ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 41, MAY 2024, 767–776

• **News & Views** •

Scientific Advances and Weather Services of the China Meteorological Administration's National Forecasting Systems during the Beijing 2022 Winter Olympics

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(Received 3 September 2023; revised 7 November 2023; accepted 27 December 2023)

ABSTRACT

Since the Beijing 2022 Winter Olympics was the first Winter Olympics in history held in continental winter monsoon climate conditions across complex terrain areas, there is a deficiency of relevant research, operational techniques, and experience. This made providing meteorological services for this event particularly challenging. The China Meteorological Administration (CMA) Earth System Modeling and Prediction Centre, achieved breakthroughs in research on short- and medium-term deterministic and ensemble numerical predictions. Several key technologies crucial for precise winter weather services during the Winter Olympics were developed. A comprehensive framework, known as the Operational System for High-Precision Weather Forecasting for the Winter Olympics, was established. Some of these advancements represent the highest level of capabilities currently available in China. The meteorological service provided to the Beijing 2022 Games also exceeded previous Winter Olympic Games in both variety and quality. This included achievements such as the "100-meter level, minute level" downscaled spatiotemporal resolution and forecasts spanning 1 to 15 days. Around 30 new technologies and over 60 kinds of products that align with the requirements of the Winter Olympics Organizing Committee were developed, and many of these techniques have since been integrated into the CMA's operational national forecasting systems.

These accomplishments were facilitated by a dedicated weather forecasting and research initiative, in conjunction with the preexisting real-time operational forecasting systems of the CMA. This program represents one of the five subprograms of the WMO's high-impact weather forecasting demonstration project (SMART2022), and continues to play an important role in their Regional Association (RA) II Research Development Project (Hangzhou RDP). Therefore, the research accomplishments and meteorological service experiences from this program will be carried forward into forthcoming high-impact weather forecasting activities. This article provides an overview and assessment of this program and the operational national forecasting systems.

Key words: Beijing Winter Olympic Games, CMA national forecasting system, data assimilation, ensemble forecast, bias correction and downscaling, machine learning–based fusion methods

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Citation: Deng, G., and Coauthors, 2024: Scientific advances and weather services of the China Meteorological Administration's national forecasting systems during the Beijing 2022 Winter Olympics. *Adv. Atmos. Sci.*, **41**(5), 767−776, https://doi.org/10.1007/s00376-023-3206-3.

1. Introduction

Accurate weather forecasting is critical for the success of the Winter Olympic Games because winter sports are severely impacted by various weather conditions (Joe et al., 2010, 2023; Chen et al., 2018; Lee et al., 2018; Li et al., 2020; Tong et al., 2020; Xia et al., 2020; Kim et al., 2021; Yang et al., 2021a, b; Deng et al., 2022; Tsai et al., 2023). Given the complex topography and scarce observational data in mountainous regions, achieving accurate and high-resolution (both spatially and temporally) weather forecasts for a specific site or sporting event represents a significant challenge (Goger et al., 2016). Therefore, dedicated weather forecasting research programs have consistently been established prior to each occurrence of the Winter Olympic Games.

The Beijing 2022 Winter Olympic Games were held inland, where the climate conditions were dominated by continental winter winds leading to cold, windy and dry conditions with low precipitation and large diurnal temperature variation. It was therefore unlikely that existing experience gained from the previous three Winter Olympic Games would be suitable in this instance. The wide areal distribution of the competition venues (Fig. 1), the tight schedule of the competitions or events, the high-level security requirements, and the heightened COVID-19 restrictions all posed considerable challenges to the meteorological services developed for the Beijing 2022 Games (Sports Department of Beijing Winter Olympic Organizing Committee, 2020).

