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Collaborative assimilation experiment of Beidou radiosonde and drone-dropped radiosonde based on CMA-TRAMS

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A R T I C L E I N F O

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关键词:
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CMA-TRAMS (中国南海台风模式)
北斗探空同化
无人机下投探空同化

A B S T R A C T

Based on the China Meteorological Administration's Tropical Regional Atmosphere Model for the South China Sea (CMA-TRAMS), the authors conducted a collaborative assimilation forecasting experiment utilizing both Beidou radiosonde and drone-dropped (HAIYAN-I) radiosonde data in September 2023. Three assimilation experimental groups were designed as follows: Beidou radiosonde assimilation, drone-dropped radiosonde assimilation, and collaborative assimilation of Beidou and drone-dropped radiosonde data (hereinafter referred to as "Beidou-drop"). Additionally, a control group of operational forecasts without these data assimilations was set up. The results indicate that the operational forecast path in the control group deviated northward from the actual path. Besides, the Beidou-drop group showed the most significant improvement in terms of forecasting the typhoon path at 60 to 90 h lead times. Specifically, the 72 h and 90 h path errors were reduced by 66.8 and 82.4 km, respectively, resulting in a much more accurate forecast of Typhoon Haikui's landing point, at the coastal junction of Fujian and Guangdong. Furthermore, the collaborative assimilation revealed a notable impact on improving the forecast of wind and rain associated with Haikui's landfall, aligning more closely with the real case. A marked rise was also seen in the precipitation score of the Beidou-drop group, where the 50 mm TS (threat score) of the 72 h lead time increased from 0.33 in the control experiment to 0.75, and the 100 mm TS rose from 0.18 to 0.39.

摘要

基于中国气象局南海台风模式CMA-TRAMS, 开展了北斗探空和无人机下投探空协同同化预报试验, 分别开展了北斗探空同化, 无人机下投探空同化, 北斗和下投探空 (beidou-drop) 协同同化试验. 结果表明, CMA-TRAMS业务预报路径较实况偏北, 协同同化了北斗和下投探空的路径预报改进效果最显著, 对60–90小时路径预报均有改进, 72小时和90小时路径误差分别较减小66.8 km和82.4 km, 且台风海葵的登陆区域更趋于向实况 (闽粤沿海交界处); 协同同化了北斗和下投探空对台风"海葵"登陆风雨影响更为显著, 与实况更加吻合, 降水评分提升明显, 72小时预报的50 mm TS评分由对照试验的0.33提高至0.75; 100 mm降水TS评分由对照试验的0.18提高至0.39.

1. Introduction

Typhoons, also known as tropical cyclones, frequently impact tropical regions, bringing disasters like strong winds, heavy rains, and storm surges, causing massive loss of life and damage to property in island and coastal areas. Forecasting typhoon paths and landfall locations is one of the most important and popular topics in the field of typhoon prediction. Scientists have revealed that relocating the typhoon position in the forecasting model using data on typhoon center positions could reduce forecasting errors (Huang et al., 2017). Others have conducted assimilation forecasting experiments on typhoon environmental wind fields using dropsonde observation data, and found it significantly improves typhoon path forecasts. This also indicates that deviations in the initial environmental field significantly affect typhoon forecasting (Zhang et al., 2012). Outside of China, based on dropsonde data, researchers performed assimilation experiments for two hurricane cases in 2014 and found that dropsondes are more effective in correcting the environmental wind errors outside the hurricane. After assimilation, the accuracy of forecasting the path, intensity, and structure improved at lead times of more than 36 h (Christophersen et al., 2017). Meanwhile, by verifying and analyzing the long-term operational forecasting results of unmanned aerial vehicle (UAV) dropsonde assimilation experiments, Ryan et al. (2019) demonstrated a positive impact on typhoon forecasting results. Along with the development and application

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of high-resolution specialized typhoon models, more refined observation data have been applied in typhoon model initialization experiments. Some researchers have attempted to obtain new types of ocean-based observation data, such as ocean surface roughness and friction velocity (Zhao, 2015; Bi et al., 2015). However, the lack of direct observations of the occurrence and development of tropical cyclones over the open ocean still limits improvements in the accuracy of typhoon path and intensity forecasting (Tang et al., 2022). Furthermore, some scientists have analyzed the number of dropsondes assimilated through comparative experiments and revealed that even a single dropsonde is sufficient to have an appreciable correction effect on the spatiotemporal structure of typhoons (Nelson et al., 2020).

In an effort to obtain more abundant ocean–atmosphere observation data, scientists have continuously conducted airborne dropsonde tropical cyclone experiments, both in China and internationally, since the 1990s. From 2010 to 2018, the "Global Hawk" large UAV system released 2700 dropsonde instruments (Wick et al., 2018), collecting a large amount of hurricane observations, such as their temperature, pressure, humidity, and winds, which have been applied in numerical forecasting models. Researchers in the Taiwan region of China successfully implemented eye-crossing observations of Typhoon Longwang using UAVs (Lin and Lee., 2008). By 2012, they had completed 64 manned flight observations and dropped over 1000 dropsondes into typhoons in the Northwest Pacific. The data obtained were assimilated into a numerical model data assimilation system, and this remarkably improved the ability to forecast the paths of typhoons (Qian et al., 2012). Based on a large UAV observation experiment in the South China Sea in 2020, the spatial differences between dropsonde data and reanalysis data were analyzed and cross-compared using conventional radiosondes as a standard, revealing that the accuracy of the temperature, humidity, and wind speed from the dropsondes were quite close to the accuracy requirements of WMO-CIMO (Gao et al., 2023). However, conventional radiosonde data are only collected twice a day, and the national stations are mostly land-based, making it difficult to meet the requirements of marine data assimilation. To overcome this problem, the China Meteorological Administration has been leading the development of a new "Beidou Smart Radiosonde System" since 2016, and conducted application tests in 2022 (Wu et al., 2023). Compared with the observation mode of traditional radiosonde equipment, the Beidou system adopts a new round-trip drifting sounding system that can extend the observation window period and obtain richer radiosonde observation data during the three "ascending–drifting–descending" stages. This provides a "Chinese solution" for enriching radiosonde observation data (Jian, 2021). Therefore, in China, it is of great research and application value to apply this new generation of radiosonde data from the Beidou system in typhoon model assimilation experiments.

