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Apparent Temperature in Northwest China: A Review of the Calculation Methods and Analysis

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Abstract

Northwest China, dominated by a temperate continental climate, constitutes one of the largest arid and semi-arid regions in East Asia. Characterized by an intricate mosaic of mountains, river valleys, and basins, this region possesses unique thermodynamic features regarding air temperature, humidity, surface wind speed, and solar radiation. Conventional universal apparent temperature models fail to adapt to such distinctive topographic and climatic properties, thereby limiting their applicability in operational meteorological services. This study systematically reviews domestic and international theories and computational methods for apparent temperature, and comparatively analyzes the performance of various algorithms in arid and mountainous environments based on previous localized studies conducted in typical Northwest Chinese regions, including Urumqi and Golmud. The results indicate that existing universal formulas inadequately account for regional climatic peculiarities of Northwest China, such as dry-hot winds, intense high-altitude solar radiation, and substantial diurnal temperature variations. The widespread deficiency of localized parameter calibration leads to prominent errors in apparent temperature forecasting at high-altitude stations. Future research should optimize the segmented correction coefficients of wind speed and solar radiation based on multi-source observational datasets in Northwest China, refine apparent temperature simulation accuracy through machine learning-based error calibration, and develop region-specific apparent temperature computational frameworks tailored to arid plateau environments. These improvements will provide robust technical support for regional health and tourism meteorological services.

Keywords

Northwest China, Apparent Temperature, Calculation Method,
Arid and Semi-Arid Region, Systematic Review

1. Introduction

Apparent temperature is a biometeorological indicator integrating air temperature, relative humidity, wind speed and solar radiation to quantify human thermal and cold stress. The respective impacts of wind speed, solar radiation and relative humidity on human thermal perception in Northwest China are schematically shown in **Figure 1**. Compared with single dry-bulb temperature, it more objectively reflects actual human thermal perception, and forms the computational basis for meteorological service products, including human comfort assessment (Zhu & Ren, 2011), heatstroke/cold wave early warning, and clothing thickness index (Wang et al., 2022). In outdoor environments, solar radiation is a dominant driver of thermal sensation and a major source of error for evaluations based solely on dry-bulb temperature (Yin et al., 2012).

Globally, Steadman laid the theoretical foundation for physically based apparent temperature models via human thermal balance theory (Steadman, 1979a, 1979b, 1984, 1994), upon which simplified empirical indices such as heat index and wind chill index have been developed and widely adopted in operational meteorological services. In China, existing studies mainly follow two research lines. One focuses on universal algorithm innovation, represented by the golden-ratio-based apparent temperature formula (Ma et al., 2013). The other emphasizes regional empirical calibration: studies in humid eastern China target humidity-induced sultriness correction, those in North China mountainous areas adopt machine learning for forecast error revision (Wu et al., 2022), and coastal city studies adjust radiation and wind parameters for land-sea breeze effects (Liu et al., 2020). However, localized studies in Northwest China remain fragmented, with only sporadic model calibrations in Urumqi and Golmud (Shi, 2011; Yang, 2002) and a lack of systematic synthesis and comprehensive evaluation.

This systematic review covers peer-reviewed articles, conference proceedings and operational technical reports published between 1990 and 2025, retrieved from three databases: CNKI, Web of Science Core Collection and Wanfang Data. Search terms combined apparent temperature-related keywords (“apparent temperature”, “thermal comfort index”, “sensible temperature”, “calculation method”, “local calibration”) with regional keywords (“Northwest China”, “Golmud”, “Urumqi”, “Yinchuan”, “Hexi Corridor”, “Qinghai Plateau”). Eligible studies include: 1) index development, correction or application in five northwestern provinces; 2) studies with explicit formulas, parameter coefficients or local observation-based validation; 3) fundamental methodological and classic thermal balance theory papers. Studies applying only generic formulas without local validation, pure reviews without original regional analysis, or those with incomplete meteorological data were excluded. The initial search yielded 192 records; after deduplication, title/abstract screening and full-text assessment, 27 studies were finally included, comprising 9 regional localized studies and 18 fundamental methodological papers.

