Analysis of Different Modern Methods and Technologies in Typhoon Track Prediction

Junyan Wu [1,*]

[1] University of the West of England, BS16 1UU, Bristol, United Kingdom

* Corresponding Author Email: Junyan2.Wu@live.uwe.ac.uk

Abstract. Typhoon track forecasting is of great significance for disaster prevention and mitigation in coastal areas. In recent decades, due to advances in methods like numerical weather prediction, ensemble forecasting, or data-driven modeling. In this paper, an overview will be provided on the current state-of-the-art typhoon track forecasting methods such as traditional NWP system, novel DL or PDE-based hybrid methods. In particular, the review gives an overview on basic concepts, key publications and performance in applications for both direct methods and for ensemble methods. The benefits and drawbacks of data-driven deep learning models will also be reviewed and compared, such as single-modal, multimodal, and physics-informed structures, in terms of prediction accuracy, uncertainty expression, physical consistency, and commercialization relevance. Finally, key challenges and outlooks are presented. These challenges include probabilistic calibration, model generalizability, physical model interpretability and incorporating AI into operation forecasting system. It is hoped that this review will provide an organized guide for readers who are interested in advancing current methods on typhoon tracking forecasts.

Keywords: Typhoon track prediction, Weather forecasting, Artificial Intelligence, Deep learning.

1. Introduction

Among all the ocean areas, the tropical cyclone activity in the North-West Pacific is the most dynamic. All of the tropical cyclones that are generated and active in this area are universally referred to as typhoons. As an important component of the ecosystem of the Earth, typhoons can form in all twelve months of a single year. Typhoons usually bring violent winds, floods, and storm surges that lead to disaster and property damage to residents of coastal communities. Meanwhile, typhoons regulate the climate and deliver fresh drinking water supplies to cities. Therefore, monitoring and forecasting the track and intensity of typhoons are extremely important. By doing so, valuable information will be provided to enable meteorological centers to forecast extreme weather catastrophes that may be caused by typhoons and prevent potential personal and economic losses.

Typhoon forecasting has changed from using traditional methods based on experience to advanced techniques that rely on science and data. Early predictions were based on weather maps and basic principles of guided airflow. With the arrival of the satellite era, the development of statistical models has been promoted, enabling climate factors and circulation indices to be considered in forecasting. Since the beginning of the 21st century, the initialization of typhoon vortex, assimilation of multi-source satellite and radar data, and the perspectives of physical process parameterization have greatly improved the perspectives of Numerical Weather Prediction (NWP). At the same time, systems for predicting weather using groups of models, such as CMA-GEPS, TRAMS-EPS, and TEDAPS, are also taking root. Models like these allow the uncertainty in track prediction to be more scientifically expressed and utilized [1].

Nowadays, predicting typhoon tracks with higher efficiency and accuracy remains a main focus for meteorological agencies and the field of studying typhoons. In 2019, Heming et al. summarized the latest progress in deterministic and ensemble track prediction. They pointed out that improving model resolution, ameliorating physical processes and adopting advanced data assimilation schemes are key points to reducing track errors [2]. In recent years, ensemble perturbation strategies have also been continuously optimized. For instance, in 2025, Zhang et al. found in research that using new disturbances based on O-CNOP can greatly enhance the reliability of ensemble forecasting for typhoons with unusual tracks. It can be inferred that improving initial disturbance design has a significant meaning in reducing the uncertainty of typhoon track prediction [3].

