the coastline for mainland of Asia as shown in Figure 67. Storms passing within 250 kilometers radius from each kilometer post are selected. The approaching rate of simulated storms are compared with the observed storms. Figure 68 shows the trend of approaching rate of simulated storms along the kilometer posts is similar to that of IBTrACS database.
The distributions of key parameters such as the translational speed, heading angle and central pressure of selected simulated storms are compared with the observed values for each kilometer post. The statistics of simulated and observed key parameters for each kilometer post are plotted in Figure 69 - Figure 71. The median values vary in the similar trend of observed values along the kilometer posts. The trends of 5 percentile and 95 percentile values match well with the observed values indicating the similarity between both the catalogues.
Figure 68. Comparison between the simulated and observed annual approaching rate for kilometer posts along the mainland of Asia.

Figure 69. Comparison between simulated and observed translational speeds (median, 5 and 95 percentiles) along the coastline of the mainland of Asia.
Figure 70. Comparison between simulated and observed heading angles (median, 5 and 95 percentiles) along the coastline of the mainland of Asia.

Figure 71. Comparison between simulated and observed Central Pressures (median, 5 and 95 percentiles) along the coastline of the mainland of Asia.

The simulated typhoon tracks are also validated by comparing the cumulative distribution functions (CDFs) of simulated track parameters with observation data at
kilometer posts in mainland Asia. The simulated track parameters of typhoons passing with in 250km radius from each kilometer post are selected. The CDF curves of these selected track parameters compared with IBTrACS track parameters for selected kilometer posts in mainland Asia are shown in Figure 72 - Figure 74.

Figure 72. CDF comparison of simulated vs observed translational speeds for selected kilometer posts in mainland Asia.

Figure 73. CDF comparison of simulated vs observed heading angles for selected kilometer posts in mainland Asia.
Like the kilometer posts selected for the mainland, key locations were chosen in the coast of Japan to compare the simulated and observed storm statistics as shown in Figure 75. The storms passing within 250 km radius from each key location are selected to compare the approaching rates, storm translational speeds and heading angles between simulated storms and IBTrACS data. The statistics of simulated and observed key parameters for each key location in Japan are plotted in Figure 76 - Figure 79. The statistics of approach rate, translational speeds and heading angles of simulated storms in the key locations and kilometer posts agreed reasonably well with observed parameters.
Figure 75. Key locations along the coast of Japan.

Figure 76. Comparison between the simulated and observed annual approaching rate for key locations in Japan.
Figure 77. Comparison between simulated and observed translational speeds (median, 5 and 95 percentiles) for selected locations along the coastline of Japan.

Figure 78. Comparison between simulated and observed heading angles (median, 5 and 95 percentiles) for selected locations along the coastline of Japan.
Similar to mainland Asia, simulated typhoon tracks are validated by comparing the cumulative distribution functions (CDFs) of simulated track parameters with observation data at key locations of Japan. The simulated track parameters of typhoons passing within 250km radius from each kilometer post are selected. The CDF curves of these selected track parameters compared with IBTrACS track parameters for selected key locations in Japan are shown in Figure 80 - Figure 82.
Figure 80. CDF comparison of simulated vs observed translational speeds for selected kilometer posts in mainland Asia.

Figure 81. CDF comparison of simulated vs observed heading angles for selected kilometer posts in mainland Asia.

Figure 82. CDF comparison of simulated vs observed central pressures for selected kilometer posts in mainland Asia.
Similar to Japan, key locations were chosen in the coast of Philippines and Taiwan to compare the simulated and observed storm statistics as shown in Figure 83 (Philippines) and Figure 84 (Taiwan). The storms passing within 250 km radius from each key location are selected to compare the approaching rates, storm translational speeds and heading angles between simulated storms and IBTrACS data. The statistics of simulated and observed key parameters for each key location in Philippines are plotted in Figure 85 - Figure 88 and plots for Taiwan are plotted in Figure 89 - Figure 92. The statistics of approach rate, translational speeds and heading angles of simulated storms in the key locations showed reasonable agreement with observed parameters.

![Figure 83. Key locations along Philippines coast.](image_url)
Figure 84. Key locations in Taiwan coast.

Figure 85. Comparison between simulated and observed approach rate for selected locations along the coastline of Philippines.
Figure 86. Comparison between simulated and observed translational speed (median, 5 and 95 percentiles) for selected locations along the coastline of Philippines.

Figure 87. Comparison between simulated and observed heading angles (median, 5 and 95 percentiles) for selected locations along the coastline of Philippines.
Figure 88. Comparison between simulated and observed central pressures (median, 5 and 95 percentiles) for selected locations along the coastline of Philippines.

Figure 89. Comparison between simulated and observed approach rate for selected locations along the coastline of Taiwan.
Figure 90. Comparison between simulated and observed translational speed (median, 5 and 95 percentiles) for selected locations along the coastline of Taiwan.
Figure 91. Comparison between simulated and observed heading angles (median, 5 and 95 percentiles) for selected locations along the coastline of Taiwan.

Figure 92. Comparison between simulated and observed central pressures (median, 5 and 95 percentiles) for selected locations along the coastline of Philippines.
Simulated typhoon tracks are validated by comparing the cumulative distribution functions (CDFs) of simulated track parameters with observation data at key locations of Philippines and Taiwan. The simulated track parameters of typhoons passing within 250km radius from each key location are selected. The CDF curves of these selected track parameters compared with IBTrACS track parameters for selected key locations in Philippines are shown in Figure 93 - Figure 97.

Figure 93. CDF comparison of simulated vs observed heading angles for selected locations in Philippines.

Figure 94. CDF comparison of simulated vs observed central pressures for selected locations in Philippines.
4.8. Central Pressure Return Period

Another demonstration for validation of central pressure model is comparing return periods of central pressure with observation data for coastal regions of Asia. For this purpose, mainland Asia coastline is divided to five regions depending on latitude. Coastline below latitude 15°N is considered as Region 1, coastline above 15°N latitude and below 25°N latitude is considered as Region 2, coastline above 25°N latitude and below 30°N latitude is considered Region 3, coastline above 30°N latitude and below 35°N latitude is considered Region 4, coastline above 35°N latitude is considered as Region 5. Figure 98
shows the five divisions of mainland Asia and observation data of typhoons (IBTrACS) before making landfall for each division.

