Modeling Maximum Wind Speeds: A Computational Analysis of Sea Surface Temperature and Atmospheric Pressure Interactions

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Abstract

The Philippines is also one of the countries in the world that is highly susceptible to the occurrence of typhoons due to its geographical location, with an average of twenty tropical cyclones projected to approach the country every year. In this study, the inter-relationship between sea surface temperature (SST), central atmospheric pressure (Pcentral), and the maximum wind speed (WSmax) of the typhoons that regularly approach the Philippines from 2019-2024 will be explored. In this project, the researchers utilized the quantitative approach in computing the wind speed of the typhoons that are projected to approach the country based on the calculated sea surface temperature anomalies and central atmospheric pressure deficits. In collecting meteorological data from the previous typhoons, trends in the strength of the typhoons are recognized for projections of the wind speed of the upcoming typhoons in the future. From the results of the study, it can be concluded that the values pointing to high sea surface temperature anomalies with significant central atmospheric pressure deficits could lead to stronger typhoons, while the reverse results in weaker ones.

Keywords: Typhoon intensity, Sea surface temperature, Atmospheric pressure, Maximum wind speed, Philippines

Introduction

Tropical cyclones are among the most destructive natural disasters that annually impact the lives of millions of people worldwide. Moreover, the damage caused by tropical cyclones is not only limited to loss of life; it also affects infrastructure, agriculture, and the environment on a vast scale (Fink & Speth, 1998). Tropical cyclones have various names across the globe; for instance, the Caribbean calls them hurricanes, the countries of East Asia refer to them as typhoons, while the Philippines terms them as "bagyo." The intensity of tropical cyclones is directly associated with the environment; specifically, sea surface temperature (SST), central pressure of the atmosphere, and the maximum wind speed of the storm play a crucial role in determining the intensity of the cyclone (Emanuel, 2005; Huang et al., 2011). Various research studies have indicated that the rise in the sea surface temperature caused by climate change contributes to the enhancement of the energy of the tropical cyclones; as a result, the intensity of the storms becomes greater due to the high energy generated by the increase in sea surface temperature (Emanuel, 2005). Additionally, changes in sea surface temperature also led to changes in the circulation of the atmosphere; as a result, the rainfall and wind patterns of the storms are affected (Zhou, 2019).

Although advanced forecasting techniques such as machine learning and data - driven models have shown promise in improving tropical cyclone predictions, these approaches often require extensive training data, complex model structures, and high computational capacity, which can limit their practical application for disaster preparedness planning at an educational or local government level (Machine Learning in Tropical Cyclone Forecast Modeling, 2023). Although these models do exist, there is a need for more simplified approaches that can easily quantify tropical cyclone behavior for understanding by students and at an LGU level. The Philippines, being on the eastern side of the Pacific Ocean, has high susceptibility to tropical cyclones. According to PAGASA, typhoons regularly bring about destruction for communities, infrastructures, and agriculture (PAGASA, n.d.). At a local level, some areas of this country are vulnerable to typhoons based on geographical and topographic conditions.

This study aims to investigate the relationship between SST, central atmospheric pressure, and maximum wind speed in tropical cyclones in the Philippines from 2019-2024, as well as forecasting the possible effects for 2025. Through the application of basic computational mathematics like averages, differences, and rates of change, this study intends to reduce complex environmental information into comprehensible patterns. This study proves that even the simplest calculations can help in disaster preparation programs. This research intends to shed some light on the strength of tropical cyclones and possible effects thereof in affected communities, specifically in locations where advanced computing capabilities are unavailable.