Notably, several widely used domestic frameworks (Li & Yang, 2002; Chen et al., 2009; Liu et al., 2001) have not been systematically validated for Northwest China's unique climate, and relevant judgments remain at the stage of conceptual interpretation rather than empirical evidence. Specifically, Li and Yang's (2002) model, calibrated for humid eastern plains, is conceptually expected to overestimate sultriness in arid Northwest China due to mismatched humidity thresholds and unaccounted high-altitude radiation effects. Chen et al.'s (2009) regression model lacks altitude and atmospheric pressure correction terms, and thus theoretically cannot capture enhanced convective heat dissipation under high-altitude low-pressure conditions. Liu et al.'s (2001) thermal balance model, calibrated with plain-region radiation data, is conceptually likely to underestimate sunny-day outdoor apparent temperature and overestimate winter wind chill effects in arid zones, due to missing corrections for atmospheric clarity, desert surface albedo and valley local wind fields. None of these inferences have been confirmed by systematic local observation studies.

Focusing on five provinces in Northwest China (Shaanxi, Gansu, Ningxia, Qinghai, Xinjiang), this review has three core objectives: 1) to classify mainstream apparent temperature methods into empirical and mechanistic categories and compare differences in their core correction terms; 2) to synthesize existing localized studies in Northwest China and evaluate model adaptability across arid, plateau and basin landscapes; 3) to identify key limitations of current regional research and propose targeted directions for localized optimization and refined simulation, filling the gap of a systematic academic review on this topic for arid plateau regions.

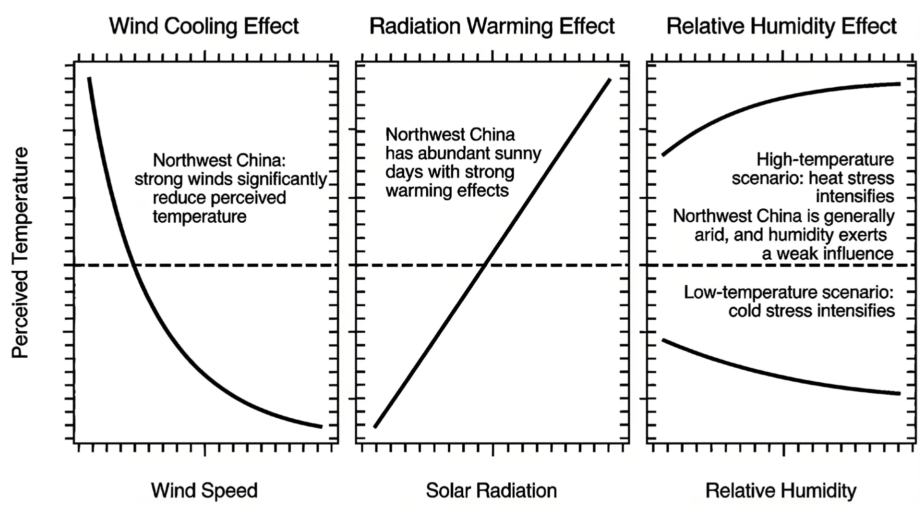

Figure 1. Schematic diagram of effects of wind speed, solar radiation and relative humidity on human thermal perception in Northwest China.

2. Classification and Main Calculation Methods of Apparent Temperature

Current apparent temperature calculation methods can be broadly categorized into two types: empirical statistical indices and physical mechanism-based indices. Typical empirical statistical indices include the Temperature-Humidity Index (THI), Wind Chill Index (WCI), and three-factor Apparent Temperature (AT), which establish simple statistical relationships based on conventional meteorological observations. In contrast, mechanism-based indices are derived from complete human thermal balance theories, mainly covering three widely adopted models: Predicted Mean Vote (PMV), Physiological Equivalent Temperature (PET), and Universal Thermal Climate Index (UTCI).

