Science Bulletin 70 (2025) 1424–1428

Contents lists available at ScienceDirect

Science Bulletin

journal homepage: www.elsevier.com/locate/scib

Short Communication

Pronounced advance on typhoon track forecast with global convection-permitting model

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ARTICLE INFO

Article history:
Received 11 July 2024
Received in revised form 8 December 2024
Accepted 9 December 2024
Available online 20 January 2025

Typhoons pose significant threats to coastal and inland regions, with their impacts exacerbated by climate change and population growth [1]. Recent studies have shown increased frequency of powerful storms, slower translation speeds, northward shifts in the Western North Pacific (WNP) basin, and a near tripling of global exposure to typhoons since 1970 [1–4]. These changes present new challenges for forecasters and researchers, particularly in predicting impacts on inland and high-latitude populations lacking prior exposure or resilience to typhoon effects.

Accurate track forecast is crucial for effective disaster mitigation, yet improvements in track forecasting have slowed in recent years. A recent study suggests that predictability limits have been reached [5], while another argues that there is still room for improvement based on continuously updated observing, modeling, and data assimilation systems [6]. Emerging artificial intelligence approaches, such as the Pangu-Weather model [7], have shown promise in enhancing typhoon track forecasting. However, these data-driven models may struggle to predict unprecedented extreme events in a rapidly changing climate, as they rely on historical data that may no longer represent future scenarios, and their "black box" nature limits their ability to provide explainable results and physics-based reasoning [8]. Regarding physics-based model development, while improving physics and data assimilation techniques is crucial, increasing model resolution is also a promising approach to enhance typhoon track forecast accuracy and provide more reliable physical insights [9]. Essentially, typhoons present significant challenges for numerical simulation due to their complex physical attributes, with intensely frontogenetical flow within the eyewall resulting in entropy gradients that control the storm's intensity being confined to spatial scales of merely tens of kilometers (km) or less, while the overall storm diameter can reach 1000 km or more [10]. This mismatch in scales necessitates convection-permitting resolution, especially in the storm core, combined with expansive simulation domains to properly capture the full typhoon system. The pursuit of higher resolution to explicitly resolve deep convection processes has gained significant momentum in the research community, as it holds the potential to reduce uncertainties and improve forecast accuracy. However, achieving this feat poses substantial computational and data throughput burdens, especially when employing non-hydrostatic configurations, which only cutting-edge supercomputers can afford [11]. Nowadays, with the development of high performance computing and the exascale computing system in practice, global nonhydrostatic atmospheric models at 3-km horizontal resolution named integrated Atmospheric Model Across Scales (iAMAS) have been realized, enabling deep convection processes resolved globally on the heterogeneous Sunway supercomputer of China [12]. Such capabilities reduce uncertainties associated with parameterized deep convection [13] and enable a more accurate representation of large-scale circulation patterns compared with coarser resolution, potentially improving the simulation of steering flows that guide typhoon motion.

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https://doi.org/10.1016/j.scib.2025.01.032

In this study, we investigate the track prediction of Typhoon In-fa (2021), recognized as one of the top ten weather and climate events in China that year. Typhoon In-fa contributed to extreme precipitation in Zhengzhou and posed significant forecast challenges due to its slow movement and complex environmental interactions. A previous study forecasted the sudden track change, but with a 24-h delay and large forecast errors, using a variable mesh spanning from 8 to 64 km resolution [14]. Motivated by the continuing increase in attainable model resolution, forecasts are conducted employing global uniform meshes of 60 km (U60KM, typical for climate modeling), 15 km (U15KM, common for operational weather prediction), and 3 km (U3KM, convection-permitting scales), as well as various variable-resolution mesh configurations (Table S1 online for experimental details). The U3KM simulation dramatically improves forecast skill, maintaining track errors under approximately 100 km throughout the 120-h prediction period. This performance surpasses both the official 2021 China Meteorological Administration (CMA) average forecast error of 278 km in the WNP (Fig. 1e) and forecasts from other operational centers initialized at the same time (Fig. S1 online). U3KM accurately captures In-fa's sudden northward deflection and dual landfall locations, which coarser resolutions failed to reproduce (Fig. 1a). Analysis of the U60KM forecast shows that the model captures the slow movement of the typhoon. However, the coarse grid spacing fails to resolve small-scale movements, resulting in the typhoon appearing stationary within a single grid cell for 12 h (Fig. 1d). This limitation prevents the model from detecting sudden track change and accurately representing the typhoon's precise location and turn angle. In contrast, the U3KM resolves these small-scale movements, providing a more accurate depiction of the typhoon's slow but continuous progression (Fig. 1b). Meanwhile, the slow movement is reproduced by both coarse and fine horizontal resolutions, validating the utility of our modelling approach in simulating the typhoon's translation speed, to some extent irrespective of the horizontal grid spacing. However, higher-resolution grids remain essential for accurately tracking the detailed typhoon location, movement, and structure. The U3KM case also furnishes skillful predictions of the dual landfall