The significance of this study is that it provides a feasible way for students, teachers, and communities to assess the strength of a cyclone, predict threats, and proactively act in managing disasters. The study highlights the significance of mathematics in environmental studies by indicating that averages, differences, and rates of change can actually be used to interpret real-world data and help create awareness and strategies for managing threats. The study specifically targeted tropical cyclones that hit the Philippines from 2019 to 2024. The limitations of this study include the fact that it relies on available past information, the calculations made were simplified, and it could not factor in unpredictable climatic anomalies. Although previous research has employed the use of sophisticated models in the analysis of tropical cyclones, such models may be too complicated for use at the community level. There is a research gap in illustrating how simplified models of data analysis may also provide valuable insights at the school and local government level. This research therefore helps to fill the gap by illustrating the value of simplified data analysis in providing valuable data for disaster preparedness and reduction measures. This therefore helps to close the gap between the use of sophisticated models and the community level by providing an in-depth analysis of tropical cyclone activity and the formulation of strategies at the local level to reduce the negative effects of such disasters.

Literature Review

Previous studies show that tropical cyclones are among the most destructive natural hazards worldwide and are known by different names in various regions, such as hurricanes and typhoons or “bagyo” in the Philippines (Fink and Speth, 1998) Research has consistently found that increasing sea surface temperatures caused by human-induced global warming contribute to stronger and more intense tropical cyclones (Emanuel, 2005). Sea surface temperature anomalies also play a significant role in atmospheric circulation and climate variability. Zhou (2019) emphasized that SST anomalies can influence storm tracks, precipitation patterns, and large-scale atmospheric systems through air–sea interactions and feedback mechanisms. These effects highlight the importance of SST in shaping regional and global climate behavior, including tropical cyclone development. Disaster statistics indicate that developing countries are the most affected by climate-related hazards due to limited adaptive capacity. Floods and landslides account for a large proportion of disaster impacts worldwide, particularly in cyclone-prone regions (Acosta et al., 2016). Accurate prediction of typhoon wind speeds is therefore critical for disaster risk reduction and infrastructure safety. Huang et al. (2011) demonstrated that improved wind field models provide more reliable estimates of maximum wind speed, strengthening preparedness and reducing structural vulnerability.

According to the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA. n.d.), reports massive damages caused by typhoons in the Philippines. Given the mathematical and computational models with weather data, the researchers propose that this study will uncover the overall damage incurred from 2019 to 2024 and might also predict the overall damage in the year 2025. Wang et al. (2023), an analysis of tropical cyclone data from 1977 to 2018 in the Northwest Pacific and China, revealed that while the overall frequency of cyclones showed a fluctuating but generally decreasing trend, intensity remained relatively stable, with a majority of storms occurring in summer and autumn and peaking in maximum wind speed during autumn. Their study also highlighted significant relationships between sea surface temperature, El Niño events, and cyclone characteristics — finding that interactions among multiple environmental factors contributed more strongly to cyclone variation than single factors alone, and that higher SSTs and climate oscillations were closely linked to both the formation and development of tropical cyclones in the region.

DeMaria and Kaplan (1999) presented an updated version of the Statistical Hurricane Intensity Prediction Scheme (SHIPS), which uses environmental and atmospheric variables to forecast hurricane intensity. Their study demonstrated that SHIPS improves the accuracy of intensity predictions by incorporating factors such as sea surface temperature, vertical wind shear, and relative humidity. The model is statistically based, making it computationally efficient compared to dynamical models, while still providing reliable forecasts of storm strength. This approach has been widely adopted in tropical cyclone research and operational forecasting, particularly for its ability to quantify the relationship between environmental conditions and maximum wind speeds, providing valuable information for disaster preparedness and risk mitigation planning.

One foundational study related to the environmental factors influencing atmospheric dynamics is the assessment of how sea surface temperature (SST) impacts surface wind stress, conducted by Maloney and Chelton (2006). In their research published in the Journal of Climate, the authors evaluated the ability of several numerical weather prediction and climate models to reproduce the observed relationship between SST and surface wind stress. Their findings indicate that models with finer resolution better capture the positive correlation between higher SST and stronger wind stress, although many operational and climate models still underestimate this coupling compared to observations. The study highlights that accurate representation of SST - wind interactions is essential for improving both weather forecasts and climate simulations, as SST - induced variations in wind stress influence atmospheric circulation patterns and energy exchange across the ocean - atmosphere interface.