Due to the unique complex topography and synoptic differences of the competition areas, we could not simply adopt existing forecasting techniques but needed to develop new ones to better serve this Olympic Games in particular. In China, the China Meteorological Administration (CMA) Earth System Modeling and Prediction Center (CEMC) is responsible for the development and operation of national numerical weather prediction (NWP) models and products, representing the highest level of NWP research and operations nationally. To provide enhanced meteorological services for the Beijing 2022 Winter Olympics, a dual-pronged strategy was implemented: (1) to make ongoing improvements to existing CMA operational models to enhance their forecasting capability; and (2) to carry out new research and development efforts, as outlined in this article. The final support system encompassed refined and calibrated numerical weather forecasts along with corresponding applications (detailed in Fig. 2). A comprehensive forecasting system of CMA models was formed, including global, regional and

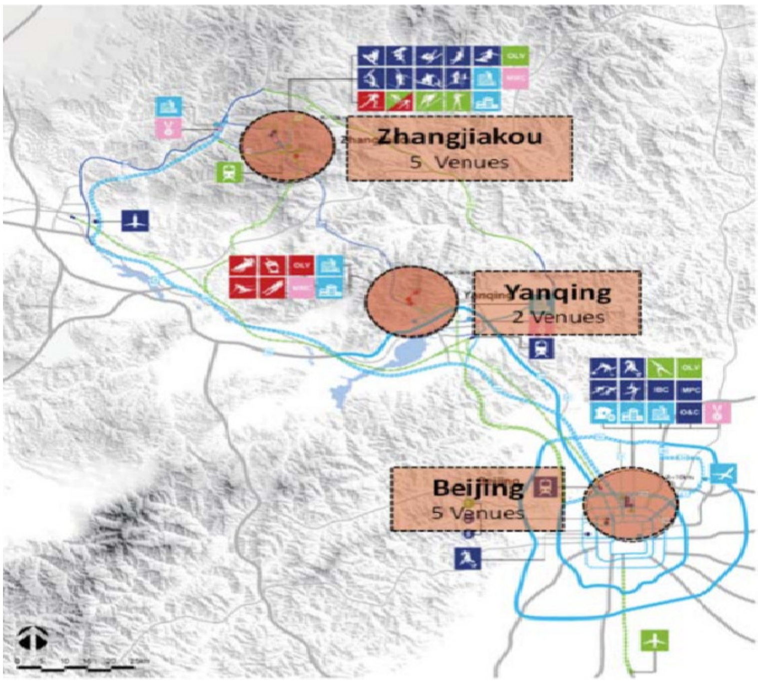


Fig. 1. The three competition areas (Zhangjiakou, Yanqing, and Beijing) of the Beijing Winter Olympics, showing the venue locations and associated sports.