At the same time, Deep Learning (DL) is also showing promising results in typhoon track prediction by learning and understanding temporal/spatial characteristics of historical data. In 2023, Wang et al. built a DL model combining past tracks and large-scale environmental fields, leading to a high accuracy of 6-72 hours forecasting in North-West Pacific area [4]. More works start to integrate multimodal information or add physical constraints. In 2022, Qin et al. proposed a multimodal framework that fuses various modalities with CNN-LSTM architecture for better track forecasting, which proves that combining track sequences and satellite cloud images could greatly enhance the predictive performance [5]. In 2024, the physical constraint model LT3P of Young-Jae Park et al. learns to embed the dynamical guidance field in a deep network that is able to produce more physically consistent track forecast products without relying on reanalysis data and exceptionally at long-range prediction[6]. Such works suggest that combining DL with physical model will become one promising approach to improve the skill of typhoon path prediction.

According to what was mentioned above, this article aims to review and compare the current mainstream technologies for typhoon track prediction. The dissertation will first present a brief review of progress and limitations of conventional NWP. Secondly, representative DL models will be introduced, including single mode and multiplex mode architectures as well as physics-informed or hybrid frameworks. Their qualities and shortcomings will be analyzed from the viewpoints of model design, data requirements, and forecasting performance. Based on these discoveries, the article will systematically summarize the remaining challenges and look forward to future research development trends, particularly the vulnerability measurement, physical consistency construction and the operational usage of DL models. Aim for this dissertation is to provide an organized reference for researchers and practitioners to understand, evaluate, and advance current typhoon track prediction techniques.

2. Literature Review

2.1. Numerical Weather Prediction–based typhoon track forecasting

Numerical Weather Prediction (NWP) has long been the foundation of commercial typhoon track forecasting. The NWP model simulates the evolution of atmospheric systems by numerically solving the fluid dynamics and thermodynamic control equations of the atmosphere, thereby physically and consistently representing the large-scale circulation structure and the movement characteristics of tropical cyclones.

In NWP-based track forecasting, a typhoon's movement depends on the interaction of typhoon vortex with air flow affected by its surroundings. The early numerical models are limited in spatial resolution and simple physics parameterization scheme, making it hard to reproduce well the small-scale details and intensities of typhoons. In recent times, there has been considerable progress in terms of increasing the model resolution and improving the vortex initialization as well as developing data-assimilation techniques, and continued improvements to the parameterization of physical processes have significantly enhanced numerical model forecast skill for tracking. Data assimilation from various sources (e.g., satellites, radars) also improves initial field quality, thus considerably reducing track prediction errors.

Meanwhile, the business NWP system has been gradually trending toward aggregation so as to make it possible to run deterministic and probabilistic track forecasting in parallel. It was shown through the study coordinated by Heming et al. that the mean track error from state-of-the-art global and regional numerical models still shows a decreasing trend over most ocean basins, particularly for shorter term forecasts. The above progress has strengthened the position of NWP as a world-leading typhoon prediction model [2].

However, despite great success, this doesn't imply that there are no challenges affecting the NWP approach. Track prediction is very sensitive to error in the initial conditions, especially for weakly guided flows or highly non-linear atmospheres. The computational expense associated with running high resolution numerical models also restricts them from being used at a higher update frequency and on larger scale ensembles. Nevertheless, due to good physical consistence and mature operation mechanism, it is still necessary that NWP model can be used as one of the main tools in typhoon track forecast and also acts as one of the key references for new data-driven models.

2.2. Ensemble Forecasting and Perturbation-based Methods for Typhoon Track Prediction

Nowadays ensemble forecasting has been incorporated into operational typhoon track forecasts because the primary goal of ensemble forecasting is to characterize the forecast uncertainty. Instead of providing one deterministic forecast, ensemble methods create several forecast members through perturbation of initial conditions or model parameters that captures sensitivity of typhoon movement on uncertainty in the atmosphere's state.

In 2025, Zhang et al. made an outstanding study on using Optimal Condition Nonlinear Optimal Disturbance(O-CNOP) to improve ensemble forecasting of anomalous typhoon track. They designed a disturbance scheme which can maximize the expansion of the forecast error growth under the physical constraint of the abnormal behavior of typhoon, such as sharp turns and stagnation, in which the ensemble member data samples can be better covered by high-impact uncertainties. This approach was applied to a numerical ensemble forecasting system and verified with several typhoon cases [3].