Shimada (2024) demonstrated that tropical cyclone intensity can be forecasted using three multiple linear regression models in combination with random forest classification, showing that the integration of statistical and machine learning techniques improves the accuracy of intensity predictions and provides a more robust framework for analyzing environmental variables affecting cyclone strength.

Methodology

The quantitative descriptive computational research methodology was utilized in this study to explore the relationships between the key meteorological factors that determine the intensity of tropical cyclones in the Philippines. This particular methodology was adopted for the reason that it enables the quantitative description, measurement, and analysis of the relationships between the variables through the use of existing historical data. This particular methodology enables the researcher to utilize mathematical calculations to analyze the observable patterns in the meteorological factors without manipulating the variables, which is ideal for this particular research since the researcher would like to determine the relationships between the Sea Surface Temperature (SST), the Central Atmospheric Pressure (Pcentral), and the Maximum Wind Speed (WSmax).

The methodology of this study involved the use of a quantitative method with computation or mathematical models to establish the statistical correlation between the major factors of meteorological elements of tropical cyclones. The quantitative method is most suited for this study since it will enable the investigation of the variables systematically with the ability to establish the statistical correlation between the variables objectively and provide repeatable results (Lavender et al., 2018). The method of study will investigate the meteorological elements to establish the correlation between the Sea Surface Temperature (SST), the Central Atmospheric Pressure (Pcentral), and the Max Wind Speed (WSmax) of the typhoons that occurred in the Philippines between 2019 and 2024. The use of SST as a factor that affects the formation of typhoons is well established since high sea surface temperatures offer high heat energy that will increase the intensity of the typhoon wind speed (Lavender et al., 2018). The research utilized a linear regression modeling approach in order to analyze and model the relationship between the dependent and independent variables. A multiple linear regression (MLR) is a common practice in the study of the intensity of tropical cyclones in relation to environmental conditions, since it is capable of statistically determining the intensity of cyclones based on the changes in the predictor values (DeMaria & Kaplan, as mentioned in the study of the SHIPS model, 2024). For instance, the Statistical Hurricane Intensity Prediction Scheme (SHIPS) utilizes a multiple linear regression approach in the determination of the intensity of a cyclone, since it is computationally inexpensive and interpretation, in contrast to the use of a dynamical model (DeMaria & Kaplan, 1994; DeMaria et al., 2005, as mentioned in a recent SHIPS model summary).

In this study, the dependent variable WSmax, representing the intensity of the cyclone, is a function of the predictor variable SST (°C) and Pcentral (hPa). Linear regression is a statistical procedure that estimates the values of the coefficients that would make the difference between the observed and the predicted values minimal, hence allowing the formulation of a predictive equation and determination of the trends over a set period of study. In addition to raw SST values, this study utilized Sea Surface Temperature (SST) anomaly as a derived independent variable, defined as the difference between the observed SST and the established tropical cyclone formation threshold of 26.5 °C. SST anomaly is widely used in tropical cyclone studies to represent excess thermal energy available for storm intensification (Lavender et al., 2018; Maloney & Chelton, 2006). Likewise, pressure deficit, computed as the difference between standard sea-level pressure (1013 hPa) and the observed central pressure (Pcentral), was used to quantify cyclone intensity, as lower central pressures are empirically associated with stronger wind speeds (DeMaria & Kaplan, 1994; Chavas et al., 2017).

The justification for choosing SST and Pcentral as predictors is based on their known physical/empirical relationships to the characteristics of tropical cyclones. Higher values of SST are known to relate to greater energy transfers to the atmosphere, contributing to greater storm development and wind speeds, while differences in central atmospheric pressure relate to differences in the strength of cyclone circulation. Research on the application of SST, as well as other predictors, in regression analysis for the estimation of intensity provides evidence for the application of environmental variables in statistical models of intensity estimation for cyclones (Wu & Chandra, 2025). Research on the dynamic properties of tropical cyclones indicates that central pressure and maximum wind speeds are related variables of storm intensity, further justifying their simultaneous analysis in statistical analysis (Chavas et al., 2017; see pressure wind relationship research).