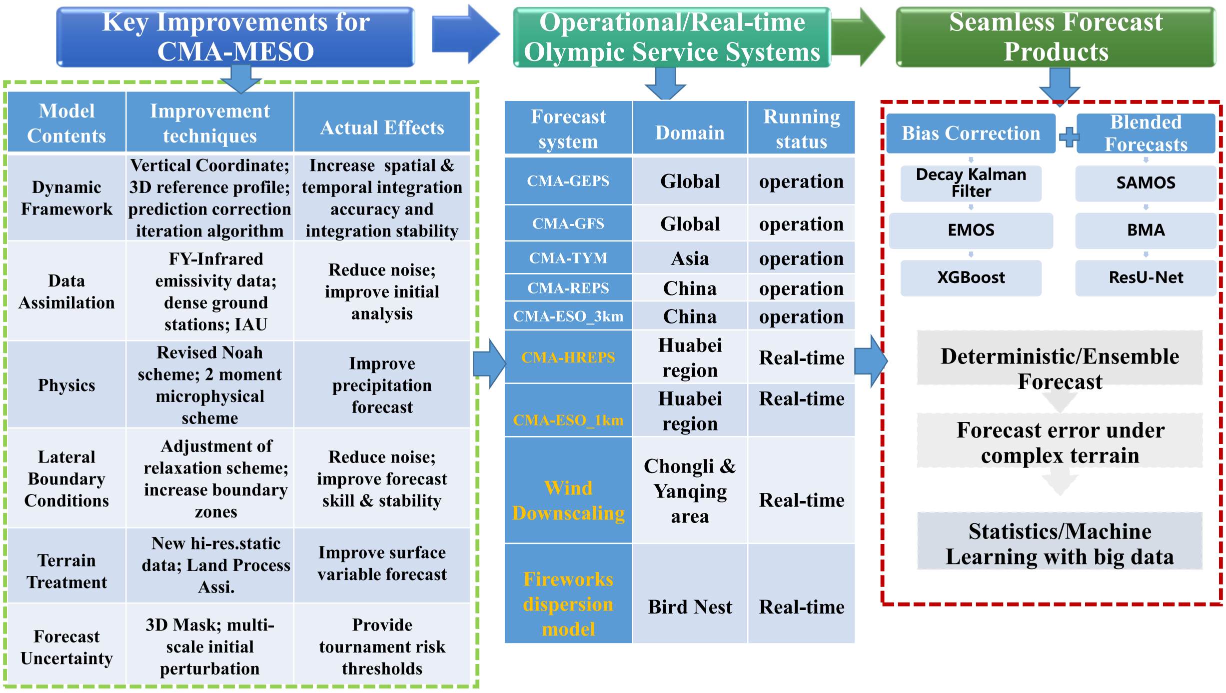


Fig. 2. Weather forecasting models and products used to provide meteorological services for the Beijing 2022 Winter Olympic Games.

high-resolution rapid-cycle assimilation and forecasts from both deterministic and ensemble models. The scientific progress central to the precise winter weather services provided are described in section 2. The real-time operational forecasting systems for the Olympics are presented in section 3, followed in section 4 by a focus on several typical Olympic services. Finally, a summary is provided in section 5.

2. Scientific progress

Successful meteorological services cannot be separated from advances in meteorological science and technological innovation. The key supporting technology for Winter Olympics weather forecasting and prediction is numerical weather forecasting and its application. To better serve the Beijing 2022 Winter Olympics, a weather forecasting research program was implemented. The goal of the program (Chen et al., 2018) was to improve techniques for short- and medium-range (1–15 days) predictions based on the CMA's Global and Regional Analysis and Prediction System (GRAPES) (Xue and Chen, 2008; Shen et al., 2013). To reach this goal, the program was organized into the following four research components: model and data assimilation; ensemble prediction system; forecast bias correction; and forecast integration. The accomplishments include the following six aspects.

(1) Improved high-resolution regional NWP model over complex terrain. Adapted from CMA-GFS (Su et al., 2018, 2020), firstly, a 3D reference atmosphere profile was introduced to the regional model CMA-MESO to improve the fine-resolution forecasting skill. The second improvement was to the predictor and corrector within the time integration scheme in the regional model (Zhang et al., 2022). And thirdly, improvement was made to the lateral boundary relaxation scheme, whereby the specified and relaxed area of the lateral boundary conditions were revised.

(2) Assimilation of high spatial and temporal resolution observations (satellite, radar, and surface observations) into the model. This category of improvements included the assimilation scheme of surface moisture data and surface temperature (Xu et al., 2023), a multi-scale hybrid filtering data assimilation technique (Xu and Wang, 2022), and the assimilation of new satellite imager data (FY-4A AGRI; Di et al., 2022). Furthermore, improvement to the assimilation of dense ground-level data increased the use of surface automatic station data by approximately 40% (Xu et al., 2021). These techniques were used to construct the real time, 1-km, hourly cycle assimilation version, as well as the operational 3-km fast-cycle version, of the CMA-MESO modeling system. Figure 3 shows an example of the improvement in 2-m temperature.

(3) Establishment of a cloud-resolving ensemble forecast system. The initial condition (IC) perturbation quality is important to the performance of an ensemble prediction system, especially for storm-scale and short-range forecasts (Du et al., 2018). Two improvements related to IC perturbation methods were achieved in this program. One was the 3D rescaling of the IC perturbation magnitude (Deng et al., 2023), and the other was the mixing or blending of large-scale and small-

