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The Role of Applied Mathematics in Typhoon Hazard Assessment: From Statistical Models to Risk Prediction

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Abstract: Typhoons, as tropical cyclones occurring in the western Pacific, are one of the most destructive natural disasters, often causing severe impacts on coastal areas. With the gradual increase in typhoon intensity, predicting typhoon paths and their strengths is crucial to mitigate their threat to human lives and economic infrastructure. In recent years, the importance of applied mathematics, especially statistical modelling, in typhoon hazard assessment has become increasingly prominent. This paper discusses the application of statistical models such as extreme value theory, time series analysis and multiple regression analysis in typhoon risk prediction, aiming to reveal the key role of applied mathematics in typhoon disaster assessment, and to provide a theoretical basis for improving the accuracy of prediction and formulating effective response strategies. Through this study, it helps to improve the accuracy of typhoon track and intensity prediction, and provides scientific support for coping with the increasing typhoon disasters. In addition, this study provides an important theoretical basis and reference direction for relevant departments to formulate disaster prevention and mitigation strategies.

Keywords: Typhoon hazard assessment, Applied mathematics, Risk prediction.

1. Introduction

Typhoons, tropical cyclones occurring in the Western Pacific, are among the most destructive natural disasters, frequently affecting coastal regions. According to the World Meteorological Organization, there are approximately 85 tropical storms that develop over the world's warm tropical oceans every year. They will cause various kinds of damage due to strong winds and heavy rain. For instance, the severe Tropical Cyclone Debbie which made landfall at Airlie Beach, in North Queensland, Australia on 28 March 2017 affected many surrounding communities and caused widespread damage to homes, businesses, crops, and infrastructure. Unfortunately, 12 lives were lost as a result of this disaster. [1] In addition, Tropical Storm Harvey affected six million people in southern Texas in 2017, causing major transportation disruptions, while Typhoon Shanzhu impacted nearly three million people in China in 2018, resulting in a direct economic loss of 5.2 billion dollars. [2] Thus, it is clearly demonstrated that typhoons can happen over a wide area and cause damage to many countries. Typhoons affect a wide geographical area, including countries in the Western Pacific such as Japan, the Philippines, and China, often causing extensive damage to both coastal and inland regions. Even worse, the intensity of typhoons is gradually increasing. According to the mathematical models in the article "Recent increases in tropical cyclone intensification rates", the tropical storm's intensity will

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increase. [3] Since typhoons are a kind of disaster that happen globally and will pose a threat to human safety and economic infrastructure, especially in coastal areas, and occurring with increasing intensity, it is crucial to predict the track and intensity of the typhoon in advance. Moreover, with the current acceleration of climate change, there is a growing need for accurate predictive models. In recent years, applied mathematics, particularly through the use of statistical models, has emerged as a vital tool in improving people's understanding and management of natural disasters. Given the increasing intensity and frequency of typhoons, accurate prediction models are essential. In the following sections, we will explore several statistical models used to predict typhoon-related disasters. Therefore, by applying advanced mathematical models to analyze historical weather data, researchers and governments can better understand the patterns, behavior, and potential risks associated with typhoons. These mathematical models are based on related physical and mathematical principles to analyze and predict the formation, growth and movement of typhoons. For example, predicting typhoon paths through dynamics-based methods, also known as numerical prediction techniques, rely on extensive historical data to formulate atmospheric dynamic equations, turning the issue of typhoon forecasting into a mathematical problem. [4] Also, applied mathematics and statistical methods enable the quantification of both the probability of typhoon events and the potential damage they might cause. According to previous studies, Extreme Value Theory can be used to analyze exceptionally strong winds or heavy rains, which can help people make better protections when extreme weather happens, and Probabilistic Risk Assessment can be used to predict the frequency and intensity of typhoons, which plays an important role in developing strategies that enhance resilience to future climate-related disasters. As mathematical models are able to contribute to both the preparedness before typhoons and the assessment after the disaster, it is crucial to utilize these models to get accurate forecasting of the track, intensity and risk of typhoons. These models enable the government, scientists, and the general public to be better prepared and take immediate actions in case of typhoons, reducing economic loss and human casualties. The aim of this essay is to discuss the importance of applied mathematics in the assessment of typhoon-related disasters. Specifically, the research will be carried out to find how statistical models and predictive methods can forecast some basic information such as routine and wind speed of typhoons, early warning for areas probably affected by disasters, and the ways of risk management strategies. This paper will highlight some ways in which forecast accuracy can be improved to reduce the toll of typhoons in economic terms and human loss in most vulnerable coastal areas with the help of statistical models.

