

From Index Evaluation to Intelligent Sensing: Paradigm Shift in Research on Tourism Climate Comfort and Prospects under Technological Enabling

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Abstract Research on tourism climate comfort is undergoing a paradigm shift from classic static assessment to intelligent dynamic sensing. Early models (such as temperature-humidity index and tourism climate index) established based on data of meteorological stations laid the foundation for the discipline but were unable to meet the dynamic demands of climate change, spatial heterogeneity, and individual experience. Global climate change is reshaping the landscape of tourism comfort and driving the assessment to shift towards future risk prediction. Downscaling technology becomes the key to connecting global scenarios and local assessments. Remote sensing and Internet of Things technologies have constructed a "sky – ground" collaborative sensing network, achieving a revolution in data acquisition. Artificial intelligence and big data analysis serve as the intelligent core to drive research from description to prediction. The new paradigm has significant potential in improving assessment accuracy and timeliness, but also faces challenges such as data integration, model interpretability, interdisciplinary integration, and ethical privacy. In the future, it is needed to develop interpretable AI, construct climate digital twins, and promote full-chain coupling research. This transformation is not merely an upgrade of methods, but a fundamental shift in the study of philosophy from an "environment-centered" perspective to an "experience-centered" one, providing key scientific support for sustainable tourism.

Key words Tourism climate comfort; Paradigm shift; Climate change; Remote sensing; Internet of Things; Artificial intelligence

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Climate is the core natural element that constitutes the resource endowment and carrying capacity of a tourist destination. Through the combined effects of factors such as temperature, humidity, wind, and sunlight, it directly shapes tourists' physiological sensations and psychological experiences, and is the foundation for influencing the suitability of tourism activities, the attractiveness of the destination, and the seasonality of the industry^[1-2]. How to scientifically assess the comfort level of the climate environment has long been a key topic in the interdisciplinary research of tourism geography and climatology.

From the development of this field over the past several decades, it is seen that its research methodology is undergoing a profound evolution. Early studies followed the classical index assessment paradigm: based on the observation data of meteorological stations, as well as the theory of human body heat balance, models such as the temperature-humidity index (THI), wind-chill index (WCI), and tourism climate index (TCI) have been constructed, and continuous climate conditions have been simplified into static homogeneous grade rating^[3-4]. This paradigm has made significant contributions in macro zoning and seasonal analysis, but its "environment-centered" logic becomes increasingly limited when dealing with micro spatial heterogeneity, temporal dynamics, individual perception differences, and future climate risks^[5].

Currently, the convergence of three technological revolutions, namely high-resolution remote sensing, the Internet of Things (IoT), and artificial intelligence (AI), is driving the fundamental transformation of the research paradigm towards an intelligent dynamic perception paradigm^[6-8]. The integration of technologies promotes the research focus to shift from "climate conditions themselves" to "the experience of people in the climate", aiming to achieve real-time monitoring at the entire scale, personalized precise assessment, and risk scenario simulation. Its core is the dynamic service logic centered on "tourist experience".

1 Contributions and limitations of the classical paradigm

The classical assessment paradigm is rooted in biometeorology, and its core is the establishment of a quantitative model between meteorological observation values and human thermal sensation. This paradigm has developed a hierarchical index system; the basic layer consists of general bioclimatic indices such as THI for assessing the effect of humidity and heat and WCI for quantifying wind chill; the application layer is represented by TCI proposed by Mieczkowski, and multiple factors such as thermal comfort, sunlight, precipitation, and wind speed are integrated to achieve a conceptual leap from "physiological comfort" to "tourism suitability", becoming a benchmark tool for macro climate potential assessment^[3,9]. Subsequent developed holiday climate index (HCI) and comprehensive comfort indices (CCI) constructed in various regions reflect its efforts at optimization and lo-

calization. The classical paradigm successfully simplifies complex processes into calculable and comparable indicators, laying a methodological foundation for the discipline. However, its "staticity" based on long-term averages, "homogeneity" that ignores spatial details, and "posteriority" mainly used for historical evaluation result in insufficient explanatory and predictive power when dealing with dynamic impacts of climate change, microclimate differences in scenic areas, and individualized needs of tourists, constituting the internal driving force for paradigm transformation.

2 Global climate change: driving the innovation of assessment scales and methods

Global climate change is the most urgent external pressure driving a paradigm shift. It reshapes the global geographical landscape of tourism comfort unevenly through changes in temperature, precipitation patterns, and the frequency of extreme events, such as exacerbating the risk of heat discomfort in summer in low latitudes and threatening the survival of alpine skiing industry^[10]. This forces assessment work to shift from a static description of historical averages to the process simulation and prediction of future dynamic risks. The key to achieving this shift lies in downscaling techniques. Global climate models (GCMs) have coarse resolutions and cannot be directly used for the assessment of the scale of a scenic area. Downscaling techniques (especially statistical downscaling combined with machine learning algorithms) have become the bridge connecting global scenarios and local assessments^[11]. Cases such as assessing the future "seasonal flattening" trend of Mediterranean coastlines or simulating the feasibility of ski resorts demonstrate that these complex dynamic simulation problems have far exceeded the capability of classic static indices, strongly promoting the transition to an intelligent, process-oriented new paradigm.