This paper reports the findings from a collaborative assimilation forecasting experiment using Beidou radiosonde and new-type UAV (HAIYAN-I) dropsonde data, based on the China Meteorological Administration's Tropical Regional Atmosphere Model for the South China Sea (CMA-TRAMS) (Zhong et al., 2020; Xu et al., 2020). The model system is a localized and upgraded operational version of China's self-developed numerical model system named GRAPES (also called CMA-MESO; Xue and Chen, 2008;). New technical schemes were applied in CMA-TRAMS, such as a three-dimensional reference atmosphere scheme in a dynamic framework (Chen et al., 2016), and a near-ground scheme of ocean surface roughness and cyclone genesis (Li et al., 2024). With a horizontal resolution of 9 km and a vertical stratification of 65 layers, the model meets the basic needs of domestic typhoon operational forecasting (Ma, 2019). This is the first time that a collaborative assimilation of the UAV dropsonde and Beidou system data has been applied in an operational forecasting system of the South China regional model. Therefore, the analysis of new data and its impact in operational model systems is of great importance and lays a foundation for future application of the new data. The landing process of Typhoon Haikui in 2023 severely affected the coastal areas of southern China, and the divergences of path forecasting among multiple models were quite large. This paper uses the case of Typhoon Haikui to analyze the impact of Beidou radiosonde and UAV dropsonde data on forecasting after ingestion in the CMA-TRAMS assimilation system.

2. Data and methods

As shown in Table 1, real-time operational CMA-TRAMS forecasting products that use conventional cloud analysis assimilation technology were selected to be the control group in this experiment (Li et al., 2024). On this basis, three experimental groups were set up: the Beidou group additionally ingested Beidou radiosonde data into the assimilation system; the Drop group additionally ingested drone-dropped radiosonde data; and the Beidou-drop group additionally ingested both Beidou radiosonde and drone-dropped radiosonde data. This paper analyzes the differences in the typhoon path and intensity and precipitation forecasts when data of different sources are ingested in the assimilation system; and for future reference, it provides a basic analysis for the operational application of new observation data.

This study employed the best-track data of typhoons as the standard for verifying typhoon paths and intensities, and used gridded Chinese regional national meteorological station and satellite fusion precipitation observations as the standard for verifying typhoon precipitation events.

3. Results and discussion

3.1. Analysis of assimilation profile and increment

To confirm whether the analysis fields have already assimilated the observational information, profiles of meteorological elements such as wind, temperature, and relative humidity (RH) for the analysis field and background field at the site of No. 482 dropsonde are shown in Fig. 1(a–c). The Beidou radiosonde is in the Guangdong mainland area while the drone-dropped radiosonde data are ocean-based in the South China Sea area (Fig. 1(d)). Those profiles were obtained by interpolating the control group initial background field and assimilation analysis field to the observation point, respectively. As shown in the figure, the profiles of *U*-wind, *V*-wind, and RH in the Drop group lie between those of the observations and control group, with the profiles of the Drop group being generally closer to the observed profiles. What is interesting is the profiles of the *U*-wind field in the control group and the observation converge at around 850 hPa (Fig. 1(a)). That is to say, the model underestimates the *U*-wind field below 850 hPa and overestimates it above that level. However, the deviation in the control group diminishes significantly after data assimilation.

Regarding the *U*-wind field after assimilation, wind speeds at each level align closer to the observation profile. The deviation of the *V*-wind field in the Drop group is also reduced between 600 and 800 hPa (Fig. 1(b)), while the correction effect of assimilation on RH is more noticeable below 850 hPa (Fig. 1(c)).

To further investigate the impact of different data in the assimilation system, Fig. 2 depicts the horizontal distribution of water vapor and wind field increments at 850 and 500 hPa for the Drop group, Beidou group, and Beidou-Drop group, separately. As illustrated in Fig. 2(a, b), the initial field of the control group is wetter compared to the actual situation at 850 hPa, while it is drier at 500 hPa. The main wind increment in the Drop group is anticyclonic, which corresponds to a negative water vapor increment in most areas. This means the cyclonic circulation from the coastal area of western Guangdong to the eastern part of Hainan Island is weakened, while the entire layer of the atmosphere is drier in the coastal area of western Guangdong. A positive increment of humidity can be observed from Hainan Island extending southeasterly to the central South China Sea. In the Drop group, at the lower level of 850 hPa, a trend of decreasing humidity and drier air is apparent, while at the middle and upper levels of 500 hPa, there is a trend of increasing

Table 1 Experiment details.

