Application of Analog Ensemble Method in Predicting Surface Meteorological Elements in Hebei Region

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Abstract Analog Ensemble (AnEn) is a statistical interpretation method based on historical similarity, big data sample retrieval, and ensemble forecasting ideas. It can form deterministic correction results based on numerical model outputs and further provide probability ranges and uncertainty information. In this paper, the surface meteorological elements in Hebei Province were taken as the research objects. Focusing on the forecasting of 2 m temperature, 10 m wind speed, total cloud cover, and low cloud cover, with comprehensive reference to relevant AnEn research results and phased experimental data of AnEn in Hebei Province, a similar sample screening and ensemble weighting scheme suitable for the complex terrain background of Hebei Province was constructed. The results showed that AnEn had a relatively stable correction effect on 2 m temperature forecasts and can significantly reduce the systematic bias of the model. For a wind speed of 10 m, the average effect of the entire region was not yet better than EC direct forecasting, but it had strong potential for improvement in complex terrain, non urban stations, and areas with large local errors. In cloud cover forecasting, the effect of low cloud cover was better than that of total cloud cover, and the accuracy of forecasting slightly decreased with the extension of time efficiency. The sample size experiment showed that when the number of members in the ensemble increased from 5 to 10, the MAE and RMSE overall decreased, and the ranking weight method was superior to the median method. Research has shown that AnEn can serve as an important objective interpretation tool for short- and medium-term surface element forecasting in Hebei region.
Key words Analog ensemble; Hebei region; Interpretation of numerical forecasting; Wind speed; Temperature; Cloud cover; Ensemble forecast
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Hebei Province is located in the convergence area of the North China Plain, the Taihang Mountains, and the Yanshan Mountains, featuring complex and diverse terrain that includes plains, hills, mountains, and coastal zones. Influenced by the East Asian monsoon, the westerly wind system, cold air activity, and local topographic effects, the spatial and temporal variations of surface meteorological elements in Hebei are relatively significant. In winter, frequent cold air processes lead to drastic changes in surface wind speed, temperature, and boundary layer structure. In summer, under the influence of subtropical high, moisture transport, and local convection, daily variations of cloud cover, precipitation, and temperature exhibit complex characteristics. Hebei Province is also an important agricultural production area, industrial base, energy corridor, and densely populated region. It is crucial for agricultural disaster prevention and mitigation, energy dispatching, transportation, urban fine-grained management, and ecological environmental services by accurately forecasting surface temperature, wind speed, and cloud cover.

With the development of high-resolution numerical forecast models and rapid updating cycling systems, the models' ability to describe large-scale weather systems continues to improve. However, in areas with complex terrain and diverse underlying surfaces, direct model outputs still exhibit systematic biases, local errors, and insufficient parameterization of physical processes. Near-surface air temperature and wind speed are highly sensitive to terrain height, surface roughness, urban underlying surfaces, boundary layer mixing, and radiative processes, while cloud cover is closely related to moisture, vertical motion, temperature stratification, and mesoscale systems, making its physical processes even more challenging to accurately describe with a single model. Therefore, statistical interpretation and error correction of model outputs remain crucial approaches to improving forecast accuracy in operational forecasting[1].

The fundamental idea of analog forecast method is to identify historical cases similar to the current forecast scenario and use the observed data from these historical cases as a reference for the current forecast[2-3]. The analog ensemble method builds upon the traditional analog forecast approach by incorporating the concept of ensemble forecasting. By selecting multiple historically similar members to form an ensemble, it can not only generate deterministic correction results in the form of ensemble averages but also represent forecast uncertainty[4]. Existing studies have shown that the analog ensemble method can significantly reduce forecast errors for 2 m air temperature and 10 m wind speed. Given that Hebei Province features a combination of plain, mountainous, and coastal environments, it is necessary to establish an analog ensemble forecasting process tailored to the regional characteristics of Hebei[5-6].

1 Data and research methods

1.1 Data source and preprocessing The materials used in this paper mainly included three categories. The first type was the observation data from automatic weather stations in Hebei Prov-

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ince, mainly including hourly observation information of 2 m temperature, 10 m wind speed, and cloud cover. There are 135 stations covering the mountainous areas of northern Hebei, the plains of central Hebei, the hills of western Hebei, and the coastal areas of eastern Hebei. The second type was numerical model forecasting and reanalysis data, including EC model forecast fields, T639 model outputs, ERA-Interim reanalysis data, and forecast variables involved in related research. The third type was the phased experimental materials for analog forecast in Hebei region, including comparison results of low cloud cover, total cloud cover, wind speed forecast, different numbers of similar members, ranking weights, and median weighting.