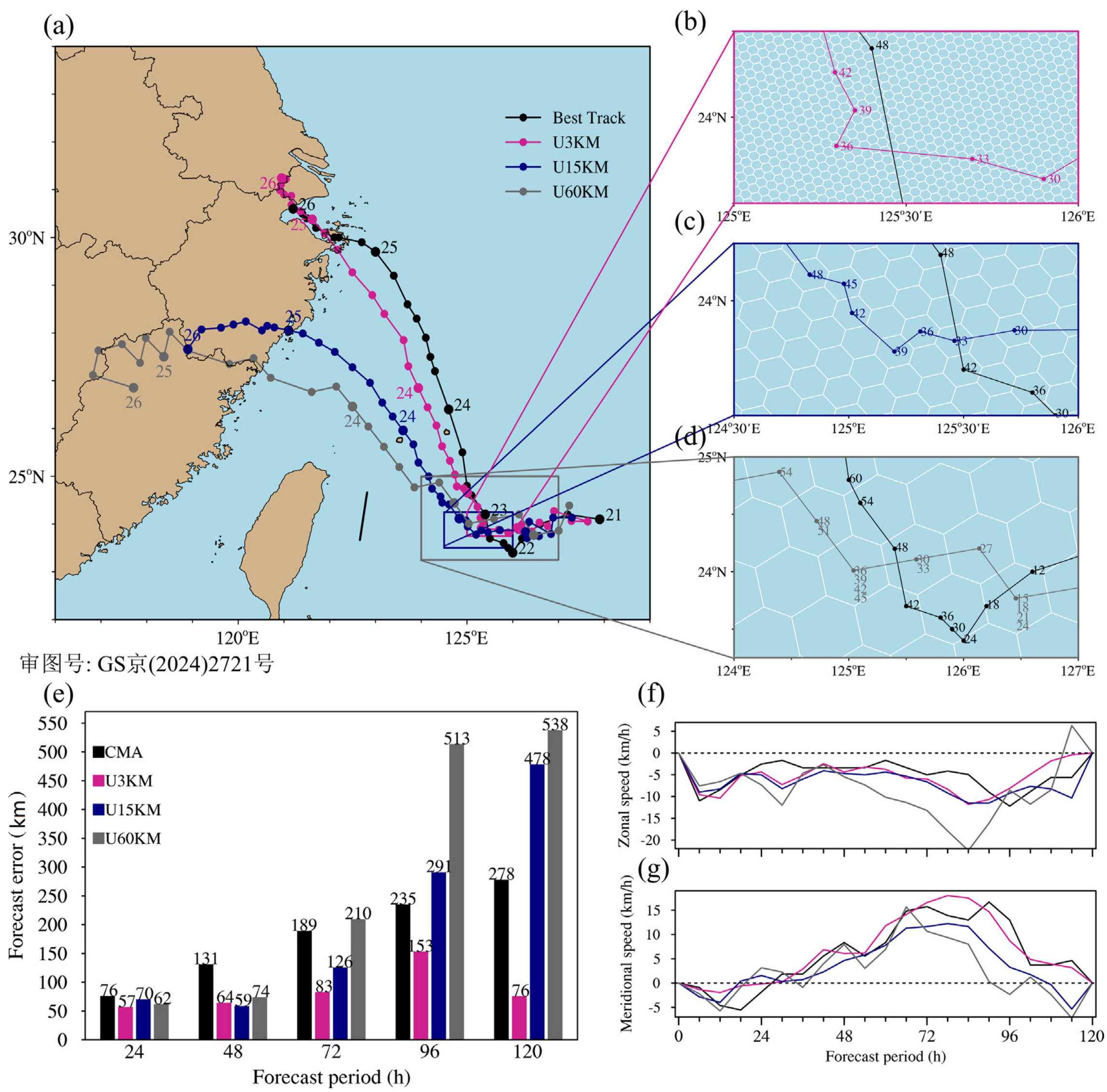

Fig. 1. Track comparison using global uniform resolution. (a) Spatial track comparison of best track data and forecast results from three global uniform resolutions (U3KM, U15KM, U60KM). The dots represent the location of typhoon. Larger colored dots and text labels indicate typhoon locations at 00 UTC on that day in July 2021. (b) Detailed track within the pink box in (a). The hexagonal grid represents the uniform 3 km grid used in model. (c) As in (b) for U15KM. (d) As in (b) for U60KM. (e) Forecast track errors in different forecast periods. The black box indicates the average track forecast error of all typhoons that occurred in WNP in 2021 reported by CMA. (f) Zonal translation speed comparison between different resolutions, the black dashed line is the best track speed. (g) As in (f) for meridional translation speed.

