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INVESTIGATION OF LONG-TERM HURRICANE ACTIVITY

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Abstract

This paper presents a new approach of applying numerical methods to model storm processes. A storm empirical track technique is utilized to simulate the full tracks of hurricanes, starting with their initial points over the sea and ending with their landfall locations or final dissipations. The theoretical framework was first described in the literature by Vickery et al. (2000) and is extended in this study by introducing a new formula and several substantial adjustments. The results show acceptable accuracy, even if the input data are for a short period. For the Vietnam area, the research successfully generates a large database of synthetic storm tracks on the basis of a limited historical track record and a local climatological variable (i.e. sea surface temperature). The model is evaluated through the comparisons between the key storm statistics derived from the observed and simulated data over the entire research area (i.e. the South China Sea). In addition, some possible applications of this method to coastal structure design and coastal risk assessment are proposed.

Keywords: empirical tracks; hurricanes; numerical models; storm surges; risk management; Vietnam.

1. INTRODUCTION

Hurricane, typhoon, and tropical cyclone are different names for the same phenomenon, which is a cyclonic storm system initiates over the seas. Among natural hazards, hurricane is the main extreme weather event that causes massive damages to affected areas along its track over the tropical belt (Ariffin & Moten 2009). The resulting disasters have enormous human, economic and social consequences; affect numerous sectors and bring about billions US dollars of property damages. In addition, storm surge and large waves generated by typhoons can erode the beach and dune system and reshape the coastal landscape (Brettschneider 2006). According to Tompkins (2002), three of the top five costliest and deadliest weather related disasters for 1970-2001 were hurricanes.

Located in one of the five storm-prone areas of the Asia Pacific region, with a long coastline of approximately 3440 km (Oanh et al. 2011) and densely populated river deltas and coastal areas, Vietnam is among the top five countries most affected by weather related loss events, particularly by typhoons (Dasgupta et al. 2009). The country has annually affected by flooding, and frequently by hurricanes. On average, there are six to eight typhoons each year, according to United Nations Development Program (UNDP 2007). Figure 1 shows the geographic range of the South China Sea - the ocean region that has directly effects on Vietnam.

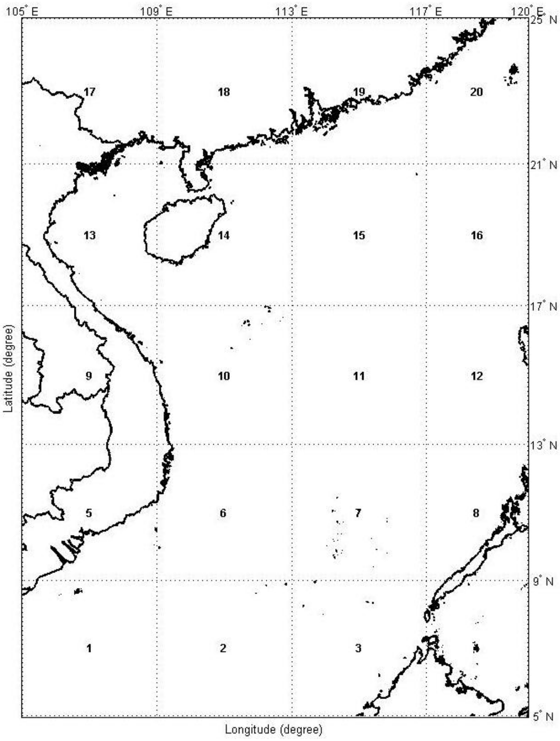

Figure 1. The South China Sea.

An easy to understand definition of hurricane risk is the estimated degree of threat facing a vulnerable group of people through exposure to hurricanes (World Vision 2009). The more susceptible the community (in various means, such as physically, economically, environmentally, or socially) the more expensive and deadly the typhoons. While hurricanes are unavoidable, their risk can be considerably lessened. It can be done either by decreasing the vulnerabilities and/or by increasing the capacities of the affected population to withstand typhoons, that is, their resilience.

Numerous approaches have been executed to lessen hurricane risk, including both structural and non-structural methods. Structural solution is basically a sufficient number of proper-design coastal defense structures (i.e. hard engineering methods such as sea walls, floodgates, revetments, and offshore breakwaters), which can cope with the impacts of severe typhoon winds and storm surges at a certain level. Non-structural techniques are based on the successful hurricane early warning programs and predictive models of morphological impacts induced by extreme typhoons. They include soft engineering approaches (e.g. beach nourishment, sand dune stabilization, beach drainage), advanced building codes and their enforcement, master planning of coastal zone, increasing the effective of preparative solutions (e.g. evacuation strategies), and giving more helpful warning time for hurricanes.