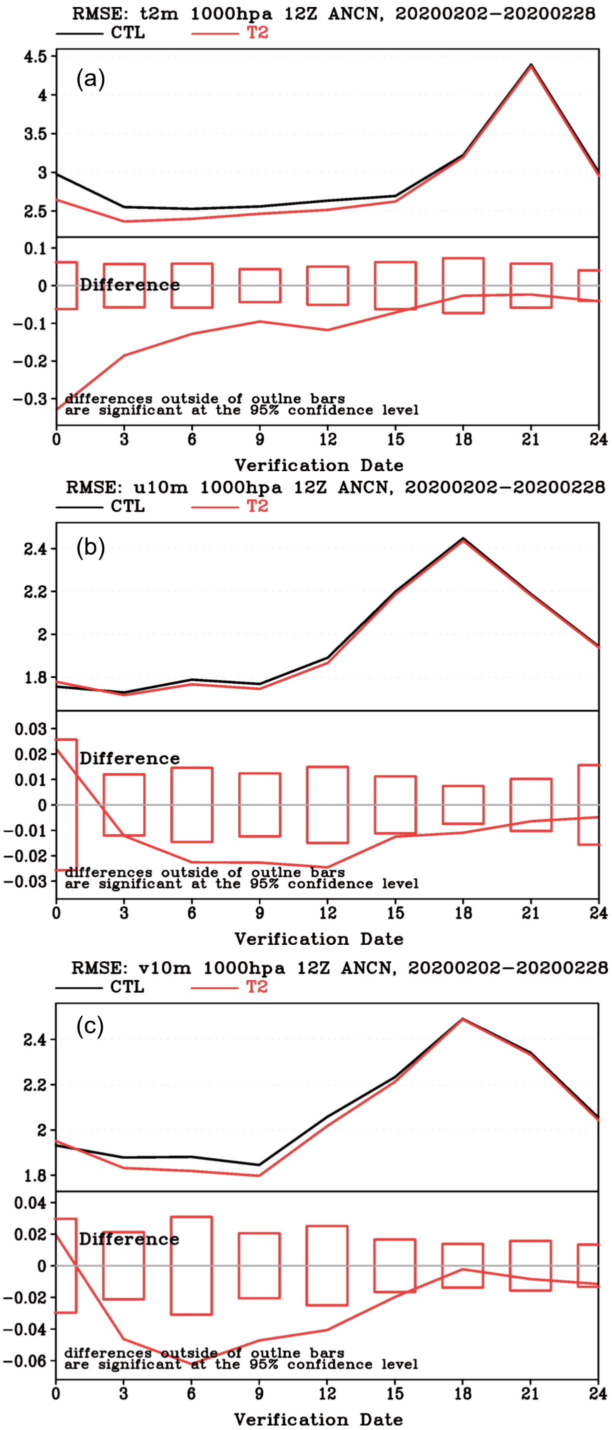


Fig. 3. RMSEs of the control (CTL, black) and the new scheme (T2, red) for (a) 2-m temperature (units: °C), (b) 10-m zonal wind (units: m s^{-1}), and (c) 10-m meridional wind (units: m s^{-1}) in the 24-h forecasts of the 3-km version of CMA-MESO. The experimental period was 2–28 February 2020 on a 0000 UTC cycle. Reproduced from Xu et al. (2023).

scale perturbations. As demonstrated by Deng et al. (2023), 3D rescaling is superior to a 2D rescaling mask, as it benefits from both the vertical structure of IC perturbations and the forecast performance. A blended multi-scale IC perturbation via the 3DVar framework for a high-resolution regional ensemble prediction system (CMA-REPS) was established for real-time forecasting during the Olympics.

(4) Dynamical downscaling and small-scale fireworks dispersion forecasting techniques of CMA-MESO surface wind fields. In order to meet the "100-meter level, minute-level" requirement, i.e., very high resolution forecasting capability, for special events like the opening and closing ceremonies of the Beijing 2022 Games, a CMA-MESO-based wind field dynamical downscaling technique (Wang et al., 2008; Xin and Chen, 2014) and small-scale fireworks dispersion method (Pokhrel and Lee, 2019) were developed. This represented the first time that the CMA model had realized such refined, fine-resolution wind field forecast products with a 100-m spatial resolution and 10-min output frequency.

(5) Bias correction and machine learning approach. To reduce the forecasting errors of surface variables and efficiently extract useful information from "massive" forecast data at both short- to medium-range scales, various bias correction techniques were applied to the raw deterministic and ensemble numerical forecasts to produce calibrated final forecast products at both grid points and stations. The bias correction techniques included traditional statistical methods (e.g., the adaptive Kalman filtering method; Zhang et al., 2020), machine learning algorithms (e.g., XGboost and ResUnet), and ensemble model output statistics (EMOS; Scheuerer and König, 2014). These bias correction methods significantly reduced the forecast errors of surface variables in the competition region and at venue sites. For example, on average, the 24-h forecast error based on the adaptive Kalman filtering method was less than 2°C for 2-m temperature and close to 2 m s^{-1} for 10-m wind speed, which met the service requirements of the Winter Olympic Games.

