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Challenges in the Forecasting of Severe Typhoon Koinu in 2023

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Abstract: Hong Kong was under the direct hit of Severe Typhoon Koinu (2314) on 8 and 9 October 2023, necessitating the issuance of the Increasing Gale or Storm Signal, No. 9. Koinu was a very challenging case for TC forecasting and warning services due to its compact size and erratic movement over the northern part of the South China Sea. This paper reviews the difficulties and challenges of the forecasting aspect of the severe typhoon. The predicted tropical cyclone track and intensity from both conventional models and emerging artificial intelligence models are examined, as well as local wind and rainfall forecast. Experience in this case study showed that while deterministic global models only performed moderately and were not able to adequately support early warning, a regional model and AI models could more effectively support decision making for an operational tropical cyclone warning service.

Keywords: tropical cyclone; track; intensity; wind; rainfall

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1. Introduction

Tropical cyclones (TCs) are a type of severe weather system that commonly affect Hong Kong. On average, approximately six TCs come within 500 km of Hong Kong in a year. These TCs can bring strong winds, heavy rain, and severe storm surge to Hong Kong and neighboring regions depending on their track and intensity. To warn the public about potential strong wind hazards brought by TCs, a numbered TC warning system was introduced in Hong Kong in 1917. The current 1-3-8-9-10 numbering scheme for TC warning signals has been in use since 1973 [1] and is very well known by the public in Hong Kong.

Hong Kong was directly hit by two TCs within a few weeks in 2023. First, in early September 2023, Super Typhoon Saola (2309) was bringing hurricane-force winds to Hong Kong, which was a rather difficult case in terms of TC forecasting due to its relatively small circulation and the interaction with Tropical Cyclone Haikui (2311) near Taiwan. The forecasting aspect of Saola has been summarized in a paper by Chan et al. [2]. Then, about a month later, Hong Kong was directly hit by Severe Typhoon Koinu (2314) in early October 2023 (Figure 1). In He et al. [3], an observational study was made about Koinu. Since Koinu might bring about hurricane-force winds to some places in Hong Kong, the TC warning signal No. 9 was issued for Hong Kong, meaning that gale or storm force wind is increasing or expected to increase significantly in strength [1]. Under the successive strikes of TCs Saola and Koinu, this was the first time since 1999 that TC warning signal No. 9 or above was issued twice within a single TC season.

While Saola brought about big challenges in terms of operational forecasting, Koinu was even more difficult to forecast, as far as its impact on Hong Kong was concerned, due to a number of factors. During the operational forecasting for Koinu, even with today's technological advancement of numerical modeling, it was basically technically infeasible to give advance warning on local wind strength over Hong Kong one day or even several hours ahead. Meanwhile, expectation from the general public for an accurate early warning has risen rapidly. This manuscript will review the forecast difficulties of Koinu, aiming to help in the following several aspects: first, a documentation for later reference by forecasters in Hong Kong, which may also benefit other parts of the world; second, a stimulation for further study for this case in the research community, hopefully to address and resolve forecast difficulties in the future with further technological advancements; and third, a call for the operation of numerical weather prediction (NWP) models with higher spatial resolution and the availability of more observations over the vast ocean, namely the South China Sea in this case.

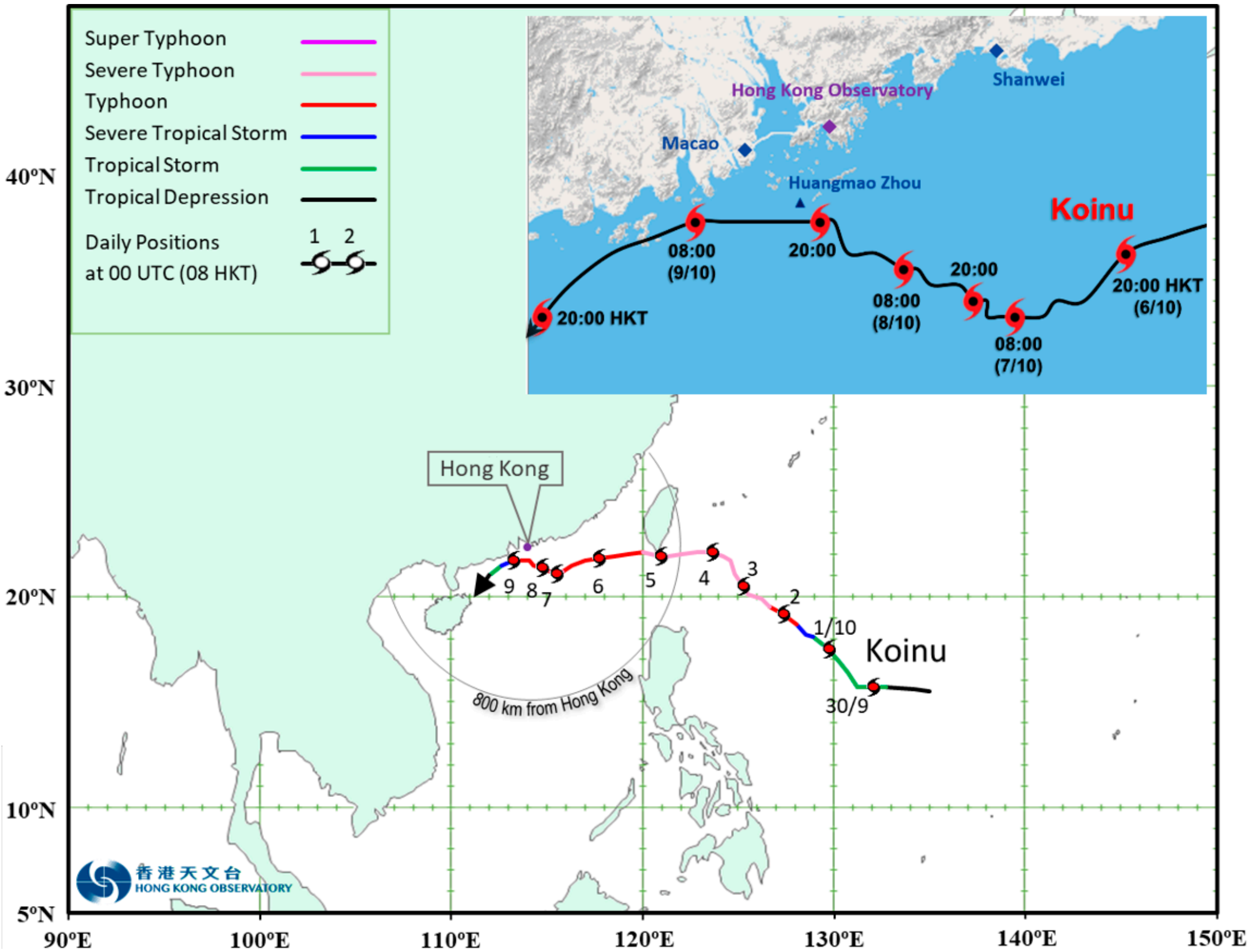

Figure 1. Provisional best track of Severe Typhoon Koinu and (insert) its track near Hong Kong (Hong Kong Time (HKT) = UTC + 8 h). The movement of Koinu was slow and erratic during 6–8 October 2023.

2. Major Challenges of the Forecast of Koinu

As in the case of Saola, one major challenge in forecasting the track and intensity of Koinu is its rather small and compact circulation. In fact, Koinu was even smaller than Saola. From the surface isobaric pattern when Koinu was close to Hong Kong (Figure 2a), its circulation was around less than 200 km. Given such a small system, it would be rather difficult for the current global NWP models, with a spatial resolution as high as 9 to 10 km, to properly resolve the TC and forecast its movement and track.