Figure 98. Five regions of mainland Asia and typhoon data points before making landfall for each region.

Typhoon central pressures before making landfall in each region are collected for simulated storms and return period is calculated using equation 4.1.

\[ R_{P_c} = \frac{Y}{n_{P_c}} \] (4.1)

Where \( R_{P_c} \) is the return period of central pressure \( P_c \), \( Y \) is number of years in the database, \( n \) in number of typhoons made landfall with central pressure \( P_c \). Figure 99 shows return period comparison of central pressure of simulated storms with IBTrACS data for all the five regions in mainland Asia.
Figure 99. Return period graphs for five regions of Mainland Asia.

Similar to mainland Asia, return periods are compared for regions of Japan. Return period of simulated central pressures are compared with IBTrACS data individually for Kyushu, Honshu and Hokkaido. Figure 100 shows the three regions of Japan and observation data of typhoons (IBTrACS) before making landfall for each division.
Figure 100. Three regions of Japan and typhoon observations before making landfall for each region.

Figure 101 shows return period comparison of central pressure of simulated storms with IBTrACS data for the three regions in Japan.

Figure 101. Return period graphs for three regions of Japan.

Similarly, return periods are compared for two main regions of Philippines. Return period of simulated central pressures are compared with IBTrACS data for Luzon and
Mindanao regions. Figure 102 shows both regions of Philippines and observation data of typhoons (IBTrACS) before making landfall for each region.

Figure 102. Regions of Philippines and typhoon observations before making landfall for each region.

Figure 103 shows return period comparison of central pressure of simulated storms with IBTrACS data for both regions of Philippines.
Figure 103. Return period graphs for regions of Philippines.
5. WIND SPEED DATABASE DEVELOPMENT

Simulated typhoon track database is used to develop a database of typhoon wind speeds. The procedure for windspeed database generation begin with developing a variable resolution grids (VRG) in the coast of mainland Asia, Japan, Philippines and Taiwan. Resolution of the VRGs in mainland is of $0.02^\circ \times 0.02^\circ$ up to 30 km from the coastline, $0.05^\circ \times 0.05^\circ$ beyond 30 km and till 200 km from coast and $0.1^\circ \times 0.1^\circ$ resolution beyond 200 km from the coast covering approximately 16 provinces in China and all the regions of Vietnam and Korea and as shown in Figure 104. Also, grids are generated in islands of Japan, Philippines and Taiwan with resolution $0.02^\circ \times 0.02^\circ$ up to 30 km from the coastline, $0.05^\circ \times 0.05^\circ$ beyond 30 km from coastline as demonstrated in Figure 105 to Figure 106.

Figure 104. VRG Mainland.
Figure 105. VRG Japan.
The gradient wind speed at 3000m elevation is calculated using Georgiou’s wind field equation 5.1.

\[ V_g(r) = \frac{1}{2} (c \sin \alpha - fr) + \frac{1}{4} (c \sin \alpha - fr)^2 + \frac{B \Delta \rho}{\rho} \left( \frac{R_{\text{max}}}{r} \right)^B \exp \left[ - \left( \frac{R_{\text{max}}}{r} \right)^B \right] \]  \tag{5.1} 

where \( V_g \) is the gradient wind speed at radius \( r \) from storm center, \( c \) is translational speed of storm, \( \rho \) is the air density, \( \alpha \) is angle from storm forward direction to the location of interest, \( r \) is the distance from storm center to the location of interest, \( R_{\text{max}} \) is the radius of maximum winds, \( B \) is the Holland B parameter, \( f \) is the Coriolis parameter and \( f = 2 \Omega \sin \varphi \), where \( \Omega \) is rotation rate of earth and \( \varphi \) is the latitude.
5.1. Boundary Layer Model

The gradient wind speed at 3000m elevation is converted to surface level elevation using equation 5.2

\[ U(z) = \frac{u_*}{k} \left[ \ln \left( \frac{z}{z_0} \right) - a \left( \frac{z}{H^*} \right)^n \right] \quad (5.2) \]

Where, \( z \) is height from the surface, \( U(z) \) is wind speed at height \( z \), \( k \) is Karman coefficient, \( z_0 \) is surface roughness, \( H^* \) is boundary layer height parameter, \( u_* \) is friction velocity.

5.2. Land Use Data

Wind speed is a mainly function of surface roughness (\( z_0 \)). Appropriate surface roughness must be used for calculation of wind speeds over land or sea. Wind travels at relatively lower speed on ground compared to sea due to the drag force by earth’s surface. The speed further decreases with addition of buildings and other obstacles. This effect is caused due to increase in surface roughness with addition of obstacles on the ground. Rougher the surface, more the reduction in wind speed. This surface roughness effect is incorporated in this model by allotting a surface roughness value for each site in the database. The roughness values are derived from MODIS land cover data. The land cover data types include agricultural land, water bodies, urban land, forests etc. Surface roughness value differ with the land cover type. The surface roughness used for mainland and other islands of Asia are shown in Figure 107 to Figure 109.
Figure 107. Surface roughness values for locations in mainland derived from MODIS data.
Figure 108. Surface roughness values for locations in Japan derived from MODIS data.
Figure 109. Surface roughness values for locations in Philippines and Taiwan derived from MODIS data.