Experiment	Assimilation data	Forecast duration
1. Operation (Control)	Operational cloud analysis data	90 h
2. Beidou	Cloud analysis data + Beidou radiosonde observations	90 h
3. Drop	Cloud analysis data + Dropsonde observations	90 h
4. Beidou-drop	Cloud analysis data + Beidou + Dropsonde observations	90 h

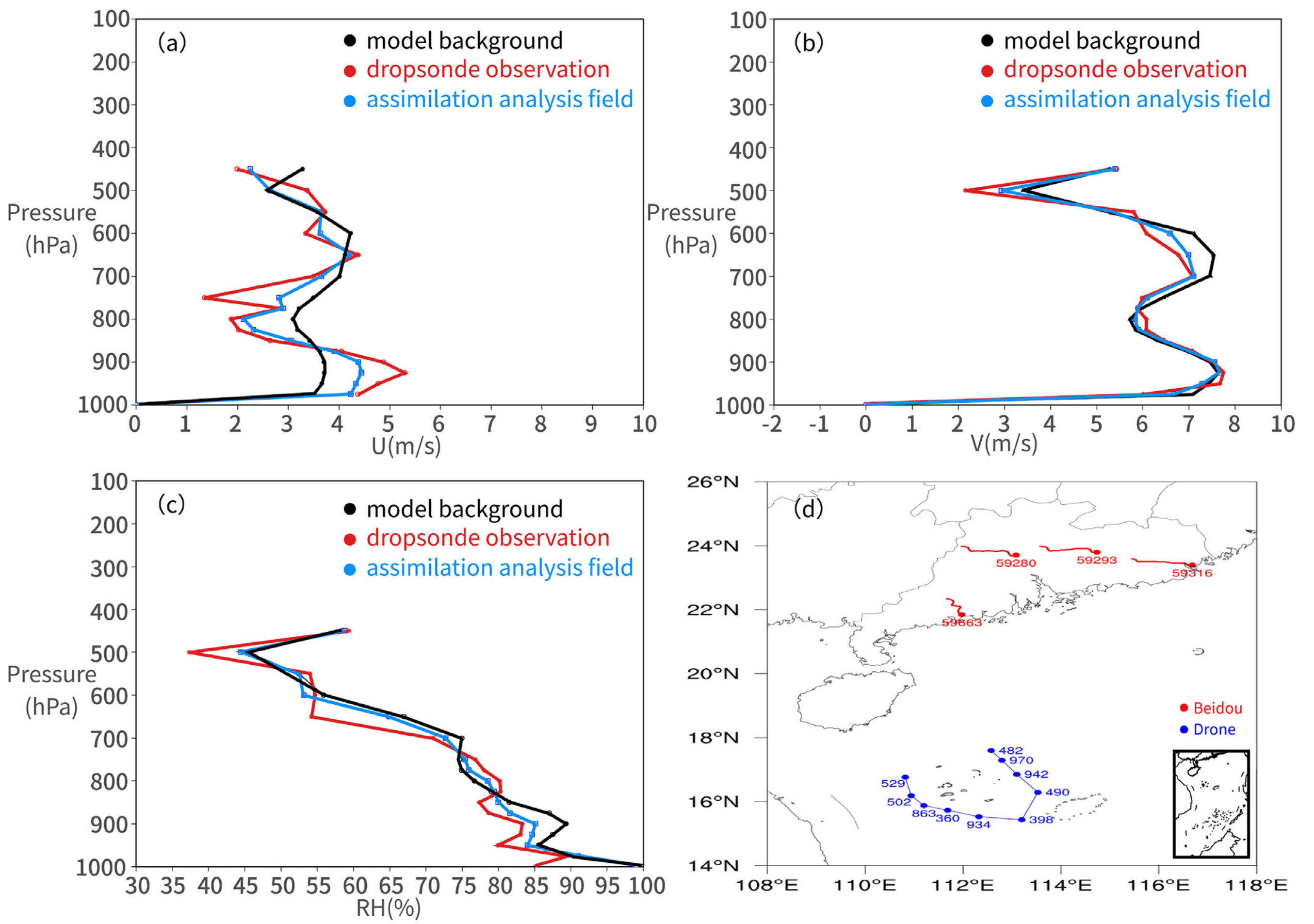

Fig. 1. Vertical profiles of the dropsonde observations (red), model background (black), and analysis field with assimilation (blue): (a) horizontal *U*-wind; (b) *V*-wind; (c) RH; (d) Observation distribution map.

humidity. This indicates the initial conditions revised by data assimilation become more baroclinic in the South China Sea and allow a deeper development of the weather system in this area, which is closer to the realistic conditions.

In contrast to the Drop group, the Beidou group shows an enhancement in easterly winds along the Guangdong coast and in its center, as well as for the westerly winds in Guangxi and Hunan. There is also a positive humidity increment along Guangdong's southwestern coast, contrasting with a negative increment inland. This suggests that Beidou radiosonde assimilation enables water vapor to accumulate along the coast, which differs from the "unfavorable" dryness in the control group. This kind of data assimilation favors the occurrence of typhoon-induced cloud precipitation over Guangdong's southwestern coast, which is more aligned with reality.

With regard to the Beidou-drop group, which merges both drone dropsonde and Beidou radiosonde data into CMA-TRAMS, its increment distribution along the coast is similar to that of the Drop group, while in inland areas it shows a pattern that is more similar to the Beidou group. Different wind field and water vapor increment distributions can influence the future path of typhoons and precipitation patterns. The dry structure at the bottom layer makes the easterly airflow over the South China Sea stronger, and the typhoon path follows the southwesterly guidance of the airflow, suggesting a higher likelihood of typhoons making landfall in Guangdong.