The experimental results show that this O-CNOP-based disturbance strategy can effectively improve the predictability of an ensemble forecast, compared with a traditional perturbation method. This method generates an acceptably large yet physically meaningful spread in the ensemble that offers improved representation of predictability uncertainty under anomalous track scenarios. This is especially true for typhoon cases that have strong nonlinearities or complicated interactions with the environment as it has successfully reduced the ensemble mean track error. In addition, this approach can identify the sensitive areas influencing typhoon track significantly, which would be helpful in the probabilistic prediction and adaptive observing.

But for ensemble forecasting the computer power required will be huge as well as people have to use more than one models too. Also, the high dimensional optimization problem of an optimal perturbation method like O-CNOP might make its application difficult for practical use. However, ensemble forecasting provides an encouraging direction for enhancing the robustness and reliability of typhoon track prediction.

2.3. Data-driven Deep Learning Models for Typhoon Track Prediction

As historical TC datasets continue to accumulate and the evolving of ML methods, data-driven DL models have become a popular method to predict the typhoon track with ML algorithms. In contrast with numerical weather prediction models that obtain the physical equation directly based on a numerical data system, DL methods attempt to directly learn the nonlinear mapping relationship of typhoon features and its subsequent location from historical records.

Wang, et al. proposed a DL model for predicting typhoon tracks of North-west Pacific Ocean in year-2023.The model is combination of track history and large scale environment fields such as geopotential height, wind field elements, etc., and predict the typhoon position within the following 6-72 hours. The authors use recurrent neural network structure, the time-dependent behavior of a moving typhoon can be well captured by the model. The experiment result shows that the prediction accuracy of this deep learning model is no worse than, but rather better than, some operational numerical modeling techniques of the short-and medium-term forecast [4].

Another benefit for using data-driven DL models is that once trained, they are computationally efficient and quickly make a prediction for proceeding track, making them applicable in online prediction, as well as the fact that DL techniques could capture the non-linear correlations between the environment variables and storm paths which is hard to model purely with physics-based equations.

However, there are some drawbacks as well with data driven model. The performance of prediction by ANN is dependent on the quality, quantity and representation of the characteristic features of the training data, and could drop out when applying it to rare events or unusual track data. Furthermore, most single-modal DL models (mainly based on the track information and big environment) lack explicit physical constraints, which can result in uncertainties for dynamical forecasts especially for long-range forecasts. This motivates us to explore deeper neural network structures with additional data sources that are able to better characterize typhoon structure and life cycles.

2.4. Multi-modal Deep Learning Models for Typhoon Track Prediction

To overcome the limitation in using single-modal data-driven methods recently some researches start utilizing multi-modal information for predicting typhoon tracks. The multi-modal deep learning model aims at integrating different types of heterogeneous data sources, such as historical tracks and satellite images, in order to simultaneously characterize the spatial and temporal characteristics of typhoon evolution.

Qin et al. have recently proposed another novel multi-modal typhoon track prediction framework, combining the track time series and satellite cloud images as input. This work was done due to the help of a Convolutional Neural Network (CNN), whose architecture extracts spatial feature information on the remote sensing image, and a Long Short-Term Memory (LSTM) network that characterizes the temporal track evolution characteristic of typhoon. Then, the feature computed on different modalities is integrated together for predicting typhoon tracks. The result shows that compared to a single-modal model which only uses the tracks as input information, the proposed multi-modal model can provide better predictions, especially for the rapid changes and complicated motion periods of typhoon structure [5].

The key aspect for multi-modal DL models is extracting complete spatial information from satellite observations. Cloud system characteristics, together with convection patterns, capture aspects of storm intensity, structure and asymmetry related to their motion. Combining such spatial features together with past trajectories' information, multi-modal models give us better insight into the behavior of typhoons than do single-modal ones.

