Meteorological and Environmental Research 2026, 17(4): 12 -16, 21

Spatiotemporal Differentiation Characteristics and Evaluation Model Applicability of Climate Suitability for Tourism in Hebei Province: Comparison Based on TCI, HCI, and MHCI Models

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Abstract The climate suitability for tourism is an important natural condition that affects the development of tourism activities, the attractiveness of tourism destinations, and the level of refinement of tourism meteorological services. To explore the applicability of different tourism climate evaluation models in Hebei Province, three models were selected in this paper: tourism climate index (TCI), holiday climate index (HCI), and modified holiday climate index (MHCI) based on the tourism climate evaluation results of various regions in Hebei Province from 1981 to 2020. Combined with county-level administrative division data, spatial mapping, descriptive statistics, one-way ANOVA, and paired t-test were used to comprehensively analyze the temporal variation, spatial differentiation, and model differences of climate suitability for tourism in Hebei Province. The results indicate that all three models can reflect the seasonal changes in the suitability of tourism climate in Hebei Province, but there are significant differences in the evaluation range and regional identification ability. The annual average of Hebei Province is as follows: MHCI (73.62) > HCI (71.26) > TCI (65.04). Seasonally, the summer mean of HCI is the highest (81.39), indicating a certain overestimation of high temperature and high humidity weather. MHCI remains at a high level in spring, summer, and autumn, and can significantly correct for the effects of hot and humid summers and cold winters. TCI is generally low, especially with a winter average of only 51.64. The analysis of variance shows that there are significant differences in the evaluation results of the three models throughout the year and four seasons ($P < 0.001$). In terms of space, the overall suitability of tourism climate in Hebei Province presents a pattern of significant differences among mountainous areas, coastal areas, and Bashang regions. Chengde has the highest MHCI in summer, Qinhuangdao performs outstandingly in TCI evaluation, and the suitability for spring and autumn in plain of central and southern Hebei is relatively high. After comprehensive comparison, it is believed that the MHCI model can better reflect the characteristics of monsoon climate, high temperature and stuffiness, cold winter, and terrain differentiation in Hebei Province, and is suitable as the preferred model for evaluating tourism climate resources and applying tourism meteorological services in Hebei Province.

Key words Climate suitability for tourism; Tourism climate index; Holiday climate index; Improved holiday climate index; Hebei Province; Tourism meteorological services

DOI 10.19547/j.issn2152 -3940.2026.04.002

Tourism activities have obvious outdoor and seasonal characteristics, and their development is closely related to climate and environmental conditions. Appropriate climate conditions can improve tourists' comfort and satisfaction, and enhance the attractiveness of tourist destinations. High temperature, severe cold, rainstorm, strong wind and other adverse weather could reduce the travel experience and even affect the travel safety. Therefore, it has become an important research content for tourism resource development and tourism meteorological services by scientifically evaluating climate suitability for tourism.

TCI is one of the most widely used tourism climate evaluation models, but it has shortcomings such as a high weight for thermal comfort. Based on TCI, HCI optimizes the weights of factors such as thermal comfort, precipitation, and weather conditions, improving the explanatory power of evaluation results for tourism experience. In response to the climate background in China and sensory characteristics of tourists, scholars have further proposed the MHCI model, which improves the recognition ability of high temperature, high humidity, and extreme weather through temperature and humidity index and localization threshold correction.

Hebei Province has multiple types of landforms including Bashang plateaus, mountainous areas, plains, and coastal areas, with abundant tourism resources and significant climate differences. At present, there is still relatively insufficient systematic comparative research on the TCI, HCI, and MHCI models at the scale of Hebei Province. Based on this, tourism climate evaluation data from 1981 to 2020 were used to compare and analyze the temporal changes, spatial distribution, and statistical differences of three models, in order to clarify the optimal model applicable to tourism meteorological services in Hebei Province.

1 Research area, data and methods

1.1 Overview of the study area Hebei Province is located in the North China region, with an area of approximately 188 800 km^2. The overall terrain is characterized by northwest high and southeast low, including the Bashang plateaus, mountains, plains, and coastal areas. Hebei Province has a temperate continental monsoon climate, with cold and dry winters and hot and rainy summers. The climate in spring and autumn is more suitable

Received: June 16, 2026 Accepted: July 6, 2026

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for tourism activities.