2. LITERATURE REVIEW

One meaningful approach to assess typhoon risks, which can occur at a specific location, is to analyze what already happened in the past. Thus, all current hurricane estimation methods are based on historical records of typhoon tracks and intensities. The typical representations of these compilations are the alleged "best track" records, which are stored, maintained and annually updated by several meteorological agencies, such as the global dataset provided by the United States Navy's Joint Typhoon Warning Center (JTWC) or National Oceanic and Atmospheric Administration's (NOAA's) Tropical Prediction Center (TPC) and the local one from the Regional Specialized Meteorological Center (RSMC) operated by the Japan Meteorological Agency (JMA) (Emanuel et al. 2006). For each reported hurricane, the catalogs generally give some typhoon-related information such as the storm center position in geodetic coordinate (i.e. latitude and longitude) together with intensity estimation (i.e. maximum sustained wind speed and/or central pressure) at six-hour intervals along hurricane track since its initiation (Darling 1991, Jarvinen et al. 1984). These data sets provide a crucial reference in understanding typhoons occurred previously, from which proper risk assessment techniques can be initiated and evolved.

Typhoon estimations has developed in great demand for reliable risk-based technical evaluation, which is rising along with the increasing in exposure to stronger, more often, rapidly changing and less predictable storms (Vickery et al. 2009). Because existing approaches directly base on available observed data (Emanuel et al. 2006), the most crucial limitation relates to the small sample size because hurricanes are both relatively infrequent and small in terms of the length of coastlines affected by these typhoons each year. When coupled with the often low-quality data sets, these techniques can lead to very unreliable evaluations of hurricane frequencies and intensities along the coast. Therefore, it is difficult to derive accurate key parameter of the strongest typhoons, on which risk analysis and design of coastal defense structures must be relied (Hallegatte 2007). In some particular places (e.g. New England in the United States), although the locations have been hardly stricken by hurricane, the possible consequences of a land falling typhoons are massive due to current densely populated urban areas, great economic values of properties and high insurance levels. However, due to the shortness of reported hurricane compilation, there is no trustful estimate available at the moment.

In Vietnam, storm risk study is especially problematic and preliminary research usually faces numerous difficulties. Generally, there is not any complete database on natural hazards, particularly typhoon, and a systematic method, tool or software to store, maintain and analyze this record (Oanh et al. 2011). Observations have been measured, stored and assessed locally, at provincial level. This collection and management methodology leads to an inconsistent and normally non-electrically national compilation. Moreover, the potential problem with sole reliance on observed hurricanes becomes more serious because of budget constraints, lack of suitable techniques, use of observing equipment that produces little reliable data, and also, historically, the aftermath of war in the country from 1945 to 1975. While data sets of typhoon tracks and intensities for more than 150 years are available for many other regions (e.g. North and South Atlantic, East Pacific, North Indian), hurricanes in the South China Sea - the ocean region that has directly effects on Vietnam, have only been monitored since the end of World War II by RMSC - a foreign organization. Because local nearshore measurements are not presented, typhoon risk assessment in Vietnam suffers a lot from the data scarcity issue.

Therefore, there is a rising demand for advanced techniques that can compensate for the lack of reliable hurricane observations, in order to step up classical hurricane estimation methods and upgrade current risk assessment and management.

Taking into account the abovementioned situation, it is important to review existing methods and the manner in which these approaches are being applied to specific situations. Currently, numerical modeling is the most widely accepted technique for estimating hurricane wind speed and is most widely used to design coastal structures and to assess the risks associated with storm winds. According to Resio et al. (2007), at least five techniques have been utilized to investigate hurricane parameters in past studies. These methodologies include the formulation of design storm events, the Peaks Over Threshold (POT) approach, Empirical Simulation Technique (EST), Joint Probability Method (JPM), and empirical track model. Among them, the design storm method inhibits the real variation in typhoon parameters. This approach utilizes only one factor, typically hurricane intensity, for the modeling processes of typhoon's initiation and evolution. On the other hand, other conventional methods (e.g. POT, EST, and JPM) suffer greatly from a paucity of historical hurricane compilations (Resio et al. 2007).