(6) Processing of seamless 0- to 360-h forecast products. There were several operational and developmental CMA modeling systems used for weather forecasting during the Beijing 2022 Games (Tong et al., 2020). Different modeling systems with different resolutions have their own unique characteristics and advantages for certain variables and levels, and it is desirable to efficiently extract and integrate information from these available systems to construct a unified forecast. The methods explored included Bayesian model averaging, EMOS, and machine learning fusion models (Veenhuis, 2013; Scheuerer et al., 2014; Zhi and Huang, 2019; Zhi et al., 2022; Roberts et al., 2023). A fusion model, using different forecast fields, was constructed based on the U-Net model. Results showed that forecast errors could be further reduced by adding the attention mechanism, random depth, point-by-point regression, and residual training.

3. Real-time operational weather forecasting systems

Successful Olympic services cannot be separated from continuous improvement to operational technology. Besides the scientific achievements mentioned above, several real-time operational systems were also improved and used for the Beijing 2022 Winter Olympics according to the Science and Technology Winter Olympics Special Program. Based on both operational and experimental modeling systems, a whole set of seamless, refined numerical forecast model technologies and forecasting systems were established (Table 1). These NWP systems are highlighted below.

Table 1. Atmospheric model configurations for the Beijing 2022 Games.

Model	Domain	Horizontal resolution (km)	Forecast length (hour)	Run frequency (hourly)	Main technological improvements
CMA-GEPS	Global	50	360	6	Vertical coordinate upgrades; enhancements of initial SV perturbations
CMA-GFS	Global	25	240	6	Correction algorithm to mass conservation; 4DVar; satellite data assimilation; microphysics and cumulus parameterization
CMA-TYM	Asia	9	120	6	Static data (MODIS); SAS convection scheme; cloud analysis
CMA-REPS	China	10	84	6	3D rescaling masks of initial perturbation; revisions to background fields; SPP model perturbation scheme
CMA-MESO_3km	China	3	72	3	Terrain filtering; 3D reference profile; boundary layer scheme based on C-P grid
CMA-HREPS	Huabei region	3	36	6	Error analysis over complex terrain; data assimilation–related ensemble techniques; multi-scale blending
CMA-MESO_1km	Huabei region	1	24	1	Dynamics (more vertical levels; hybrid coordinates); 3DVar (B Matrixes; multi-analysis; IAU initialization); microphysics (new Noah, new static data; double-moment microphysical scheme
Downscaling	Chongli and Yanqing competition area	0.1 (100 m)	24	1	CALMET wind downscaling; small-scale atmospheric dispersion forecasts

CMA-GFS is the CMA's global forecasting system, wherein a new hybrid vertical coordinate (87 vertical layers with 0.1 hPa as the model top) was implemented. The new coordinate improved the forecasting capability at upper levels. The horizontal resolution is 25 km globally, and a 4DVar data assimilation system uses the maximum amount of satellite and conventional observations from global sources and generates ICs for the global forecasts. It makes a 10-day forecast at 0000/1200 UTC and a 5-day forecast at 0600/1800 UTC.

CMA-GEPS stands for CMA Global Ensemble Prediction System, in which a total energy norm–based approach with singular vectors (SVs) is implemented to create initial perturbations. These SV perturbations are closely related to the development of the CMA global 4DVar system. The Stochastically Perturbed Parameterization Tendencies (SPPT) scheme was applied to represent the model uncertainty. There are 31 ensemble members with a forecast lead time of 15 days.

CMA-TYM is the CMA's operational Typhoon Forecast Model, based on the CMA-MESO software infrastructure. The key techniques include a vortex initialization scheme, physical process tuning, and highlights on data assimilation. It replaced the original 10-km resolution CMA-MESO and extended its forecast domain from China to Asia and the western Pacific.

CMA-REPS is the CMA's Regional Ensemble Prediction System. It uses an Ensemble Transform Kalman Filter for IC perturbation, and the SPPT scheme for model perturbation. A cloud analysis scheme was added to each ensemble member, which assimilates radar and satellite data. The model's horizontal resolution is 0.1°, and the forecast length is 84 h.

CMA-MESO_3km is a 3-km fast-cycle assimilation version of CMA-MESO. The main improvements include better calculation accuracy and stability of the model dynamic framework, improved microphysics for the high-resolution model, and the establishment of a convection-resolving assimilation system and land surface data assimilation system to make use of conventional and unconventional local dense data such as those from radar, wind profile radar, FY-4A, surface precipitation, and near-surface measurements.