5.3. Wind Field Directionality

Wind speed calculation at any specific location requires surface roughness value assigned to the location. Sensitivity of surface roughness to directionality of the wind is explicitly accounted in this model. Which means instead of using a single surface roughness value for a location, surface roughness is estimated in sixteen directions surrounding the location using land use data. When calculating the wind speed, direction from which wind is blown is determined and roughness value attributed to that direction is used for $z_0$ value used in equation 5.2. Figure 110 shows an example of a location in China for which surface roughness values are estimated in 16 directions.
5.4. Fetch Calculation

During sea-land transition of wind, it undergoes transition up to 20km from coastline which means roughness coefficient of neither land nor sea can be used for calculating wind speed up to 20km from coast. The wind speed in this transition phase can be calculated using the fetch factor which accounts for distance travelled from the coast. This fetch factor is calculated using methodology by Vickery 2009b. The wind speed adjusted for fetch factor is calculated using the equation 5.3.

\[ U_{10} = K_s(U_{101}, U_{102}) \times U_{102} \]  

(5.3)
Where, $U_{101}$ is fully transitioned wind speed on the upwind side with surface roughness $z_01$ (i.e. the sea), $U_{102}$ is fully transitioned wind speed on the downwind side with surface roughness $z_02$ (i.e. the land), $K_x$ is the fetch factor which is a function of $U_{101}$ and $U_{102}$.

Figure 111. Wind profile undergoing transition.

Figure 111 shows the procedure for accounting the sea-land transition of wind profiles. Time conversion is performed to obtain 3s wind gust at 10m elevation. The procedure for wind speed calculation is performed for all the grids using the typhoon track database.
6. WIND DATABASE VALIDATION

6.1. Historical Typhoon Wind Footprints

The following plots show comparison between calculated wind speeds (without exposure correction) with H*Wind data. In Figure 112, Figure 114 and Figure 116, the wind contour plot to the left shows H*wind results and that to the right shows calculated footprint. Scatter plots of calculated wind speeds and H* wind data are compared in Figure 113, Figure 115 and Figure 117.

![Figure 112. Wind contour plot comparing H*wind results to the calculated footprint for Jangmi (27 Sep 2008, 01:30).](image-url)
Figure 113. Scatter plots comparing H*wind results to the calculated wind speeds for Jangmi (27 Sep 2008, 01:30).

Figure 114. Wind contour plot comparing H*wind results to the calculated footprint for Jangmi (27 Sep 2008, 07:30).
Figure 115. Scatter plots comparing H*wind results to the calculated wind speeds for Jangmi (27 Sep 2008, 07:30).

Figure 116. Wind contour plot comparing H*wind results to the calculated footprint for Rammasun (2 July 2002, 13:00).
6.2. Comparison with Observations (Scatter Plots)

Figure 118 to Figure 126 show the comparison between the calculated surface wind speeds (10 m–10 min) and the corresponding wind speeds provided by Global Summary Of the Day (GSOD) data at various locations in China, Japan, and the Philippines.
Figure 118. 10m-10min Wind speeds, Lumbia Airport (Philippines).

Figure 119. 10m-10min Wind speeds, Hinatuan (Philippines).
Figure 120. 10m-10min Wind speeds, Science Garden (Philippines).

Figure 121. 10m-10min Wind speeds, Baguio (Philippines).
Figure 122. 10m-10min Wind speeds, Choshi (Japan).

Figure 123. 10m-10min Wind speeds, Asosan (Japan).
Figure 124. 10m-10min Wind speeds, Aburatsu (Japan).

Figure 125. 10m-10min Wind speeds, Dechen dao (China).
Figure 126. 10m-10min Wind speeds, Cheung Chau (China).
7. PROJECTIONS OF WIND SPEEDS UNDER CLIMATE CHANGE

The impact of climate change on the typhoon activity is examined by coupling the baseline typhoon simulation model with the climate change factors. The two climate change factors considered in the study are (1) poleward shift of typhoon spawn locations and (2) sea surface temperature.

7.1. Poleward shift:

In this study, three cases of poleward shift are analyzed assuming the typhoon spawn locations shift towards North pole by 0.5°N, 1°N and 1.5°N. Hence the probability density of the historical typhoon initial locations calculated using kernel density estimator are shifted by 0.5°N, 1°N and 1.5°N. Figure 127 to Figure 129 shows the new contour of typhoon genesis after the poleward shift plotted over the contour of historical genesis locations.
Figure 127. Contour plot of typhoon spawn locations after poleward shift of 0.5°N and initial spawn locations of historical storms.

Figure 128. Contour plot of typhoon spawn locations after poleward shift of 1°N and initial spawn locations of historical storms.
Figure 129. Contour plot of typhoon spawn locations after poleward shift of 1.5°N and initial spawn locations of historical storms.

7.2. Sea surface temperature:

Sea surface temperature is a factor used in relative intensity model. Change in sea surface temperature in future are projected by Global Climate Models (GCMs). A comparison of sea surface temperature taken from Coupled Model Intercomparison Project Phase 5 (CMIP5) under scenario RCP8.5 and historical monthly average SST are shown in Figure 130. SST\textsubscript{RCP} represent sea surface temperature projection from an RCP scenario and SST\textsubscript{MERRA} represent monthly mean sea surface temperature data from Modern-Era Retrospective analysis for Research and Applications (MERRA) data. More ratios of future SST to current SST plots are shown in Appendix C. The projected sea surface temperatures obtained the RCP data are incorporated in relative intensity model.
7.3. Climate change scenarios:

Using the two climate change factors described in sections above, thirteen different scenarios including the baseline model are used for examining the typhoon activity under climate change conditions. These thirteen scenarios are obtained by varying the changes in SST and poleward shift of storms. Table 6 shows the different climate change scenarios analyzed in this study. 10000-year typhoon track database is generated for each scenario.
Approach rates and wind speeds are calculated for each scenario and compared with the baseline model for selected locations.