1.2 Data source and processing The tourism climate evaluation data used in this paper came from the daily meteorological element calculation results of various regions in Hebei Province from 1981 to 2020, involving indicators such as temperature, relative humidity, precipitation, wind speed, cloud cover, and sunshine hours. The original evaluation results were organized by region and county unit, including the average values of TCI, HCI, and MHCI models from January to December, the annual average values, and the average values of spring, summer, autumn, and winter. The administrative division data adopted county-level boundary vector data from Hebei Province for spatial expression of tourism climate suitability.

1.3 Evaluation model The tourism climate evaluation model has undergone a continuous optimization process from tourism climate index (TCI) to beach climate index (BCI), climate index for tourism (CIT), and holiday climate index (HCI)[1-3].

1.3.1 Tourism climate index (TCI). The TCI model comprehensively considers factors such as daytime thermal comfort index, all-day thermal comfort index, precipitation, sunshine, and wind speed[1], expressed as $TCI = 2\ (4CID + CIA + 2P + 2S + W)$. Among them, CID is the daytime thermal comfort index, CIA is the all-day thermal comfort index, P is the precipitation, S is the sunshine, and W is the wind speed. The advantage of TCI is that it is easy to calculate and has a wide range of applications, but the weight of its thermal comfort is relatively high, and its limiting effect on precipitation and wind speed in tourism activities is insufficient.

1.3.2 Holiday climate index (HCI). The HCI model is a tourism climate evaluation model developed on the basis of TCI[3], expressed as: $HCI = 4TC + 3P + 2A + W$. Among them, TC is the thermal comfort index, P is the precipitation, A is the aesthetic index, and W is the wind speed. HCI uses meteorological data at daily scale, reducing the relative dominant role of thermal comfort factor in traditional TCI model and increasing the influence weight of precipitation and weather conditions on tourist experience.

1.3.3 Modified holiday climate index (MHCI). MHCI is a localized optimization model based on HCI[4], and main improvements include replacing the effective temperature index with the temperature and humidity index; reclassifying thermal comfort levels based on human body sensory tolerance; optimizing precipitation and wind speed ratings based on China's precipitation and wind level standards; setting negative levels for extremely high and low temperatures, heavy precipitation, and strong winds, and strengthening the constraints of hazardous weather on tourism activities; simplifying cloud level to enhance the convenience of business applications. This model emphasizes the actual sensory experience of tourists under the climate background of China[3], and is suitable for evaluating regional climate suitability for tourism.

1.4 Statistical analysis methods In this paper, the annual average, monthly average, and seasonal average of three models in Hebei Province and various cities were calculated firstly, and their temporal variation characteristics were analyzed. Secondly, using county-level spatial data, spatial distribution maps of annual and seasonal means were drawn, to identify high- and low-value areas of tourism climate suitability. Finally, one-way ANOVA was used to test the overall differences in the evaluation results of TCI, HCI, and MHCI models, and paired t-test was used to further compare the significance of the differences between the two models. The significance level was set at 0.05, with $P < 0.01$ and $P < 0.001$ indicating significant and extremely significant differences, respectively.

2 Results and analysis

2.1 Provincial average levels and annual changes of three models From the average results of Hebei Province, there were significant differences in the evaluation of tourism climate suitability in Hebei Province by the three models (Table 1). The average annual value showed that MHCI (73.62) was the highest, followed by HCI (71.26), and TCI (65.04) was the lowest, indicating that the model structure, thermal comfort indicators, and meteorological element threshold settings could significantly affect the evaluation results of regional tourism climate resources. TCI was generally low, especially in winter when the value was significantly lower than HCI and MHCI. The summer average of HCI reached 81.39, making it the model with the highest summer evaluation among the three models. The annual average of MHCI was the highest, but the summer average was 77.75, lower than HCI, indicating that it had a certain corrective effect on the high temperature and high humidity environment in Hebei Province in summer.

