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ORIGINAL PAPER

Spatial and temporal assessment of China's skiing climate resources

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Abstract

This study introduces an improved Ski Climate Index (SCI) designed to assess skiing suitability in China by applying fuzzy logic. Using daily meteorological data from 733 weather stations for the periods 1961–1990 and 1991–2020, the study identifies significant changes in SCI distribution over time. Additionally, a coupled analysis is performed, integrating the SCI results with the distribution and spatial vitality of 389 ski resorts in China. This analysis provides a comprehensive understanding of the interplay between actual ski resources and the ongoing evolution of the skiing industry in China and three significant results:1) The snow module has a major impact on SCI distribution, while other non-snow natural elements, such as sunshine duration, wind speed, and thermal comfort, influence the overall SCI assessment less; 2) High SCI values are concentrated in Northwestern and Northeastern China, with increased ski climate resources being observed in Shaanxi-Gansu-Ningxia, Southwest Tibet, and Sichuan due to climate change and noticeable declines in the Southern regions of Northeast China.; 3) In terms of the distribution and vitality of ski resorts, the SCI also partially reflects the development of ski resorts. This skiing suitability model uses climate resources to offer valuable insights for key decision-making in resort development and operation, thereby supporting advancement of the ice-snow economy.

Keywords Ski climate index · Ski resort vitality · Ski industry · Tourism climate · Spatial distribution

Introduction

Climate conditions play a crucial role in determining successful ski resort operations and the demand for skiing. The availability of consistent snowfall is vital for ski resorts with a minimum depth of 30 cm required for the safety of skiers (Damma et al. 2014). Snowfall patterns are significantly influenced by various climatic factors. These include temperature, precipitation, and humidity (McClung & Schaerer 2006; Matzarakis et al. 2012). Additionally, the pace at which snow melts is determined by fluctuations in temperature (Zhong et al. 2018). Ski resorts are also affected by climate conditions. For example, aerial lifts will be closed if wind speeds exceed 30 km/h (Andersen et al. 2004). Various climate factors, such as wind speed, temperature, extreme weather events, and visibility will also directly impact skier safety and the skiing experience (Demiroglu et al. 2016). Optimal skiing conditions prevail when the daily maximum temperature falls within the range of -12 °C to 2 °C and coupled with wind speeds that are below 2 on the Beaufort scale. Conversely, skiing becomes less viable when the daily maximum temperature plunges below -16 °C or when wind speeds escalate beyond 5 on the Beaufort scale (China Meteorological Administration 2017). Additionally, extended periods of exceptionally cold weather can lead to a hardening of the snow, consequently heightening the potential for skiers to encounter increased falling risks on the slopes.

Skiing, as an activity that is closely tied to climatic conditions, is being confronting by a substantial peril due to the escalating impacts of global climate warming (Steiger et al. 2019). The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) predicts that climate change will result in reduced snowfall and natural snow cover across the majority of regions

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(Gajić-Čapka 2011; Steiger et al. 2019; IPCC 2014). With such future climate warming, outdoor ski resorts worldwide will experience varying degrees of shortened skiing seasons and reduced available skiing terrain, leading to an increased demand for artificial snowmaking (Scott et al. 2020). Consequently, some ski resorts may be forced to close due to decreased revenue and higher operating costs. For instance, in North America alone, climate change already puts 31% of outdoor ski resorts at risk of extinction (Scott & Steiger 2024). Further still, skiing demand is highly sensitive to the ongoing changes in weather patterns. A study conducted at a Slovak ski resort indicated that for every 1 °C rise in temperature, there was a 6% decline in lift ticket sales (Demiroglu et al. 2015).

With the successful bid and hosting of the Beijing 2022 Winter Olympics and Paralympics, along with favorable national policies and growing public enthusiasm for skiing, China's skiing industry today is experiencing rapid development. According to the White Paper on Ski Industry in China for the Snow Season of 2022–2023 (Wu 2023), ski resorts are being constructed and expanded at a strong pace, attracting a total of 19.83 million skiers. Nevertheless, despite boasting about their highest count of ski resorts globally, less than 10% of these resorts meet international standards. For example, only 166 out of 697 ski resorts are currently equipped with chairlifts (Wu 2023). Further still, China's skiing industry is still in its early stages and requires extensive development approaches (Yang et al. 2019). Therefore, promoting high-quality development after the Winter Olympics has become crucial by emphasizing the interplay between the process of industry foundation, the consumer demand for skiing activities, and ski resort capacity (Wang and Man 2022; Jiang & Li 2021).

The Policy and Action for Climate Change in China highlights the importance of addressing climate change as a key driver for promoting high-quality economic development. However, there remains a lack of research on the climatic perspective of the ski industry's development in China. Although the Skiing Meteorological Index (QX/T386-2017), an industry standard, defines skiing weather suitability and provides meteorological services to the public, it does not comprehensively evaluate China's specific skiing climate. Consequently, there is limited understanding of the temporal and spatial characteristics of that skiing climate in China, and that issue hampers positive and effective responses to the climate change impacts on the ski industry (Fang et al. 2021) and thus impedes its sustainable and high-quality development.

Various indices have been developed to assess the climate resources for successful ski tourism. The first notable index was the 100-day rule for snow reliability (Abegg 1996). Yu et al. (2009) later introduced the Modified Climate Index for Ski Tourism, which expanded the assessment to include perceived temperature, wind speed, visibility, and present weather conditions. Following the offering of this data, the Optimal Ski Day index was developed. It integrated such factors as temperature, precipitation, sunshine duration, wind speed, snow cover, and snow depth (Berghammer & Schmude 2014). Li et al. (2016a) then further refined the approach by creating a climate index that rated and weighted factors like snow depth, snowfall duration, snow quality, temperature, wind, and annual precipitation. The most recent advancement in this field is the Ski Climate Index (SCI), which was introduced by Demiroglu et al. (2021) and applied to ski resorts in Turkey. Unlike previous indices, which primarily focused on either snow or non-snow components, the SCI includes a comprehensive range of both, such as snow-water equivalent (SWE), temperature, humidity, sunshine duration, and wind speed. Further still, the SCI offers greater flexibility for the industry by allowing its components to be combined in various ways thereby avoiding the limitations of fixed ratings and weights that are found in other indices. This flexibility is achieved through the use of fuzzy logic, which effectively manages the uncertainties that clearly inherent in ski tourism climatology.

The primary aim of this study is to adapt the SCI to China's specific conditions to assess snow reliability and skiing comfort there. The SCI is calculated for two distinct periods– 1961–1990 and 1991–2020 using daily observation data from 733 meteorological stations. ArcGIS 10.5 software is used to describe the temporal and spatial evolution characteristics of skiing climate resources in China. To further illustrate the impact of the SCI on China's skiing industry growth, a comparative analysis is t hen conducted between the obtained results and Fang et al.'s (2023) comprehensive skiing resort development indicator—Ski Resort Vitality. These research findings provide a scientific basis for coordinating ski climate resources across different regions and best optimizing the spatial configuration of ski resorts. Figure 1 presents an overview of the research process and the methodology, data, and content.

Data and model

Data source and data processing

This study primarily utilizes the "China Surface Climate Daily Dataset" that is provided by the China Meteorological Administration Data Service Center (http://data.cma.cn/). That dataset includes daily meteorological elements from 733 reference and basic meteorological stations across China, encompassing a daily average temperature (°C), wind speed (km/h), atmospheric pressure (0.1 hPa), sunshine hours (h), and relative humidity (%). The SWE data (kg/m^2) is obtained from the re-analysis project of the National Environmental Prediction Center (NCEP) and the National Center for Atmospheric Research (NCAR) with a resolution of 2.5°×2.5°. Bilinear interpolation is used to standardize the resolution of SWE data and the daily meteorological element stations (Zha et al. 2020; Khan et al. 2021).