Table 6. Climate change scenarios

<table>
<thead>
<tr>
<th>SN</th>
<th>Climate Scenario</th>
<th>Poleward Shift</th>
<th>Sea Surface Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Scenario 1</td>
<td>-</td>
<td>RCP2.6(2100)</td>
</tr>
<tr>
<td>2</td>
<td>Scenario 2</td>
<td>-</td>
<td>RCP4.5(2100)</td>
</tr>
<tr>
<td>3</td>
<td>Scenario 3</td>
<td>-</td>
<td>RCP8.5(2100)</td>
</tr>
<tr>
<td>4</td>
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<td>RCP2.6(2100)</td>
</tr>
<tr>
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<td>Scenario 5</td>
<td>1°N</td>
<td>RCP2.6(2100)</td>
</tr>
<tr>
<td>6</td>
<td>Scenario 6</td>
<td>1.5°N</td>
<td>RCP2.6(2100)</td>
</tr>
<tr>
<td>7</td>
<td>Scenario 7</td>
<td>0.5°N</td>
<td>RCP4.5(2100)</td>
</tr>
<tr>
<td>8</td>
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<td>1°N</td>
<td>RCP4.5(2100)</td>
</tr>
<tr>
<td>9</td>
<td>Scenario 9</td>
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</tr>
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<tr>
<td>12</td>
<td>Scenario 12</td>
<td>1.5°N</td>
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</tr>
<tr>
<td>13</td>
<td>Baseline Model</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

7.4. Change in Approach Rates

Annual approach rates are calculated for selected locations in Japan, Philippines, China and Korea by counting the number of storms passing within 250km radius from each selected location. Approach rates calculated for all the climate scenarios to assess the changes compared to the baseline model. Figure 131 and Figure 133 shows the annual approach rates comparison all the climate scenario for locations in China, Korea, Japan and Philippines. From the comparisons, increasing radioactive forcings is causing more storms to hit these countries. Effect of poleward shift is negligible in RCP2.6 and RCP4.5. Subtle changes can be seen in the approach rate due to poleward shift under RCP8.5 scenario. Clearly, effect of poleward shift is increasing with rise of radioactive forces for passing
rates in Japan. This is because storms not only spawn at higher latitudes but also sustain longer due to rise in sea surface temperatures in higher radioactive emission cases.

Figure 133 show the approach rate comparisons for selected locations in Philippines. Significant changes cannot be seen in passing rates for Philippines due to the climate change. Minute rise in the storm count can be seen under all the three RCP scenarios but no proportional relationship is observed between radioactive emissions and storm count in Philippines. Poleward shift is observed to be lowering the passing rate of storms which can be due to rise in average genesis latitude of storm making less storms to hit Philippines.
Figure 131. Annual approach rates calculated for all the climate scenarios for selected locations in China and Korea.
Figure 132. Annual approach rates calculated for all the climate scenarios for selected locations in Japan.
Figure 133. Annual approach rates calculated for all the climate scenarios for selected locations in Philippines.

7.5. Change in Central Pressures:

Central pressures of historical typhoon data is compared with simulated track data for $1^\circ \times 1^\circ$ grids. Central pressures of storms passing through each grid are collected. The central pressure for 5, 10, 25, 50, 100-year return periods are calculated for each grid and compared with different climate change scenarios. Figure 134 show the central pressure return period maps for baseline mode, whereas Figure 135 to Figure 139 show the central pressure return period maps for all the climate change scenarios. Decrease in central pressure value represent increase in storm intensity. Observing the projections of central pressures, high intensity storms are expected to increase with increase in radioactive forces. With rise of radioactive forces, the overall area experiencing the stronger typhoons is going to get wider in the basin and islands of Philippines and Taiwan, coast of China and Vietnam.
are expected to see much intense storms compared to current climate. More intense storms are expected to hit southern regions of Japan like Kyushu and Shikoku. However, considerable changes are not observed in Korea and northern regions of Japan. No contribution of poleward shift is observed in the increase of intense storms in the basin.

Figure 134. Central pressure return periods for baseline model.
Figure 135. 5-year return period central pressures.
Figure 136. 10-year return period central pressures.
Figure 137. 25-year return period central pressures.
Figure 138. 50-year return period central pressures.
7.6. Projected Wind Speeds for selected locations

To assess the impact of climate change on wind hazard, wind speeds are calculated for selected locations in China, Japan and Philippines and Korea. The mean recurrence interval of wind speeds for each climate scenario are plotted for selected locations of China and Korea in Figure 140, Japan in Figure 142 and Philippines in Figure 144. Comparing the wind speeds, there is increase in wind speeds in most of the locations due to increased temperatures. Guangxi, Guangzhou, Fuzhou, Hangzhou, Shanghai and Nanjing in China experience a significant increase in wind speeds under three RCP scenarios. However, impact of increased temperatures are minor in Nanjing. The wind speeds in Nanjing under RCP2.6 scenario are equivalent to wind speeds under RCP4.5 and RCP8.5. Increase in
wind speeds are relatively lower in Shandong and Shenyang under the three RCP scenarios. Daejeon, Kangwon-Do and Chongjin in Korea experience a lower impact due to increased temperatures. For regions in Japan like Kagoshima, Miyazaki, Kochi, Ise Grand Shrine, Shizuka, Yokohoma, Tokyo, Mito, Matsue and Nagasaki, all the RCP scenarios are observed to be causing a significant increase in wind speeds and the wind speed increase is proportional to the radioactive forcings. For locations like Sendai, Matsushima, Kamaishi, Aomori, Sapporo, Niigata and Noto peninsula, the impact of RCPs are relatively lower in the increase of wind speeds. Impact of poleward shift is minor in increase or decrease of wind speeds for all the locations. Wind speed projections of all the climate change scenarios for selected locations in Philippines are plotted in Figure 144. From the figures, the impact of climate change is significant in Philippines. The RCP emissions are observed to be causing a notable increase in the wind speeds and RCP8.5 is causing way higher increase in wind speeds than RCP2.6 and RCP4.5. Impact of RCP2.6 scenario is lower in locations like Manila, Tacloban and Chocolate hills. The wind speeds in these regions are almost equivalent to the wind speeds under current climate. Impact of poleward shift in minor in altering the wind speeds for all the regions.
Figure 140. Projections of 10min wind speeds of climate change scenarios for selected locations in Mainland.