2. Statistical models for typhoon disaster

Statistical models have now become an effective tool for enhancing preparedness and reducing damage since they can help predict typhoon-related disasters. In this section, three main statistical models applied in typhoon assessment will be introduced, including Extreme Value Theory (EVT), time series analysis, and multivariate regression analysis. Each model contributes to the prediction of typhoon disasters from a different perspective. EVT can be used to estimate the most intense wind speeds during a typhoon, time series analysis is able to provide seasonal trends in typhoon frequency and intensity and multivariate regression analysis has the ability to predict how temperature and atmosphere pressure affect the path and intensity of a typhoon.

Extreme Value Theory. Extreme Value Theory (EVT) is especially designed to tone and determine the probability of unusual circumstances, especially when it comes to some unusual and extreme situations such as higher wind speeds or extreme rainfall. As a result, when a typhoon happens, EVT may be applied to see the highest wind speeds, rainfall amounts, and storm surges that are caused by the typhoon. Statistical distributions, such as the Gumbel distribution or the Weibull distribution, are frequently used to simulate these elements ' strong beliefs. The Weibull distribution is frequently used to assess wind speeds because it can take various climate information into account. In a variety of

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locations, it can monitor wind speeds and track over. Additionally, the Gumbel distribution aids in assessing the possibility of extraordinary occasions like storms, such as significant storm surge amounts, peak wind speeds, and the heaviest weather. Furthermore, Gumbel copula is also considered as a reliable way to analyze the joint behavior of multiple meteorological factors during a typhoon disaster. [5] In short, EVT provides people with a numerical framework to estimate the probability of future severe weather. These models can help analyze some important information of typhoons to predict the potential frequency and magnitude of typhoons, which helps coastal regions make better preparation for severe weather events.

Time Series Analysis. Time Series Analysis is also a useful method in the statistical modeling of typhoon disasters, especially in analyzing the temporal trends in typhoon frequency and intensity. Among all of this kind of models, ARIMA (Autoregressive Integrated Moving Average) and SARIMA (Seasonal ARIMA) are the most common ones that can explore how typhoons evolve over time and detect any underlying seasonal or long-term trends in the data. ARIMA can be used to detect long-term trends in typhoon frequency and intensity by analyzing past events. For instance, there was research that established a model based on ARIMA to predict the cyclone storms. [6] As the extending model of ARIMA, SARIMA incorporates seasonal components, which is more critical for typhoons. Because typhoon is a kind of natural disaster that show strong seasonal trend and SARIMA can provide accurate predictions for typhoon season start times, peak intensities, and seasonal frequency. Therefore, time series models provide the basis for forecasting future typhoon activity. These models can help predict the likely frequency and intensity of typhoons in the following years. They are extremely helpful in both long-term planning and short-term warnings and thus help reduce the damage of a typhoon event.

Multivariate Regression Analysis. Another general method for the analysis of the relationship between typhoon disasters and other meteorological variables is multivariate regression analysis. After modeling and analyzing the interaction among those variables, one would get a more thorough understanding of what contributes both to the formation and intensification of typhoons. This can include such variables as atmospheric pressure, sea surface temperature, and humidity. Applying the multivariate regression model allows the researcher to find out how the other meteorological variables-sea surface temperature and atmospheric pressure-may influence typhoon wind speed. It would enable better prediction of typhoon characteristics and the possible impacts on the specific regions. For example, a study uses Multivariate Ensemble Sensitivity Analysis to analyze various atmospheric and oceanic variables such as temperature, humidity, wind field, and circulation patterns to identify the sensitivity of super typhoon Haiyan's prediction. [7] The multivariate regression analysis will enable people to understand which factors can influence the formation and intensity of typhoons so that it can make an earlier and more precise prediction and warning. This also provides people with more time to prepare for typhoons and reduces the loss and casualties.