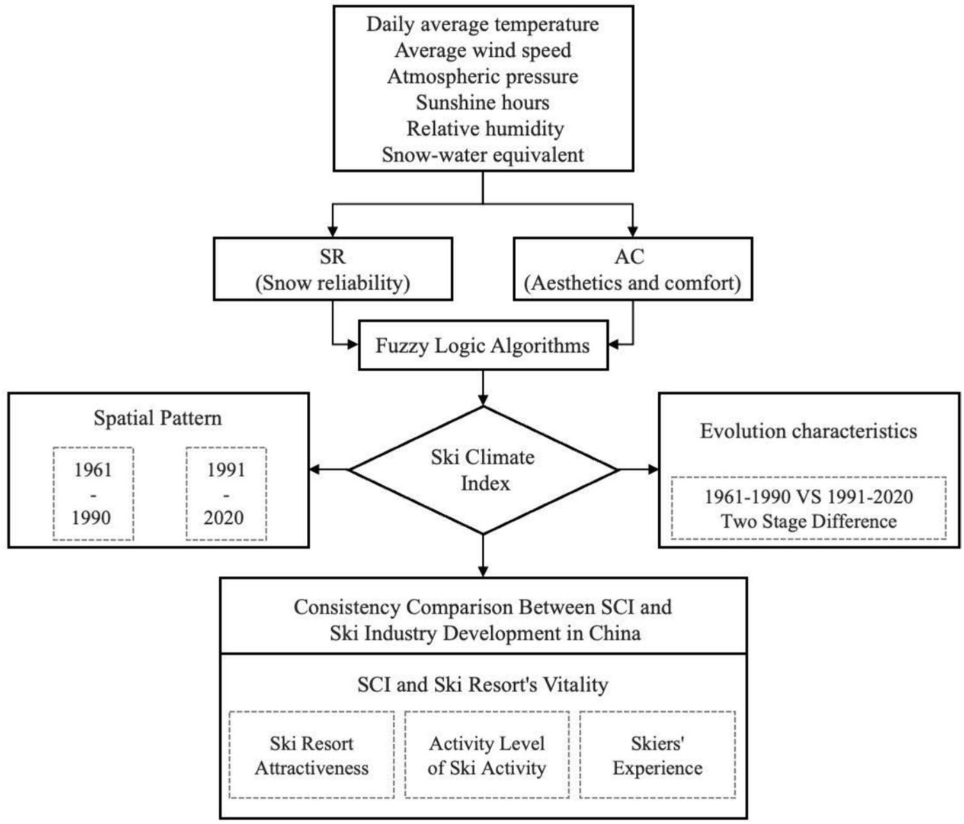
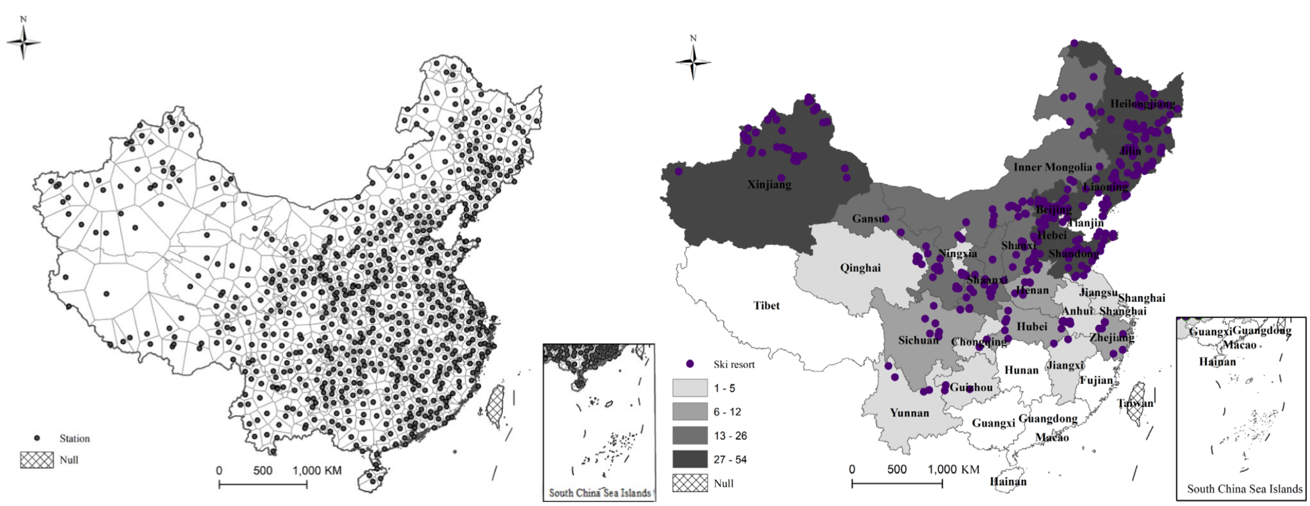


Fig. 1 Flow chart for the research

Considering the data availability and stability, we chose the most recent climate standard period as a key reference (1991 to 2020), while also using a historical reference period (1961 to 1990). We analyze and process data from December to March each year, which is the primary skiing season for outdoor ski resorts in China. Due to uneven spatial distribution of these stations, we performed a weighted analysis based on Thiessen polygons' area size where the meteorological stations are located (Fig. 2a). The utilization of the Thiessen polygon method significantly enhances



(a) Meteorological stations (b) Spatial location of 389 ski resorts

Fig.2 Study Area

both its rationality and accuracy compared to employing just an arithmetic mean method since it incorporates the weightage assigned to each station's control area within a watershed. Moreover, Kriging interpolation can be used to comprehensively understand the spatial distribution of SCI in the entire region by interpolating the measured values and filling data gaps. Unlike other techniques like inverse distance weighting and spline interpolation, Kriging not only accurately assesses unknown areas, but also provides reliable error estimates, thereby offering more comprehensive parameter information. To compare ski resort vitality, we collected latitude and longitude data for 415 ski resorts using web crawler technology from the Pow Snow Technology App as outlined by Fang et al. (2023). This study, therefore, focuses exclusively on examining the 389 outdoor ski resorts obtained from this dataset (Fig. 2b).

Calculation model

SCI model and standard optimization

The SCI model, proposed by Demiroglu et al. (2021) for the Turkish skiing market, consists of two modules: Snow Reliability (SR) and Aesthetics and Comfort (AC). SR focuses on snow conditions, while AC considers aesthetics and comfort factors. The measurement indicators encompass SWE, wet bulb temperature (temperature and humidity), sunshine duration, average wind speed, and other meteorological factors. The SCI model applies fuzzy logic algorithms to evaluate ski climate conditions by combining various climate factors from both the snow and non-snow modules into a single index. It employs a fuzzification process to convert raw data into a 0–1 scale, where 0 represents the least favorable skiing conditions and 1 indicates the most favorable. This conversion involves assigning fuzzy membership values to each data point, based on its alignment with the predefined criteria in both modules. These membership values are calculated using functions like LINEAR and GAUSSIAN, which assess the degree to which the conditions fit within the defined set of favorable skiing conditions. Consequently, the index provides a detailed and continuous assessment of ski climate suitability. The application of fuzzy logic in tourism climatology studies is today becoming increasingly common (Cai et al. 2019; Olya & Alipour 2015). The SCI is comprised of the snow module and the non-snow module, as follows:

$$SR = NSR \cap SM \tag{1}$$

$$AC = 1 - (1 - SS) * (1 - WC) * (1 - TC) \tag{2}$$

$$SCI = (1 - (1 - SR) * (1 - AC))^{G} * (SR * AC)^{1-G} \tag{3}$$

In this formula (1), SR considers the depth of the natural snow and the duration of artificial snowmaking during a DJFM skiing season(from December 1st to March 31st), with "∩" accounting for the impact of certain absent conditions. NSR (Natural Snow Reliability) is determined based on average number of days in the DJFM with SWE(Water Equivalent of Snow Cover) ≥ 53 kg/m^2.