Figure 141. Projected 10-min wind speeds for 100-year MRI for locations in China and Korea.
Figure 142. Projections of 10min wind speeds of climate change scenarios for selected locations in Japan.
Figure 143. Projected 10-min wind speeds for 100-year MRI for locations in Japan.
Figure 144. Projections of 10min wind speeds of climate change scenarios for selected locations in Philippines.
7.7. Genesis index

To investigate the influence of climate change on genesis activity, Tippet’s (2011) Poisson regress equation is used which is shown in equation 7.1

\[ \mu = \exp(b + b_\eta \eta + b_H H + b_T T + b_V V + \log\cos\phi) \]  \hspace{1cm} (7.1)

Where, \( \eta \) is absolute vorticity at 850mb, \( H \) is relative humidity at 600mb, \( T \) is relative SST and \( V \) is wind shear between 850mb and 200mb. \( \phi \) is latitude, \( b \) is constant and \( b_\eta, b_H, b_T, b_V \) are coefficients for vorticity, relative humidity, SST and wind shear respectively. Genesis index equation is used for modeling monthly genesis rate \( \mu \) per \( 5^0 \times 5^0 \).
7.8. Data Sources

Sea surface temperature data is obtained from MERRA. NCEP/NCAR reanalysis data provides 4-times daily, daily and monthly values global climate data since from 1948 to preset with a grid resolution $2.5^\circ\times2.5^\circ$. Relative humidity data at 600mb pressure level is used in this model. Wind shear is calculated using U-wind and V-wind data between 850mb and 200mb pressure levels. The procedure for calculating wind shear from U-wind and V-wind data is discussed in Fitzpatrick (1997). Vorticity data used in this model is obtained at 850mb. Monthly mean values of relative humidity, wind shear and Vorticity form NCEP/NCAR reanalysis data are shown in Appendix D.

7.9. Methodology

Monthly tropical cyclone genesis are simulated using the equation by substituting the monthly average values of the climate variables. The comparison between simulated and historical annual rates are plotted in Figure 146. Monthly genesis rate of storms generated using the equation 7.1 are compared with historical rates in Figure 147. Comparing the rates, Tippet’s genesis index provides a good estimate of the storm genesis number.

Monthly tropical cyclone genesis are simulated using the equation by substituting the monthly average values of the climate variables. The comparison between simulated and historical annual rates are plotted in Figure 146. Monthly genesis rate of storms generated using the equation 7.1 are compared with historical rates in Figure 147.
Comparing the rates, Tippet’s genesis index provides a good estimate of the storm genesis number.

Figure 146. Annual count comparison between historical storms and simulated storms using genesis index.
Typhoon tracks are simulated for 10000 years using the genesis index. The simulated tracks are validated by comparing the track parameters with historical storm parameters for selected locations in the coastal regions of China, Philippines, and Japan.

Figure 147. Comparison of monthly genesis rate of simulates storms with historical storms, bars show the 5-95 percentile rates of historical storms.

Figure 148. Approach rate comparison of storms simulated using genesis index with historical data in selected locations of China and Korea.
Influence of climate change on tropical cyclone genesis in analyzed by using the climate variables under RCP2.6, RCP4.5 and RCP8.5 in 2100. The future genesis number and spawn locations are sampled by substituting the environmental variables from three RCP emission scenarios in equation 5. The monthly average environmental variables of the three RCP scenarios obtained from GFDL are shown in Appendix D. The CDF plots for annual genesis count obtained by substituting the future environmental variables under
three RCP scenarios are shown in Figure 151. Figure 152 shows the monthly genesis rate of simulates storms under three RCP scenarios compared with monthly rates of historical storms. The CDF plots shows more storms are expected to happen under the radioactive emmission scenarios compared to current climate. However RCP4.5 shows relatively lower number of storms compared to RCP2.6 and RCP8.5. The reason for RCP2.6 predicting more storms than RCP4.5 can be attributed to higher relative humidity in RCP2.6 scenario. Figure 153 show the Kernel Density contours of historical storm locations. Figure 154 show the Kernel Density contours of simulated spawn locations using genesis index which is similar to the historical contours.

![Annual Count](image)

Figure 151. CDFs of annual genesis rates under three RCP scenarios.
Figure 152. Comparison of monthly genesis rate of simulates storms under three RCP scenarios with those of historical storms.

Figure 153. Kernel Density contours of historical genesis locations.
Figure 154. Kernel Density contours of simulated genesis locations using genesis index.

7.10. Changes in Approach Rates

10000-year storm tracks are simulated for each RCP scenario. Annual approach rates are calculated for selected locations in Japan, Philippines, China, and Korea by counting the number of storms passing within 250km radius from each selected location. Approach rates calculated for all the RCP scenarios to assess the changes compared to the baseline model. Figure 155 to Figure 157 to shows the annual approach rates comparison all the climate scenario for locations in China, Korea, Japan, and Philippines. From the comparisons, RCP2.6 makes more storms to hit these countries than RCP4.5 due to high genesis rate. RCP8.5 predicts the highest number of storms to hit these countries.
Figure 155. Projected approach rates for the three RCP scenarios for locations in China and Korea.

Figure 156. Projected approach rates for the three RCP scenarios for locations in Japan.
Figure 157. Projected approach rates for the three RCP scenarios for locations in Philippines.

7.11. Wind Speed Projections

The mean recurrence interval of wind speeds for each climate scenario are analyzed for selection locations in China, Korea, Japan and Philippines. Return period curves are plotted for selected locations of China and Kora in in Figure 158. From the figures the wind speeds increase with increased radioactive emissions. Percentage increase in 100-year return period wind speeds in selected key cities in China and Korea are plotted in Figure 160. The highest impact of climate change is observed in Guangxi with 40% increase in wind speeds under RCP2.6, 60% increase under RCP4.5 and 100 percent increase under RCP8.5. Kangwon-Do experience the least impact due to climate change with rise in wind speeds ranging from 0-10%. Return period curves under three RCP scenarios for selected locations in Japan are shown in Figure 161 and Figure 164. From the curves, three emission scenarios show significant increase in wind speeds and the impact increase with warming climate scenarios. Figure 163 and Figure 166 show the percentage changes 100-year return
period wind speeds under three scenarios for key cities selected in Japan and Philippines respectively. Sapporo in Japan experience the highest impact of climate change with increase in wind speeds ranging between 20-50% where as Kamaishi experience the lease impact with 5-25% increase in wind speeds. Calapan in Philippines experience the highest impact with 17-40% rise in wind speeds whereas Tacloban experience the lowest with 50%-30% increase in wind speed. Under RCP2.6 scenario, Philippines experience the lowest 5%-10% increase, Korea and Japan experience medium 5%-20% increase and China experience the highest 30%-40% increase in wind speeds. Under RCP4.5 scenario, Korea experience the lowest 0%-17% increase, Japan and Philippines experience medium 10%-30% increase and China experience the highest 10%-60% increase in wind speeds. Under RCP8.5 scenario, Korea experience the lowest 10%-30% increase, Japan and Philippines experience medium 25%-50% increase and China experience the highest 40%-100% increase in wind speeds.
Figure 158. Projections of 10min wind speeds of climate change scenarios for selected locations in China and Korea.
Figure 159. Projected 10-min wind speeds for 100-year MRI for locations in China and Korea.