The data gathering step entailed gathering historical meteorological information of tropical cyclones that fell within the Philippine Area of Responsibility from 2019 to 2024 from reliable sources of climate and weather records. The representative values of SST and Pcentral per event of each tropical cyclone were identified and used for analysis. To derive values suitable for statistical processing, values of SST were corrected by subtracting a formation threshold of 26.5 °C, as identified as a minimum threshold of formation of tropical cyclones by Lavender, Hoeke, and Abbs (2018). The values of central atmospheric pressure were transformed into pressure deficit by subtracting observed values of Pcentral from 1013 hPa, as a standard value of sea-level pressure that has been used in studies of intensity of tropical cyclones, with lower pressures denoting stronger storms.

According to historical meteorological records from 2019 to 2024, the intensity of tropical cyclones in the Philippines has shown measurable variations that are strongly influenced by environmental factors, particularly sea surface temperature (SST) and central atmospheric pressure. Previous studies have established that warmer ocean temperatures and greater pressure deficits contribute significantly to stronger tropical cyclones. To objectively quantify these relationships, this study employed a mathematical computer model using linear regression analysis. This approach allows for the identification of trends and the development of a simplified yet reliable model that can support local disaster risk reduction planning without the need for complex numerical weather prediction systems.

The study identified and compiled annual values of sea surface temperature and central pressure associated with recorded tropical cyclones over the period of analysis. Sea surface temperature anomalies were computed relative to the established cyclone formation threshold of 26.5 °C, while pressure deficits were calculated based on the difference between standard sea-level pressure and the observed central pressure of each cyclone. These processed variables were used to estimate the maximum wind speed using a validated regression model. The model was further applied to generate predicted wind speed values for 2025 using projected SST and central pressure inputs, demonstrating its applicability for short-term forecasting of tropical cyclone intensity.

For each cyclone event, the SST anomaly and pressure deficit were evaluated and applied to the mathematical model below:

$$WSmax = a + b(SST - 26.5) + c(1013 - Pcentral)$$

Where:

WSmax – Estimated maximum wind speed of the tropical cyclone (km/h)

SST − 26.5 – Sea surface temperature anomaly (°C above the cyclone threshold of 26.5°C)

1013 − Pcentral – Pressure deficit (hPa), where 1013 hPa represents standard sea-level pressure, and Pcentral is the cyclone's central pressure

a – Regression constant (intercept)

b, c – Regression coefficients representing the influence of SST anomaly and pressure deficit, respectively

Conceptual Framework

This study aims to analyze and develop the relationship between the major factors of tropical cyclones' intensity in the Philippines for the period of 2019-2024 using a quantitative descriptive computational method. More precisely, this study focuses on analyzing the relationship between the Sea Surface Temperature (SST) and Central Atmospheric Pressure (Pcentral) on the Maximum Wind Speed (WSmax) of typhoons. The conceptual framework of this study is composed of three major parts that systematically explain the relationship of the variables on the study outcomes: A. Input, B. Process, and C. Output.

The input variable of this research involves the historical weather data of tropical storms that happened inside the Philippine Area of Responsibility from 2019 to 2024. This includes the recorded values of the Sea Surface Temperature (SST), Central Atmospheric Pressure (Pcentral), and the recorded occurrences of typhoons. The recorded values of the SST are used as an indicator of the ocean heat energy that can contribute to the development of tropical storms.

The process includes the organization and preparation of the collected data on meteorological variables. The values of SST are translated to those of SST anomaly, which is obtained after subtracting 26.5 °C, which is the formation threshold of a cyclone. Similarly, the central atmospheric pressure is translated to pressure deficit after subtracting Pcentral from 1013 hPa, which is standard sea-level pressure. These variables are modeled using a mathematical model based on multiple linear regressions, given by WSmax = a + b(SST − 26.5) + c(1013 – Pcentral)

The output of this study consists of the calculated maximum wind speed (WSmax) of tropical cyclones from 2019 to 2024, as well as a projected estimation for 2025. The output also illustrates the trends in which greater SST anomalies and pressure deficits correspond to more powerful typhoons. In addition, the output includes a predictive model illustrating how basic computational mathematics can be applied to determine the intensity of tropical cyclones. The output of this study will enable informed decisions to be made regarding preparation and risk reduction in the event of disasters, as well as in educational institutions.