Due to the inconsistent spatial resolution, temporal resolution, and variable hierarchy of different data sources, unified preprocessing was required in the research. The grid pattern data was interpolated to match the stations or unified grid in Hebei region. Quality control of station observation data was conducted, and missing measurement values and obvious outliers were eliminated. Different physical quantities were organized according to forecast validity period, start time, and level to form a historical sample library that can be used for similarity calculation. To avoid certain factors occupying too much weight in similarity calculation due to dimensional differences, the physical factors participating in the screening were standardized before calculation.

1.2 Analog ensemble method The core process of analog ensemble method includes selecting forecast factors, calculating similarity, screening historical similar cases, constructing ensemble members, and ensemble weighted forecasting[1]. For a certain forecast object, several relevant factors were first selected based on its physical causes and model error characteristics. For example, variables such as 10 m wind speed, 10 m wind direction, ground pressure, low-level potential height, high-altitude wind speed, and temperature and humidity field can be selected for 10 m wind speed forecasting. 2 m temperature forecast can select 2 m temperature, 2 m specific humidity, ground pressure, boundary layer temperature, and terrain related information. Cloud cover forecasting focused on factors such as temperature, humidity, and vertical velocity in the middle and lower layers.

In similarity calculation, the current forecast was compared with the multidimensional factor field of historical samples, taking into account both morphological similarity and value similarity. The configuration of weather patterns had a significant impact on weather evolution in terms of altitude and temperature fields. The numerical values of variables such as humidity, wind field, and vertical velocity were also directly related to the target elements. Therefore, referring to the analog deviation idea in existing research[6] and combining with the ranking weight method in the Hebei experiment, historical cases were sorted from high to low in similarity, and the top n cases were selected as the members of analog ensemble. The ensemble forecast results were obtained by weighted averaging the corresponding real-time values of similar members[2].

1.3 Layer by layer filtration and inspection indicators In response to the complex terrain and weather system impact range in Hebei region, this paper adopted a layer by layer filtering scheme from the outer layer to middle and inner layers. The outer layer was used to describe the background of large-scale circulation, mainly considering the geopotential height field that affects the weather situation in the North China region. The middle layer was used to characterize the main weather systems that affect the Hebei region, selecting a combination of height and temperature fields for filtering. The inner layer focused on Hebei and adjacent areas, incorporating temperature, humidity, vertical velocity, and near ground elements to improve the targeting of locally similar samples. This process took into account both large-scale circulation constraints and local physical quantity configuration, and was suitable for element forecast correction in complex terrain backgrounds in Hebei region[6]. Three-level nested filtering area domains for analog ensemble forecasting in Hebei region was shown as Fig. 1.

The forecast verification indicators included root mean square error (RMSE), mean absolute error (MAE), bias (BIAS), and accuracy. Among them, RMSE reflected the impact of large error samples on the overall forecast quality, MAE reflected the average error level, and BIAS was used to determine whether there was systematic bias in the forecast. Cloud cover forecasting used the proportion of samples with errors within a certain range as an accuracy indicator. For ensemble forecasting, ensemble reliability can also be evaluated through ensemble dispersion and Talagrand distribution. However, this paper focused on analyzing the deterministic error indicators obtained in the staged experiment of Hebei.

2 Analog ensemble forecast results in Hebei region

2.1 Wind speed and temperature forecast The 10 m wind speed test in Hebei region showed that the average MAE and RMSE of current analog ensemble scheme in the entire region were 1.44 and 1.97 m/s, respectively; MAE and RMSE of corresponding EC direct forecast were 1.13 and 1.48 m/s (Fig. 2). From the perspective of average indicators, current analog ensemble forecasting of wind speed has not yet fully outperformed EC direct forecasting. However, according to the site inspection, it was found that some sites with complex terrain or large model errors had certain improvement effects, indicating that the analog ensemble method still had potential value in local correction. The reasons for the insufficient average effect in the entire region may included: the selection of similar samples still focused on the cloud cover forecasting process, and the weight of wind speed related factors has not been fully optimized; the near surface wind was greatly affected by the underlying surface, the terrain channels, and the stability of boundary layer, and it was difficult to fully capture the local wind speed response by relying solely on the situation field screening.

Based on existing research results and comparison of indicators in Hebei experiments, the analog ensemble method can effectively weaken the systemic bias of model temperature, reducing RMSE from about 2.83 ℃ to about 2.21 ℃ (Fig. 2)[5], while also making BIAS close to 0. This indicated that the analog ensemble method can utilize the statistical relationship between "similar forecast situation – actual temperature response" in historical samples to correct systematic biases caused by model (cold at daytime and warm at nighttime) or complex terrain height errors. Due to the significant temperature difference between the mountainous areas and the plains of Hebei, it may further improve the effectiveness of temperature forecasting by constructing a similar sample library based on terrain grouping. Spatial distribution of RMSE for 2 m temperature in Hebei region was shown as Fig. 3.