Figure 160. Percentage change in 100-year return period wind speeds under three RCP scenarios in selected key locations of China and Korea.
Figure 161. Projections of 10min wind speeds of climate change scenarios for selected locations in Japan.
Figure 162. Projected 10-min wind speeds for 100-year MRI for locations in Japan.

Figure 163. Percentage change in 100-year return period wind speeds under three RCP scenarios in selected key locations of Japan.
Figure 164. Projections of 10min wind speeds of climate change scenarios for selected locations in Philippines.
Figure 165. Projected 10-min wind speeds for 100-year MRI for locations in Philippines.

Figure 166. Percentage change in 100-year return period wind speeds under three RCP scenarios in selected key locations of Philippines.
8. SUMMARY AND CONCLUSIONS

An improved track model for typhoons in Asia is developed which could be used for simulating long-term typhoon track database. A methodology is presented for fitting the coefficients of typhoon track and relative intensity models to obtain geographically dependent model parameters using GWR method. The track model is simplified using GWR approach which accounts for spatial behavior of the track parameters. New storm decay rate functions after landfall are derived individually for Japan, Philippines as well as mainland of Asia. New regression equations are established for radius of maximum winds and Holland B parameter and GWR method is also adopted for RMW and B parameter models. Each module in the simulation model is assessed for its performance by re-simulating the historical storms taking its initial conditions as input. Storm track database is simulated for 10000-year using the simulation model and using atmospheric data as predictors. The distribution of simulated storm tracks resembled with historical storm tracks. Performance of the model is assessed by comparing the frequency distribution of simulated tracks with historical tracks in locations selected in coastal regions. Also, the distribution of storm parameters is compared in these selected locations and key cities in mainland Asia, Japan, Philippines and Taiwan. There is a good agreement observed between the distribution of frequency and track parameters in these selected locations.

The simulated track database is used to generate wind hazard database for coastal regions of Asia. Variable resolution grids are generated for coastal regions with \(0.02^\circ\times0.02^\circ\) resolution within 30km from the coastline, \(0.05^\circ\times0.05^\circ\) resolution from 30km to 200km and \(0.1^\circ\times0.1^\circ\) beyond 200km from coastline in mainland, Japan, Philippines and
Taiwan making approximately 200,000 locations. Wind speeds are calculated for each of these locations using the simulated track database. These wind speeds can be used to generate mean recurrence interval curves for any given location. The wind field model is validated by comparing the wind speeds calculated for historical storms with data obtained from H*wind and Global Surface summary of the day (GSOD).

To assess the impact of climate change on typhoon activity in Asia, sea surface temperature projections by Representative Concentrated Pathways (RCP) are incorporated in the typhoon simulation model. The sea surface temperature projections by RCP2.6, RCP4.5 and RCP8.5 scenarios combined with poleward shift of typhoon genesis is analyzed in this study. Sensitivity study of poleward shift of storm genesis is performed. Twelve different climate change scenarios with combinations of poleward shift and RCPs are analyzed to understand the impact of these scenarios on typhoon activity in Asia. 10000-year typhoon track databases are generated using the twelve climate change scenarios and compared with the typhoon activity under current climate condition. Changes in annual approach rates of typhoons under multiple climate change scenarios are calculated. Wind speeds are calculated using each climate change scenario for multiple locations in the coast of Asia. The return period curves under three emission scenarios show an increase in wind speeds with increase in radioactive forcings in most of the locations. Poleward shift has shown negligible impact on the wind speeds in all regions.

To investigate the influence of environmental variables on genesis activity, a genesis index regression equation is considered with sea surface temperature, relative humidity, wind shear and absolute vorticity as inputs. Influence of climate change on
genesis activity is estimated by substituting the environmental variables from RCP2.6, RCP4.5 and RCP8.5 in year 2100 in the genesis index equation. New track databases are generated by incorporating the genesis index and using the sea surface temperature in relative intensity model under RCP2.6, RCP4.5 and RCP8.5 scenarios. Wind speeds are calculated for selected locations in the coast of China, Korea, Japan and Philippines. 100-year return period wind speeds are compared with wind speed under current climate. From the comparisons, Philippines experience the lowest 5%-10% increase, Korea and Japan experience medium 5%-20% increase and China experience the highest 30%-40% increase in wind speeds under RCP2.6 scenario. Korea experience the lowest 0%-17% increase under RCP4.5 and 10%-30% increase under RCP8.5 scenario. Japan and Philippines experience medium 10%-30% increase under RCP4.5 and 25%-50% increase under RCP8.5 scenarios. China experience the highest 10%-60% increase in wind speeds under RCP4.5 scenario and 40%-100% increase in wind speeds under RCP8.5 scenario.
9. RESEARCH LIMITATIONS AND RECOMMENDATIONS FOR FUTURE WORK

In the current study, sea surface temperature is considered in modeling the relative intensity whereas there can be other environmental factors effecting the relative intensity like relative humidity, wind shear etc. So, it is recommended to consider relative intensity and wind shear in relative intensity model. Only wind component is estimated in the current study for estimating the typhoon hazard in coastal regions of Asia. The track database can be used for estimating storm surge and rainfall hazard due to typhoons in coast of Asia. This require developing rainfall and storm surge models for Asia Pacific basin. Another recommendation for future work is estimating the economic losses considering the damage due to typhoon winds in coastal locations. The losses can be estimated more accurately by considering the typhoon induced storm surge and rainfall.