However, it should be noted that the initial design of the SCI model was not tailored to China's specific context, so adjustments and optimizations were undertaken to ensure its best suitability. Considering that China's average snow depth falls below the evaluation standard proposed by the U.S. Bureau of Land Management for ski tourism resources (Li 1985) and that third-class ski resorts in China require a minimum snow depth of 20 cm on ski tracks according to the Classification of Quality Grades for Ski Resorts(LB/T 037–2014), SR meets its minimum conditions when SWE reaches 53 kg/m^2 (calculated based on a snow density of 265 kg/m^3 and a snow depth of 20 cm) (Demiroglu et al. 2016; Sorman & Beser 2013). Artificial snowmaking considers temperature and relative humidity by using Wet Bulb Temperature (WBT) with the following formulation (Stull 2011):

$$WBT = Tas * a\tan\left[0.151977(Hurs + 8.313659)^{1/2}\right] + a\tan(Tas + Hurs) - a\tan(Hurs - 1.676331) \tag{4}$$

The average temperature (*Tas*) is represented in degrees of Celsius, while the relative humidity (*Hurs*) is expressed as a percentage.

Formula (3) comprehensively considers snow reliability, aesthetics, and comfort through AC. For this study, we chose a gamma coefficient (G) of 0.9. The specific definitions for the facets and sub-indices of the SCI are outlined in Table 1 and follow Demiroglu et al.'s (2021) framework.

To provide a more intuitive representation of the SCI, we established a simplified 4-level rating standard inspired by perceived tolerance width (Yu and Li 2019) and guided by Scott et al.'s (2016) classification scheme using quartiles as the foundation. The rating criteria are as follows: Excellent ([0.75–1]), Good ([0.5–0.75), Fair ([0.25–0.5), and Poor ([0–0.25). A SCI score below 0.25indicates severe inadequacy in skiing climate resources in that ski area.

Kernel density method

The kernel density method assigns weights to ski resort locations based on their proximity to the study area center, thereby generating a continuous density distribution map indicating clustering or the dispersion of ski resorts. The concentration is indicated by higher values, while dispersion is suggested by lower values. ArcGIS 10.5 software was used for analyzing and visualizing kernel density. The specific formula for estimating ski resort kernel density is as follows (Liu et al. 2022):

Table 1 Definitions of the SCI facets and sub-indices (Demiroglu et al. 2021)

Facet	Sub-index	Definition
Snow reliability (SR)	Natural snow reliability (NSR)	Seasonal (DJFM) average number of days when SWE is larger than 53 kg/m^2 in a 30-year range
	Snowmaking (SM)	Pre- and actual seasonal (DJFM) average number of hours when WBT is <—7 °C in a 30-year range
Aesthetics and comfort (AC)	Sunshine duration (SS)	Seasonal (DJFM) average number of days when the sunshine duration is more than 6 h in a 30-year range
	Wind conditions (WC)	Seasonal (DJFM) average number of days when the top wind speed is less than 40 km/h in a 30-year range
	Thermal comfort (TC)	Seasonal (DJFM) average number of days when WBT is between -7 and 2 °C in a 30-year range

Note: DJFM indicates December to March of the following year

$$f_n(x) = \frac{1}{nh} \sum_{i=1}^{n} k\left[\frac{x - x_i}{h}\right] \quad (5)$$

Here k is the kernel function, n is the number of points within the bandwidth, $x - x_i$ is the distance between$x$, and x_i which is the estimated location of the ski resort, and h is the bandwidth.

The vitality of ski resorts

The term "vitality" traditionally refers to the dynamic life force existing in organisms. However, in the mid-twentieth century, this concept was cleverly adapted into urban studies as a crucial measure to use for evaluating urban spatial quality (Lynch 1984). Urban vitality is essentially manifested through the diverse interplay between people, activities, and place (Fang et al. 2023). Recently, Fang et al. (2023) explored ski resort vitality by assessing their attractiveness ("place"), support for skiing activities ("activity"), and skiers' perception of them ("people"). Critical factors when evaluating a ski resort's vitality from a "place" perspective include accessibility, skiing facilities, supporting amenities, and operational hours. The assessment of "activity" revolves around two key aspects: (1) the number of participants involved in skiing activities within the ski area (aggregation) and (2) participation consistency across different days that include weekdays, weekends, and holiday periods like Spring Festival (stability). The aspect of "people" finds its embodiment in subjective evaluations provided by skiers regarding the diverse elements they identify related to facilities and services. China's ski resorts' vitality characteristics were analyzed using the linear combination method to calculate combined weights of evaluation indexes for a ski resort's vitality. Please refer to Table 2 for indicators for each dimension and their corresponding weights.

Table 2 Evaluation index system and weight of ski resort's vitality

Dimensions	Indicators	Descriptions
Ski resort attractiveness (0.14)	Accessibility (0.01)	Overall Accessibility including local and regional accessibility outside these areas
	Operation time (0.02)	The length of a ski season; Daily business hours
	Skiing facilities (0.08)	Ski slopes variety (i.e., green/blue/black runs); The number and combination of ski-lift facilities
	Supporting facilities (0.03)	The number and combination of service infrastructure like hotels, restaurants, parking lots
Activity level of ski activity (0.53)	Aggregation (0.40)	Kernel density analysis using the number of visits to the ski resort as the weight parameters
	Stability (0.13)	Changes in the skier visitors between the working days, weekend days and the Spring Festival holiday
Skiers' experience (0.33)	Facilities experience (0.13)	Experience evaluation of the perception of traffic, snow slopes, restaurants, and accommodation
	Service experience (0.20)	Ski and snowboard rental and education services

Source: Fang et al. 2023

Results

It is significant and important to assess the temporal and spatial distribution of skiing resources from a climatic perspective for tourism development and management. In this study, we developed the SCI to assess the suitability of skiing climate resources in China based on their spatial distribution characteristics during 1961–1990 and 1991–2020, and the changing patterns. Additionally, we compared SCI with the spatial distribution of outdoor ski resorts in China by employing the kernel density estimation method. Furthermore, this study compared China's ski climate resources with the spatial vitality of the ski resorts to emphasize the significant role of ski climate assessment in representing industry development.

Spatial pattern of SCI in China

The fuzzy spatial representation of sub-indicators for SCI is illustrated in Fig. 3. In the SR module (Fig. 3a), altitude strongly correlates with NSR, with higher values predominantly found along the Tianshan, Qilian, Hengduan, and Da Hinggan Mountains. For SM, there is a distinct latitudinal distribution pattern, with the Qinling-Huaihe Line as the dividing line between higher values in the north and lower values in the south. Additionally, SM shows elevated values in regions with high latitudes and altitudes, peaking in third-tier cities as well as in northern Gansu and eastern Inner Mongolia.

For aesthetics and comfort (Fig. 3b), SS gradually increases from the southeastern coastal regions to the northwestern inland areas. Higher values are seen in the western and northern parts of China while lower ones are found in the eastern and southern regions. The southeastern region is significantly impacted by a maritime climate, leading to more cloudy/rainy weather conditions as well as shorter sunshine duration compared to the northwestern counterparts. WC levels are high, with maximum concentration occurring in the northeastern region and most parts of the southern region, including specific locations like Gansu, Ningxia, and the Beijing-Tianjin region. Low values occur on the southwestern slopes of the Tibetan plateau and the borders of Shanxi and Hebei. TC indicates heat comfort, with higher values found in Heilongjiang, northern Inner Mongolia, and northern Xinjiang.