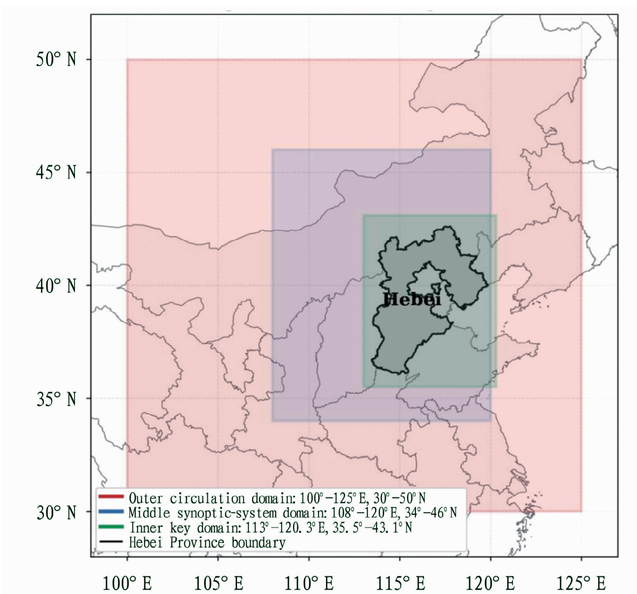

Fig. 1 Three-level nested filtering area domains for analog ensemble forecasting in Hebei region

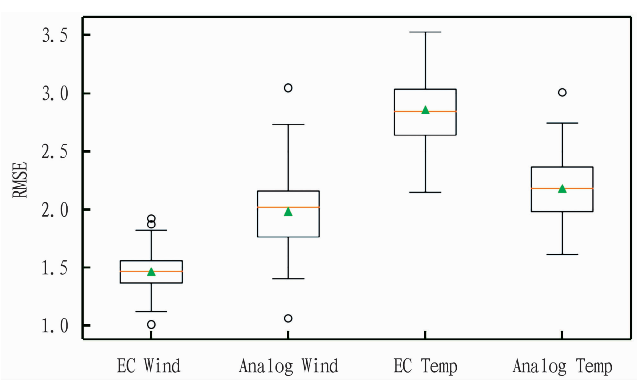

Fig. 2 RMSE box plot of wind speed and temperature at 135 stations of Hebei

2. 2 Cloud cover forecast In terms of cloud cover forecasting, based on the test results of low cloud cover in Hebei, the overall effect of low cloud cover forecasting was better than that of total cloud cover. In the experiment, the accuracy of analog forecasting for low cloud cover was close to or slightly lower than EC direct forecasting in some time periods, but it showed certain competitiveness in time periods such as 12 – 18 h (Fig. 4).

The cloud cover forecast error had significant seasonality. In summer, there is abundant water vapor, frequent convective activity, and fast cloud generation and dissipation rates. Local medium- and small-scale processes have a significant impact on cloud cover, resulting in relatively large errors in total cloud cover and low cloud cover[6]. The evolution of cloud systems in spring and winter is relatively stable, and analog forecasting effects are easier to achieve. For the Hebei region, based on the existing three-layer nested filtering scheme, it is necessary to further distinguish the physical factor combinations of low cloud, medium cloud, and total cloud cover in the future, and introduce variables such as cloud water content, relative humidity, and vertical velocity that more directly reflect cloud physical processes.