In the current study, the effects of climate change considered are genesis, approach rates and typhoon intensities. There are other effects of climate change such as impact of climate change on typhoon tracks, storm surge and rainfall and developing a wind database for different RCP scenarios. Change in sea surface temperature is the only factor of climate change used in relative intensity model Other factors such as changes in relative humidity, wind shear can be considered for climate change study. The climate change study can be used for quantifying the losses due to typhoon influence by future climate.
Appendix A

Each site in the study domain has its own set of coefficients which can be mapped over the domain to observe pattern of each coefficient. Coefficient patterns on the domain for track, relative intensity, Rmax and Holland B parameter models are shown in figures. The mean and standard deviations of error for each model are mapped to demonstrate the sites where the model is over predicting and under predicting the parameters.
Figure 167. Coefficients of track model for heading direction mapped over the study domain.

Figure 168. Error parameters for heading direction mapped over the study domain.
Figure 169. Coefficients of relative intensity model mapped over the study domain.

Figure 170. Error parameters of relative intensity model mapped over the study domain.
Figure 171. Coefficients of RMW model mapped over the study domain.

Figure 172. Error parameters of RMW model mapped over the study domain.
Figure 173. Coefficients of Holland B parameter model mapped over the study domain.

Figure 174. Error parameters of Holland B parameter model mapped over the study domain.
Appendix B

The scatter plots of modeled errors of translational speed and heading angles of selected locations are shown. The dispersion of error has shown no trend indicating the randomly distributed errors and the mean of the error is closer to zero. The dispersion of the modeled and observed values of forward speed and heading angles of few locations are plotted in the figures below.

Figure 175. Dispersion of modeled and observed values of logarithmic change of forward speeds (left) changing in heading angles (right) for Westward moving storms at 10°N and 114°E
Figure 176. Dispersion of modeled and observed values of logarithmic change of forward speeds (left) changing in heading angles (right) for Westward moving storms at 15°N and 138°E.

Figure 177. Dispersion of modeled and observed values of logarithmic change of forward speeds (left) changing in heading angles (right) for Westward moving storms at 16°N and 113°E.
Figure 178. Dispersion of modeled and observed values of logarithmic change of forward speeds (left) changing in heading angles (right) for Westward moving storms at 17°N and 123°E.

Figure 179. Dispersion of modeled and observed values of logarithmic change of forward speeds (left) changing in heading angles (right) for Westward moving storms at 19°N and 137°E.
Figure 180. Dispersion of modeled and observed values of logarithmic change of forward speeds (left) changing in heading angles (right) for Westward moving storms at 20°N and 127°E.

Figure 181. Dispersion of modeled and observed values of logarithmic change of forward speeds (left) changing in heading angles (right) for Westward moving storms at 22°N and 135°E.
Figure 182. Dispersion of modeled and observed values of logarithmic change of forward speeds (left) changing in heading angles (right) for Eastward moving storms at 35°N and 131°E.

Figure 183. Dispersion of modeled and observed values of logarithmic change of forward speeds (left) changing in heading angles (right) for Eastward moving storms at 34°N and 132°E.
Relative Intensity Model Plots

The dispersion of the modeled and observed values of relative intensities are plotted for selected locations.

Figure 184. Dispersion of modeled and observed values of logarithmic change of forward speeds (left) changing in heading angles (right) for Eastward moving storms at 35°N and 138°E.

Figure 185. Dispersion of modeled and observed values of Relative Intensity (left), Error dispersion of Relative Intensity (right) at 15°N and 118°E.
Figure 186. Dispersion of modeled and observed values of Relative Intensity (left), Error dispersion of Relative Intensity (right) at 18°N and 123°E.

Figure 187. Dispersion of modeled and observed values of Relative Intensity (left), Error dispersion of Relative Intensity (right) at 20°N and 118°E.
Figure 188. Dispersion of modeled and observed values of Relative Intensity (left), Error dispersion of Relative Intensity (right) at 21°N and 145°E.

Figure 189. Dispersion of modeled and observed values of Relative Intensity (left), Error dispersion of Relative Intensity (right) at 22°N and 134°E.
Figure 190. Dispersion of modeled and observed values of Relative Intensity (left), Error dispersion of Relative Intensity (right) at 25°N and 144°E.

Figure 191. Dispersion of modeled and observed values of Relative Intensity (left), Error dispersion of Relative Intensity (right) at 28°N and 125°E.
Figure 192. Dispersion of modeled and observed values of Relative Intensity (left), Error dispersion of Relative Intensity (right) at 30°N and 128°E.

Figure 193. Dispersion of modeled and observed values of Relative Intensity (left), Error dispersion of Relative Intensity (right) at 33°N and 134°E.
Figure 194. Dispersion of modeled and observed values of Relative Intensity(left), Error dispersion of Relative Intensity (right) at 36°N and 145°E.

Radius of Maximum Wind Plots for selected locations

The scatter plots of the modeled and observed values of logarithmic RMW plotted against central pressure difference and logarithmic RMW of previous time steps are shown in figures below.

Figure 195. Dispersion of modeled and observed values of log(Rmax)(left), Error dispersion of H log(Rmax) (right) at 8°N and 140°E.
Figure 196. Dispersion of modeled and observed values of log(Rmax) (left), Error dispersion of H log(Rmax) (right) at 10°N and 134°E.

Figure 197. Dispersion of modeled and observed values of log(Rmax) (left), Error dispersion of H log(Rmax) (right) at 12°N and 126°E.

Figure 198. Dispersion of modeled and observed values of log(Rmax) (left), Error dispersion of H log(Rmax) (right) at 14°N and 128°E.
Figure 199. Dispersion of modeled and observed values of log(Rmax)(left), Error dispersion of H log(Rmax) (right) at 16°N and 138°E.

Figure 200. Dispersion of modeled and observed values of log(Rmax)(left), Error dispersion of H log(Rmax) (right) at 18°N and 130°E.