The spatial distribution of SCI in China from 1991 to 2020 is shown in Fig. 4(a). Around 54% of the country's land area has a favorable skiing climate, falling into the "Excellent" [0.75–0.98) and "Good" ([0.5–0.75) categories based on a weighted analysis by area. Among these, the "Excellent" category ([0.75–0.98) is 40.9%, mainly concentrated in the Western regions beyond the Hu Huanyong Line, especially in the Northwest, Northeast, and certain areas of North China. Notably, the Xinjiang Uygur Autonomous Region has the highest SCI, with peak values observed in the Bayinbuluke and Altay regions of Xinjiang. Altay is officially designated as the "Snow City of China" by the China Meteorological Bureau, offering compelling evidence for this recognition. Heilongjiang Province closely follows in the high esteem category as a region renowned for its traditional winter sports and exceptional geographical advantages and thriving on a rich snow and ice culture as well as a flourishing ice-based economy. The regions with low values [0–0.25) total approximately 36.5% of China's land area and are mainly concentrated in East China, Central China, South China, Southwest China (especially Southern Sichuan), and Yunnan Province. This distribution can be mainly attributed to the scarcity of natural ice and snow resources in these regions, resulting in fewer snowfall days and shorter ones.

The spatial distribution of China's skiing climate resources, however, does not align well with the current distribution of ski resorts. Generally, the existing ski resorts demonstrate a spatial distribution pattern centered around Beijing and its surrounding areas, with the Northeast and Northwest regions forming what can be called the "two wings". Comparing Fig. 4a to Fig. 3a in terms of snow reliability module reveals that the SR module, particularly the NSR indicator, significantly impacts SCI's overall performance and exhibits a highly similar spatial pattern. The strong correlation between SCI and the NSR indicator emphasizes natural snow and its reliability playing a crucial role in assessing an area's suitability for skiing. Higher SCI values correspond to higher levels of natural snow reliability, while lower SCI values indicate lower natural snow reliability. This strong correlation reinforces the importance of considering natural snow reliability whenever evaluating an area's skiing climate. In contrast, AC modules, which include metrics like sunlight duration, wind speed, and thermal comfort conditions, show relatively weak correlations. While these metrics are significant in their own right, their impact on the overall performance of the SCI is comparatively minor compared to the NSR indicator. These weaker correlations suggest that factors associated with the AC modules actually have limited influence on determining an area's suitability for skiing.

To further clarify the contribution of each of the factor noted here, we conducted a principal component analysis. This methodology allows for an objective assignment of weights to each variable based on its contributions to the overall variability captured by the principal components. Notably, NSR emerged as the most influential factor, with a weight of 0.31, thereby highlighting its crucial role in determining SCI. This finding indicates that variations in natural

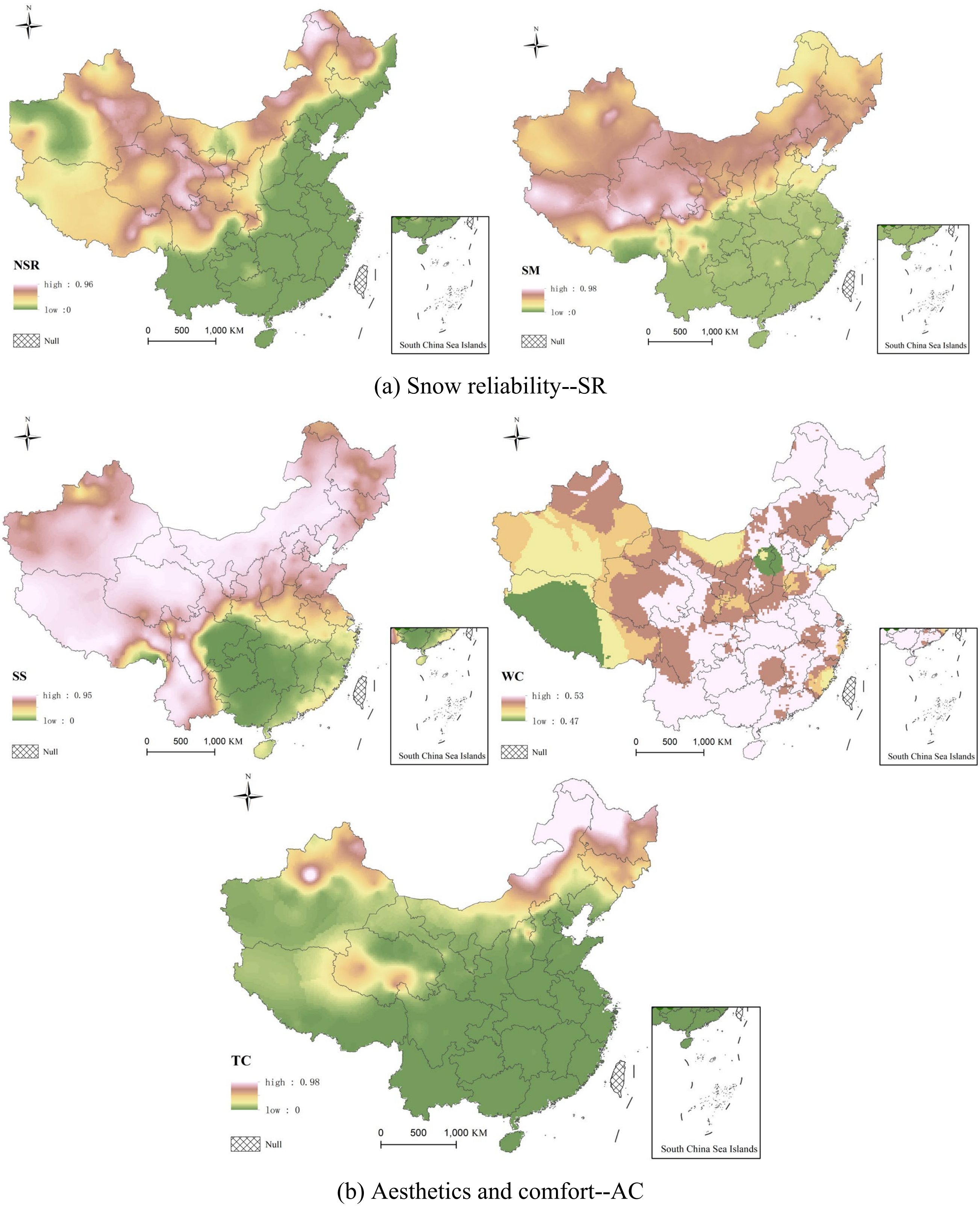


Fig.3 The fuzzification space display of SCI sub-indexes (1991–2020)