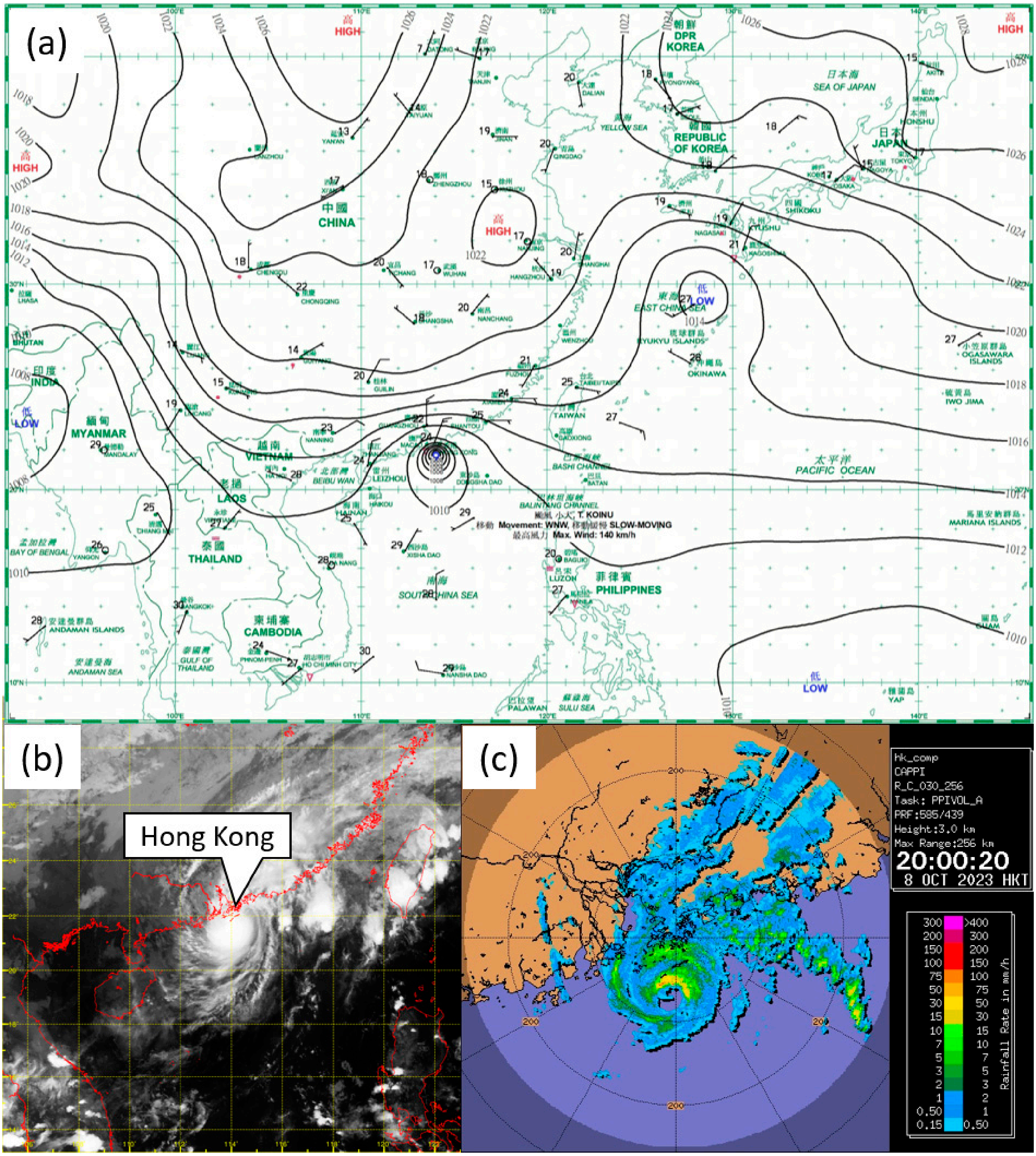

Figure 2. (**a**) Surface weather chart at 1200 UTC on 8 October 2023 as analyzed by the Hong Kong Observatory (HKO), where Koinu was at its closest to Hong Kong. Koinu had a small circulation, and the northeast monsoon dominated over Southern China. (**b**) Infrared satellite image of Himawari-9 Satellite of the Japan Meteorological Agency at 1200 UTC on 8 October 2023 showing Koinu just to the south of Hong Kong. (**c**) HKO radar image at 1200 UTC on 8 October 2023. Koinu had a compact eye, estimated to be less than about 30 km in diameter.

The second complication is the impact of the weak northeast monsoon. In early October, it is climatologically the commencement of the northeast monsoon affecting Southern China. Weak monsoon flow, with slightly cooler and drier air from the continent, may occasionally reach the coast of Southern China, but this is not yet strong enough to dominate in this region. The interaction between the northeast monsoon and a TC has long been a problem for TC warning in Hong Kong (e.g., in the case of Tropical Cyclone Nalgae in 2022, as documented in Chan et al. [4]). On the one hand, cooler and drier continental air might cause weakening of the TC as it gets close to the South China coast. On the other hand, the east to northeasterly monsoon winds to the northern flank of the TC and the southwesterly flow still prevailing over much of the South China Sea might enhance the horizontal shear over the region, thus perhaps favoring the intensification (or at least maintaining the intensity) of the tropical cyclone along the inter-tropical convergence zone (ITCZ). This is expected to be a rather difficult problem for global NWP models to correctly predict which of the two potentially competing factors would become dominating. Koinu may be such a case for which further research effort could be explored.

Thirdly, with the arrival of a weak surge of the northeast monsoon over the South China coast, the upper flow at the middle troposphere (e.g., 700 hPa to 500 hPa) would typically be westerly. Yet, the upper westerly flow will not be particularly strong in early autumn (as compared to winter time). There may be occasions of perturbations in the westerly flow, especially at the lower latitude of around 20 degrees north. Such westerly short waves may "drag" a TC, resulting in slight northward movement or at least a quasi-stationary situation for the TC for a certain period of time. As such, the movement of the TC is not so steady. Given that global NWP models are still struggling to pick up short waves in the westerly flow, TC track forecasting will become rather difficult. At the same time, the vertical shearing resulting from the westerly short wave might cause the gradual weakening of the TC, but it would be rather difficult to precisely predict when and where the weakening would occur. As shown in the satellite image (Figure 2b) and radar picture of Hong Kong (Figure 2c) when Koinu was close to the territory, there was an extensive cloud band and rain band to the north and northeast of Koinu, suggesting the passage of a westerly wave/trough in the middle troposphere, which partly explains the quasi-stationary or even slight northwest movement of Koinu, as well as the gradual weakening of the cyclone at that time. The accurate forecast of the timing of the impact of such westerly waves remains a major challenge for NWP models.

3. Track Forecast

In the Hong Kong Observatory (HKO), tropical cyclone track forecasting is mainly based on the consensus of four global NWP models, namely the European Centre of Medium-Range Weather Forecasts (ECMWF) Integrated Forecast System (IFS), Japan Meteorological Agency (JMA), National Centers for Environmental Prediction (NCEP) of the U.S., and United Kingdom Met Office (UKMO) Unified Model. In the last couple of years, a mesoscale model with a spatial resolution of 9 km developed by the Guangdong Meteorological Service of the China Meteorological Administration, named the Tropical Regional Atmospheric Modelling System (TRAMS) [5], has also been introduced for trial in HKO.

With the advancement of artificial intelligence (AI), some AI-based weather prediction models have been introduced to HKO. Starting from mid-2023, HKO has begun to run the Pangu-Weather model [6] and Fengwu model [7]. Both AI models can be initialized by ECMWF operational analysis to provide operational guidance for TC forecasting.

The comparison between the various model outputs with the HKO operational analysis track is given in Figures 3 and 4. For the early model run initialized at 12 UTC, 2 October 2023 (Figure 3), the majority of conventional global models, including ECMWF, JMA, and UKMO, forecast that Koinu would dissipate along the eastern coast of Guangdong or its adjacent waters due to the impact of the northeast monsoon, namely the cold and dry intrusion of the monsoon is expected to play a rather significant role. However, TRAMS and the AI models suggested that Koinu may get close to Hong Kong, or at least in the vicinity of Hong Kong (mainly for the AI models). Among them, TRAMS forecast that Koinu would persist at typhoon intensity (intensity forecast to be discussed in a later section in detail), whereas AI models forecast the weakening of Koinu into an inverted trough in the low-level northeasterly winds.