Figure 201. Dispersion of modeled and observed values of log(Rmax)(left), Error dispersion of H log(Rmax) (right) at 20°N and 132°E.
Figure 202. Dispersion of modeled and observed values of log(Rmax) (left), Error dispersion of $H \log(Rmax)$ (right) at 22°N and 142°E.

Figure 203. Dispersion of modeled and observed values of log(Rmax) (left), Error dispersion of $H \log(Rmax)$ (right) at 26°N and 138°E.

Figure 204. Dispersion of modeled and observed values of log(Rmax) (left), Error dispersion of $H \log(Rmax)$ (right) at 30°N and 144°E.

Holland B parameter model plots for selected locations

The scatter plots of the modeled and observed values of B parameters plotted against square root of A are shown in the figures below.
Figure 205. Dispersion of modeled and observed values of Holland B parameter (left), Error dispersion of Holland B parameter (right) at 134°E and 8°N.

Figure 206. Dispersion of modeled and observed values of Holland B parameter (left), Error dispersion of Holland B parameter (right) at 134°E and 18°N.

Figure 207. Dispersion of modeled and observed values of Holland B parameter (left), Error dispersion of Holland B parameter (right) at 114°E and 22°N.
Figure 208. Dispersion of modeled and observed values of Holland B parameter (left), Error dispersion of Holland B parameter (right) at 128°E and 24°N.

Figure 209. Dispersion of modeled and observed values of Holland B parameter (left), Error dispersion of Holland B parameter (right) at 140°E and 24°N.

Figure 210. Dispersion of modeled and observed values of Holland B parameter (left), Error dispersion of Holland B parameter (right) at 138°E and 26°N.
Figure 211. Dispersion of modeled and observed values of Holland B parameter(left), Error dispersion of Holland B parameter(right) at 132°E and 28°N.

Figure 212. Dispersion of modeled and observed values of Holland B parameter(left), Error dispersion of Holland B parameter(right) at 136°E and 30°N.

Figure 213. Dispersion of modeled and observed values of Holland B parameter(left), Error dispersion of Holland B parameter(right) at 148°E and 38°N.
Figure 214. Dispersion of modeled and observed values of Holland B parameter (left), Error dispersion of Holland B parameter (right) at 158°E and 32°N.
Appendix C

Figures show $\text{SST}_{\text{RCP}}/\text{SST}_{\text{MERRA}}$, comparing the sea surface temperature projections under four RCP scenarios to MERRA monthly mean SST data.

Figure 215. $\text{SST}_{\text{RCP26(2100)}}/\text{SST}_{\text{MERRA}}$
Figure 216. $\text{SST}_{\text{RCP4.5(2100)}} / \text{SST}_{\text{MERRA}}$. 
Figure 217. $\text{SST}_{\text{RCP8.5(2100)}}/\text{SST}_{\text{MERRA}}$
Appendix D

Figures show the environmental variable under three RCP scenarios in 2100 used for modeling genesis index.

Figure 218. Monthly average relative humidity at 600mb pressure level for Asia basin.
Figure 219. Monthly average wind shear between 850mb and 200mb for Asia basin (m/s).

Figure 220. Monthly average vorticity at 850mb pressure level for Asia basin (m/s).
Figure 221. Monthly average Relative humidity at 600mb pressure level under RCP2.6 scenario in 2100 for Asia basin.

Figure 222. Monthly average Relative humidity at 600mb pressure level under RCP4.5 scenario in 2100 for Asia basin.
Figure 223. Monthly average Relative humidity at 600mb pressure level under RCP8.5 scenario in 2100 for Asia basin.

Figure 224. Monthly average Wind shear between 850mb and 250mb pressure levels under RCP2.6 scenario in 2100 for Asia basin.
Figure 225. Monthly average wind shear between 850mb and 250mb pressure levels under RCP4.5 scenario in 2100 for Asia basin.

Figure 226. Monthly average wind shear between 850mb and 250mb pressure levels under RCP8.5 scenario in 2100 for Asia basin.
Appendix E

Assessment of typhoon track model is performed by examining more historical storm tracks. To inspect the performance of the track model, possible 3-day tracks are simulated using the track coefficients for selected historical storms which are shown in the figures below.

Figure 227. Eve 1996.
Figure 228. Krosa 2001.

Figure 229. Lingling 2001.
Figure 230. Mitag 2002.

Figure 231. Rammasun 2002.
Figure 232. Koppu 2015.

Figure 233. Tokage 2016.
Figure 234. Damrey 2017.

Figure 235. Prapiroon 2018.
Figure 236. Maria 2018.
Appendix F

Performance of central pressure model is assessed by simulating the central pressure of historic tracks. Typhoon time histories of central pressures for more historical storms are selected to perform the assessment of central pressure model.

Figure 237. Yuri 1991.
Figure 238. Linfa 2015.

Figure 239. Fung-Wong 2014.
Figure 240. Tokage 2016.

Figure 241. Haikui 2017.
Figure 242. Mawar 2017.

Figure 243. Nesat 2017.
Appendix G

Performance of radius of maximum wind model is assessed by simulating the RMW of historic tracks. Typhoon time histories of RMW for more historical storms are selected to perform the assessment of RMW model.

Figure 244. Lupit 2009.
Figure 245. Khanun 2012.

Figure 246. Jelawat 2012.
Figure 247. Pabuk 2013.

Figure 248. Haiyan 2013.
Figure 249. Halong 2014.

Figure 250. Kompasu 2016.
Figure 251. Tokage 2016.

Figure 252. Mawar 2017.
Figure 253. Haikui 2017.
Appendix H

Performance of Holland B parameter model is assessed by simulating the B parameter of historic tracks. Typhoon time histories of B parameter for more historical storms are selected to perform the assessment of B parameter model.

Figure 254. Kalmaegi 2014.
Figure 255. Nuri 2014.

Figure 256. Krovanh 2015.
Figure 257. Champi 2015.

Figure 258. Sarika 2016.
Figure 259. Haima 2016.

Figure 260. Merbok 2017.
Figure 261. Talas 2017.

Figure 262. Haikui 2017.
Figure 263. Maria 2018.
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