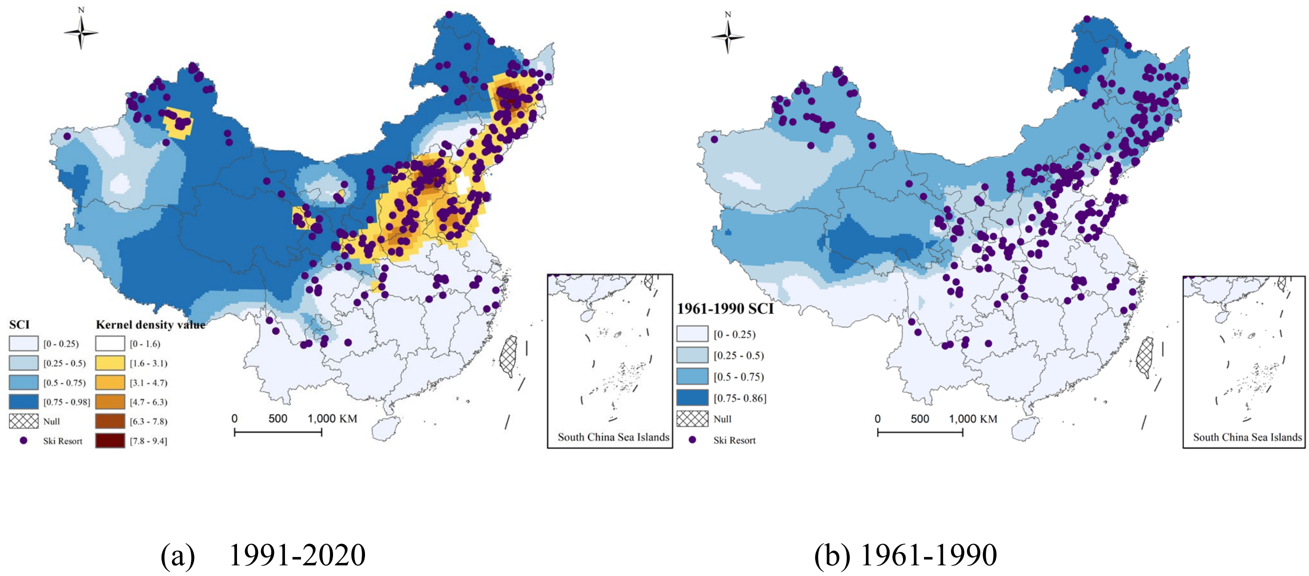


Fig.4 Spatial pattern of the SCI and ski resorts in China

snow conditions substantially affect the overall performance or quality of SCI. In addition, the coefficients for the other factors were: TC at 0.20, WC at 0.19, SM at 0.18, and SS at 0.12. While these factors are important, they have comparatively lesser impacts on SCI than NSR. These coefficients do accurately quantify the relative contributions of each factor and thus enhance our understanding of their individual and combined effects. Therefore, the paramount importance of NSR when evaluating the skiing climate is emphasized, clearly highlighting its crucial role in assessing the suitability of an area for skiing as shown by the SCI. The robustness of the observed correlations and the consistent spatial patterns seen between the SCI and NSR indicators further enhance the credibility of our findings and their reliability.

To understand the dynamic characteristics of climate resources in ski resorts better, Fig. 4b illustrates the spatial distribution of SCI in China from 1961 to 1990. The results reveal that around 34% of the country's land area had favorable skiing conditions, falling into the "Excellent" and "Good" categories based on a weighted analysis by area. Notably, only 5.4% of the total land area was classified as "Excellent" during this period. That area was primarily concentrated in Northeastern China and certain areas of Qinghai Province, thereby offering optimal opportunities for ski tourism and its related activities.

When comparing the spatial distribution of SCI between 1991–2020 (Fig. 4a) and 1961–1990 (Fig. 4b), a notable distinction emerges, with the earlier period that showed limited land area in the "Excellent" category compared to the extensive coverage observed during the latter period. The significant difference in the extent of this category highlights potential changes and variations in skiing climate resources over time, further emphasizing the importance of considering long-term trends and patterns whenever assessing ski destinations' suitability and reliability. This insight is crucial for ongoing informed decision-making for ski tourism and climate resilience.

The observed increase in the SCI in certain regions of China also challenges the expectation that climate change would lead to worsening skiing conditions. The SCI model includes several components, such as temperature, precipitation, snow reliability, wind speed, and other weather-related factors. The rise in SCI scores over the past 30 years can be attributed to improvements in these specific components, as supported by both relevant literature and empirical evidence.

In some regions of China, climate change has led to favorable changes in skiing conditions. For instance, higher air temperatures in the cold regions of North, Northwest, and Southwest China have reduced the extreme cold, creating a more pleasant environment for skiers and opening new opportunities for the ski industry (Deng et al. 2021). This trend is linked to unique atmospheric conditions that either increase snowfall or maintain the temperatures conducive to skiing, mirroring other global trends where localized climate variations can and have enhanced specific activities (Ma et al. 2021).

Precipitation in Northwest China has significantly increased ($P < 0.01$) at a rate of 0.61 mm/year, compared to the national average decrease of -0.16 mm/year during the same period, particularly in regions like Gansu and Ningxia (Li et al. 2016b). This increase in precipitation improves natural snow reliability, a key factor in the SCI. Enhanced precipitation also directly affects the quantity and quality of snow cover, thereby also benefiting skiing conditions.

Furthermore, other studies show that near-surface wind speeds in China decreased by approximately -0.109 m/s per decade from 1958 to 2015, a trend associated with the weakening of summer and winter monsoons (Zhang et al. 2019). Reduced wind speeds can improve ski resort operations and safety and positively impact the SCI. Lower wind speeds reduce snow drifting and enhance the stability and quality of ski slopes.

Advancements in snowmaking technology also play a critical role. Modern snowmaking equipment enables ski resorts to produce artificial snow even in less than ideal temperatures, thereby extending the skiing season and enhancing slope conditions (Dannevig et al. 2021). This combination of localized climatic benefits, improved snow reliability, favorable wind conditions, and technological advancements provides a comprehensive explanation for the observed increase in SCI in select regions of China, contrary to the deterioration that was expected.

Evolution characteristics of SCI in China

In the context of climate change, the "two-stage difference" visually illustrates spatial changes in SCI more intuitively, as shown in Fig. 5. Warm hues (e.g., red) indicate an increase in SCI, while darker shades signify a more pronounced increase during 1991–2020 compared to 1961–1990. Conversely, cool colors (such as green) denote a reduction in SCI, and white regions depict negligible alterations. Drawing clear insights from this graph, several observations can then be made as noted below.

The SCI has increased in 41.8% of China's land area, with significant rises concentrated in regions like the Shanxi-Gansu-Ningxia regions and certain parts of Tibet and Sichuan. Approximately 34.7% of these areas fall into the "Excellent" category of SCI. However, around 12.5% of the country's land area has experienced a decline in SCI, primarily near the Changbai Mountain region due to decreasing annual precipitation observed in Southern Northeast China. The research by Wang et al. (2020) supports this idea by showing a decreasing trend in the annual snow-covered period at Changbai Mountain Ski Resort from 1981 to 2018 along with low levels of accumulated precipitation. Additionally, approximately 45.7% of the land area has shown relatively little change and is mainly located in Southern China. These findings provide valuable insights into spatial distribution and the changes in skiing climate resources within China.

After weighting the SCI values of each province based on the Thiessen polygon area, slight adjustments were observed in the rankings between the research baseline and historical reference period. The top three provinces remain relatively consistent, with Xinjiang ascending from second place to first. Despite a slight drop in ranking, Heilongjiang still maintains its high position. Qinghai closely follows suit by rising from fourth to third place. These leading provinces have distinct advantages in terms of skiing resources. Notably, Jilin Province experienced a significant decline in ranking, dropping from fifth to eleventh place. Conversely, the Shanxi-Gansu-Ningxia regions emerged prominently and hold a noteworthy position among the top provinces. For regions undergoing substantial growth, it is essential to

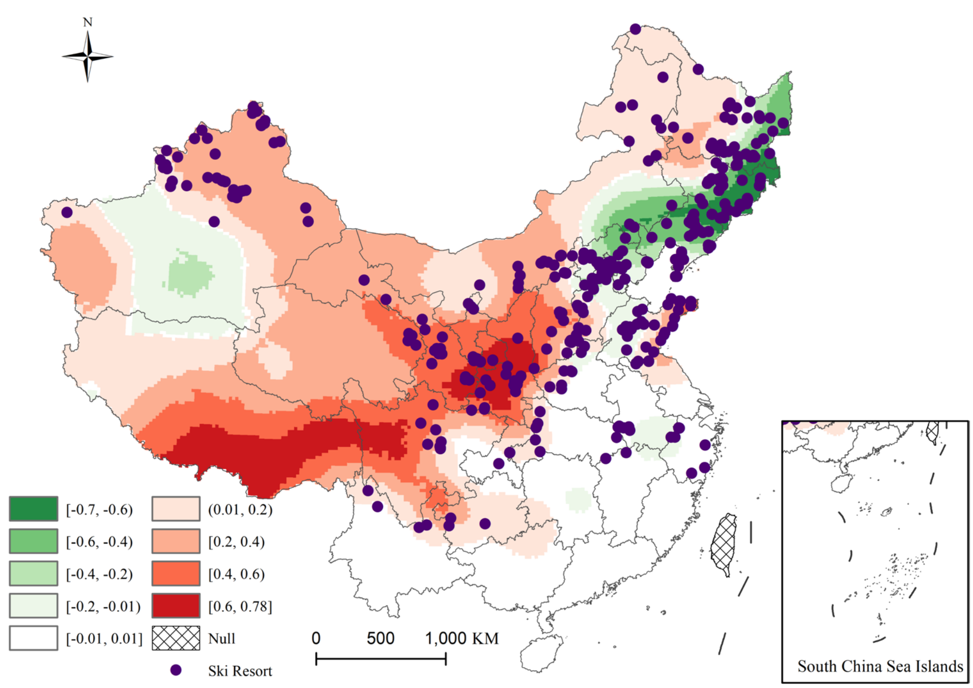


Fig.5 Spatial change pattern of the ski climate resources in China between 1961–1990 and 1991–2020

recalibrate the local ski industry development strategies and maximize ski climate resources' potential and do so fully. In areas that are experiencing notable declines, swift actions are necessary to mitigate and address any adverse impacts.