3.2. Path and intensity forecast of Typhoon Haikui

Fig. 3 compares the predicted and actual observed typhoon paths. In the control group, the forecast path is shifted northward to the actual path, and the northerly deviation keeps increasing with forecast lead time, resulting in a forecast of landfall in Fujian. This is attributable to the overestimated westerly wind in the control group. All three assimilation experiments weaken the easterly wind in the initial conditions, and therefore steer the forecast path more to the southwest. The weakening effect on the easterly wind is more remarkable in the Beidou group than the Drop group, and thus a higher path accuracy is seen in the Beidou group. However, the Beidou-drop group produces the best forecast, predicting Haikui's landfall near the junction of Fujian and Guangdong, which is more in line with the observation. It should be noted that path forecasts in the Beidou group and Drop group show westerly deviations

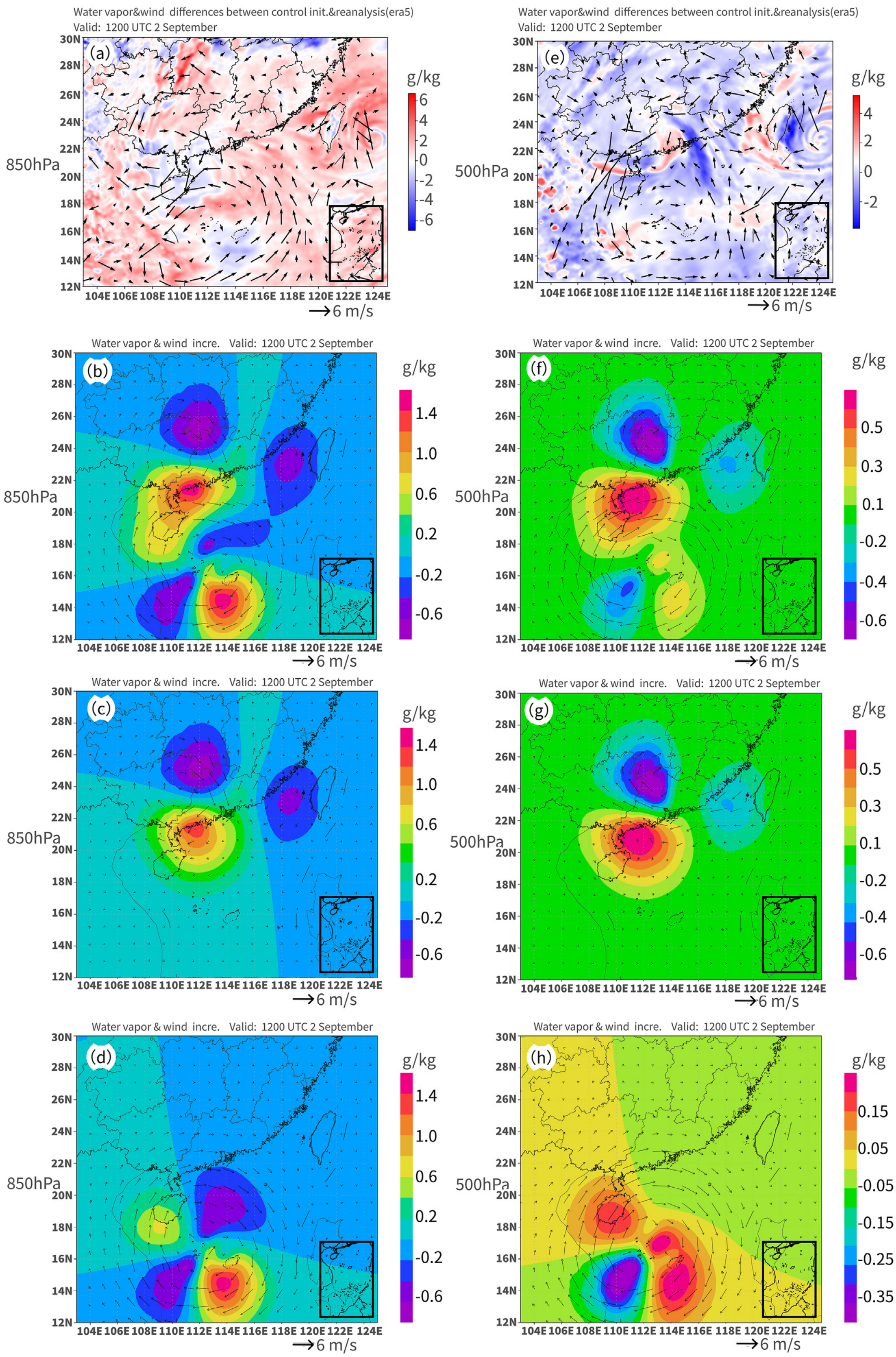

Fig. 2. Water vapor (units: g kg^{-1}) and wind (units: m s^{-1}) differences between (a, e) "Control&reanalysis" (ERA5) and the analysis increments of different groups ((b, f) Beidou-drop; (c, g) Beidou; (d, h) Drop) at (a–d) 850 hPa and (e–h) 500 hPa.