Nevertheless, shortcomings, such as the limitation of multi-modal model, cannot be ignored. Preprocessing satellite data often requires a lot of computing resources, and the data is well controlled in terms of quality. Moreover, as multi-modal features fuse information together into a more complex model it might increase the risk of over-fitting when having few training examples. Similar to one-modal DL methods, only a small number of multi-modal studies still employ explicit physics constraints that may result in an unstable prediction for long-term lead time forecasts. The above problems suggest further improvements on incorporating physics information into the multi-modal DL model.

2.5. Physics-informed and Hybrid Deep Learning Models for Typhoon Track Prediction

The goal to combine both the adaptability provided by data driven learning and the regularity imposed by physical dynamics in physically constrained hybrid deep learning models, has become increasingly attractive as opposed to pure data driven approaches. This model incorporates the physics knowledge directly in the neural network architecture for improving not only the forecasting performance of typhoon track predictability but explainability as well.

In 2024, Park et al. presented an outstanding physics-based constraint model Long-Term Typhoon Trajectory Prediction (LT3P). Its main idea was to incorporate the dynamic guidance field generated by numerical weather prediction into DNN, thus offering physical constraints to the track prediction. Such an approach, in turn, relies on real-time forecast fields instead of lagged reanalysis, making the predicted result more dynamically relevant. LT3P restricts the large-scale guided flow and thus guarantees the generated typhoon track is dynamically consistent with the surrounding atmospheric environment [6].

The empirical results show that the prediction ability of LT3P remains relatively robust in predicting a long-term horizon (i.e., up to 72h) compared to pure data-driven models, this model has lower error growth rate and more stable long-range forecasts, which is an extremely promising research direction to bridge the gap of NWP with data-driven typhoon trajectory prediction.

The advantage of the physically constrained hybrid models is, in essence, to provide a way to balance between the model's freedom and its physicality. By incorporating the physical constraints, these models mitigate the danger of producing tracks that break dynamic laws, whilst retaining the powerful learning ability of deep nets to capture nonlinearities. However, this model architecture is highly complex to implement and depends upon the quality of the dynamic guidance field. Further, substantial domain knowledge is required to design the right physical limits, potentially needing the input of specialists.

3. Literature References

The effectiveness of the typhoon track prediction techniques can be generally verified by analyzing historical cases and performing statistical analysis for different forecasting horizons. Benefiting from good physics compatibility, traditional NWP models are still considered as a benchmark in operation forecast. The mean track error for all of the NWP models, likewise, has decreased on both the short- and medium-range by virtue of increased horizontal resolution, vortex initialization, and data assimilation method development [2]. However in cases where there is a weak flow field or when highly non-linear atmospheric atmospheres exist, NWP forecasts are still highly error-prone and hence it is important that they be complemented by other approaches.

The ensemble forecasting system provides a good basis to quantify the forecast uncertainties through generation of multiple plausible track scenarios. In addition to producing ensemble mean tracks, recent work is also considering the provision of probabilistic track products and reliability assessments. For instance, Titley et al. evaluated the multi-modal ensemble tropical cyclone track probabilistic forecast globally, and showed that the ensemble based probabilistic guidance can provide useful information to support risk-based decisions [7]. In addition, perturbation-based ensemble methods like O-CNOP method from Zhang et al. have demonstrated better robustness to typhoons of abnormal trajectories, such as peaks, valleys, bends, plateaus, etc. Nevertheless, despite its advantages, such an approach remains very costly in terms of computing time and strongly depends on the selected perturbation scheme [3].