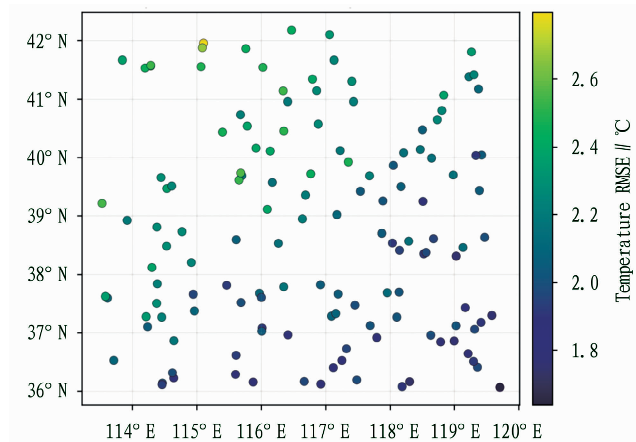

Fig. 3 Spatial distribution of RMSE for 2 m temperature in Hebei region

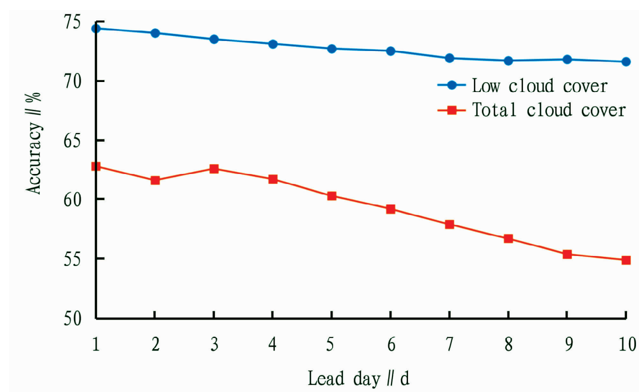

Fig. 4 Forecast accuracy of total cloud cover and low cloud cover with lead day

2. 3 Sample size and weight scheme The number of analog ensemble members n is an important parameter that affects the stability of the forecast. In the wind speed test of Hebei, when n increased from 5 to 10, the MAE decreased from 1. 464 4 to 1. 441 4 m/s and the RMSE decreased from 1. 999 5 to 1. 972 7 m/s under the ranking weight method. Under the median method, MAE and RMSE also decreased overall, but their volatility was greater than that of the ranking weight method (Table 1). It showed that appropriately increasing the number of similar members can improve the stability of ensemble average, and the ranking weight method can more fully reflect the idea of "the more similar, the greater the weight", making it suitable as the main weighting method for current analog ensemble forecasting.

Table 1 Comparison of wind speed forecast errors under different numbers of similar members *n* m/s

n	Rank MAE	Rank RMSE	Median MAE	Median RMSE
5	1.464 4	1.999 5	1.498 1	2.054 8
6	1.457 2	1.991 2	1.483 7	2.038 4
7	1.451 7	1.984 9	1.484 8	2.042 9
8	1.447 4	1.979 8	1.475 9	2.032 7
9	1.444 2	1.976 0	1.476 7	2.036 1
10	1.441 4	1.972 7	1.471 1	2.029 8

2.4 Correlation of high-altitude physical quantities An analysis was conducted on the correlation between different high-altitude physical quantities and 10 m wind speed in Hebei experimental materials (Fig. 5). The results showed that there was a significant correlation between the geopotential height field and the near surface wind speed in the 800 – 400 hPa layer; the correlation with temperature was strong around 500 – 400 hPa, and the correlation coefficient was also high in the 100 – 70 hPa layer; there was a certain correlation with specific humidity in the lower layer and the 50 – 20 hPa layer; the overall correlation of vertical velocity was weak. This indicated that wind speed similarity forecasting cannot rely solely on traditional cloud cover screening processes, but should redesign factor combinations based on the physical causes of wind speed. Ground pressure, high-altitude wind speed, geopotential height, and near ground thermal conditions should be the key variables for subsequent wind speed similarity screening.

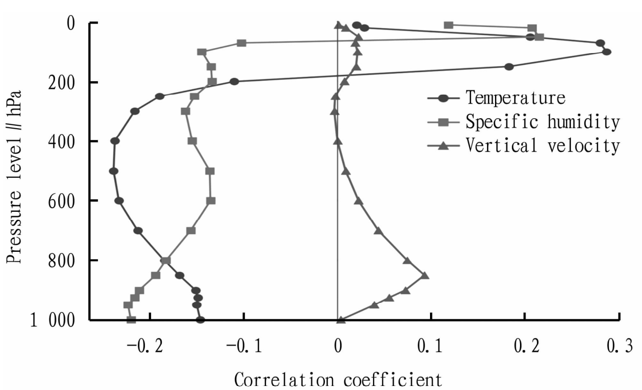

Fig. 5 Vertical distribution of correlation between different high-altitude physical quantities and 10 m wind speed

3 Comparison between analog ensemble and traditional model

From the current experiments in Hebei, the advantages and disadvantages of analog ensemble method and EC direct forecasting varied depending on the factors involved. In terms of wind speed, the full-region average error of EC direct forecasting was relatively small, and analog ensemble still needed to be further optimized in factor screening and weight setting. In terms of temperature, the correction effect of analog ensemble was relatively stable, which can significantly reduce RMSE and weaken system bias (Fig. 6). In terms of cloud cover, analog ensemble forecasting of low cloud cover was more effective than total cloud cover, but there were still time differences compared to EC direct forecasting.