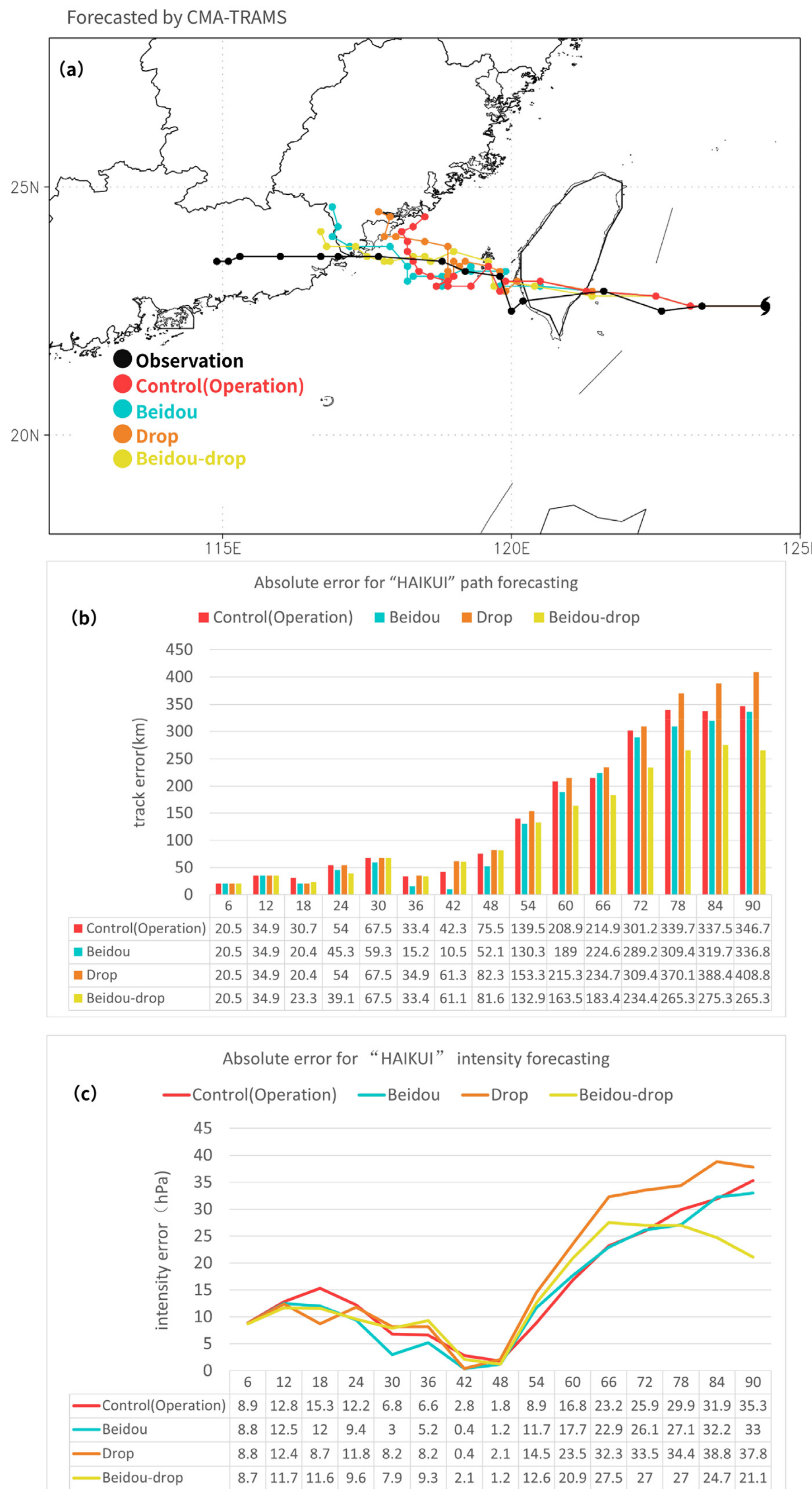

Fig. 3. Comparison of the model assimilation experiments in terms of (a) forecasting the track of Typhoon Haikui (forecast initialized at 1200 UTC 2 September 2023), (b) the forecast error of the track, and (c) the forecast error of the intensity. The x-axis in (b, c) is the forecast lead time (in hours).

to different extents, but the predicted typhoon speeds are instead slower than observed.

In terms of the average path forecast error at different forecast lead times (Fig. 3(b)), the three groups of assimilation experiments were not stable within 0–24 h, which was related to the newly added assimilated data information needing to be gradually integrated and absorbed in the numerical model, known as the spin-up time. Typically, the spin-up time is 0–12 h, but the incorporation of new data requires a longer time for the current model framework to reach a balanced state. On the later forecast, however, the forecast performance of each experimental group gradually stabilized, and the forecast increment of the assimilation experiments gradually became clear. The Beidou-drop group, which simultaneously assimilates Beidou and drone dropsonde data, shows a significantly improved path forecast at lead times from 60 to 90 h. The path errors at the 72- and 90 h lead time are reduced by 66.8 and 82.4 km, respectively, of which the proportions are also 22.18 % and 23.48 % less than that of the control group. Therefore, simultaneously assimilating Beidou and drone dropsonde data can significantly enhance CMA-TRAMS's forecasting ability of the typhoon path, and this kind of improvement becomes more pronounced with increasing forecast lead times.

The forecasting of the typhoon center pressure represents the forecasting of typhoon intensity. The Beidou group outperforms others in the forecasting of typhoon intensity, as shown in Fig. 3(c), with only a 10–3 hPa intensity error from a lead time of 0 to 30 h. In this typhoon's weakening phase, at a lead time from 72 to 90 h, the Beidou-drop group yields the minimum error, while other methods have errors exceeding 27 hPa. It is worth mentioning that the intensity error propagates with increasing lead time in the Drop group, which reaches 38.8 hPa at the 84 h lead time. These experiments reveal that collaborative assimilation of multi-source data is crucial for the application of new, unconventional observation data in numerical models. The Beidou dropsonde assimilation significantly improves the path forecast, but with less improvement in the intensity forecast at longer lead times. It does affect the intensity forecasts within a 48 h lead time, but in an unstable way. Overall, simultaneous assimilation of Beidou and drone dropsonde data yields the best intensity forecasts. However, underestimation of the typhoon speed forecast is not fully attenuated in the Beidou-drop group, which can still lead to weaker intensity forecasts at a later stage and path deviations after landfall.