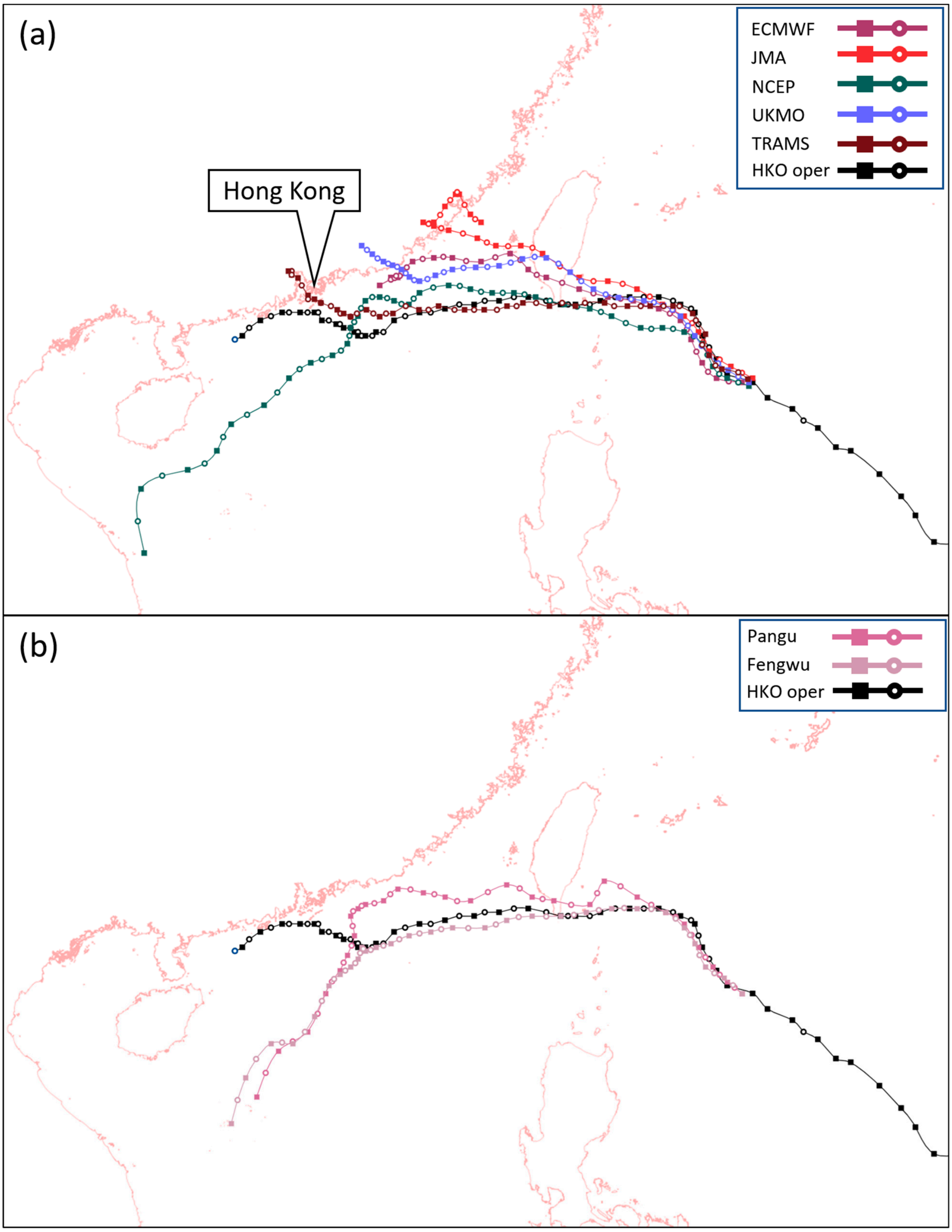

Figure 3. Models' forecast tracks of Koinu at 1200 UTC run on 2 October 2023. Also shown on each panel is Koinu's analysis positions (black) based on HKO operational analysis track. (**a**) Forecast tracks from ECMWF, JMA, NCEP, UKMO, and TRAMS. (**b**) Forecast tracks from AI models Pangu-Weather and Fengwu; both were initialized by the operational analysis of ECMWF.

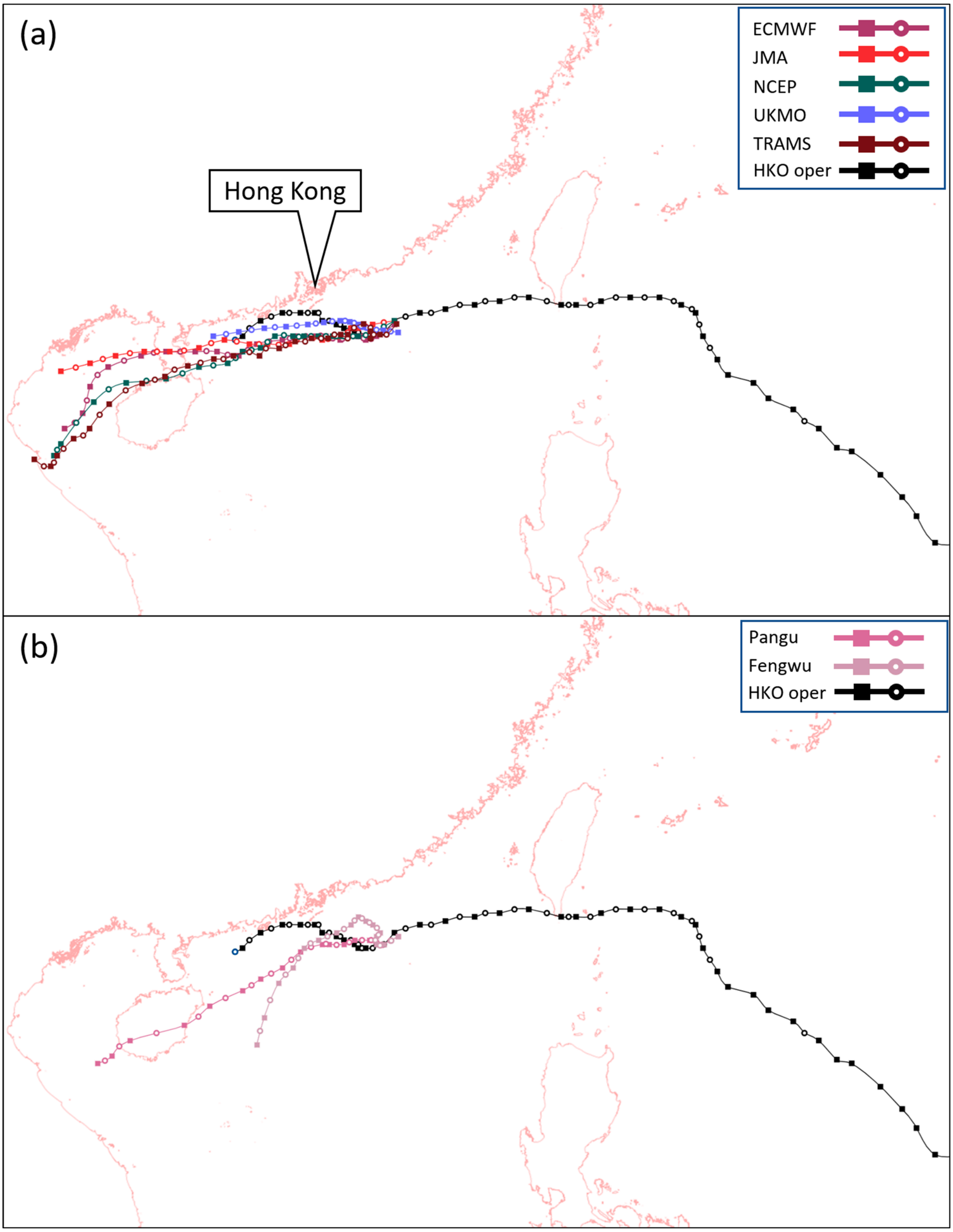

Figure 4. Models' forecast tracks of Koinu at 1200 UTC run on 6 October 2023. Also shown on each panel is Koinu's analysis positions (black) based on HKO operational analysis track. (**a**) Forecast tracks from ECMWF, JMA, NCEP, UKMO, and TRAMS. (**b**) Forecast tracks from AI models Pangu-Weather and Fengwu; both were initialized by the operational analysis of ECMWF.