locations, preceding the first Zhoushan landfall by approximately 10 h and the second Pinghu landfall by 19 h in Zhejiang Province. In contrast, the two coarser meshes exhibit substantial errors in the predicted landfall position, with deviations of 290 and 513 km from the actual location. Comparison of U15KM and U60KM cases shows limited improvements in track, landfall locations, and translation speed forecast. Dramatic reduction in track error is achieved only at convection-permitting resolutions. Analysis of zonal and meridional steering flow components and associated translation speed reveals strong quantitative alignment (Fig. 1f, g and Fig. S2 online), instilling confidence that the U3KM capably resolves not only the typhoon's inner core but also accurately depicts the larger-scale environmental flows governing the actual direction and translation speed.

To balance the benefits of convection-permitting simulations with computational feasibility, we explore variable-resolution meshes. This approach refines the region of interest while coarsening the rest of the globe, balancing computational burden with the necessary high-resolution details. Initial attempt with 4–60 km refinement naturally covering only the In-fa's trajectory (V4KM_28N117E) yields limited improvements (Fig. 2a). Increasing the resolution to 2–30 km (V2KM_28N117E) provides only marginal error reduction despite an eight-fold computational cost (Fig. 2b). Weather analysis reveals an influencing monsoon depression southeast of the typhoon exhibiting significant regional convective activity that impacted the motion and direction of In-fa [15] (Fig. S3 online). Adjusting the refined region to encompass this critical weather system (V4KM_24N125E) improves track prediction comparably to the much costlier V2KM_28N117E mesh. The comparisons suggest that refining the mesh to encompass interacting weather systems could potentially match U3KM performance at substantially reduced computational expenses. This highlights the promise of selective refinement strategies that optimize forecast accuracy and computational efficiency, rather than uniformly increasing resolution to convection-permitting scales or higher.

In-fa's track forecasting was inherently challenging due to weak steering flow governing its slow movement, uncertain motion with abrupt track change, and secondary landfall. These factors largely contributed to significant forecast errors [16]. Accurate prediction of sudden track change remains an ongoing issue for numerical weather prediction [17], partly due to limited understanding and inadequate model representation of the complicated interactions between a typhoon and nearby systems. During In-fa's evolution, several relevant weather systems were present, including a high-altitude cold low, monsoon depression southeast of In-fa, Typhoon Cempaka inducing binary typhoon effects, Typhoon Nepartak east of In-fa, and critical subtropical high over WNP. The iAMAS's unstructured grid and adaptive mesh refinement enable flexible sensitivity experiments to examine these systems' impacts on typhoon motion. The approach can identify key phenomena governing sudden track change and slow movement using targeted mesh refinement. Through a series of sensitivity experiments with different refinement configurations (Figs. S4, S5 and Text S1 online), we identify an optimal circular refinement region