The empirical track model, which was introduced by Vickery et al. (2000), is one of the most recent techniques. The authors successfully generated typhoons over a very long period (i.e. 20,000 years) using available track observations and local climatological variables (Brettschneider 2006). According to Ravela & Emanuel (2010), the most important improvement of this method over conventional techniques is that it removes the need to specify a parametric form for the distributions of key hurricane parameters in the critical range of values. Therefore, this approach provides an excellent source for validating the statistical characteristics of the typhoon (Resio et al. 2007).

3. METHODOLOGY

In this study, the empirical track model is chosen as the theoretical framework for its potential advantages over other techniques. The track of a typhoon is modeled, starting with its initial point over the sea and ending with its landfall location or point of final dissipation. Using this approach, a user can compute 6-h changes in hurricane heading, translation speed, and wind speed along this track as linear functions of previous values of those parameters as well as typhoon center location and Sea Surface Temperature (SST). Thus, a large database of synthetic tracks is generated that is based on a limited observed track record and a local climatological variable (i.e. SST). This method is validated through comparisons between the hurricane statistics derived from the historical data and the simulated ones over the whole South China Sea region.

The most important input for an empirical track model is the observed track record. For the Vietnamese case study, the RSMC Best Track Data (JMA - RSMC Tokyo - Typhoon Center 2012) is used. This compilation is one of the most complete and recent databases, which includes the historical track for every single hurricane that occurred within the South China Sea area from 1951 to 2011.

Another data collection used is the NOAA NCDC ERSST version 3b (IRI/LDEO Climate Data Library 2012). This library contains the global extended reconstructed monthly SST values, which were measured from January 1854 to February 2012. Finally, the digital coastline map of the South China Sea region is provided by the NOAA National Geophysical Data Center (NGDC) Marine Geology & Geophysics Division and collocated by World Data Center for Marine Geology & Geophysics, Boulder (Signell 2012).

The number of typhoons which have to be simulated each year is sampled from a negative binomial distribution with a mean value of 10.05 (hurricanes/year) and a standard deviation of 3.61 (hurricanes/year). This distribution is estimated using the observed annual number of hurricanes in the research area (i.e. the South China Sea). The starting position of typhoon center and all relevant parameters including the month of occurrence, heading, translation speed, and wind speed are sampled from a set of hurricane initiations. This series is derived from the surveyed track database by selecting the first location of each historical typhoon, which was inside the research area. The significance of this sampling method is to retain all the climatology data combined with any seasonal preferences for the point of hurricane initiation (Vickery et al. 2000).

Given these original conditions, the new position, translation speed, heading, and wind speed are estimated based on the changes in these parameters over the current 6-h period using Equations 1, 2, and 3. They are written in a general form, which can be used for any time period (i.e. between the time steps i and i + 1):

$$\Delta \ln c_i = \ln c_{i+1} - \ln c_i = a_1 + a_2 \times \Psi_i + a_3 \times \lambda_i + a_4 \times \ln c_i + a_5 \times \theta_i + a_6 \times \theta_{i-1} + \varepsilon_{i1} \qquad (1)$$

$$\Delta \theta_i = \theta_{i+1} - \theta_i = b_1 + b_2 \times \Psi_i + b_3 \times \lambda_i + b_4 \times c_i + b_5 \times \theta_i + b_6 \times \theta_{i-1} + \varepsilon_{i2} \qquad (2)$$

$$\Delta u_i = u_{i+1} - u_i = c_1 + c_2 \times T_i + c_3 \times T_{i-1} + c_4 \times u_i + c_5 \times u_{i-1} + \varepsilon_{i3} \qquad (3)$$

where Ψ and λ = typhoon center latitude and longitude, respectively; c = translation speed; θ = heading; T = sea surface temperature; u = maximum sustained wind speed; ε = random error.

The symbol Δ situated before each parameter denotes the change of this quantity over the current period; the subscripts i and i + 1 specified for each parameter express the value at the corresponding time step; and a1, a2, etc. is a set of constants for each rectangular grid cell within the research area. When the hurricane travels from one grid cell to another, these values are changed accordingly. The constants are computed using a multiple linear regression solution. Because this process is repeated until the synthetic typhoon makes landfall or final dissipation, a full track is created, along with all main parameters, at each time step.