Table 1 Statistics for average tourism climate suitability in Hebei Province by three models

Model	Annual	Spring	Summer	Autumn	Winter	Highest month	Lowest month
TCI	65.04	69.45	75.13	66.31	51.64	June (79.66)	January (48.51)
HCI	71.26	71.78	81.39	71.42	61.60	June (83.00)	January (59.69)
MHCI	73.62	77.69	77.75	76.89	63.83	May (86.35)	January (61.13)

From the perspective of monthly changes, both TCI and HCI exhibited high values in summer (Fig. 1). The highest value of TCI was in June (79.66), and the lowest value was in January (48.51). The highest value of HCI appeared in June (83.00), and the lowest value was in January (59.69). MHCI exhibited a clear bimodal structure in late spring and early autumn, with the highest average in May (86.35), followed by September (86.08), and a significant decrease to 72.68 in July. It indicated that MHCI can recognize the limitations of high temperatures and stuffiness in midsummer on tourism activities. This change feature was more consistent with the actual experience of tourists, that is, although most plain areas in Hebei Province have better precipitation and sunshine conditions in summer, the hot and humid environment has a significant adverse effect on the comfort of outdoor tourism.

2.2 Differences in climate suitability for tourism in different regions At the city scale, the high-value and low-value areas identified by different models were not completely consistent (Table 2). Under the TCI evaluation, Qinhuangdao had the highest annual average (68.71), and Zhangjiakou had the lowest annual average (61.00), indicating that TCI was more sensitive to the milder thermal environment in coastal areas and the relatively lower cold restrictions in winter. Under HCI evaluation, Shijiazhuang had the highest annual average (72.83), while Xiong'an New Area had the lowest (66.18). According to the MHCI evaluation, Baoding had the highest annual average (74.77), and Qinhuangdao had the lowest (67.51). This indicated that the differences in response of different models to thermal comfort, precipitation, cloud cover, and wind speed could alter the ranking of regional tourism climate resource advantages.

Table 2 Comparison of annual average values by three models in various regions of Hebei Province

Region	TCI	HCI	MHCI
Baoding	63.83	72.69	74.77
Tangshan	64.29	71.85	74.40
Langfang	65.12	72.65	74.69
Zhangjiakou	61.00	67.80	71.99
Chengde	62.08	70.39	73.54
Cangzhou	66.28	72.70	74.36
Shijiazhuang	65.85	72.83	74.55
Qinhuangdao	68.71	69.90	67.51
Hengshui	66.42	72.81	74.59
Xingtai	66.18	72.60	74.16
Handan	65.32	72.67	74.13
Xiong'an New Area	65.44	66.18	74.68

From the perspective of seasonal high-value areas, the highest MHCI in summer was in Chengde (84.83), and the lowest was in Xingtai (74.82), which better reflected the climate advantages of cool and suitable summer escape in the mountainous areas of Chengde and Bashang. The highest MHCI in winter was in Shijiazhuang (65.64), and the lowest was in Qinhuangdao (54.99), indicating that MHCI had a strong ability to distinguish the differences in thermal environment in different regions during the low temperature season. TCI identified Qinhuangdao as a high-value area in spring, autumn, and winter, reflecting the positive impact of climate regulation in coastal areas on traditional tourism climate indices.

2.3 Spatial distribution of annual average tourism climate suitability The spatial distribution of annual mean by the three models showed that there were significant regional differences in the tourism climate suitability in Hebei Province (Fig. 2). In the spatial distribution of TCI, Qinhuangdao and surrounding coastal areas performed relatively well, while the values in the northern part of Zhangjiakou and some high-altitude areas were relatively low. The overall level of spatial distribution by HCI has improved, and the differences between plains and mountains have weakened. The average annual value of MHCI was generally higher than the other two models, but the impact of midsummer high temperatures made that some areas in central and southern Hebei has not been simply judged as the best for the whole year.

From the perspective of spatial pattern, the climate suitability for tourism in Hebei Province was not simply manifested in latitude zones, but was influenced by altitude, land and sea location, urban thermal environment, and monsoon precipitation. Chengde and Zhangjiakou in the north had obvious advantages in summer, but were strongly limited by low temperatures in winter. The temperature fluctuations in the coastal areas of Qinhuangdao during the year were relatively small, and the advantage of TCI evaluation was obvious. The suitability of spring and autumn in plain of central and southern Hebei was relatively high, and high temperature and humidity in summer were the main factors limiting tourism comfort.