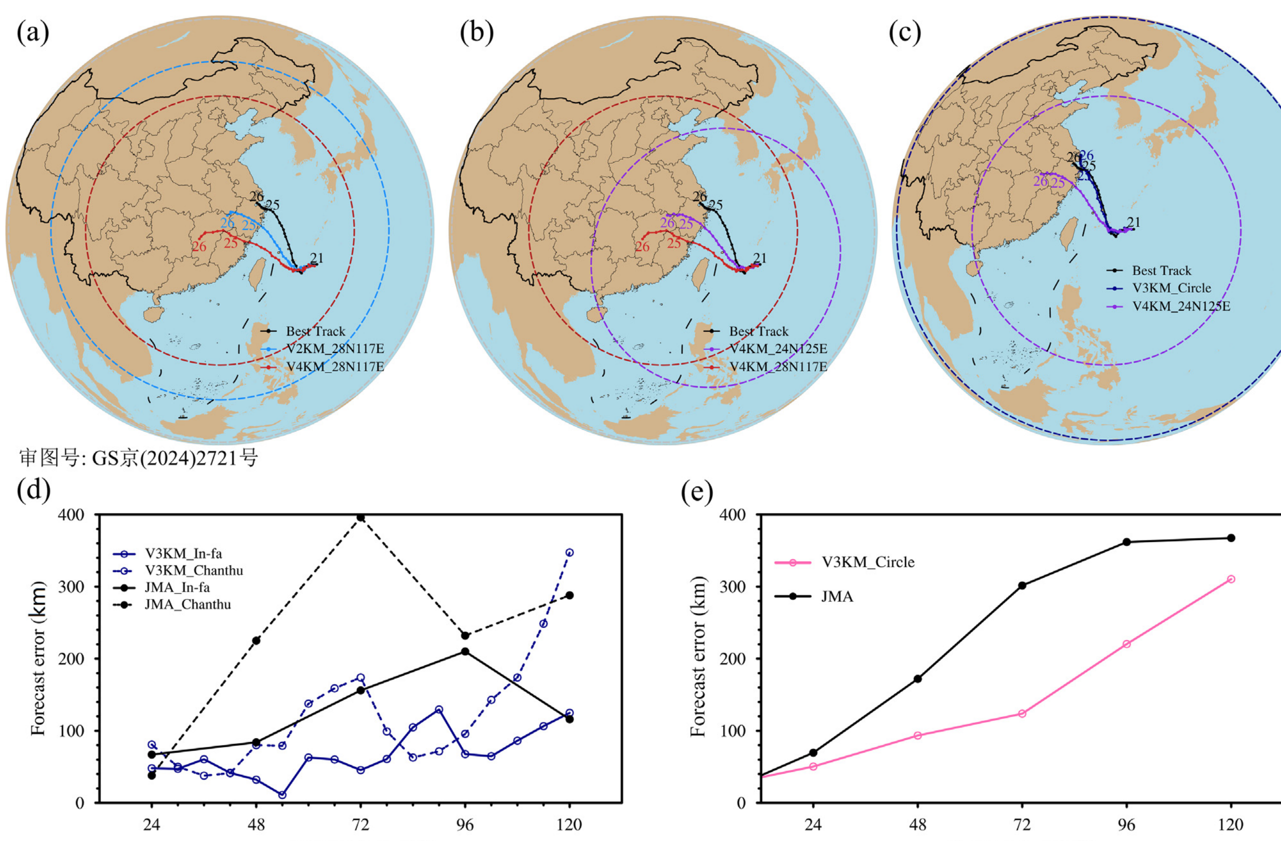

Fig. 2. Track comparison using variable uniform resolution. (a) Spatial track comparison between best track data and forecast results from two variable resolution meshes (V2KM_28N117E, V4KM_28N117E). Red and blue dashed circles indicate refinement regions ≤ 4 km for two meshes, respectively. The red dashed circle lines also indicate the refinement of V2KM_28N117E where the mesh resolution is less than or equal 2 km. The dots show typhoon locations every 3 h, the larger dots and text labels indicate typhoon locations at 00 UTC on that day in July 2021. (b) As in (a) but for another variable resolution mesh (V4KM_24N125E). (c) As in (a) but for another variable resolution mesh (V3KM_Circle). (d) Forecast track errors for two typhoons in 2021 (06 In-fa, 14 Chanthu). Blue lines show forecast results using V3KM_Circle mesh; black lines show operational forecast results from JMA at the same initial time. (e) Average forecast track errors for ten selected typhoons since 2013. The pink line shows forecast results using V3KM_Circle mesh and the black line indicates the average operational forecast track errors from JMA at the same initial time.

(V3KM_Circle) that achieves comparable performance to U3KM while reducing the total grid cells by 92%. This mesh design maintains track errors within approximately 100 km throughout the 120-hour forecast period for In-fa by capturing critical weather systems affecting In-fa's motion. This mesh configuration even improves upon the U3KM benchmark, despite a slight displacement in the second landfall location (Fig. 2c). To gain deeper physical insights into track forecasting improvements, we employ the widely used potential vorticity (PV) tendency diagnostic approach (Text S2 online) to understand the contributions of various physical processes in typhoon motion. Comparative results show that U3KM and V3KM_Circle capture similar PV structures and apparent northward translation speed, mainly contributed by horizontal advection and corresponding to the sudden track change. In contrast, the V4KM_28N117E fails to capture these features (Fig. S6 online). Through stepwise mesh refinement covering individual weather systems, we identify their contributions to the typhoon motion's direction and translation speed (Fig. S7 and Text S1 online). A comparison of typhoon convective structures shows continuous improvement with increasing resolution (Fig. S8 online), but only enough large refinement shows significant improvement in the track forecast. This indicates that accurately predicting convective structures is necessary but not sufficient for improved track forecasts and aligns with the previous findings [18] that expanding the high-resolution area to capture large-scale circulation features leads to improved track forecasts. Regarding intensity evolution, the forecast results are not as favorable as the track forecasts (Fig. S9 online). All simulations exhibit a virtual rapid intensification, likely due to poor initial intensity representation and lack of data assimilation, challenging our approach and highlighting the need to further explore the intensity forecasts with increasing resolution.