Equation 3 is a new mathematical expression that is first introduced by this research. Unlike the conventional empirical track approach by Vickery et al. (2000) that gives an indirect estimation using a hurricane wind field model, this method can be used to directly compute the most important typhoon parameter, that is, wind speed. Furthermore, various model alternatives are also considered to determine the options that are best suited to the specific conditions of the South China Sea region. For instance, three different multiple linear regression solutions are utilized: the ordinary least-squares solution and the robust and stepwise algorithms. However, none of the above techniques can generally be employed for datasets with less than 6 data points. In this case, the application of these methods leads to very unreliable results. Although the small grid size can result in a better correlation between parameters, it also increases the number of lacking-data grid cells (i.e grid cells containing fewer than 6 data points). Therefore, various grid sizes (i.e. 2.5° × 2.5°, 4° × 4°, and 5° × 5°) are examined.

4. MODEL EVALUATION

The above methodology is validated through comparisons between historical and modeled statistics, which are obtained from a 50,000-year hurricane simulation over the entire South China Sea area. Because the evaluation is given within the whole region, all typhoons are taken into account, even if they end at the ocean or completely pass through the research area. This is an improvement over the conventional approach, which only considers storms that enter a sub-region around certain Points Of Interest (POIs) during model validation. As those POIs are normally situated at the coastline, hurricanes that do not make landfall were ignored in the research by Vickery et al. (2000), although they are still very important for various sectors.

Synthetic typhoons are initiated using available historical track records and propagated over water using Equations 1, 2, and 3 to estimate their locations and parameters. The ordinary least square technique and 4° × 4° grid size are chosen as the optimal multiple linear regression solution and the optimal spatial size, respectively, due to their better performance in terms of model results (i.e. higher correlation coefficients) than other options.

In terms of qualitative evaluation, the mean and standard deviation of translation speed, heading, and wind speed of both observed and simulated data are computed and plotted in the same figures as shown in Figure 2. As one can clearly see in the figures, the modeled data are very close to the historical ones.

Quantitative validation is also carried out by plotting the Probability Density Function (PDF) of both observed and simulated main statistics and computing the correlation coefficients between these values. The correlation coefficients are always between -1 and 1. When these quantities are close to 1, the historical and modeled data are highly (positively) correlated. In addition, a comparison between these PDFs can also be made with a chi-square statistic. When it is smaller than the critical value, the observed and simulated key parameters are considered to have the same distribution shape. With degree of freedom of 1 and significance level of 0.05; the critical chi-square value is 3.84 (Boslaugh & Watters 2008). Figure 3 gives these comparisons for translation speed, heading, and wind speed. In this figure, all the correlation coefficients are close to 1 (i.e. 0.9937, 0.8971, and 0.92803 for the translation speed, heading, and wind speed statistics, respectively). The chi-square statistics are much smaller than 3.84 (i.e. 0.049381, 0.28898, and 0.14483 for the translation speed, heading, and wind speed, respectively). Therefore, one can conclude that the main typhoon statistics derived from simulated data can describe observed hurricanes remarkably well.

5. POSSIBLE RESEARCH APPLICATIONS

The theoretical approach described in this paper can be utilized for various purposes.

First, this methodology can be coupled with a storm surge model. Because hurricane statistics are computed at any location within the research area, one can calculate the wind-induced surges that are needed for the design of coastal structures. Figure 4 shows a parameter estimation for winds in grid cell number 10 (refer to Figure 1) obtained from simulations of different lengths. In this figure, each point presents the maximum wind speed that is relative to its return period. Although the linear interpolation between those data points is not a perfect solution, it still gives an approximation of any other run. Therefore, the result covers the entire range of values. Moreover, because the method is able to simulate typhoons for an unlimited time (e.g. 50,000 years in this research), it is also applicable to hurricanes with an extremely large return period, even if these conditions have never happened. For instance, the figure shows the highest wind, corresponding to a 50,000-year return period, at nearly

280 knots (i.e. 322 mph or 518 km/h). This value is higher than the fastest wind speed ever recorded (i.e. 200 mph or 322 km/h), which was observed during Hurricane Camille in August 1969 (Hearn 2004).

Another important application is the integration of model results in risk assessments. This can be done by estimating the typhoon landfall rate along the coastline, which is one of the most crucial inputs for typhoon risk analyses.