Four days later (Figure 4), the conventional global models' deterministic forecasts converged and forecast the westward movement of Koinu as it got close to Hong Kong, though the tracks were far too south of Hong Kong, so its impact on Hong Kong would be expected to be rather minimal, whereas in reality (the operational analysis track), Koinu would take a more northwest track and get much closer to Hong Kong for a while. Such a slight northward movement of Koinu was picked up by Fengwu (Figure 4b), though occurring at an earlier time at a rather upstream location.

To appreciate the model forecasts in depth, two strategic time instances are selected for discussion in more detail. Figure 5 shows the 96 h forecast by ECMWF and TRAMS as initialized at 12 UTC, 4 October 2023. For comparison, the ECMWF analysis at that time is also shown (Figure 5a,d). It can be seen that, for ECMWF 96 h forecast, while the circulation of Koinu is still maintained at the 700 hPa level, the TC's surface circulation is basically dissipated, possibly because of the impact of the northeast monsoon, bringing significant dry intrusion (700 hPa relative humidity in Figure 5b). On the other hand, TRAMS kept forecasting Koinu to remain a rather strong system when it gets close to Hong Kong, and this forecast trend is persistent in various forecast runs at different initial times, though the forecast circulation is too large compared with the analysis (e.g., comparing Figure 5f with Figures 2a and 5d).

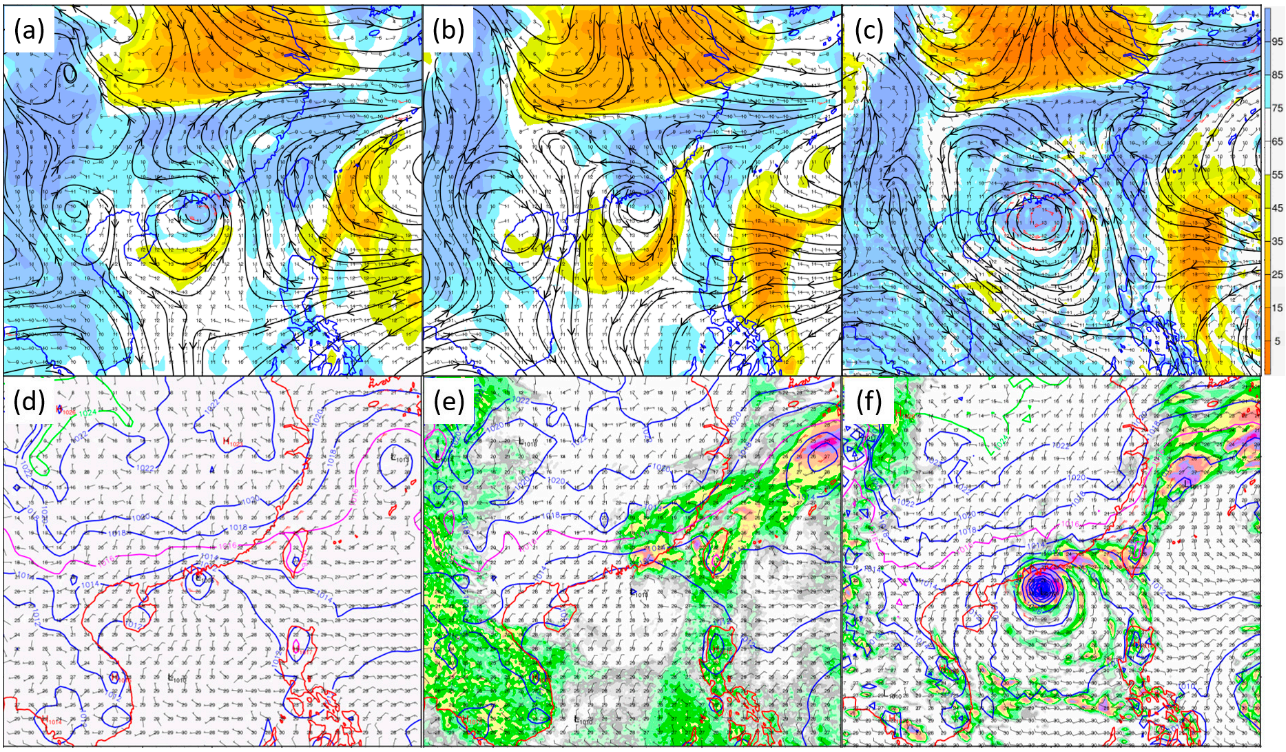

Figure 5. ECMWF's operational analysis of (**a**) 700 hPa relative humidity (color-filled contours) and winds (barbs and streamlines), as well as (**d**) mean seal-level pressure (contours) at 1200 UTC on 8 October 2023. Note that according to the HKO operational analysis, Koinu was at that time still a typhoon with central pressure 975 hPa and maximum sustained winds 75 kt. (**b**,**e**) 96 h forecast of ECMWF valid for 12 UTC, 8 October 2023, where Koinu was forecast to be dissipating possibly due to significant dry intrusion from the northeast monsoon, while its remaining surface vortex would have been pushed southwestwards by the monsoon. (**c**,**f**) 96 h forecast of TRAMS valid for the same time. TRAMS successfully forecast Koinu to remain as an intense and intact tropical cyclone at its closest to Hong Kong.

Another point of interest in the steering flow for Koinu is depicted in the 500 hPa geopotential height (Figure 6). The ECMWF operational analysis showed that a ridge axis was built to the southeast of Koinu on 8 October (e.g., the evolution of the 5910 m geopotential height contour in Figure 6a,b). It can be seen on Figure 6c,d,e that the various conventional models could not forecast the establishment of such a ridge to the right extent or strength. Possibly due to the underestimated intensity of Koinu and low-level northeasterlies brought by the monsoon, the models generally maintained a continual westward movement of the cyclone. On the other hand, Fengwu forecast a slight ridging flow (Figure 6f), and thus possibly the northwest movement of Koinu in the direction of Hong Kong (Figure 4b).