In 2021, Typhoon Chanthu posed another forecasting challenge with its complex trajectory, contributing to huge forecast errors reported by CMA [16]. To validate the optimized V3KM_Circle configuration, we conducted a forecast for Chanthu, initialized at 00 UTC on 10 September. The resultant errors remain lower than those from the operational Japan Meteorological Agency (JMA) typhoon prediction system throughout the 120-h forecast (Fig. 2d). This performance demonstrates the variable mesh design's potential to provide robust forecasting skill for future WNP typhoons, even those involving unusual drift velocities or complicated tracks. Notably, this improvement is achieved with a reduced computation burden, as the variable mesh design only requires approximately 8% (5,338,790 cells) of the total grid cells (65,536,002 cells) of the U3KM configuration. To further validate the forecast skill improvements offered by this efficient and cost-effective method, we conduct more forecasts of historical typhoons. We randomly select 9 typhoons from the past decade over the WNP (Table S2 online) for this validation. Our model's average forecast track errors are smaller than those from the JMA operational forecasts, indicating improved accuracy in typhoon track predictions (Fig. 2e). Individual forecast tracks over maps and comparisons are displayed (Fig. S10 and Table S2 online). We also conduct additional forecasts of these typhoons using coarse resolution (U60KM) and limited refinement (V4KM_28N117E) to assess the general improvement in track forecasts when increasing resolution to convection-permitting scales (Fig. S11 online) and expanding refinement areas (Fig. S12 online).

In summary, we increase the horizontal resolution of a global non-hydrostatic model to convection-permitting scales to investigate the track prediction of Typhoon In-fa (2021). This approach dramatically improves forecast skill, affirming the significant sensitivity of typhoon trajectory representation to model horizontal resolution. Leveraging the capabilities of the variable mesh, we examine the relative influence of interacting weather systems on In-fa's motion by adjusting targeted refinement regions and identifying critical weather systems impacting typhoon motion. This process reveals an optimal variable mesh design that achieves track forecast performance of U3KM while reducing computations by an order of magnitude. To validate this framework, we apply it to Typhoon Chanthu, which also exhibited the largest operational forecast errors in 2021 over WNP basin [16]. The resulting track predictions also outperform JMA operational forecast. Further validations with 9 more typhoons yield improved average forecast tracks compared to the JMA forecasts. For typical northwestward-moving typhoons in the WNP basin, our V3KM_Circle appears optimal. It effectively covers interacting weather systems (such as monsoon gyres, cold lows, subtropical highs, potential nearby typhoons, and important topographical features) at convection-permitting scales, yielding improved forecasts with minimal computational burden. However, for specific cases, enlarged refinement may not yield such significant improvements due to the complex characteristics of individual typhoons, suggesting that improving model physics could be a potential avenue for forecast improvement. Further investigation is therefore needed to test this approach with more cases across individual basins and to guide the selection of critical refinement regions.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgments

This research was supported by the Strategic Priority Research Program of Chinese Academy of Sciences (XDB0500303), the Natural Science Foundation of Anhui (2208085UQ09 and 2208085UQ02), the USTC Research Funds of the Double First-Class Initiative (YD2080002007 and KY2080000114), the Science and Technology Innovation Project of Laoshan Laboratory (LSKJ202300305), and the National Key Scientific and Technological Infrastructure project "Earth System Numerical Simulation Facility" (EarthLab). The study used the computing resources from the Supercomputing Center of the University of Science and Technology of China (USTC) and the Qingdao Supercomputing and Big Data Center.

Author contributions

Chun Zhao and Hong An conceived the study and led the overall scientific questions. Jun Gu, Gudongze Li, and Jiawang Feng developed the model and designed the mesh. Jun Gu conducted the experiments and performed the data analysis. All authors are involved in discussing and writing the paper.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scib.2025.01.032.

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