3. Mathematical models for typhoon risk assessment

Typhoon risk assessment is quite important to better understand the potential consequences and damage of typhoon issues so that people can create more effective disaster management plans. In this part, various kinds of mathematics models that are able to examine and forecast typhoon-related risks are demonstrated.

Risk Assessment Framework. A statistical framework for the assessment of risk, such as PRA, provides a helpful approach to judge the risks induced by natural disasters such as typhoons. It not only can provide a framework to estimate the probability of different disaster intensities and frequencies, but it can also be used for damage analysis to the surrounding environment and financial losses by combining historical data, statistical models, and probability theory. For instance, there is research using PRA in assessing tropical cyclone wind risk which mainly focuses on how different

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wind speeds may affect infrastructure and communities. [8] Another study pay attention to the impacts that hurricane-generated debris has on coastal transport infrastructure. It applies PRA to analyze the frequency of debris generation and its risk on the transport network. [9] By conducting such extensive analyses, the PRA will be able to give a scientific theoretical basis for emergency management, raise the resisting ability of the society to typhoon disasters, and mitigate potential damages and losses.

Risk Prediction Models. Various kinds of prediction models are applied to evaluate the potential impacts on infrastructure and safety during typhoon hazards. Among these, Bayesian statistical methods, which offer a comprehensive and practical framework for chance modeling, stand out as an efficient method. Bayesian models offer a comprehensive framework for probability-based modeling, enabling researchers and authorities to evaluate likely damage and financial loss. For example, the Bayesian method is used by researchers to assess the stability and security of typhoon-damaged electric power lines. The Bayesian method is suggested for evaluating the likelihood of discharge failure in overhead transmission lines under such situation. [10] Risk prediction models like this are very useful, as it provides people more accurate assessments of potential economic and social losses caused by typhoons. These statistical methods in risk prediction not only improves the accuracy of assessments in loss but also contributes to the resilience of cities facing natural disasters.

Dynamic Risk Assessment Models. Dynamic risk assessment models, based on Partial Differential Equations (PDEs) and stochastic processes, simulate the time-dependent changes in typhoon paths and intensities. These models are essential since they capture the complexities and uncertainties inherent in typhoon dynamics, which allows researchers to analyze how various factors evolve over time. These models are able to predict some information about typhoon like its track and intensity based on the current situation of the typhoon. All these predictions are real-time and may change as conditions evolve. A typical example is a study that focuses on the urban flood disaster risk assessment conducted in Fuzhou, Fujian Province due to Typhoon “Lupit” in 2019. The study considers four components including the cause of the disaster, the environment, disaster-bearing body, and disaster prevention and reduction capacity, incorporating different time scales during the typhoon process to enable a more precise evaluation of flood risks. [11] Such dynamic models are especially effective way in monitoring the progress of typhoon. This allows the government to adapt their emergency response and provide more accurate protective strategies. Therefore, dynamic risk assessment models can enhance situational awareness and improve response effectiveness during typhoon events.

4. Conclusion

Typhoons are one of the most destructive natural disasters in the world, posing a serious threat to coastal areas in particular. With the intensification of climate change, the intensity and frequency of typhoons are gradually increasing. Through the application of statistical models in mathematics, such as extreme value theory, time series analysis and multiple regression analysis, the path and intensity of typhoons and their possible risks can be effectively predicted, thus helping the government and society to better formulate disaster prevention and mitigation strategies. In addition, mathematical tools such as dynamic risk assessment models play an important role in monitoring and responding to typhoon disasters in real time. In summary, applied mathematics is of key significance in improving the accuracy of typhoon disaster prediction and reducing economic and human losses.

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