3.3. Precipitation forecasting skills for Typhoon Haikui

It should be noted that forecasting of precipitation events requires consideration of various factors such as the water vapor conditions and atmospheric dynamic and thermal conditions. However, the areas of heavy precipitation in severe weather events with large-scale circulation backgrounds, such as typhoons, are mainly influenced by the typhoon's path and landing location. We found that all three assimilation experiments had an impact on the typhoon path at a long forecast lead time. Therefore, this part focuses on the direct effects of changes in the typhoon forecast path and landing point on the main rain areas and precipitation scores.

Due to the large size of the assimilation experiment area (as shown in Fig. 2), it is not possible to fully demonstrate the changes in typhoon precipitation. Fig. 4 shows an enlarged area specifically for typhoon precipitation. The typhoon path forecast from the Beidou-drop group is overall closer to the actual observed path, consequently resulting in a more accurate precipitation area forecast (Fig. 4). In particular, the precipitation area forecast of over 50 mm coincides well with the actual observation. This indicates data assimilation can improve not only the typhoon path forecast, but also the main heavy rainfall area of typhoon-induced precipitation, to a great extent. Thus, it can be seen that after collaborative assimilation of Beidou sounding and drone dropsonde data, the model improves the path forecast of Typhoon Haikui, thereby improving the forecasting skill for typhoon-induced precipitation during landfall.

To evaluate the impact of the assimilation experiments on Typhoon Haikui's precipitation, precipitation forecast scores, referring here to the threat score (TS), are separately verified for the landfall area along the Fujian and Guangdong coasts, and the forecast domain area of CMA-TRAMS at the 72 h forecast lead time. The verification areas are divided as follows:

(1) The coastal area from eastern Guangdong to Fujian (22°–26°N, 114°–120°E), including 205 national observation stations, representing the Fujian and Guangdong coastal areas.
(2) The model forecast domain, covering most of mainland China, with a total of 2200 national observation stations, referred to as the national area.

For the coastal area, the precipitation forecast skill scores of the assimilation experiments have significantly risen. Since all three experiment groups have shown improvements in the typhoon path forecast, each experiment group has increased the TS for the forecast of over 25 mm, especially in the vicinity of the landfall point. In this case, the Beidou-drop group has the highest skill score. The TS for the 72 h forecast (Fig. 5(a)) increases from 0.43 to 0.71 in the 10 mm group; from 0.29 to 0.81 in the 25 mm group; from 0.33 to 0.75 in the 50 mm group; and from 0.18 to 0.39 in the 100 mm group. The significant improvement in precipitation forecasting skill contributes to the more accurate precipitation area forecast of typhoon-induced heavy rainfall in the Beidou-drop group. The precipitation scores for the national area at the same forecast lead time are similar to those for the coastal area. Each assimilation experiment group has improved the model's TS for heavy rain and above in the national area (Fig. 5(b)). Likewise, the Beidou-drop group still gains the highest TS overall.

4. Conclusions

Based on CMA-TRAMS, assimilation experiments were conducted utilizing Beidou sounding and drone dropsonde sounding for the case of Typhoon Haikui in 2023. Through a comparative evaluation of forecast variables' vertical profiles, analysis increments, typhoon path and intensity forecasts, and precipitation with the current operational model products as a control group, the multi-angle analysis proves that:

(1) The assimilation of drone dropsonde data can effectively improve the vertical distribution of the horizontal wind field in the model at 500 hPa, making the model's background field profile closer to the observation. The improvement in the *U*-wind is particularly noticeable.
(2) Significant differences are observed in the distribution characteristics of the analysis increments between the Drop group and Beidou group at different heights. The collaborative assimilation experiment (Beidou-drop group) using two types of encrypted observations can adjust the water vapor distribution toward the actual observation throughout the whole layer during typhoon weather processes. At the same time, it makes a significant easterly wind correction to the typhoon environmental field, thereby improving the typhoon path forecast and providing a more accurate forecast of the typhoon landing point and overall path.
(3) The improvement from the assimilation experiment regarding the typhoon path forecast also contributes to the precipitation distribution being closer to the actual situation. Quantitatively, it brings a remarkable increase in the TS of the typhoon precipitation forecast. Among the three experimental groups and one control group, the Beidou-drop group has the highest relative score. The TSs at the 72 h forecast lead time are as follows: the 10 mm group increased from 0.43 to 0.71; the 25 mm group increased from 0.29 to 0.81; the 50 mm group increased from 0.33 to 0.75; and the 100 mm group increased from 0.18 to 0.39.

The assimilation experiment for this typhoon case is a preliminary exploration of the application of new data in CMA-TRAMS, but there