Implications of SCI for ski industry development compared to ski resorts' vitality

Ski resorts' vitality offers a comprehensive depiction of their development. By comparing it to SCI, we can gain a deeper understanding of the indicative role of the SCI in guiding the growth of the skiing industry overall. Figure 6 presents the scores for spatial vitality indicators for 389 outdoor ski resorts across China and showcases the standardized values assigned to Chinese ski resorts. These values correlate with the distribution of SCI (1991–2020) across China's geography. Using the natural breakpoint method, five levels classify ski resort attractiveness, namely, ski activity level, skiers' perception, and five level classify spatial vitality as high, relatively high, medium, relatively low, and low.

These findings further reveal that:

1) The ski resorts in China generally have a dispersed attractiveness and only weak alignment with ski climate resources (Fig. 6a). Only 51 resorts, accounting for 12.3% of the total, are classified as "high" or "relatively high" in terms of attractiveness. In contrast, only 22 resorts are categorized as having "Excellent" or "Good" SCI levels. On the other hand, 145 resorts are classified as "low" or "relatively low" in attractiveness, with an additional 88 labeled as having a "Poor" SCI level. Beijing and its surrounding areas, Northeast China, and the Altay region of Xinjiang stand out as prominent ski destinations with comprehensive facilities and amenities. These areas offer good accessibility and long snow seasons, making them highly attractive

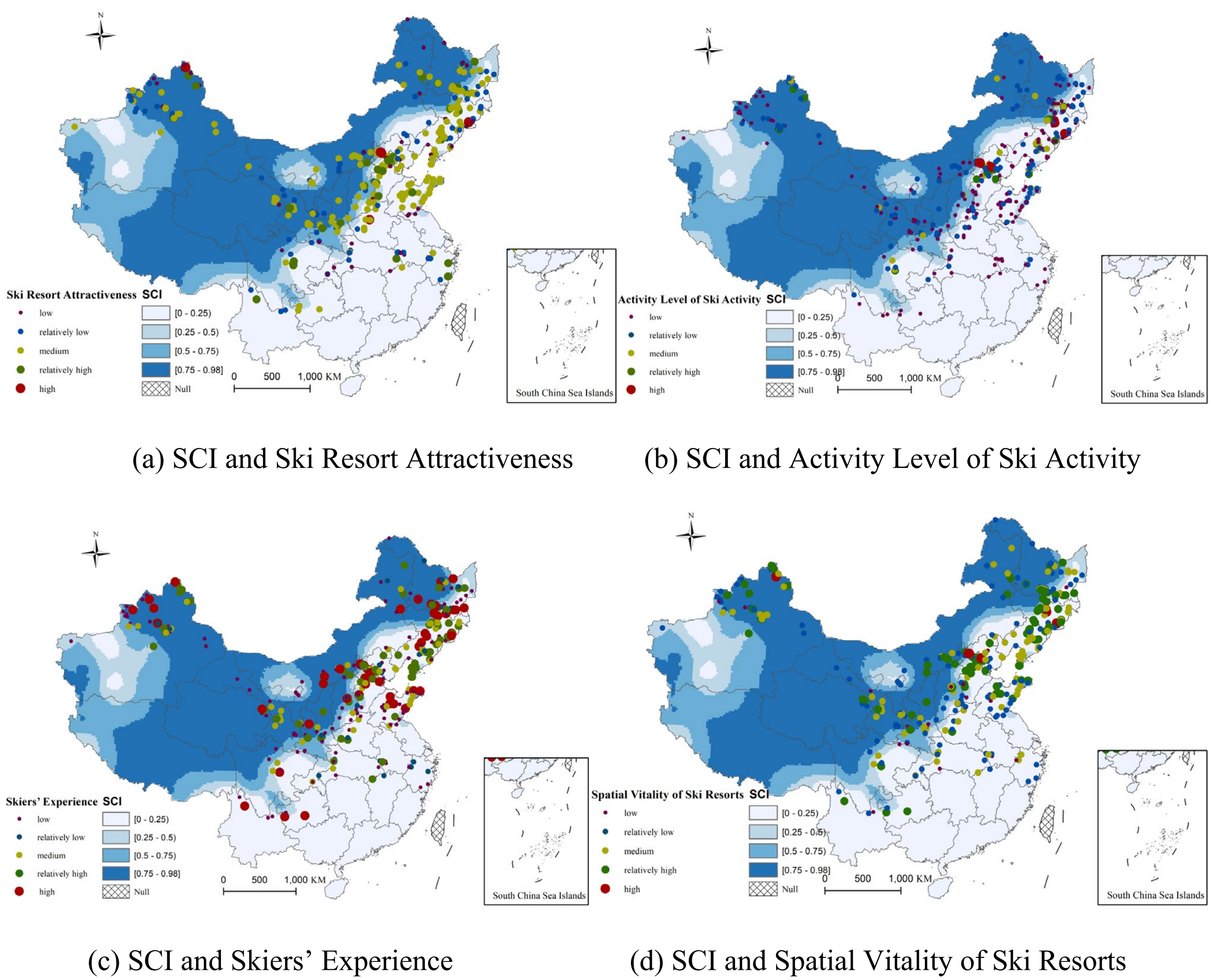


Fig. 6 SCI (1991–2020) and ski resorts' vitality in China

to visitors. Despite the natural constraints posed by climate, Southern China has seen the emergence of indoor facilities that are also highly appealing to skiers due to advancements in snowmaking and storage technologies that are driven by market demand.

2) The overall correlation between SCI and ski activity level is relatively low. However, the northern region shows a significantly higher correlation compared to the southern region (Fig. 6b). Ski activity is mainly concentrated in the Beijing-Tianjin-Hebei region and three provinces in Northeast China. The Zhangjiakou area in Hebei Province stands out for its excellence, earning an "excellent" rating based on SCI criteria. It consistently attracts a large number of skiing enthusiasts, making it their preferred destination. Despite the emergence of indoor ski resorts in southern provinces like Guangdong and Yunnan, their availability of ski climate resources remains limited. Furthermore, constraints related to venues and the tourism market have also contributed to comparatively lower levels of ski activity there.

3) The correlation between skiers' experiences and SCI showed a weak connection (Fig. 6c). Out of the 174 resorts with "good" or "excellent" SCI scores, only 58 were associated with skiers' reporting "high" or "very high" perceived activity levels, indicating a lack of alignment between these factors. Meanwhile, skiers' experiences demonstrated a multi-core clustering pattern as shown in Fig. 6c. Ski resorts with high and relatively high skiing experiences tend to cluster in Beijing-Zhangjiakou, Northeast China, and Altay regions due to superior natural resources and effective supply–demand coordination that contribute to enhanced skiing experiences. Conversely, ski resorts offering moderate and low skiing experiences are primarily located in regions like Shandong and Shaanxi. Despite Northeast China's advantageous natural resources and early involvement in the ski industry, many ski resorts in this area still provide only moderate or low skiing experiences due to the intense market competition and inadequate infrastructure development.