Finally, because all the required data can be searched and extracted from global databases, the approach mentioned in this study can be applied to all other empirical track research at different locations (e.g. the North Sea and the Dutch coastline).

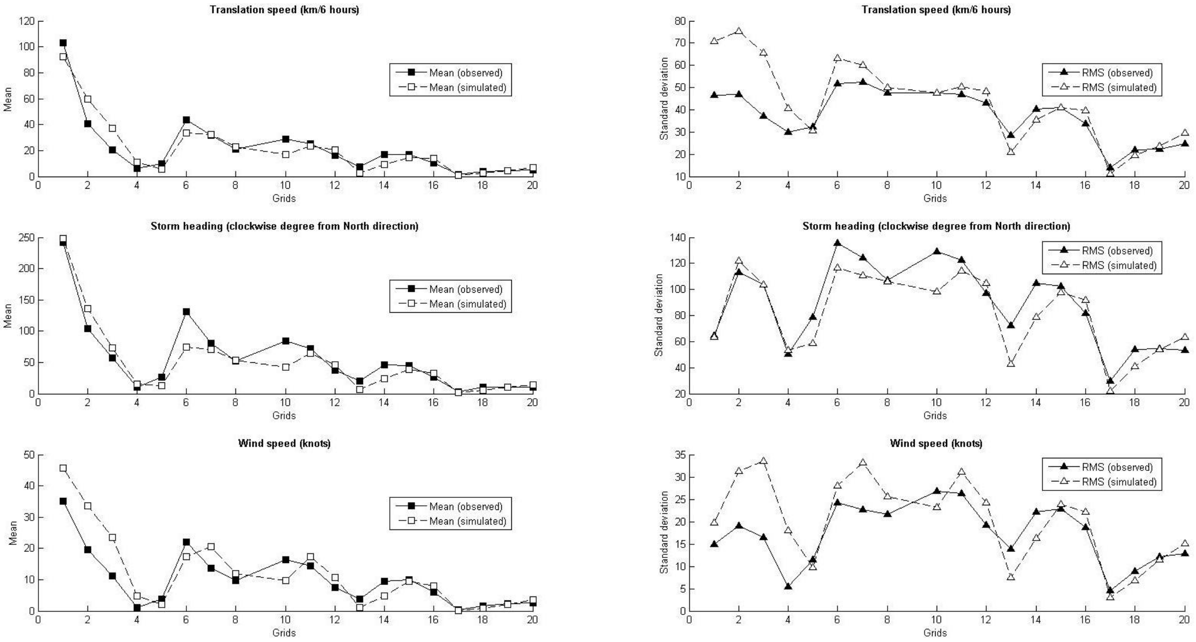

Figure 2. Qualitative evaluation.