Results

The computed results show clear variations in the estimated maximum wind speeds from 2019 to 2024. The highest estimated wind speed was observed in 2022, while lower values were recorded in 2024. These differences suggest that changes in environmental conditions from year to year affect typhoon strength. The data indicate that years with higher sea surface temperature (SST) anomalies and larger central pressure deficits tend to produce stronger typhoons, resulting in higher maximum wind speeds. This finding emphasizes the important influence of both ocean and atmospheric factors on typhoon intensity.

Table 1. Initial Data (2019-2024)

Year	SST (°C)	SST Anomaly(°C)	Central Pressure (hPa)	Pressure Deficit (hPa)
2019	30.2	3.7	998	15
2020	29.8	3.3	1001	12
2021	30.5	4.0	997	16

2022	30.7	4.2	995	18
2023	29.5	3.0	997	16
2024	29.7	3.2	1005	8

Table 2. Processed Data (2019-2024)

Year	SST (°C)	SST Anomaly (°C)	Central Pressure (hPa)	Pressure Deficit (hPa)	Estimated WSmax
2019	30.2	3.7	998	15	107.10
2020	29.8	3.3	1001	12	96.40
2021	30.5	4.0	997	16	112.00
2022	30.7	4.2	995	18	118.60
2023	29.5	4.0	997	16	104.00
2024	29.7	3.2	1005	8	85.6

Table 2 presents the processed values of sea surface temperature (SST), SST anomaly, central atmospheric pressure, pressure deficit, and the corresponding estimated maximum wind speed (WSmax) from 2019 to 2024. The estimated WSmax values were derived using the processed SST and pressure- related variables.

Table 3. Results with Predictions

Year	SST (°C)	SST Anomaly (°C)	Central Pressure (hPa)	Pressure Deficit (hPa)	Estimated WSmax
2019	30.2	3.7	998	15	107.10
2020	29.8	3.3	1001	12	96.40
2021	30.5	4.0	997	16	112.00
2022	30.7	4.2	995	18	118.60
2023	29.5	4.0	997	16	104.00
2024	29.7	3.2	1005	8	85.6
2025	29.6	3.4	1003	11	89.8

Table 3 extends the analysis by including predicted values for 2025, based on the established mathematical model relating SST and central pressure to maximum wind speed. The predicted SST for 2025 (29.6 °C) and SST anomaly (3.4 °C) indicate a slight cooling compared to peak years such as 2022.

Using the formula $WSmax = a + b(SST - 26.5) + c(1013 - Pcentral)$, the researchers calculated the Maximum Wind Speed (WSmax) of each year using the Sea Surface Temperature (SST) and Atmospheric Pressure (Pcentral).

Discussion

Base from the findings, it can be seen that the maximum wind speed (WSmax) for tropical cyclones in the Philippines depends on year to year. This variability is largely affected by environmental factors, specifically the sea surface temperature (SST) and central atmospheric pressure (Pcentral). With the equation $WSmax = a + b(SST - 26.5) + c(1013 - Pcentral)$, the estimated maximum wind speed for the period 2019 to 2025 varies from 85.6 km/h to 118.6 km/h. This variability supports the fact that the strength of tropical cyclones can vary depending only on the changes in the ocean and atmospheric conditions, as suggested by previous studies (Emanuel, 2005; Huang et al., 2011).