Every new model forecast and actual observation can become a part of the future sample library, so this method has the ability to continuously update and has achieved good application results in probability forecasting of wind and solar energy[7-8]. Compared with methods such as support vector machine and MOS[9-10], analog ensemble requires less manual intervention in model training and can naturally form set members to represent uncertainty. However, its shortcomings are also quite obvious: the selection of similar factors, the range of similar regions, the number of members, and the weighting scheme all affect the results; when the correlation between the target element and the screening field is weak, there may be situations where similar situations cannot correspond to similar cases.

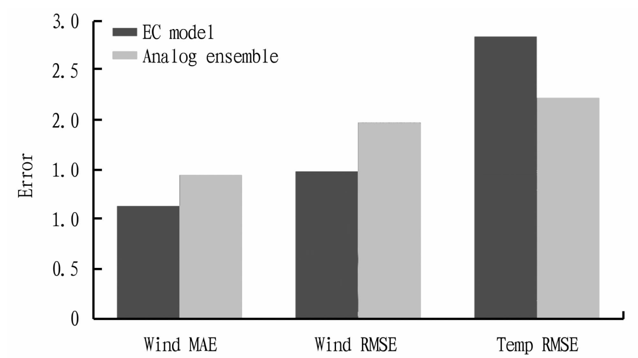

Fig. 6 Error comparison between EC mode and analog ensemble method

4 Discussion

The key issue in analog ensemble forecasting in Hebei region is how to deal with local errors caused by complex terrain and multiple underlying surfaces. The analog ensemble method has a good effect on temperature correction in complex terrain areas. Hebei region combines mountainous, plain, and coastal features, therefore a comprehensive plan should be adopted based on zoning, seasonality, and elements. For temperature forecasting, emphasis can be placed on terrain height, underlying surface type, and thermal conditions of boundary layer. For wind speed forecasting, factors such as high-altitude winds, pressure gradients, terrain channels, and boundary layer stability should be added. For cloud cover forecasting, cloud physical variables such as humidity, cloud water content, and vertical motion should be added[11-12].

The length and quality of sample library are also important factors determining the effectiveness of analog ensemble. The longer the historical sample, the higher the probability of finding high-quality similar cases. But if the model version changes significantly, the historical forecast error characteristics may become unstable, which may actually reduce the effectiveness of the similarity relationship. Therefore, it should try to use the same model version or historical data that has been processed consistently in business applications, and establish a rolling update mechanism. For extreme weather and rare weather types, insufficient samples are still an important problem faced by analog forecast. It is possible to consider introducing multimodal sets, reanalysis data, and extended samples of similar weather types.

5 Conclusions

(1) The analog ensemble method had good potential for application in surface meteorological element forecasting in Hebei region, among which the correction effect of 2 m temperature was relatively stable, and it can effectively reduce RMSE and weaken system bias.

(2) The analog ensemble forecast for 10 m wind speed has not yet outperformed the EC direct forecast in the average index of overall region, but it had the potential for improvement in stations with complex terrain and large local errors. Therefore, it was necessary to reconstruct the specific screening process for wind speed in the future.

(3) In cloud cover forecasting, analog forecasting for low cloud cover was more effective than total cloud cover, and the accuracy of forecasting slightly decreased with the extension of time efficiency. The summer error was relatively large.

(4) When the number of members n in the set increased from 5 to 10, the overall forecast error for wind speed decreased. The ranking weight method was superior to the median method and was suitable as the main weighting method for current analog ensemble forecasting in Hebei.

(5) In the future, improvements should be made in sample library expansion, factor combination optimization, terrain partitioning, seasonal subtyping, and multimodal fusion to enhance the stability and practical value of analog ensemble method in business forecasting of Hebei.

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(From page 16)

(3) In terms of spatial distribution, the climate suitability for tourism in Hebei Province was jointly influenced by terrain, land and sea location, and monsoon climate. The northern mountainous areas such as Chengde and Zhangjiakou, as well as the Bashang region, had prominent advantages in summer heat dissipation. The coastal areas of Qinhuangdao performed well under the TCI model, while the plain in central and southern Hebei had higher suitability in spring and autumn, but was limited by high temperature and humidity in summer.

(4) Statistical tests showed that the differences among the three models reached a highly significant level ($P < 0.001$) throughout the year and four seasons. Paired t-test showed that TCI was significantly lower than HCI and MHCI; summer HCI was significantly higher than MHCI, verifying the corrective effect of MHCI on the hot and humid environment in summer.

(5) Integrating model structure, statistical differences, spatial differentiation, and actual sensory interpretation ability, MHCI is more suitable as the basic model for evaluating tourism climate resources and applying tourism meteorological services in Hebei Province.

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