2.4 Characteristics of spatial differentiation in four seasons by MHCI Further analysis of spatial distribution in the four seasons using MHCI shows that the climate suitability for tourism in Hebei Province exhibits significant seasonal transition characteristics (Fig. 3). In spring, most areas in Hebei Province are at a relatively high level, with areas such as the central southern plain of Hebei and Xiong'an New Area being affected by rising temperatures and less precipitation, resulting in higher suitability. The high-altitude areas in the north are still affected by low temperatures, and the spatial values are relatively low. The spatial differences are most obvious in summer, with some mountainous areas in Chengde and Zhangjiakou, as well as the Bashang region, becoming high-value areas, indicating their outstanding advantages in summer tourism climate resources. However, plain areas such as Xingtai, Handan, and Shijiazhuang are affected by high temperatures and humidity, resulting in a relative decrease in MHCI values.

Autumn is the most stable and suitable season for tourism in Hebei Province. The precipitation decreases, and the temperature is moderate from September to October, making it suitable for sightseeing, ecological, rural, and cultural tourism. The overall suitability of Hebei Province in winter has decreased, with low temperatures becoming the main limiting factor. However, places such as Chongli in Zhangjiakou can rely on low temperatures and snowfall conditions to develop ice and snow tourism. It indicates that "climate comfort" and "climate resource utilization" are not completely consistent in winter, and it needs to be explained in conjunction with tourism activity types.

2.5 Model differences and significance testing The analysis of variance results showed that there were significant differences in the evaluation results of the three models for the whole year and the four seasons of spring, summer, autumn, and winter (Table 3). The F value for the whole year was 674.31, and the P value was 8.40×10^{-137}. The highest F value (1 113.09) was in winter among the four seasons, indicating that the three models had the greatest difference in discriminating climate suitability during the low temperature season. The F value in summer was relatively low but still reached a highly significant level ($F = 167.91$, $P = 2.43 \times 10^{-55}$). It indicated that even in the same hot and rainy season, different models' treatment methods for thermal and humid environments and physical element limitations can still lead to significant evaluation differences.

Table 3 One-way ANOVA of evaluation results for three models

Time	F value	P value
Annual	674.31	8.40e-137
Spring	449.05	2.09e-108
Summer	167.91	2.43e-55
Autumn	717.45	2.03e-141
Winter	1 113.09	5.66e-176

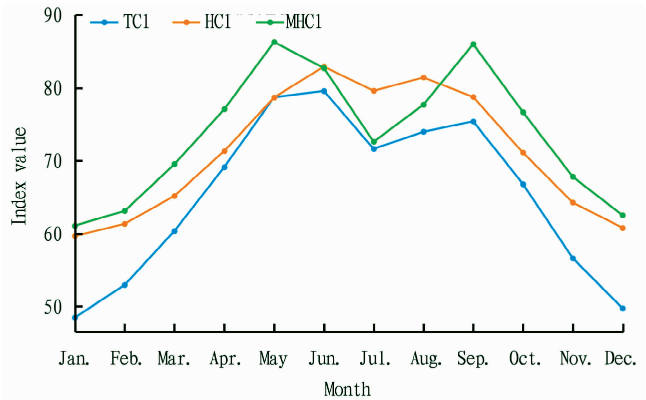
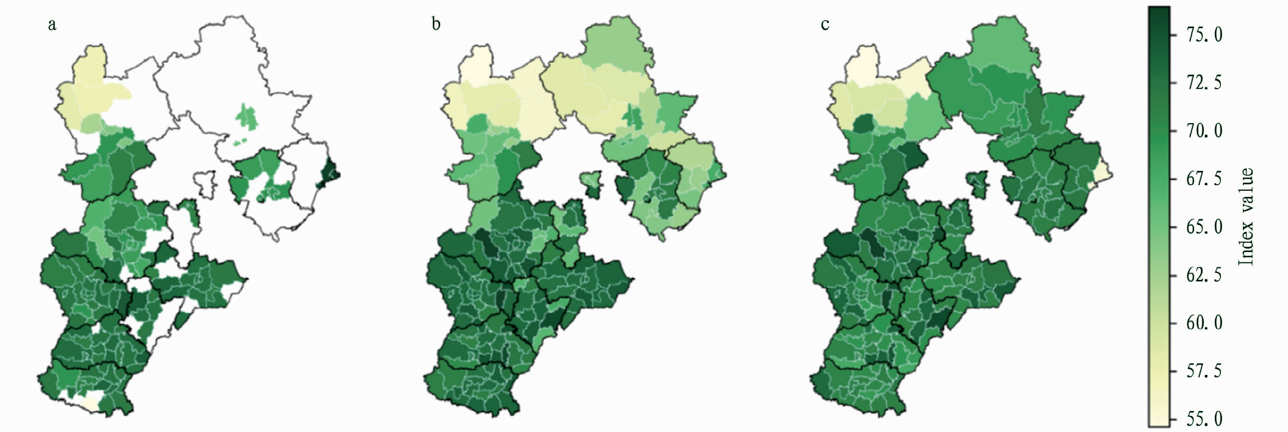
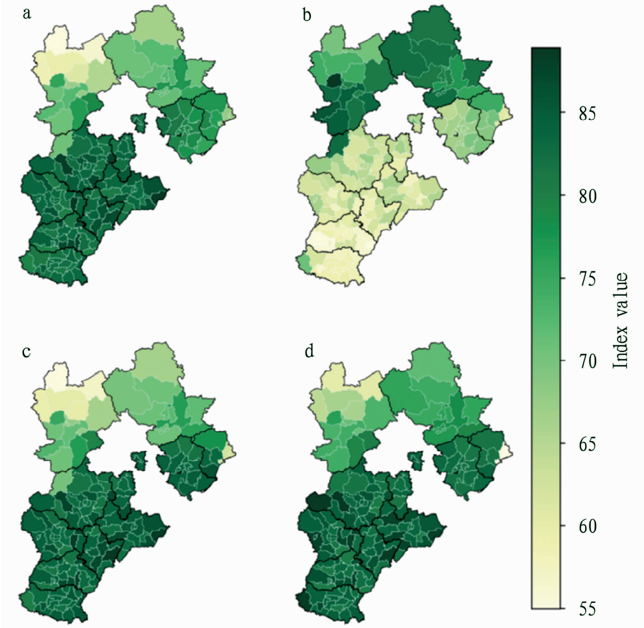