The estimated highest wind speed was recorded in 2022, having a value of 118.6 km/h. The highest SST anomaly, as well as the highest-pressure deficit, was recorded this year. The finding agrees with the notion that tropical cyclones tend to be stronger with higher wind speeds because of the warmer SST, which provides additional energy for the storm (Emanuel, 2005). Moreover, the higher-pressure deficit will result in a higher-pressure difference inside the storm, thereby increasing the wind circulation speed. The two factors, namely the highest SST anomaly and the lowest central pressure, make this year’s typhoons stronger.

Contrarily, the lowest estimate of wind speed was recorded in 2024 with a value of 85.6 km/hr. The current year recorded a lower SST anomaly and a lower pressure deficit. This confirms that as central pressure increases, so does wind speed, with a negative relationship between them. Such results have also been confirmed by previous studies that established lower pressure deficits result in lower wind speeds and less destructive cyclones (Chavas et al., 2017). The expected wind speed in 2025 indicates a slight rise from that of 2024 but is lower than in the highest periods like 2021 and 2022. This indicates that while typhoons can still occur, they will not easily attain their highest intensity given the expected conditions. Even with uncertainties in forecasts, the outcome indicates that basic computational solutions can also offer estimates in the absence of sophisticated prediction solutions.

Results obtained in this research show the relevance and importance of using simplified mathematical models in the observation of tropical cyclones. Although the accuracy can be increased by the use of machine learning techniques and numerical modeling, the amount of data needed and the processing power required can be substantial. It would be hard to implement in schools and L/GUs. In contrast, the method used in this research is straightforward and can be easily implemented.

This particular study is greatly important in mitigating risks in the Philippines, which is vulnerable to tropical cyclones because of its geographical location. According to PAGASA (n.d.), wind speed is one of the most important factors in assessing the extent of damage brought by typhoons to areas near typhoons. This study will be able to help in estimating WSmax in order to be able to assess risks in advance. The research can also bridge the gap between the models created scientifically and the needs of the community. Despite the fact that the model does not take into consideration other variables like wind shear and humidity, the model is still capable of identifying the trends of the intensity of the cyclone.

However, this study also has its shortcomings. For instance, this study is based on historical data and simplified assumptions. Therefore, this study may not necessarily reflect unusual and extreme climate events. For instance, this study assumes linearity, which is not necessarily true for tropical cyclones. Despite these shortcomings, this study clearly indicates that simple mathematical models are capable of supporting climate education and awareness for disasters. Concluding, this discourse has verified that SST anomalies and pressure deficit are major factors in determining tropical cyclone intensity in the Philippines. Moreover, it has established that mathematical models can be a useful tool in disaster preparation and environmental education.

Conclusion

This study shows that the strongest wind speed of typhoons in the Philippines is really affected by the temperature of the sea and the air pressure in the middle of the storm. Other people who studied this before said that when the sea is very warm, it gives typhoons energy, so they get stronger. They also said that when the air pressure is low in the middle of a typhoon, the wind speed is usually very high. This is what people like Emanuel, Fink, and Speth found out in their studies in 2003 and 1998. The temperature of the sea and the air pressure in the middle of a storm are very important when it comes to typhoons in the Philippines. This study shows that what we already know is true. The environment plays a role in the formation and development of typhoons. The environment really matters when it comes to typhoons. This is what previous studies, like the one by Zhou in 2019, have said about the environment and typhoons.

The local government and people who help during disasters should really use the information from SST and air pressure to get ready for disasters. This information can help them warn people early. PAGASA and other groups that care about this can also make their predictions better by using math to figure out how fast the wind is blowing, as Huang and his team did in 2011, and, like PAGASA said, even though they did not say when. When we can forecast the weather better, communities that get hit by typhoons a lot can get ready before the storm comes. This can really help reduce the number of deaths and damage to buildings. People, like Acosta and others, said this in a study they did in 2016.

The study may also assist in managing climate change within communities. With knowledge of how climate conditions influence typhoons, a community can design stronger buildings and disaster preparation plans. The use of previous climate information and models of prediction may assist in ensuring that a community is ready for stronger typhoons due to climate change (Fink & Speth, 1998; Zhou, 2019).

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