Comparison of Holland’s Model and Near-Real-Time Predicting System

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Abstract. Hurricanes have affected many tropical and coastal countries for years, but the history of hurricane simulation is short, due to the unpredictable nature of hurricanes. Although several models and methods developed by numerous scientists in the past have substantially enhanced people’s understanding of hurricanes’ formations and features, not all of the errors have been eliminated. To display the improvements of hurricane simulation in the past decades, in this paper, both the advantages and limitations of Holland’s wind model and a new near-real-time prediction model are compared by presenting their key calculations and main ideas, respectively. The modern near-real-time predicting system turns out to be more extensive and exact than the Holland’s wind model. Besides, the idea of the Monte Carlo simulation approach, an accepted hurricane simulation method, is briefly stated for the sake of complete understanding.

1. Introduction
Hurricanes, typhoons, and cyclones all refer to strong winds and storms. They are the same type of natural disaster, but due to different forming locations, they have different names. In the eastern north Pacific Ocean, the key ingredient for hurricane formation, the warm moist air, usually appears between June and November. During these months, accurate and timely hurricane prediction systems are imperative; otherwise, it will result in huge devastation both financially and socially [1].

Due to the rapidly developed technologies, hurricane predicting models and methods have constantly improved in the last few decades. Early models include but not limited to Holland’s wind model [2], Batts model of analyzing hurricane wind speeds in the United States [3], Shapiro’s model about hurricanes’ translations outcomes [4], and Yan Meng’s discovery on topographical effects [5]. Among all of these, Holland’s wind model is one of the most popular typhoon simulation models, as introduced later in the passage.

This paper will mainly discuss the mathematics principles behind the popular Holland’s wind model and a relatively new near-real-time hurricane forecasting model. It will also compare the two models and point out the limitations for the sake of future studies and investigations. Lastly, this paper discusses how the Monte Carlo simulation works for hurricane simulation based on Russell’s researches [6].
2. Typhoon Simulation Models

2.1. Holland’s hurricane wind model

Holland’s model (HM) [4] is a recognized standard model that only requires a few basic parameter values to determine other essential factors for predicting the hurricane’s activity, such as the tangential wind field, maximum wind speed, and radius of maximum winds (RMW). Event though HM is simple and clear, it neglects the important asymmetric aspect of hurricanes in nature, which deducts its accuracy.

Despite the disadvantage, HM is still a huge improvement from previous models (modified Rankie vortex [7] and Schloemer’s [8] negative exponential relation) due to its generalization and wide applicability. HM adopts the parameter \((p - p_c) / (p_n - p_c)\) to unify hurricane profiles by neglecting the differences between central and ambient pressures. In the parameter, \(p\) is the pressure at radius \(r\), \(p_c\) is the central pressure, and \(p_n\) is the ambient pressure. On the contrary, the modified Rankie vortex model’s central equation has six variables and Schloemer’s model includes ten possible formulas. The final formula for HM is \(p = p_c + (p_n - p_c) \exp(-A/r^B)\), where \(A\) and \(B\) represent scale parameters (\(A\) shows the location of a hurricane profile and \(B\) shows the shape of it). As for each parameter’s domain, RMW determines possible values of \(A\) and \(B\) ranges from 1 to 2.5.

RMW (denoted as \(R_w\)) and the maximum wind speed (denoted as \(V_m\)) of a hurricane can be calculated based on two derived formulas from HM equation and the gradient wind equation: \(R_w = A^{1/B}\) and \(V_m = C (p_n - p_c)^{1/2}\), where \(C = (B / \rho e)^{1/2}\) (\(\rho\) is the constant air density, 1.15 kg m\(^{-3}\), and \(e\) is the natural base). The results reveal that RMW only depends on the scaling parameters \(A\) and \(B\), and the maximum wind speed is independent of the RMW but dependent of parameter \(B\). This is because as parameter \(B\) increases, the hurricane profile changes: the “eye” expands and pressure concentrates at RMW, generating maximum wind speed, as shown in figure 2a. Besides this, figure 2a also displays that hurricanes with larger parameter \(B\) values have significantly higher pressure levels than others, especially at radii further than RMW. Furthermore, note from figure 2b that larger parameter \(B\) value contributes to faster wind speed near RMW and slower one at larger radii. With the affirmation from equations and figures, the discovery that the shape of a hurricane profile greatly determines the power of it leads scientists to concentrate more on the shape of a hurricane when predicting, instead of the size of it or RMW.
2.2. Near-real-time hurricane forecasting model & asymmetric wind model

The near-real-time hurricane forecasting model proposed by Lian Xie et al.[9] combines the National Hurricane Center’s (NHC) forecast guidance and buoy observational data (an integration of theoretical statements and real-time examination) to generate a new asymmetric wind model (AWM). The model also takes advantage of the near-real-time hurricane surface wind study conducted by Atlantic Oceanographic and Meteorologic Laboratory / Hurricane Research Division (HRD).