Data-driven deep learning (DL) models have been proved to be effective models in prediction of short and medium typhoons track. Wang et al. found that DL models combining historical tracks with large-scale environmental fields can achieve a prediction accuracy comparable to some operational numerical weather prediction (NWP) models for forecasts of up to 72 hours [4]. The prediction can also be improved by including satellite observation data. Research based on geostationary meteorological satellite cloud images indicates that deep networks can effectively capture cloud system evolution characteristics closely linked to typhoon movement, particularly during rapid changes in typhoon structure [8]. However, the predictive performance of DL models largely depends on the quality of training data and their ability to generalize across different scenes of studies.

Over the past few years, scientists have shown great attention in the standardization and normalization applications of methods of predicting typhoon tracks. The TropiCycloneNet dataset and its benchmark model, proposed by Huang et al., provides a unified platform for evaluating global-scale typhoon prediction methods, enabling systematic comparison of different model architectures [9]. At the same time, the physically constrained hybrid models, such as LT3P proposed by Park et al., effectively enhances the stability of long-term forecasting by embedding dynamic guidance information within deep learning frameworks [6]. Generally, the results show that no single method is superior in every scenario. Instead, a combination of Numerical Weather Prediction (NWP), ensemble forecasting, and deep learning models is more effective in optimizing track prediction accuracy, along with uncertainty quantification.

4. Challenges and Future Prospects

As discussed above, although modern techniques such as numerical weather prediction, ensemble forecasting, and deep learning have achieved substantial progress in enhancing typhoon track prediction reliability, there are still several challenges in the field that remain. First, the quantification of uncertainties continues to be significant. Although ensemble forecasting provides probabilistic data, both dynamical ensembles and data-driven models may have problems of under-dispersion or poorly calibrated estimates of the probability in outlier conditions. This lack of calibration severely restricts the interpretability and practical use of probabilistic products for operational meteorological systems, such as public weather forecasting. Therefore, improving the calibration of probabilistic forecasts and developing case-adaptive uncertainty estimation methods represent important directions for the future development of typhoon track prediction.

Second, the generalization ability and robustness of deep learning models remain major bottlenecks. Data-driven approaches often perform well under “typical conditions” represented in the training dataset, but their predictive skill may deteriorate in the presence of rare track patterns, rapid changes in circulation regimes, or evolving climate backgrounds. To address these challenges, further efforts are required to establish unified benchmarking frameworks, conduct cross-basin evaluations, and adopt training strategies that enhance out-of-distribution generalization.

Third, the physical consistency and interpretability are important to build a confidence on the prediction result. Although physics-informed or hybrid frameworks show considerable potential, the design of physically meaningful constraints, as well as their efficient combination with a dynamical steering flow is not trivial. Meanwhile, more researches are focusing on introducing new network structures with stronger ability in time sequence modelling. A representative example is the transformer architecture. For instance, Jiang et al. presented a transformer-based model to predict typhoon tracks and intensities of short-term periods over the Northwest Pacific, which was shown to be better than the recurrent neural network baselines, as well as showing the ability for attention mechanism to capture long distance dependencies [10].

5. Conclusion

Typhoon track prediction is important for disaster prevention and mitigation and have long been a core scientific interest in the area of operation meteorology and atmospheric science. In this paper, an overview and comparison have been provided on common practice approaches of typhoon track prediction, such as classical numerical weather forecast, ensemble forecasting approaches, deep learning based data driven models, multimodal models, and the nascent class of physics-informed hybrid approaches.

Numerical weather prediction is so-called because of its high physical consistency, while the ensemble forecast offers vital probabilistic information for uncertainty quantification. Deep learning methods has demonstrated promising results to improve predictive accuracy recently, especially for the shorter range forecast due to its low computation cost and the capability of modeling non-linear relations. Multimodal and physics informed models do a better job of predicting due to the incorporation of more observational information and physical guidance, enhancing resilience and sustainability over time.

In general, the obtained data in this study were not overall optimal for all the cases. Instead, integrating capabilities over different approaches provide a better approach of typhoon track prediction. Further progress in representing uncertainty, ensuring physical consistency and a standardized measurement will be key to closing the gap between research findings and valid practice.

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