4) Figure 6d indicates a limited alignment between available natural resources for skiing and the vitality of ski resorts. The spatial vitality of ski resorts exhibits regional disparities, primarily with higher concentration in the north and lower concentration in the south. High spatial vitality ski resorts are mainly clustered around Beijing, Northeast China, and the Altay region of Xinjiang due to favorable natural conditions, such as terrain and climate, abundant natural snow resources, and early development of integrated facilities that have attracted a stable customer base. The spatial distribution of ski resorts also displays significant heterogeneity, with only 28.6% demonstrating high or relatively high activity levels. Moreover, over half of these ski resorts are located in areas characterized by having a "poor" SCI rating.

Conclusion and discussion

Conclusion

In conclusion, this study has tailored the SCI so it better suits China's specific conditions. By analyzing daily meteorological data from 733 representative stations covering the period from 1991 to 2020 and comparing it with the historical data from 1961 to 1990, this study examined the alignment between China's ski climate resources and the spatial distribution of ski resorts. The findings were as follows:

1)Natural snow significantly influences the distribution of SCI, while other factors, such as sunshine duration, wind speed, and thermal comfort have a relatively minor impact.

2)Approximately 54% of China's favorable skiing regions are concentrated west of the Hu Huanyong Line, including the northwest, northeast, and parts of North China. However, there is also an evident mismatch between ski climate resources and current ski resort locations.

3)Climate change has brought significant transformations to China's skiing climate resources. Regions like Shanxi-Gansu-Ningxia and Southwestern Tibet and Sichuan have witnessed increases in their skiing climate resources while the southern parts of three northeastern provinces have experienced decreases.

The correlation between SCI and spatial vitality is relatively weak overall, as more than half of the ski resorts are located in areas with a 'poor' SCI rating. However, Xinjiang Province does demonstrate relatively high spatial vitality due to the abundance of ice and snow tourism resources there.

Discussion

Climatology is increasingly important in better understanding tourism and recreation, especially in the era of climate change. The assessment of skiing meteorological indices is crucial for the sustainable development of ski tourism, particularly in emerging ski destinations like China (Steiger et al. 2019). However, there is currently no systematic evaluation of ski climate indicators for the Chinese ski resorts; instead, climate resources are considered as part of that assessment system (Deng et al. 2021; Yu et al. 2009). From the perspective of natural conditions, the spatial distribution of natural suitability for ski areas is mainly concentrated in higher latitudes (Northeast, North, and Northwest China) and elevated terrains (e.g., the edge of the Tibetan Plateau) (Deng et al. 2021). This finding aligns closely with our research conclusions, although subtle differences do exist. For example, the North region identified as being naturally resource-rich in the mentioned study does not fall within our identified favorable skiing climate region. Conversely, the Southwest region, not mentioned in their paper, does fall within our favorable skiing climate region. The primary reason for this distinction is that the assessment of natural resources considers not only climatic conditions, but also non-climatic factors like terrain slope, vegetation coverage, and distance to water resources. Still, through an assessment of the current climate conditions at five prominent Chinese ski resorts (the Yabuli Ski Resort in Heilongjiang Province, Beidahu Ski Resort in Jilin Province, Wanlong Ski Resort in Hebei Province, Nanshan Ski Resort in Beijing, and Silk Road International Ski Resort in Xinjiang Province), both Beidahu and Yabuli Ski Resorts show a trajectory towards excellence (Yu et al. 2009). This status concurs with our research findings, as both ski resorts are positioned within favorable skiing climate conditions according to our climate assessment results.

According to our findings, natural snowfall is the main factor influencing the distribution of skiing climate resources. Well-developed ski resorts are primarily located in areas that have abundant skiing climate resources. However, certain regions like Inner Mongolia, Tibet, and Shanxi-Gansu-Ningxia have ample skiing climate resources, but limited ski market potential and a scarcity of ski resorts. The full realization of economic benefits from ice and snow tourism resources has indeed been hindered by topography, transportation limitations, inadequate supporting facilities, and market perception. Additionally, the impact of climate change on ski resorts across China has reshaped the competitiveness of skiing destinations (Fang et al. 2021). Regions, such as Shanxi-Gansu-Ningxia and Southwestern Tibet and Sichuan, have seen an increase in their skiing climate resources. These areas should fully capitalize on their favorable ski climates to unlock the potential of climate attractiveness and transforming their untapped ski resources into valuable assets for the tourism industry.

The main contributions of this study are several. This study refines the SCI for China by tailoring the model to local conditions and broadening its application. Additionally, it performs a spatial and temporal analysis of Chinese ski climate resources in terms of the actual development of the ski industry, including such aspects as ski resort distribution and spatial vitality. This analysis clarifies the relationship between ski climate resources and industry development with the goal of optimizing the utilization of ski resources.

Still we also recognize certain limitations in our study. While the SCI integrates aspects of snow reliability, aesthetics, and comfort by considering such factors as sun exposure, wind conditions, and thermal comfort, the scope of the metrics used to assess skiing climate indices should be further broadened. Specifically, factors like air quality and winter hazards warrant inclusion. For instance, air quality is particularly sensitive to climate change due to its dependence on weather patterns (Jacob & Winner 2009). Additionally, air quality impacts human physical activity, as evidenced by findings that a one-unit increase in PM2.5 concentration among UK residents correlates with a 10% decrease in outdoor activities and a 0.084-unit reduction in overall physical activity levels (Elliott et al. 2019). This circumstance highlights the complex interaction between climate conditions and human behavior further emphasizing the need for a more comprehensive approach to managing the challenges faced by the ski tourism industry under climate change. Future research should consider incorporating critical factors, such as air quality and winter hazards, into the SCI, and offer technical recommendations for its practical application. Moreover, utilizing more advanced interpolation methods could also improve the accuracy and precision of spatial interpolation techniques for compiling meteorological data.

References

Abegg, B. (1996). Klimaänderung und Tourismus: Klimafolgenforschung am Beispiel des Wintertourismus in den Schweizer Alpen. vdf Hochschulverlag AG

Andersen P, Buller D, Scott M, Walkosz B, Voeks J, Cutter G, Dignan M (2004) Prevalence and diffusion of helmet use at ski areas in Western North America in 2001–02. Inj Prev 10(6):358–362. https://doi.org/10.1136/ip.2004.005967

Berghammer A, Schmude J (2014) The Christmas—Easter shift: Simulating alpine ski resorts' future development under climate change conditions using the parameter 'optimal ski day.' Tour Econ 20(2):323–336. https://doi.org/10.5367/te.2013.0272

Cai W, Di H, Liu X (2019) Estimation of the spatial suitability of winter tourism destinations based on copula functions. Environ Res Public Health 16(2):186. https://doi.org/10.3390/ijerph16020186

China Meteorological Administration (2017) Meteorological index of skiing. (QX/T 386–2017). https://max.book118.com/html/2023/0808/8077000054005117.shtm. Accessed 6 Jan 2024

Damma A, Köberl J, Prettenthaler F (2014) Does artificial snow production pay under future climate conditions? - A case study for a vulnerable ski area in Austria. Tour Manage 43:8–21. https://doi.org/10.1016/j.tourman.2014.01.009

Dannevig H, Gildestad IM, Steiger R, Scott D (2021) Adaptive capacity of ski resorts in Western Norway to projected changes in snow conditions. Curr Issue Tour 24(22):3206–3221. https://doi.org/10.1080/13683500.2020.1865286

Demiroglu OC, Kučerová J, Ozcelebi O (2015) Snow reliability and climate elasticity: case of a Slovak ski resort. Tourism Review 70(1):1–12. https://doi.org/10.1108/TR-01-2014-0003