Fig. 1 Monthly variation of tourism climate suitability by three models in Hebei Province



Note: a. TCI; b. HCI; c. MHCI.

Fig. 2 Spatial distribution of annual mean values by three models in Hebei Province from 1981 to 2020



Note: a. Spring; b. Summer; c. Autumn; d. Winter.

Fig. 3 Spatial distribution of seasonal mean values of MHCI in Hebei Province from 1981 to 2020

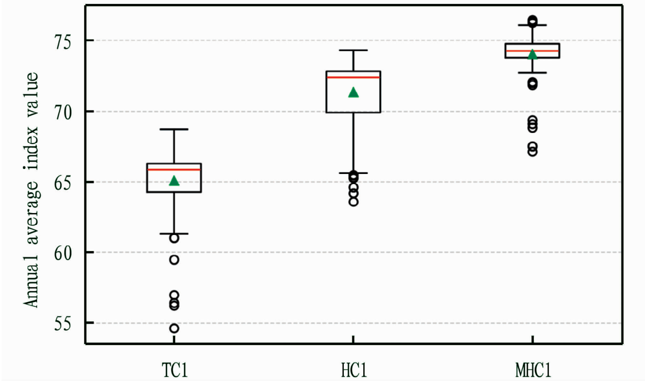


Fig. 4 Box plot of annual average values for three models at the county level in Hebei Province

Paired t-test further indicated that there were highly significant differences among TCI - HCI, TCI - MHCI, and HCI - MHCI at the annual scale. The annual t value of TCI and HCI was -42.02, and the annual t value of TCI and MHCI was -39.90, indicating that TCI was significantly lower than the other two models as a whole. The annual t value of HCI and MHCI was -18.26, indicating that MHCI was generally higher than HCI, but the direction of the difference was not completely consistent across seasons. The

t value of summer HCI – MHCI was 8.50, indicating that HCI was significantly higher than MHCI in summer, which was consistent with the corrective effect of MHCI on hot and humid weather in midsummer (Table 4).