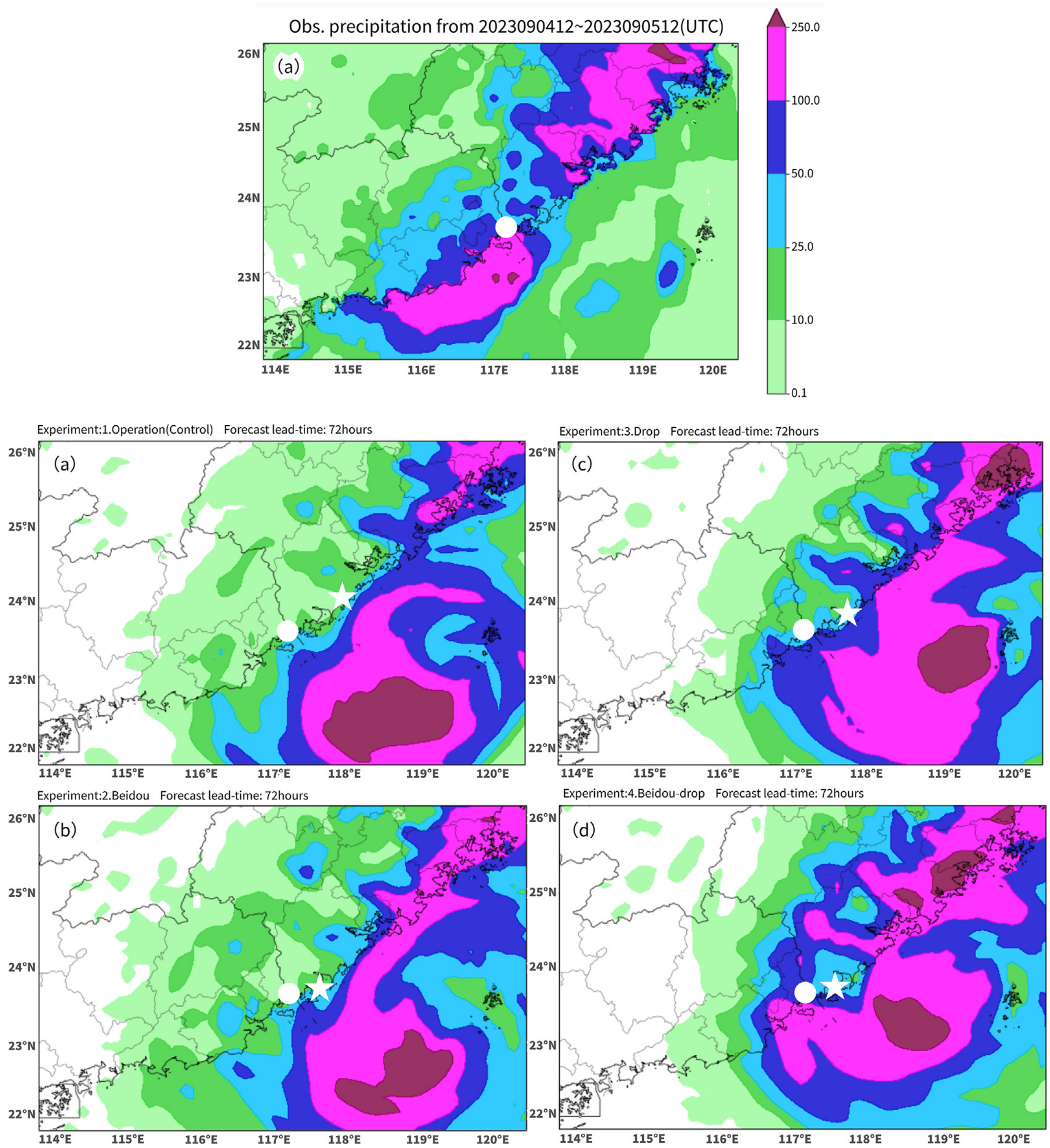

Fig. 4. Comparison of daily precipitation forecasts initialized at 1200 UTC 5 September along the Fujian and Guangdong coasts (the star marks the typhoon landing point forecast and the circle the typhoon landing point observation).

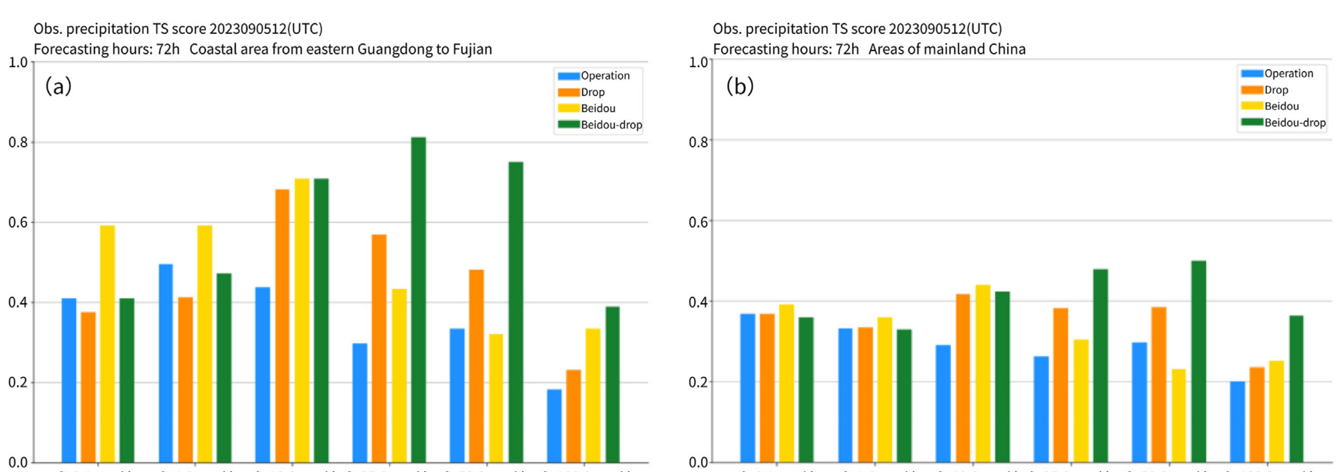

Fig. 5. Comparison of 72 h daily precipitation forecast TSs: (a) coastal area from eastern Guangdong to Fujian; (b) areas of mainland China.

are still many deficiencies. For example, the issue of a slower typhoon moving speed being forecast remains, even though the assimilation experiment significantly enhanced the overall path forecast. Additionally, in various experiments, the typhoon path forecasts shifted northward after landfall to varying extents, which was a significant divergence from the actual situation. Also, the incorporation of new data means a longer spin-up time is still a problem, which needs to be researched further. We look forward to enriching the assimilation experiments of new data and conducting additional analysis in the future, further analyzing the reasons behind the remaining problems, and hopefully improving them.