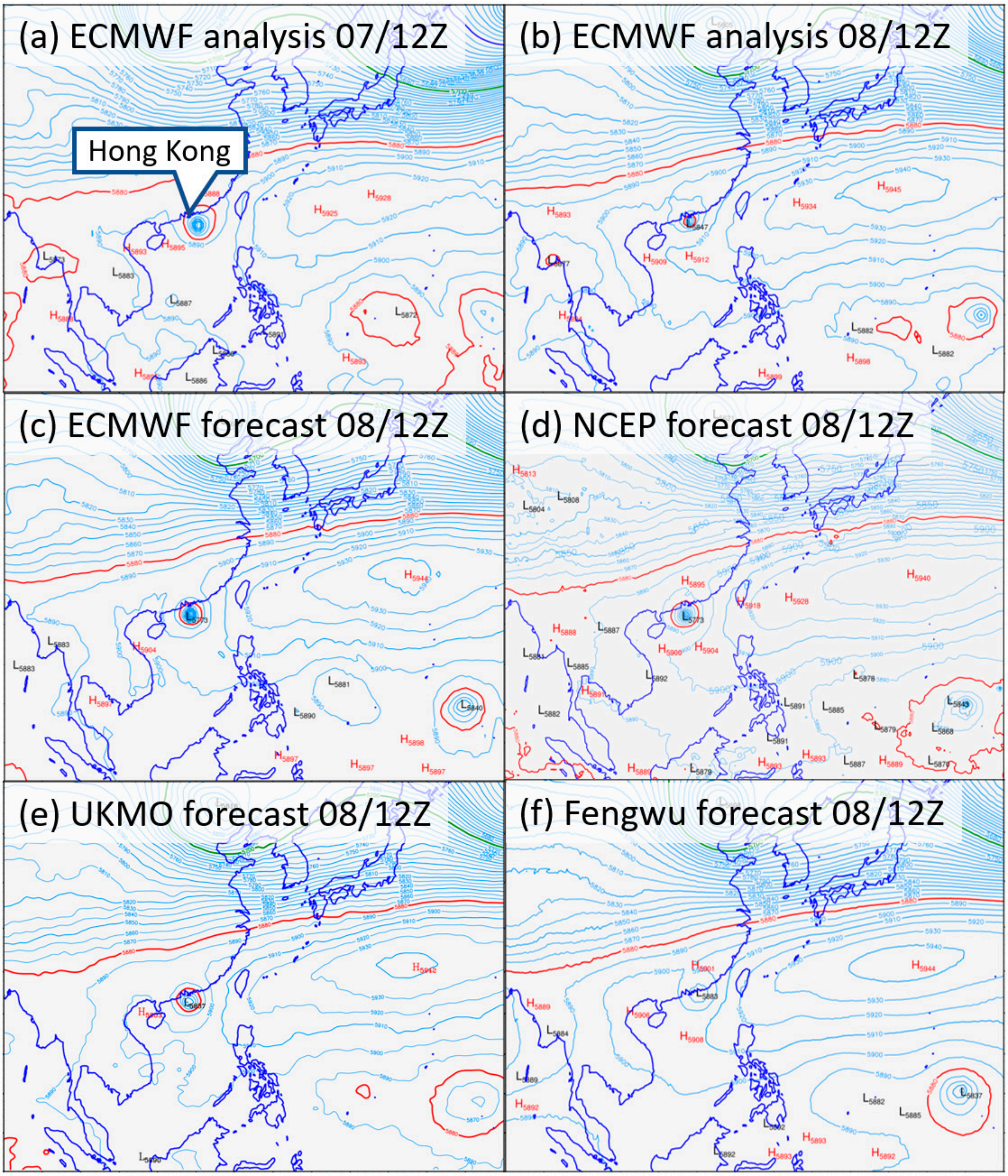

Figure 6. 500 hPa geopotential height with a contour interval of 1 dam. The 5880 m contours are plotted in red. ECMWF's operational analysis at 1200 UTC on (**a**) 7 and (**b**) 8 October 2023. Note the

evolution of 5910 m geopotential height contour for the establishment of a ridge over northern part of South China Sea. (**c**–**e**) 48 h forecast from ECMWF, NCEP, and UKMO respectively, valid for 1200 UTC on 8 October 2023. None of these models were able to fully capture the extent and strength of the ridge to the southeast of Koinu. (**f**) 48 h forecast of Fengwu initialized by the operational analysis of ECMWF, valid for 1200 UTC on 8 October 2023, where the ridge to the southeast of Koinu was most accurately forecast among available models.

Ensemble prediction systems (EPSs) are also considered in the HKO operation for tropical cyclone forecasting. The EPS strike probability maps at different forecast times are given in Figure 7. It can be seen that the ensemble forecasts managed to predict the westward movement of Koinu across the northern part of the South China Sea. However, finer details of the movement, namely the southward dip away from the South China coast followed by northwestward movement in the direction of Hong Kong, are not predicted well.

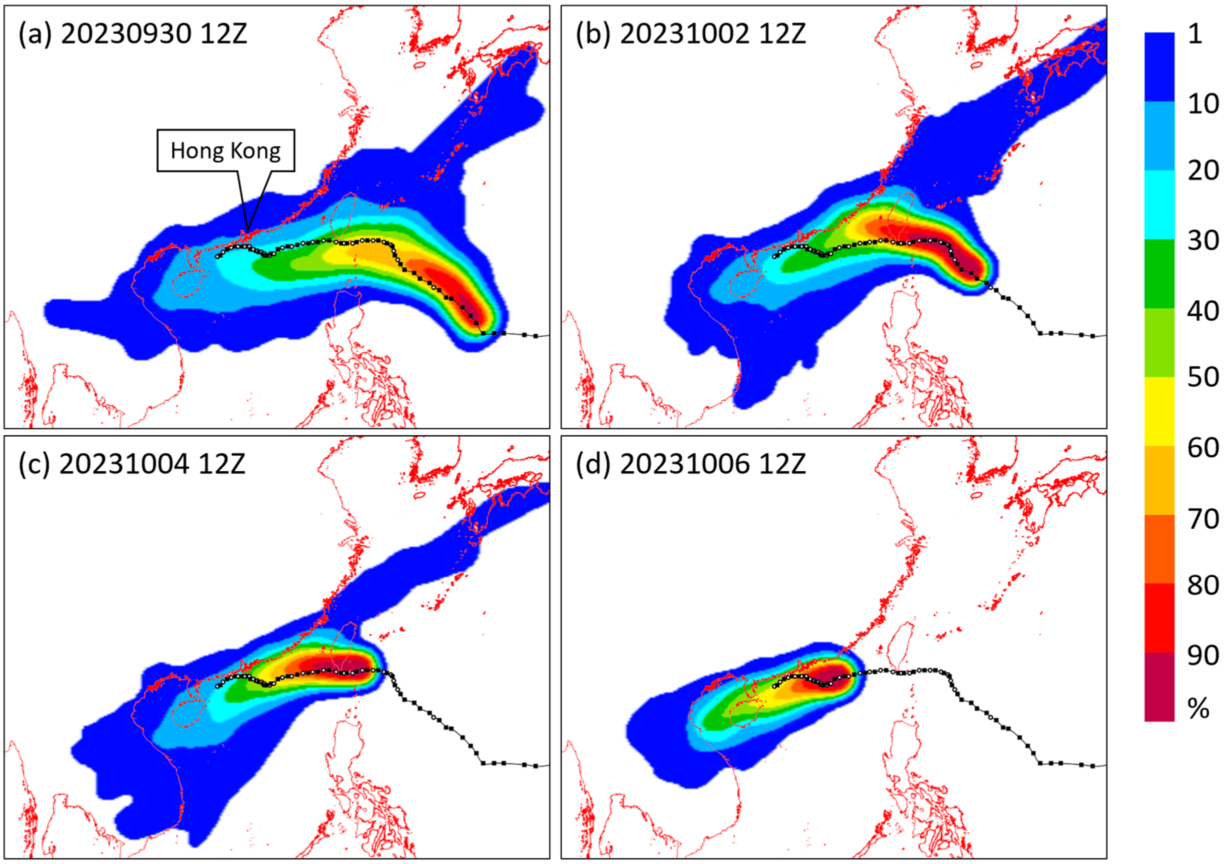

Figure 7. EPS strike probability maps of Koinu based on the ensembles of ECMWF, NCEP, and UKMO from 1200 UTC runs on (**a**) 30 September and (**b**) 2, (**c**) 4, and (**d**) 6 October 2023. Also shown is Koinu's analysis positions (black) based on HKO operational analysis track.

As a summary, the forecast track errors by the various models are presented in Figure 8. It can be seen that, though AI models are emerging very recently, they are better than the conventional NWP models in the present case. Our experience showed that AI models are becoming an indispensable tool in the tropical cyclone forecast and warning services, at least for this part of the world, as they have demonstrated a superior performance. This is consistent with the findings of a previous study for the case of Saola as well, as discussed in Chan et al. [2].