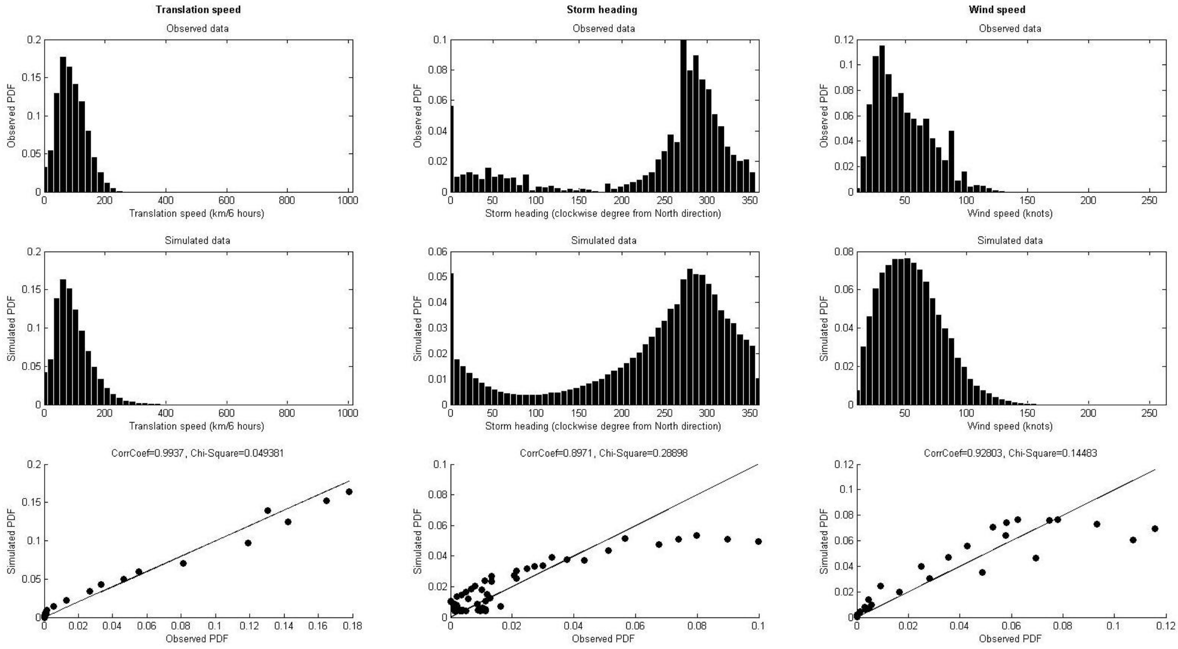

Figure 3. Quantitative comparison.

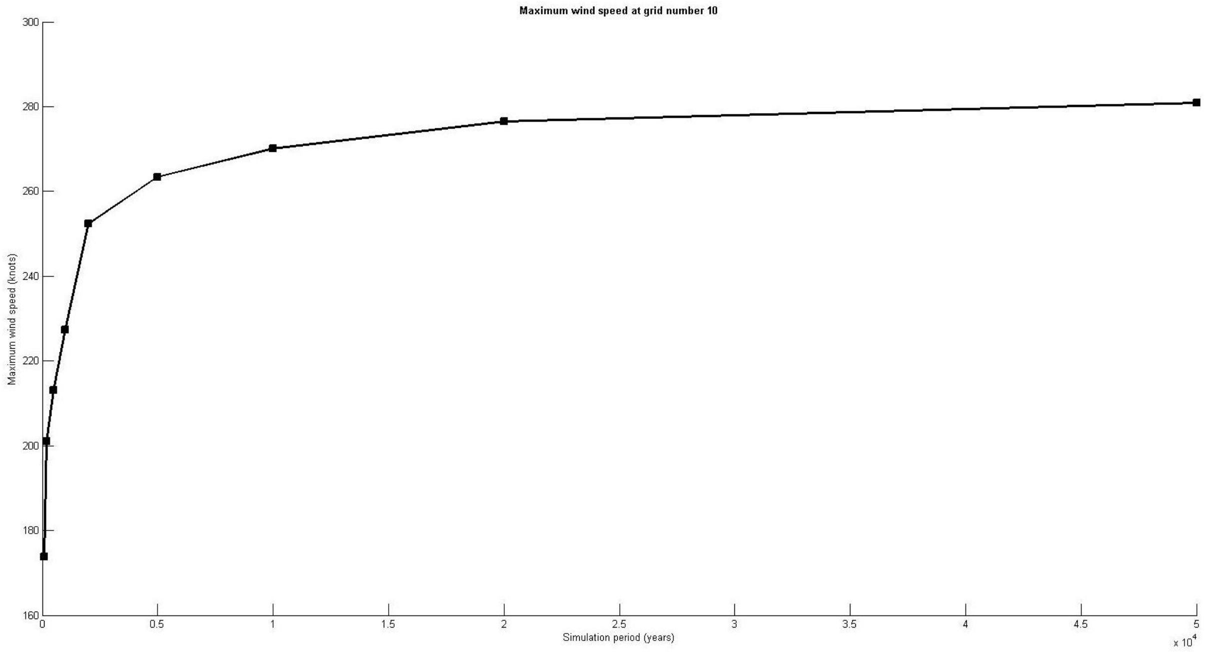

Figure 4. Maximum wind speed at grid number 10.

6. CONCLUSIONS

A new modeling technique to simulate the entire track of a hurricane in the South China Sea region has been presented. Some crucial enhancements are proposed by using the empirical track framework to compensate for conditions in which there are data shortages. The model validation is executed over the entire research area and shows a very close correlation between observed and modeled data. There is persuasive evidence that indicates that this model has many improved features compared to other models. Moreover, all the required data can be searched and extracted from global databases. Thus, the methodology mentioned in this study can be applied to other research at different locations. Finally, some possible initial ideas for further studies are proposed.

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