CMA-HREPS is an experimental 3-km cloud-resolving High-Resolution Ensemble Prediction System. Using the improved CMA-MESO model, data assimilation system, IC perturbation scheme, and model physics perturbation schemes developed for the Beijing 2022 Winter Olympics weather forecasting and research program, CMA-HREPS was established for the Beijing 2022 Games. The first-order Markov process-based model stochastic perturbation technique was used to perturb the model physics (Li et al., 2008; Fan et al., 2022). It has 15 members and runs two cycles per day (0000 and 1200 UTC) to 36 h (extended to 60 h at a later stage). Bias correction of ensemble forecasts, probabilistic products, and verification are also part of this ensemble prediction system.

CMA-MESO_1km is a 1-km hourly cycle assimilation version of CMA-MESO. In order to overcome the difficulties resulting from complex terrain and high-frequency observations, a special design involving ground temperature/humidity observation algorithms, high-resolution static data, optimization of the radiation parameterization scheme, and a mixed-scale scheme was introduced during the development of this hourly cycle assimilation system. With these improvements, the quality of 2-m temperature, 10-m wind field, and precipitation forecasts was obviously improved.

A 100-meter dynamical downscaling model and a fine-scale fireworks dispersion forecasting model were two other capabilities developed for the Beijing 2022 Games. The forecast wind fields from CMA-MESO_1km were downscaled to different height levels based on the complex mountain conditions of sporting venues. It ran 24 times per day to provide forecasters with very high spatial (100 m) and temporal resolution (every 10 min) gridded forecasts, 24 h per cycle. During the Winter Olympics, it provided "100 m-level, minute-level" wind field forecasts for Chongli station and the Yanqing competition sites. The fireworks dispersion forecasting used small-scale Lagrangian smoke diffusion forecasting technology. The 100-m resolution fireworks diffusion products were applied to some special events like the opening and closing ceremonies.

4. Olympic service

During the Beijing 2022 Winter Olympics, seamless 0–15-day numerical forecast products were provided based on the CMA real-time operational forecasts and other experimental forecasts through bias correction techniques, machine learning, and fusion methods. Figure 4 shows an example for deterministic forecasts, and Fig. 5 shows an example for ensemble forecasts.

Compared to the raw model forecasts, the final calibrated products supported by the Olympic Games significantly reduced the forecast errors of surface weather elements. The error reduction rate was about 10%–40%. Taking the 3-km cloud-resolving scale ensemble forecast as an example, after the calibration of the EMOS method, the 36-h average forecast error of the venues was lower than 2°C for 2-m temperature, and the wind speed error was close to 1.7 m s^{-1} for the 10-m wind during the entire Olympic Games (Fig. 6), besides the improvements in ensemble spread. It also provided early warning information for disruptive weather risks at individual sporting venues.

5. Summary

The International Olympic Committee President, Thomas BACH, described the Beijing 2022 Winter Olympic Games

Fig. 4. The CMA products docked to major Winter Olympics service platforms (in Chinese) for real-time applications.