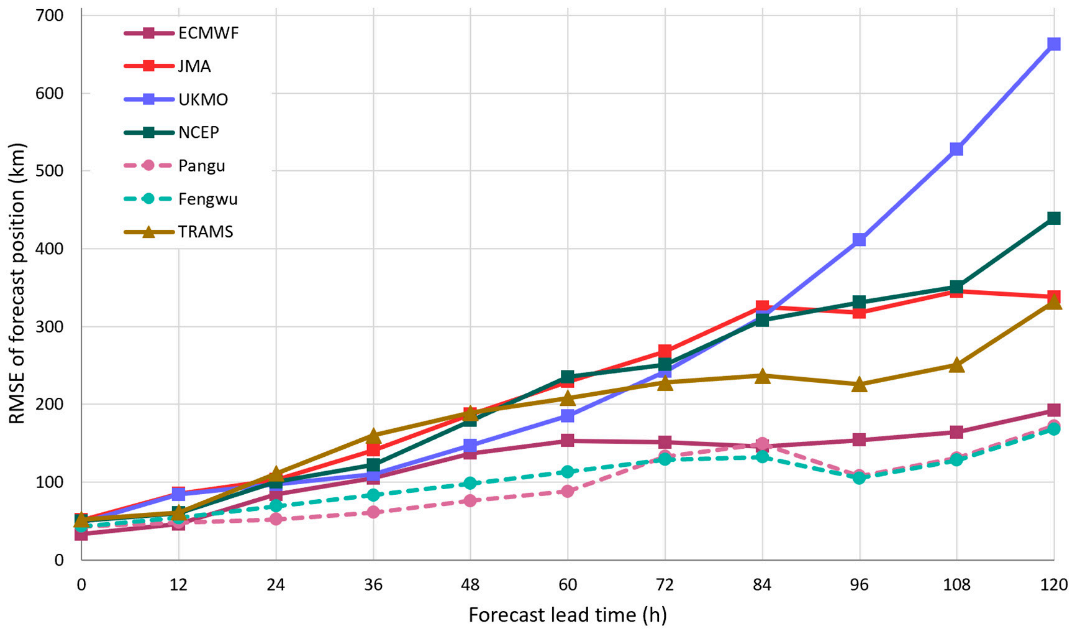

Figure 8. Root-mean-square error of models' forecast positions for Koinu as a function of lead time. Forecasts are verified against Koinu's analysis positions based on HKO operational analysis track and have a common dataset among different models.

4. Intensity Forecast

The model intensity forecast at various initial times is shown in Figure 9. As given in Figure 9a, earlier runs of conventional models generally managed to forecast that Koinu would reach the intensity of a severe typhoon, with the exception of UKMO. These models keep the intensification trend but over-forecast the peak intensity slightly in some later model runs (e.g., Figure 9b). A critical time for the warning service for Koinu is the intensity of the cyclone when it gets close to Hong Kong (highlighted in red rectangles in Figure 9b–d). A few days before Koinu's closest approach, only TRAMS was able to forecast that Koinu would remain as a strong system, whereas the other models forecast a far too rapid weakening trend. This discrepancy still continued two days later (Figure 9c), so that it would be rather difficult to judge the impact of Koinu on Hong Kong several days ahead. Even a couple of days ahead (Figure 9d), the conventional models still do not do a good job in the intensity forecast, with large model spread and little consensus on the trend of intensity change.

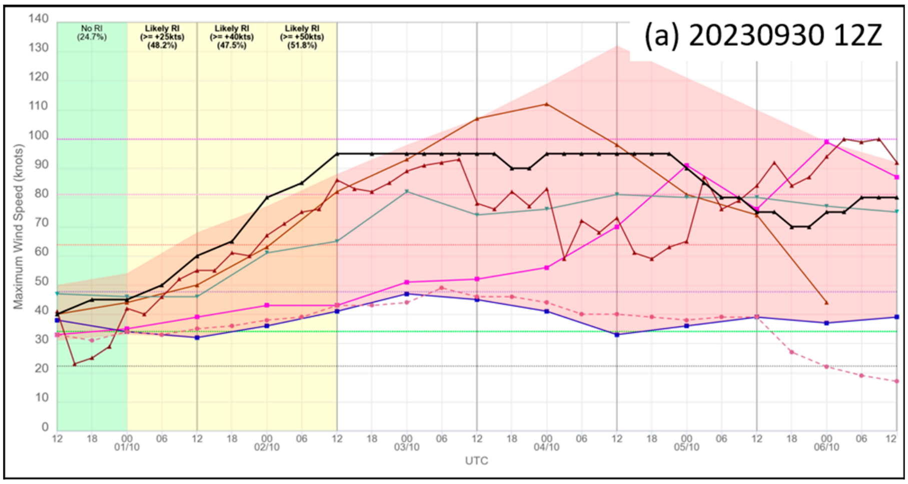

Figure 9. *Cont.*

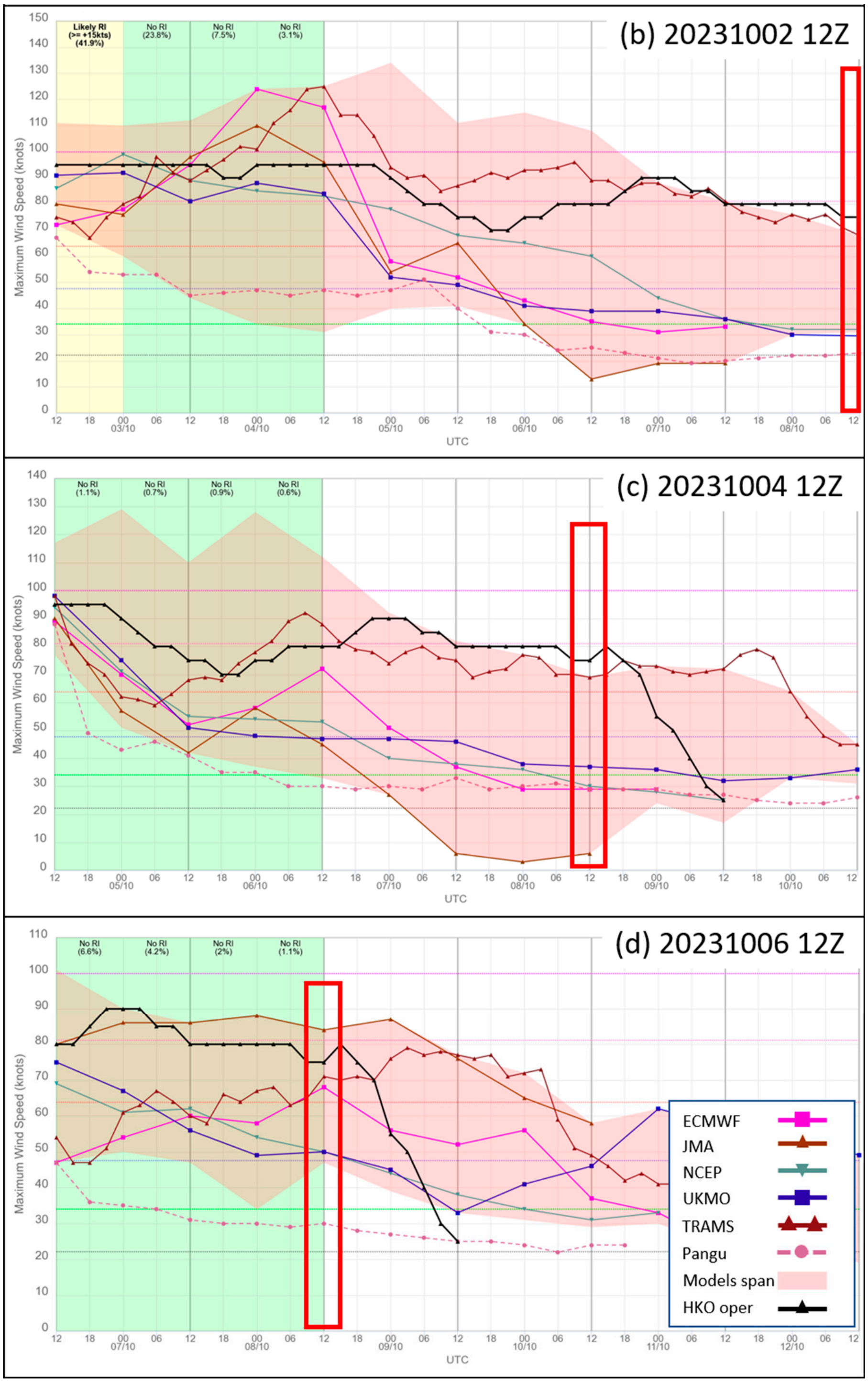

Figure 9. Intensity of Koinu as forecast by models from 1200 UTC runs on (**a**) 30 September and (**b**) 2, (**c**) 4, and (**d**) 6 October 2023. The light-red shading indicates the spread of all available models. Also shown is Koinu's analysis intensity (black line) based on HKO operational analysis track. The red rectangle indicates the time period where Koinu at its closest approach to Hong Kong.