Demiroglu OC, Turp MT, Ozturk T, Kurnaz ML (2016) Impact of climate change on natural snow reliability, snowmaking capacities, and wind conditions of ski resorts in Northeast Turkey: a dynamical downscaling approach. Atmosphere 7(4):52. https://doi.org/10.3390/atmos7040052

Demiroglu OC, Turp MT, Kurnaz ML, Abegg B (2021) The Ski Climate Index (SCI): fuzzification and a regional climate modeling application for Turkey. Int J Biometeorol 65:763–777. https://doi.org/10.1007/s00484-020-01991-0

Deng J, Che T, Jiang T, Dai LY (2021) Suitability projection for Chinese ski areas under future natural and socioeconomic scenarios. Adv Clim Chang Res 12(2):224–239. https://doi.org/10.1016/j.accre.2021.03.007

Elliott LR, White MP, Sarran C, Grellier J, Garrett JK, Scoccimarro E, Smalley AJ, Fleming LE (2019) The effects of meteorological conditions and daylight on nature-based recreational physical activity in England. Urban For Urban Green42:39–50. https://doi.org/10.1016/j.ufug.2019.05.005

Fang Y, Scott D, Steiger R (2021) The impact of climate change on ski resorts in China. J Int Soc Biometeorol 65(5):677–689. https://doi.org/10.1007/s00484-019-01822-x

Fang Y, Xu HB, Jiang YY (2023) Evaluation of spatial vitality of China's ski resorts based on multi-source data. Geogr Res 42(02):389–406. https://doi.org/10.11821/dlyj020220961

Gajić-Čapka M (2011) Snow climate baseline conditions and trends in Croatia relevant to winter tourism. Theoret Appl Climatol 105:181–191. https://doi.org/10.1007/s00704-010-0385-5

IPCC (2014) Climate Change 2013 – the physical science basis: working group I contribution to the fifth assessment report of the intergovernmental panel on climate change. Cambridge Univ Press. https://doi.org/10.1017/CBO9781107415324

Jacob DJ, Winner DA (2009) Effect of climate change on air quality. Atmos Environ 43(1):51–63. https://doi.org/10.1016/j.atmosenv.2008.09.051

Jiang JX, Li SM (2021) High-quality development of ski tourism economy in Heilongjiang Province: challenges and breakthroughs. Academic Exchange 09:72–82. https://doi.org/10.3969/j.issn.1000-8284.2021.09.007

Khan F, Pilz J, Ali S (2021) Evaluation of CMIP5 models and ensemble climate projections using a Bayesian approach: a case study of the Upper Indus Basin, Pakistan. Environ Ecol Stat 28:383–404. https://doi.org/10.1007/s10651-021-00490-8

Li Y (1985) Observing Administration. Shuxin Publishing House

Li Y, Zhao M, Guo P, Zheng J, Li Z, Li F, Shi Y, Dong S (2016a) Comprehensive evaluation of ski resort development conditions in northern China. Chinese Geogr Sci 26:401–409. https://doi.org/10.1007/s11769-016-0808-z

Li B, Chen Y, Chen Z, Xiong H, Lian L (2016b) Why does precipitation in northwest China show a significant increasing trend from 1960 to 2010? Atmos Res 167:275–284. https://doi.org/10.1016/j.atmosres.2015.08.017

Liu LW, Duan YH, Li LL, Xu LS, Zhang Y, Nie WY (2022) Spatial distribution characteristics and suitability evaluation of rural settlements in Shanxi Province. Chinese Agric Resour Reg Plan 43(01):100–109

Lynch K (1984) Good City Form. Cambridge: The MIT Press, 514

Ma S, Craig C, Scott D, Feng S (2021) Global climate resources for camping and nature-based tourism. Tourism and Hospitality 2(4):365–379. https://doi.org/10.3390/tourhosp2040024

Matzarakis A, Hämmerle M, Koch E, Rudel E (2012) The climate tourism potential of Alpine destinations using the example of Sonnblick, Rauris and Salzburg. Theoret Appl Climatol 110:645–658. https://doi.org/10.1007/s00704-012-0686-y

McClung D, Schaerer PA (2006) The Avalanche Handbook, (4th ed.) (pp. 368). The Mountaineers Books.

Olya H, Alipour H (2015) Modeling tourism climate indices through fuzzy logic. Climate Res 66(1):49–63. https://doi.org/10.3354/cr01327

Scott D, Steiger R (2024) How climate change is damaging the US ski industry. Current Issues in Tourism 1–17. https://doi.org/10.1080/13683500.2024.2314700

Scott D, Rutty M, Amelung B, Tang M (2016) An inter-comparison of the Holiday Climate Index (HCI) and the Tourism Climate Index (TCI) in Europe. Atmosphere 7(6):80–96. https://doi.org/10.3390/atmos7060080

Scott D, Steiger R, Knowles N, Fang Y (2020) Regional ski tourism risk to climate change: An inter-comparison of Eastern Canada and US Northeast markets. J Sustain Tour 28(4):568–586. https://doi.org/10.1080/09669582.2019.1684932

Sorman AU, Beser O (2013) Determination of snow water equivalent over the eastern part of Turkey using passive microwave data. Hydrol Process 27(14):1945–1958. https://doi.org/10.1002/hyp.9267

Steiger R, Scott D, Abegg B, Pons M, Aall C (2019) A critical review of climate change risk for ski tourism. Curr Issue Tour 22(11):1343–1379. https://doi.org/10.1080/13683500.2017.1410110

Stull R (2011) Wet-bulb temperature from relative humidity and air temperature. J Appl Meteorol Climatol 50(11):2267–2269. https://doi.org/10.1175/JAMC-D-11-0143.1

Wang CX, Man JH (2022) Power elements, theoretical framework, and driving mode of high-quality development of ski industry from the perspective of configuration: A fuzzy set qualitative comparative analysis. J Shanghai Univ Sport 46(08):65–76. https://doi.org/10.16099/j.sus.2021.06.17.0003

Wang XR, Zhao R, Yu H, Wang LS, Wang Q (2020) Theoretical snow period and assessment of skiing climate suitability: with Changbai Mountain Ski Resort as an example. Chin J Appl Ecol 31(4):1259–1266. https://doi.org/10.13287/j.1001-9332.202004.013

Wu B (2023) 2022–2023 China Ski Industry White Book. https://www.xdyanbao.com/doc/p2q9bhylph?bd_vid=10500499091629761789. Accessed 8 Jan 2024

Yang Y, Luo BQ, Jin YY (2019) Challenges and strategies for promoting winter sports consumption among Chinese residents. J Sports Cult 07:19–24. https://doi.org/10.3969/j.issn.1671-1572.2019.07.005

Yu DD, Li S (2019) Scale of human thermal sensation using seasonal anchor method: A Chinese case study. J Meteorol Res 34(8):1633–1653. https://doi.org/10.31497/zrzyxb.20190806

Yu G, Schwartz Z, Walsh JE (2009) A weather-resolving index for assessing the impact of climate change on tourism related climate resources. Clim Change 95(3–4):551–573. https://doi.org/10.1007/s10584-009-9565-7

Zha J, Wu J, Zhao D, Fan WX (2020) Future projections of the near-surface wind speed over eastern China based on CMIP5 datasets. Clim Dyn 54(3):2361–2385. https://doi.org/10.1007/s00382-020-05118-4

Zhang R, Zhang S, Luo J, Han Y, Zhang J (2019) Analysis of near-surface wind speed change in China during 1958–2015. Theoret Appl Climatol 137:2785–2801. https://doi.org/10.1007/s00704-019-02769-0

Zhong Z, Li X, Xu X, Liu XP, He ZJ (2018) Analysis of spatial and temporal variations in snow cover in China from 1992 to 2010. Chin Sci Bull 63(25):2641–2654. https://doi.org/10.1360/N972018-00199