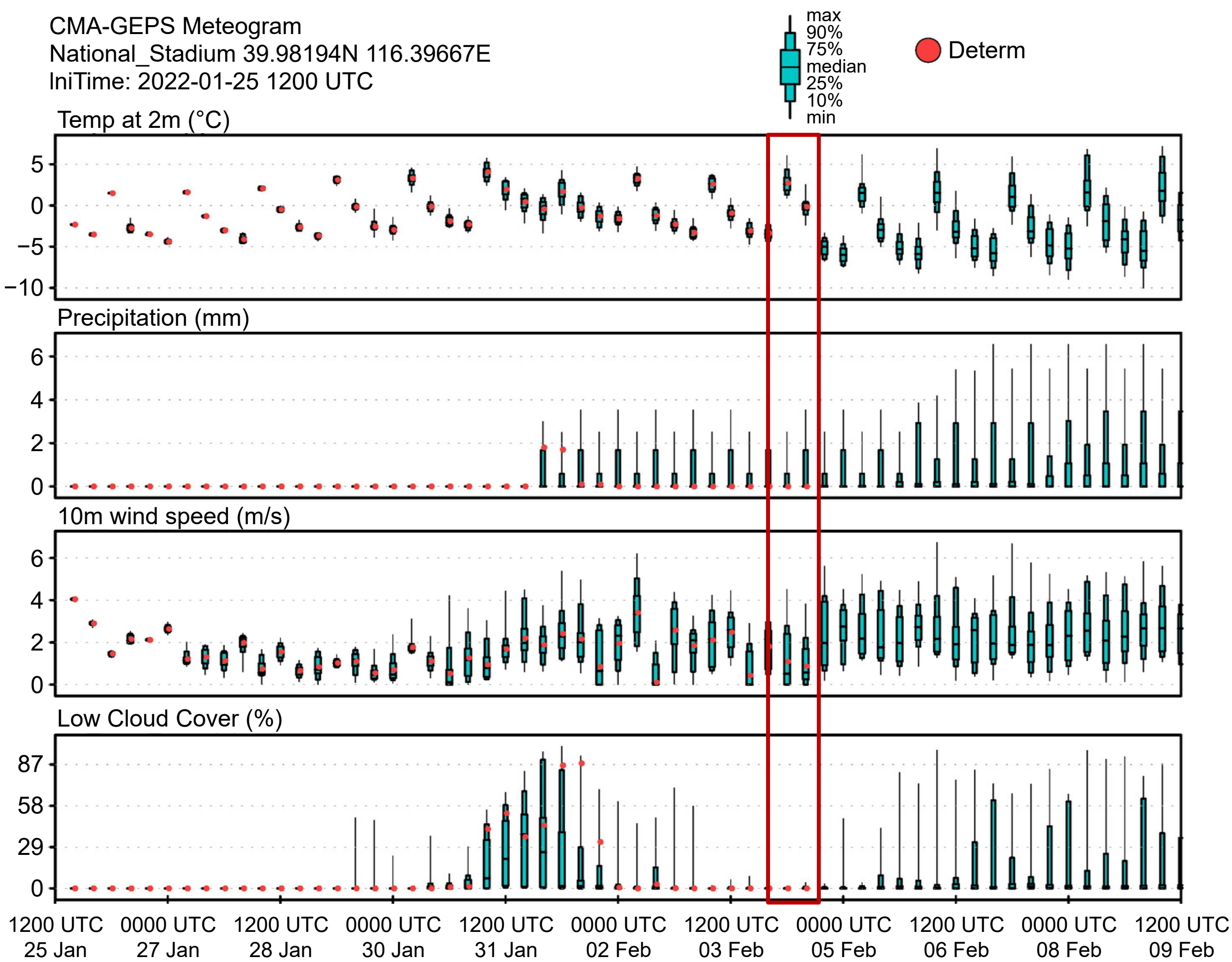
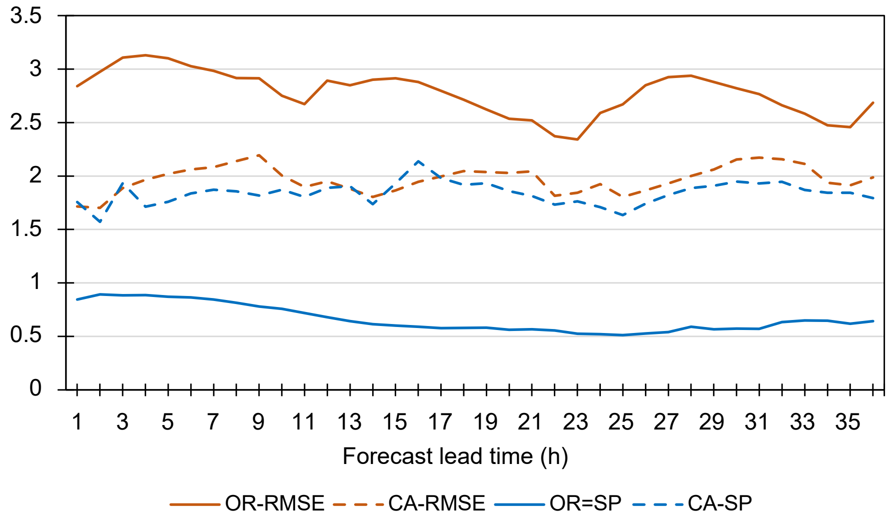


Fig. 5. Hourly ensemble forecasts of weather elements (low-cloud cover, 6-h-accumulated precipitation, 10-m wind speed, and 2-m temperature) by CMA-GEPS and CMA-BLD. Model initiation time is 1200 UTC 25 January, with a forecast length of 360 h (CMA-BLD is 240 h). The deterministic forecast is in red, and the ensemble range is expressed by the box-and-whisker plot (median, 25%, 75%, maximum and minimum). The time is in UTC, which is 8 h later than Beijing time (BT). The red box indicates the opening ceremony weather service period (0000–1600 UTC or 0800–2400 BT 4 February).