One segment of the forecasting model, the NHC forecast guidance includes storm track and intensity predictions and it can provide information of the size of the storm center, maximum wind speed, track, and the structure of the storm within four quadrants (northeast, northwest, southeast, southwest) 12, 24, 36, 48, and 72 hours before the hurricane. With the trials of real hurricanes, the forecast guidance is diagnosed as a practical tool for hurricane warning and evacuation. Yet, large errors in track predictions prevent this method from widely being adopted. The other segment is buoy data collection every hour in the Gulf of Mexico, surveilled by the National Data Buoy Center (NDBC). The statistics about sea pressure, air temperature, and wind direction garnered by those buoy stations are periodically processed with the HRD analysis so that the quality and organization of the data are ensured. The accuracy of HRD analysis is strictly bonded to the quality and quantity of data collected; therefore, some inaccuracies may be shown in the results. Despite these deficiencies, the near-real-time hurricane forecasting model is dedicated to making the NHC forecast guidance and HM more universal by including the AWM, which simulates real hurricanes more naturally.
Table 1. Maximum wind speed differences between actual data observed from buoy stations and different models: (a) AWM 6-h prediction; (b) AWM 12-h prediction; (c) HM 6-h prediction; (d) Optimized Holland’s model 6-h prediction [9].

| Storm/buoy     | (a)  | (b)  | (c)  | (d)  |
|----------------|------|------|------|------|
| Floyd/44014    | −2.57| −1.79| −3.62| −6.83|
| Floyd/FPSN7    | −1.22| 0.77 | 5.21 | 5.83 |
| Floyd/BUZM3    | 3.70 | 2.13 | −7.18| −10.44|
| Floyd/CLKN7    | 0.22 | −5.43| 1.43 | −2.95|
| Floyd/VENF1    | 4.00 | 5.70 | 17.82| 8.57 |
| Gordon/DPIA1   | −0.01| −0.59| 0.11 | −2.13|
| Gordon/SANF1   | −1.79| −1.29| 4.39 | 3.26 |
| Gordon/42041   | −0.97| −0.38| 3.89 | 2.60 |
| Gordon/LONF1   | −0.71| −0.58| 5.73 | 4.56 |
| Gordon/SPGF1   | 1.83 | 1.81 | 8.15 | 6.93 |
| Isabel/44014   | 4.52 | 2.36 | 3.85 | 2.18 |
| Isabel/44025   | −1.04| −1.21| 1.34 | −1.94|
| Isabel/CHLV2   | 0.61 | 0.14 | 0.89 | −0.07|
| Isabel/41001   | 0.37 | 1.63 | 2.80 | −0.55|
| Isabel/DUCN7   | 4.42 | 2.46 | 1.70 | 1.82 |
| Lily/DRYF1     | −1.73| −1.73| 8.15 | 5.65 |
| Lily/LONF1     | −0.33| −0.60| 8.40 | 5.52 |
| Lily/SANF1     | −1.54| −2.02| 7.44 | 4.67 |
| Lily/SMKF1     | −1.00| −1.31| 7.89 | 4.95 |
| Lily/BURL1     | 1.94 | 1.60 | 9.27 | 5.77 |
| Mean rms error | 2.26 | 2.33 | 6.93 | 5.18 |

In order to test the accuracy of the new AWM, Lian Xie et al [9] compared the calculated maximum wind speed differences acquired from HM and AWM with the actual observations generated by buoy stations. As shown in Table 1, the outcomes of AWM are further divided into a six-hour period and a twelve-hour period. The following conclusions can be drawn from the diagram: AWM has a distinctly smaller mean RMS (root mean square) error than the other models; in particular, the prediction in a shorter period with AWM is more accurate than that in a longer period with the mean RMS error of AWM six-hour is 2.26 m s⁻¹, of AWM twelve-hour is 2.33 m s⁻¹, which both are notably smaller than the error of HM and the optimized one, 6.93 and 5.18 m s⁻¹. The superiority of AWM is demonstrated even more straightforward in the following four graphs——changes in wind speed of Hurricane Floyd detected at buoy stations FPSN7, CLKN7, VENF1, and 44014 as time passes. As shown in figure 3, HM generally overestimates the wind speed of Hurricane Floyd at all four stations, and although slight errors appear, the difference between the buoy line and AWM 6-hour prediction is still the smallest.
Figure 3. Different wind speeds detected with different models during Hurricane Floyd (1999) at NDBC buoy stations (a) FPSN7 (b) CLKN7 (c) VENF1 (d) 44014 [9].