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References

Bi, X., Gao, Z., Liu, Y., 2015. Observed drag coefficients in high winds in the near offshore of the South China sea. J. Geophys. Res. Atmos. 120 (13), 6444–6459. doi:10.1002/2015JD023172.

Chen, Z., Dai, G., Zhong, S., Huang, Y., Zhang, Y., Xu, D., Li, M., 2016. Technical features and prediction performance of typhoon model for the South China sea. J. Trop. Meteorol. 32 (6), 10. doi:10.16032/j.issn.1004-4965.2016.06.005.

Christophersen, H., Aksoy, A., Dunion, J., Sellwood, K., 2017. The impact of NASA global hawk unmanned aircraft dropsonde observations on tropical cyclone path, intensity, and structure: Case studies. Mon. Wea. Rev. 145, 1637–1658. doi:10.1175/MWR-D-16-0332.1.

Gao, T., Guo, R., Liu, Z., Sun, X., Wang, B.K., 2023. Analysis of observation data from large high-altitude unmanned aerial vehicle dropsondes. Nat. Sci. J. Hainan Univ. 41, 312–320. doi:10.15886/j.cnki.hdxbzkb.2023.0020.

Huang, Y., Xue, J., Chen, Z., Dai, G., Zhang, C., Chen, X., 2017. Initial value experimental study on the forecast effect of double typhoons "Roke" and "Sangka" in 2011. J. Trop. Meteorol. 33, 01. doi:10.16032/j.issn.1004-4965.2017.01.004.

Jian, J., 2021. The new smart Beidou sounding system provides a “Chinese solution” for the development of meteorological sounding. China Meteorological News. http://www.qxkp.net/zxfw/kjjz/202112/t20211221_4317060.html.

Li, M.J., Chen, Z., Dai, G., Tian, Q., Leung, J.C., Lin, Q., Zhang, Y.X., 2024. An evaluation of tropical cyclone genesis forecast over the western North Pacific and the South China sea from the CMA-TRAMS. J. Trop. Meteorol. 30 (01), 20–28. doi:10.3724/j.1006-8775.2024.003.

Lin, P.H., Lee, C.S., 2008. The eyewall-penetration reconnaissance observation of typhoon Longwang (2005) with unmanned aerial vehicle, aerosonde. J. Atmos. Ocean Technol. 25 (1), 15–25. doi:10.1175/2007JTECHA914.1.

Ma, S.H., 2019. Impact if radius of TC intensity correction on No.1618 TC path prediction. Acta Meteorol. Sin. 77 (4), 12. doi:10.11676/qxxb2019.035.

Nelson, C.T., Harrison, L., Corbosiero, L.K., 2020. Temporal and spatial autocorrelations from expendable digital dropsondes in tropical cyclones. J. Atmos. Ocean Technol. 37, 507–522. doi:10.1175/JTECH-D-19-0032.1.

Qian, C., Li, Z., Zhang, F., Rui, C., 2012. Review on international aircraft reconnaissance of tropical cyclones. Adv. Meteorol. Sci. Technol. 2, 6–16. doi:10.3969/j.issn.2095-1973.2012.06.001.

Ryan, K., Bucci, L., Delgado, J., Murillo, S., 2019. Impact of gulfstream-IV dropsondes on tropical cyclone prediction in a regional OSSE system. Mon. Wea. Rev. 147, 2807–2827. doi:10.1175/MWR-D-18-0157.1.

Tang, J., Zhao, B., Lei, X., 2022. Progress and prospects of typhoon flight scientific experiments. Adv. Meteorol. Sci. Technol. 12, 47–55. doi:10.3969/j.issn.2095-1973.2022.05.007.

Wick, G.A., Hock, T.F., Neiman, P.J., Holger, V., Black, M.L., Ryan, S.J., 2018. The NCAR-NOAA global hawk dropsonde system. J. Atmos. Ocean Technol. 35, 1585–1604. doi:10.1175/JTECH-D-17-0225.1.

Wu, X., Ji, K., Qi, J., Wei, L., 2023. Experimental method for weather radar detection accuracy based on beidou sounding system. Meteorol. Hydrol. Mar. Instrum. 40, 01. doi:10.19441/j.cnki.issn.1006-009x.2023.01.009.

Xu, D., Chen, Z., Zhang, Y., Dai, G., Zhong, S., Zhang, B., Chen, D., et al., 2020. Updates in TRAMS3.0 model version and its verification on typhoon forecast. Meteorol. Mon. 46, 1474–1484. doi:10.7519/j.issn.1000-0526.2020.11.008.

Xue, J., Chen, D., 2008. Scientific design and application of the GRAPES numerical prediction system. Science Press, Beijing, 383pp.

Zhang, C., Wan, Q., Ding, W., Chen, Z., Huang, Y., 2012. An experiment in application of the dropsonde data to forecasting the path of Typhoon Morakot. Acta Meteorol. Sin. 70, 30–38. doi:10.11676/qxxb2012.003.

Zhao, Z., 2015. Typhoon air-sea drag coefficient in coastal regions. J. Geophys. Res. Oceans. 120 (2), 716–727. doi:10.1002/2014JC010283.

Zhong, S., Chen, Z., Xu, D., Dai, G.F., Meng, W.G., Zhang, C.Z., Zhang, Y.X., 2020. A review on GRAPES-TMM operational model system at Guangzhou regional meteorological center. J. Trop. Meteorol. 26 (4), 495–504. doi:10.46267/j.1006-8775.2020.043.