3 Data foundation of the new paradigm: establishment of a three-dimensional perception network based on remote sensing and the Internet of Things

The realization of the intelligent perception paradigm relies on the three-dimensional capability of data acquisition with "sky-ground" collaboration. Satellite remote sensing has achieved grid-based and periodic observations of environmental parameters such as land surface temperature (LST) and vegetation index, supporting the spatially refined assessment of thermal comfort in regions^[12]. The Internet of Things technology has realized real-time, high-density, and networked monitoring of microclimate parameters in a scenic area, and transmitted data through low-power wide-area networks (such as LoRaWAN), thereby providing dynamic comfort services and safety warnings for tourists after the treatment by the cloud platform^[7, 13]. Remote sensing and IoT jointly constitute the "sensory system" of the new paradigm, restoring the climate environment from an abstract score to a physical

reality that can be observed and analyzed in real time.

4 Intelligent core of the new paradigm: deep integration of artificial intelligence and big data

Massive and multi-source data require a powerful analysis engine. Artificial intelligence and big data technologies are playing the role of the "intelligent brain" in the new paradigm. Machine learning (such as random forests, and XGBoost) and deep learning (*e. g.* CNN, and LSTM) models can explore the complex nonlinear relationships among multiple variables such as climate, passenger flow, and economy, significantly improve the accuracy of tourism demand prediction, and enable intelligent interpretation of remote sensing images^[8, 14]. Moreover, through sentiment analysis technology, big data from social media provides a unique window for quantifying tourists' "perceived comfort", and as a predictive variable, it can be incorporated into the model, thereby bridging the gap between the physical environment and psychological experience^[15]. AI technology has driven the research to leap from descriptive analysis to predictive and prescriptive analysis.

5 Challenges and prospects

5.1 Current core challenges The maturity and wide application of the new paradigm still face multiple challenges. At the technical level, the integration and quality control of multi-source heterogeneous data are challenging; advanced AI models are often "black boxes", with poor explainability and unstable generalization ability across regions. From the disciplinary perspective, current research is mostly a shallow overlay of disciplines, and climate science, tourism science, computer science, psychology, *etc.* have not yet achieved the deep integration of theoretical frameworks. From the ethical and practical perspective, large-scale collection of tourist trajectories, physiological and speech data raises privacy and ethical issues; research needs to pay more attention to the impact of climate change on vulnerable destinations to reflect climate justice.

5.2 Prospects for future research directions Future research should seek breakthroughs in the following directions. Firstly, next-generation models that integrate domain knowledge and explainable AI technologies should be developed to enhance the transparency and robustness of models. Secondly, a "tourism climate digital twin" that integrates ultra-high-resolution monitoring and simulation should be built as a "policy sandbox" for planning and management. Thirdly, it is needed to promote the full-chain coupling simulation of "climate – perception – behavior – economy" and systematically evaluate the comprehensive benefits of different adaptation strategies. Fourthly, it is necessary to deepen research on tourism resilience under extreme climate events, formulate data ethics norms, and advocate for fair transition.

6 Conclusions

The research on tourism climate comfort is undergoing a profound paradigm shift driven by the urgent need for climate change

adaptation and disruptive technologies, namely moving from the classical index assessment paradigm to the intelligent dynamic perception paradigm. The classical paradigm completed its initial theorization and macro-quantification, but its static and homogeneous characteristics have become inadequate to address the dynamic and heterogeneous challenges of forward-looking perspectives. Global climate change has exposed the scale limitations of the classical paradigm, while the three-dimensional perception network constructed by remote sensing and Internet of Things technologies solves the problem of high-dimensional data acquisition. Artificial intelligence and big data technologies provide a powerful intelligent analysis engine, and jointly push the research to new heights of dynamic perception, intelligent prediction, and personalized services.

This transformation is not only a methodological upgrade but also a fundamental shift in the research philosophy from "centering on the environment" to "centering on the tourist experience". Despite challenges such as data integration, model interpretability, interdisciplinary integration, and ethical fairness, the intelligent dynamic perception paradigm will become more mature through the development of interpretable AI, the construction of digital twins, and the promotion of full-chain coupling research, providing indispensable wisdom support for the global tourism industry to enhance resilience, optimize experiences, and achieve sustainable development in the era of climate change.

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