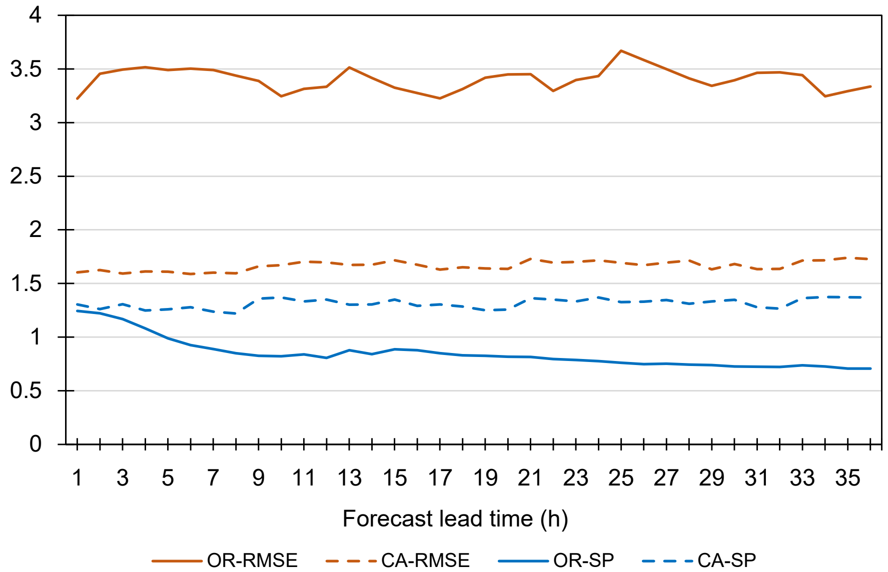


Fig. 6. The EMOS-calibrated ensemble mean forecast's error of surface temperature (upper) and wind speed (lower) from CMA-REPS_3km during the Beijing 2022 Games (29 January to 3 March 2022). The result is for the 36-h forecasts averaged over all sporting venues. RMSE is in red, and the ensemble spread is in blue. The solid lines are the original forecasts, while the dashed line indicates the calibration results, where the calibrated forecasts were used in the real time Olympic services.

as "a truly unparalleled Winter Olympics". One of the keys to the success was the meteorological service, which provided accurate and reliable 0–15-day high-resolution forecasts over complex mountainous regions. The forecast products were derived from the CMA's integrated global and regional weather forecast modeling systems and were provided in both deterministic and probabilistic formats on model grids and at venue sites. The success of this meteorological service can be attributed to the progress made in the research and development of the national weather forecasting program (as covered in this article), as well as the incorporation of advanced technologies from similar programs in previous Olympics.

Although this program was tailored for the Beijing 2022 Games, many techniques developed by the program have already been implemented into the CMA's operational forecasting systems. These developments showcase the highest capabilities currently available in China. The meteorological service provided to the Beijing 2022 Games also exceeded the level of similar services during previous Winter Olympic Games in terms of both variety and quality. Notably, achievements included the utilization of a downscaled spatiotemporal resolution at the "100-meter level, minute level", as well as extending forecasts from 1 to 15 days ahead. In addition, valuable experiences were gained in using weather forecast information to deliver effective and intelligent meteorological services for decision-making, thereby mitigating the social impacts of prominent events like the Olympic Games. This program constitutes one of the five subprograms of the WMO's high-impact weather forecasting demonstration project (SMART2022) and continues to play an important role in their Regional Association (RA) II Research Development Project (Hangzhou RDP). The research achievements and meteorological service experiences garnered from this program will be integrated into future high-impact weather forecasting and research endeavors.

Data Statement Given that this is a project review rather than a specific research result, a dataset could potentially be provided upon request for readers who express interest.

Declaration of Competing Interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements. This work was jointly supported by the National Natural Science Foundation of China (Grant Nos. 41975137, 42175012, and 41475097) and the National Key Research and Development Program (Grant No. 2018YFF0300103).

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