A summary of the intensity forecast error is shown in Figure 10. It can be seen that TRAMS provided a persistently much better forecast, followed by the conventional NWP models. The AI models, as expected, had predicted Koinu far too weak, resulting at the largest errors. The conventional NWP models performed moderately for this single case study on Koinu. While regional models (TRAMS in this case) may perform better for the intensity forecast of tropical cyclones, we may need to consider the AI models for a more accurate track forecast in the formulation of the tropical cyclone warning service several days ahead.

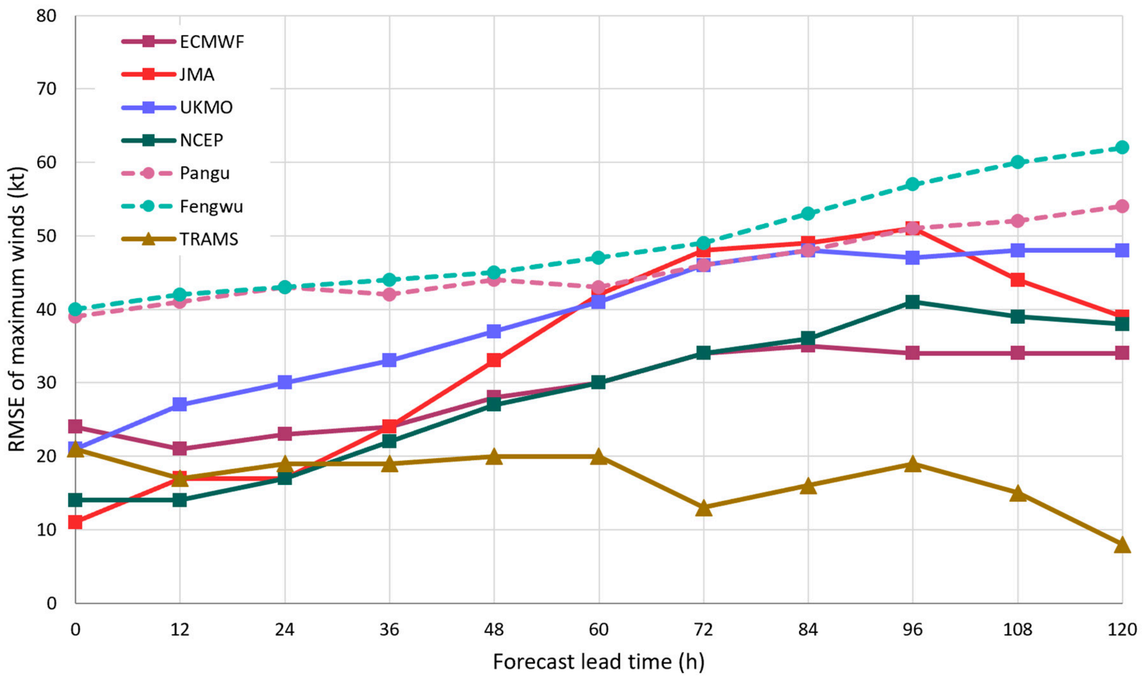

Figure 10. Root-mean-square error of models' forecast sustained maximum winds for Koinu as a function of lead time. Forecasts are verified against Koinu's analysis intensity (in knots) based on HKO operational analysis track and have a common dataset among models.

5. Wind Forecast

For the operation of the tropical cyclone warning service in Hong Kong, an accurate forecast of the wind force over the territory is the most important requirement because tropical cyclone warning signals are related to the wind strength at selected locations within the territory. A summary of the wind force forecast by the various numerical models initialized at 1200 UTC on 7 October 2023 is given in Figure 11.

A detailed discussion of the winds in Hong Kong under the influence of Koinu can be found in He et al.'s study [3]. In summary, gale-force winds were prevailing over the southern part of Hong Kong, and hurricane-force winds higher than 100 kt (10 min mean winds) were registered at Huangmao Zhou (Figure 1 insert), an island of about 50 km south of the territory [8]. It can be seen that, for ECMWF and NCEP, the wind force was forecast to be rather weak, and Koinu was expected to weaken much faster than the actual observations. Similar to the case of Saola [2], JMA appeared to be the best forecast of the wind structure of Koinu, as its forecast wind distribution is generally consistent with the actual observations. TRAMS also under-forecast the wind strength slightly; nevertheless, winds up to 64 knots (storm force wind, in magenta in Figure 11) are expected to be rather close to the southwestern part of Hong Kong. In view of this model guidance, and together with the track and intensity forecast of Koinu in this case, consideration has been made on the possibility of near-hurricane-force wind or maybe even hurricane-force wind near Hong Kong, which is one basis for the issuance of tropical cyclone warning signal No. 9 in Hong Kong.