The near-real-time hurricane prediction model and AWM incorporate the essential asymmetric aspect of hurricanes. Proved by comparisons between predicted results and real-time observational data from buoy stations, AWM is an optimal hurricane prediction model.

2.3. Monte Carlo simulation

The most popular hurricane simulation method may be the one presented by Russell [6] with the idea of Monte Carlo simulation. Monte Carlo simulation is a statistical simulation method that can calculate the probability of an event happening with random variables given. It is extensively applied in simulation and prediction of natural disasters, especially in hurricane simulation, because of the perfect fit between a hurricane’s unpredictable characteristic and the ability of Monte Carlo simulation.

In his study, Russell [6] proposed the Monte Carlo simulation method, which combines some previous mature models with real observational data to simulate hurricanes’ wind field and their maximum wind speeds. In order to utilize the Monte Carlo simulation approach, historical data from long periods of time and the derived probability distributions of multiple key hurricane parameters are required. Finally, the results obtained from the Monte Carlo simulation method need to be verified by applying it to real hurricanes and comparing the results with actual data, resembling how other hurricane models are testified. Nevertheless, one limitation of the Monte Carlo simulation method is that it is only practical when studying one specific region’s hurricane activities [10]. Another model is needed when researching the hurricane activities in a broader region: Vickery et al.’s empirical track model [11] can, for example, simulate the entire track of a hurricane in the Atlantic Basin.
3. Discussion
Hurricane forecasting is difficult because it is a study full of uncertainties and mysteries. Due to its simplification and catholicity, HM is believed to be a great modification and upgrade of the previous representations, Rankie vortex and Schloemer. However, there are still limitations. Take Holland’s assumptions and approximations in his paper: he estimated the relationship between radial distances and the parameter \((p - p_c) / (p_n - p_c)\) as rectangular hyperbolas, and he supposed that the hurricanes in his model are all axisymmetric, while real hurricanes are asymmetric. The accuracy of HM also highly depends on the correctness and precision of parameter values and data; some minor flaws in initial conditions may affect the ultimate conclusion. These deficiencies are also admitted by Holland himself: he realized that HM is more stabilized with pressure observations than with wind observations because the values obtained from pressure observations are relatively more secure and fixed. He then proposed to derive wind profiles with pressure observations as an alternative, but this approach will underestimate those fast wind speeds.

Regarding these deficiencies, AWM is introduced. It has counteracted most shortages in the original model and has elevated HM to another level. AWM incorporates the asymmetric characteristics of usual hurricanes and has validated to be more accurate and comprehensive than HM in predicting a hurricane’s wind speed and trajectory since it is supported by the buoy real-time data stations. Nonetheless, similar to one of the drawbacks in HM, AWM is also influenced by the quality and quantity of the statistics from buoy stations, which are mainly built around the Gulf of Mexico. Therefore, the outcomes predicted by the near-real-time hurricane system and AWM may be parochial.

Both HM and AWM are meaningful models for forecasting hurricanes. Since HM simplifies some key parameters of hurricanes and generalizes the calculation process, it may be more basic and theoretical, but it gives a holistic grasp on the main idea and steps of hurricane prediction. In contrast, AWM and near-real-time hurricane forecasting system may be more practical since they optimize previous models to better restore the characteristics of real hurricanes and combine theories with real-time data from buoy stations. Including other various hurricane prediction models, each has its own emphases and advantages, so scientists often embrace multiple models and extract the useful parts of each to conduct experiments or form another new model. Similarly, scientists also often incorporate the Monte Carlo approach with different models to double ensure the precision of the final results.

Lastly, future improvements on data accuracy and application areas are still possible, but the current models and methods can already well fulfill the demand for hurricane prediction and early notifications to the public.

4. Conclusion
The purpose of this paper is to show the changes in hurricane simulation methods and models in the past few decades by comparing two models, HM and near-real time forecasting system. As presented in the paper, the modern near-real-time hurricane forecasting model is indeed more advanced than HM, both in terms of accuracy and efficiency. Future studies can possibly compare more models and methods to picture a more comprehensive development history of hurricane prediction.

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