Table 4 Paired t-test of evaluation results for three models

Time	Comparison	t value	P value
Annual	TCI – HCI	–42.02	5.02e-74
Annual	TCI – MHCI	–39.90	1.76e-71
Annual	HCI – MHCI	–18.26	1.21e-41
Spring	TCI – HCI	–10.24	4.20e-18
Spring	TCI – MHCI	–38.22	2.17e-69
Spring	HCI – MHCI	–48.12	8.50e-100
Summer	TCI – HCI	–28.75	6.53e-56
Summer	TCI – MHCI	–5.19	8.51e-07
Summer	HCI – MHCI	8.50	9.92e-15
Autumn	TCI – HCI	–32.48	1.38e-61
Autumn	TCI – MHCI	–47.72	2.51e-80
Autumn	HCI – MHCI	–42.09	7.98e-91
Winter	TCI – HCI	–52.35	5.63e-85
Winter	TCI – MHCI	–52.13	9.24e-85
Winter	HCI – MHCI	–13.91	1.06e-29

The box plot also showed that the overall distribution range of TCI annual mean was lower than that of HCI and MHCI, and the median difference between models was significant. The concentration degree of HCI annual mean was relatively high, while MHCI annual mean overall shifted upward but it still retained certain regional differences (Fig. 4). It indicated that MHCI has not only improved the evaluation level consistent with Chinese human physical sensation, but also identified regional climate differences.

3 Discussion

3.1 Reasons for differences in evaluation among three models The differences in TCI, HCI, and MHCI evaluations are primarily due to differences in indicator systems and weight structures[1,3-4]. TCI emphasizes thermal comfort, and the traditional threshold system focuses more on general tourism climate conditions, with relatively limited weight on short-term weather such as precipitation and wind speed. Based on TCI, HCI adjusts the weights of thermal comfort, precipitation, cloud cover, and wind speed, enhancing the role of physical and aesthetic factors in the tourism experience. Therefore, the overall evaluation results are higher than TCI. However, the original threshold of HCI is not established for the Chinese monsoon climate background, and there are still shortcomings in identifying the stuffiness and heat sensation under high temperature and humidity conditions in summer.

MHCI adopts the temperature and humidity index and resets the thermal comfort threshold, which can simultaneously consider the comprehensive impact of temperature and humidity on human body sensation. For Hebei Province, high temperatures and concentrated precipitation occur simultaneously in summer, making it easy to form a hot and humid environment in the central and southern plains of Hebei. HCI still rated summer as the highest of the year, while MHCI significantly decreased in July, indicating that it could better reflect the real experience of tourists[4]. In winter, TCI was significantly lower, which may amplify the limitations of low temperatures on all tourism activities. While considering thermal comfort constraints, overall rating of MHCI is more suitable for comprehensive tourism climate evaluation.

3.2 Inspiration from the development of tourism climate resources in Hebei Province The tourism climate resources in Hebei Province have obvious seasonal complementarity. Spring and autumn are suitable for a wide range and are key periods for Hebei Province to carry out mass tourism, cultural tourism, rural tourism, and ecological tourism. In summer, it should highlight the advantages of high-altitude areas such as Zhangjiakou and Chengde for summer escape, and develop products such as grassland summer escape, forest health care, and mountain leisure. Although the overall comfort level is relatively low in winter, the low temperature and snowfall provide a resource foundation for ice and snow tourism in places such as Chongli of Zhangjiakou. Therefore, the evaluation of tourism climate suitability should not only be used to determine whether it is "comfortable" or not, but should also be combined with different types of tourism activities to identify the value of climate resources[5].

For meteorological service business, tourism comfort monitoring and forecasting products can be established based on MHCI, converting factors such as temperature, humidity, precipitation, wind speed, and cloud cover into comprehensive indices that are easy for tourists to understand. At the same time, it should develop tourism meteorological service products that cater to typical scenarios such as summer escape, autumn sightseeing, and winter ice and snow based on seasons, regions, and activity types. Especially in the context of frequent disasters such as high temperatures, heavy rainfall, and strong winds, tourism meteorological services should extend from simple comfort evaluation to risk warning and travel advice, in order to enhance the adaptability of tourism destinations under the background of climate change[6].

4 Conclusions

(1) The climate suitability for tourism in Hebei Province had obvious seasonal variation characteristics. All three models showed that spring, summer, and autumn had higher suitability, while winter suitability was lower. However, MHCI presented a more obvious bimodal structure of late spring and early autumn, with May and September being the optimal months. It can better reflect the limitations of midsummer heat and humidity on tourism comfort in Hebei Province.

(2) There was a significant difference in the annual evaluation results among the three models, with the annual average showing as MHCI (73.62) > HCI (71.26) > TCI (65.04) in Hebei Province. The summer average of HCI was the highest (81.39), indicating a certain degree of overestimation. TCI was generally low, especially with an average of only 51.64 in winter. The overall performance of MHCI was more stable.

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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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(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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