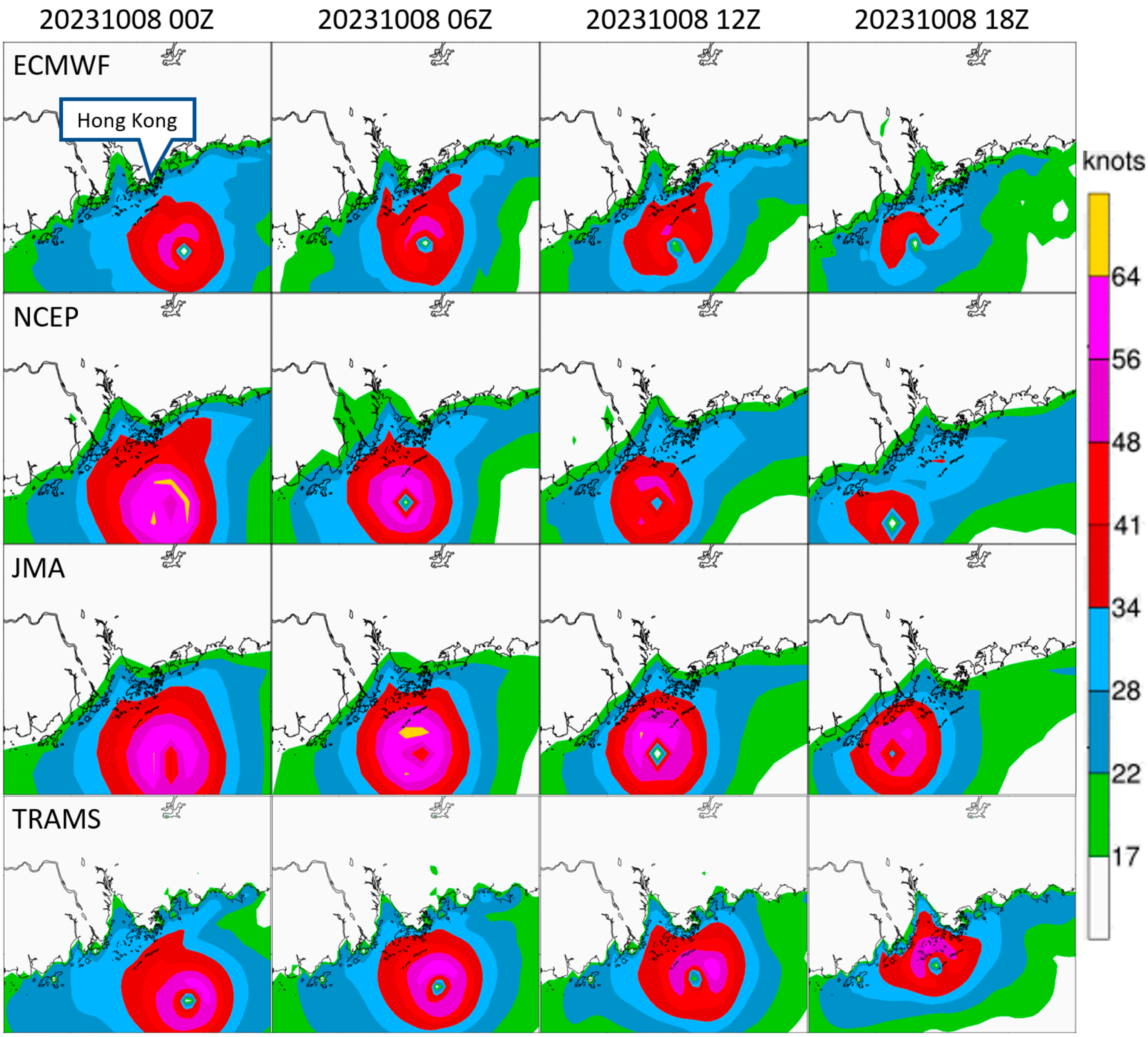

Figure 11. Forecast 10 m surface wind fields over the Pearl River Estuary in 6-hourly intervals valid from 0000 UTC (leftmost column) to 1800 UTC (rightmost column) on 8 October 2023, by models initialized at 1200 UTC on 7 October 2023. Forecast winds are colored in accordance with the Beaufort scale, specifically, hurricane-force winds in yellow, which might come to the doorstep of Hong Kong. (Top row) ECMWF. (Second row) NCEP. (Third row) JMA. (Fourth row) TRAMS.

6. Rainfall Forecast

Heavy rain was generally forecast to be on the way with the passage of Koinu, in particular for 9 October 2023, by the various NWP models. However, HKO had been asked to provide a precise estimation of the expected amount of rainfall over the territory. The rainfall forecasts over Hong Kong on 9 October 2023 by the various models are summarized in Figure 12. It can be seen that, possibly due to the constraints of the representation of the physical processes of rain in the models, the global NWP generally under-estimated the actual rainfall over Hong Kong. The recorded rainfall was over 200 mm over the whole territory and even reached 500 mm at some places within the 24 h of 9 October 2023. On the other hand, the regional model TRAMS appeared to perform better in terms of rainfall magnitude and spatial distribution. Though TRAMS has a similar spatial resolution (9 km) compared to the leading global NWP models, the rain processes are better tuned in this regional model for forecasting heavy rainfall associated with a tropical cyclone.

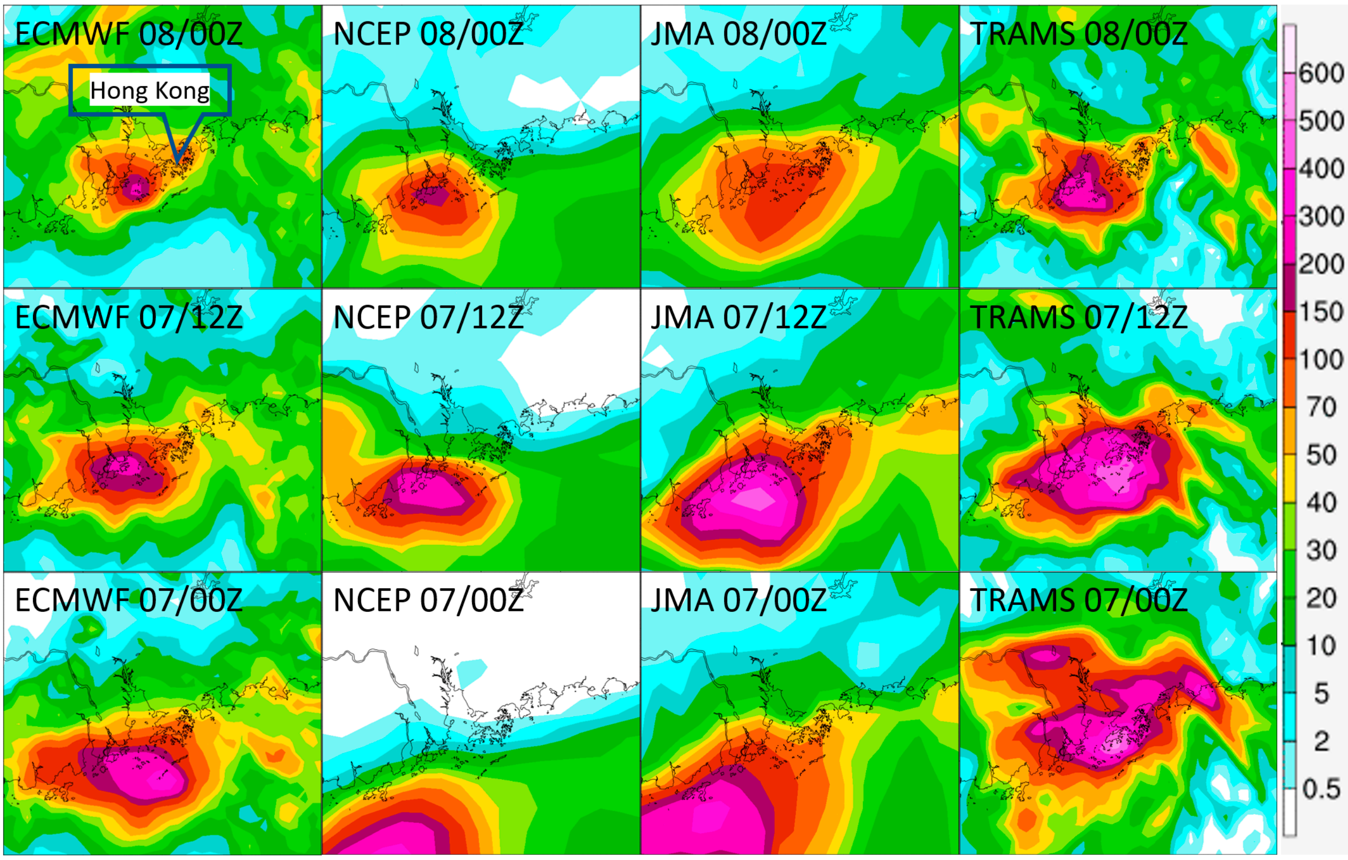

Figure 12. Models' 24 h accumulated rainfall forecast for 9 October 2023, with three consecutive runs showed on the top (initialization time 20231008 00Z), middle (initialization time 20231007 12Z), and bottom rows (initialization time 20231007 00Z). The four columns starting from the left are, respectively, ECMWF, NCEP, JMA, and TRAMS model output. TRAMS was able to predict the most accurate magnitude of local rainfall on 9 October 2023 following the passage of Koinu, but its most recent run (on top row) oppositely turned down the rainfall forecast; such a wrong trend was also given by other global models.

7. Conclusions

The forecasting aspects of Koinu in 2023 over the northern part of the South China Sea are summarized in this paper, namely the track, intensity, local wind, and rainfall forecast. Koinu had a small circulation and underwent a rather irregular track over the northern part of the South China Sea, firstly dipping to the south and later moving a bit to the northwest (in a horizontal "S" shape) when it came close to Hong Kong. Such subtle but important changes in its movement were not well captured by the available models, neither conventional nor AI, with only a weak indication by the model forecast of Fengwu, which gave not-so-accurate time and location of the changes in movement. The conventional deterministic global models are found to only have a moderate performance. On the other hand, the newly emerging AI models and a regional model appear to be better for forecasting the track and intensity of Koinu, respectively. While these results are based on one case study only, more cases and examples would need to be accumulated in order to fully assess the performance of the new technologies.

From Saola and Koinu, it appears that the regional model shows a reasonable performance in the forecast of heavy rain in association with a tropical cyclone. However, forecasting wind for a landfalling tropical cyclone still remains a rather challenging problem. All these factors posed great challenges to the warning service for this tropical cyclone. It is hoped that the present paper can stimulate further research to improve the track and intensity forecast of this rather difficult case, which form the basis of the tropical cyclone warning service, to provide better support on early alerts with a longer lead time.

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