As one of the earliest developed human thermal comfort evaluation indicators, the Temperature-Humidity Index (THI) relies solely on air temperature and relative humidity to quantify human thermal sensation based on the evaporative heat dissipation principle of human sweat. Adapted from the classic temperature-humidity index proposed by Thom (1959), the nationally recognized computational formula adopted in China is as follows:

$$\mathrm{THI} = 1.8T - 0.55(1 - RH)(1.8T - 26) + 32 \tag{1}$$

where T denotes dry-bulb air temperature (˚C), and RH represents relative humidity in decimal form. This model is primarily applicable to the hot and humid monsoon climate in southern and eastern China. Its critical limitation is the complete neglect of wind speed and solar radiation effects, leading to substantial computational biases in the dry and windy climatic conditions of Northwest China.

The Wind Chill Index (WCI) focuses on the convective cooling effect induced by wind under low-temperature conditions and quantitatively characterizes human cold stress in frigid environments. Derived from the classic wind chill index framework of Siple and Passel (1945) and calibrated by Yang (2002) for the climatic background of Urumqi in Northwest China, the calibrated WCI formula (applicable only when air temperature $T \le 10$˚C) is expressed as:

$$\mathrm{WCI} = 33 - \frac{(33 - T)\left(12.12 + 11.6\sqrt{V} - 1.16V\right)}{22} \tag{2}$$

where WCI is the wind-chill equivalent apparent temperature (˚C), V refers to wind speed at 10 m above the ground (m/s), and T is dry-bulb air temperature (˚C). The WCI is only suitable for cold periods with cold waves and low-temperature conditions in high-altitude regions during winter and spring. Excluding humidity and solar radiation parameters, it is invalid for hot and dry environments in warm seasons.

The three-factor Apparent Temperature (AT) integrates air temperature, humidity, and wind speed simultaneously, accounting for both humidity-induced thermal enhancement and wind-induced cooling effects. As a fundamental operational model adopted in early meteorological services in Wuhan, Golmud and other regions, AT can provide rough annual apparent temperature estimation.

However, the absence of critical solar radiation correction terms causes prominent simulation errors in open environments over the Northwest Plateau. Collectively, THI, WCI, and three-factor AT are simplified empirical indices with low computational complexity and minimal data requirements. Nevertheless, the lack of key meteorological forcing factors renders these models inaccurate in capturing the complex climatic characteristics of Northwest China, including intense solar radiation, frequent dry-hot winds, and drastic altitude variations, making them only suitable for preliminary qualitative reference.

Different from empirical statistical indices, mechanism-based indices take the human thermal balance equation as the core theoretical foundation, mainly including PMV, PET, and UTCI. The Predicted Mean Vote (PMV) integrates six key parameters: air temperature, relative humidity, wind speed, mean radiant temperature, human metabolic rate, and clothing thermal resistance. Featuring rigorous physical mechanisms and high simulation accuracy for indoor thermal environments, PMV is limited in large-scale outdoor operational forecasting due to the unavailability of routine meteorological observations for human activity intensity and clothing properties.

The Physiological Equivalent Temperature (PET) is a mechanistic thermal comfort index developed based on the Munich Individual Energy Balance Model. It is defined as the air temperature of a standard indoor reference environment (with mean radiant temperature equal to air temperature, wind speed 0.1 m/s, relative humidity 50%, and standard human metabolic rate) that induces the same physiological thermal response (core temperature, skin temperature) and thermal sensation as the actual outdoor environment. The unit of PET is ˚C, and a 1˚C change in PET directly corresponds to a 1˚C change in perceived apparent temperature under standard conditions, which can be directly used to quantify the degree of human thermal comfort or stress. PET comprehensively incorporates solar radiation, wind speed, and human physiological parameters to analyze outdoor thermal environments in urban blocks and effectively distinguish thermal differences among diverse underlying surfaces. However, PET requires complex iterative computation and lacks targeted parameter calibration for high-altitude arid environments in Northwest China.

As a standardized state-of-the-art global mechanism index, the Universal Thermal Climate Index (UTCI) fully incorporates air temperature, water vapor pressure, wind speed, and solar radiation, and adapts to extreme hot and cold climates worldwide with comprehensive characterization of human physiological thermal responses. Its main drawbacks lie in cumbersome computational procedures and the difficulty in acquiring high-quality radiation and human activity observational data.

Overall, the three mechanism-based models possess rigorous theoretical foundations and higher simulation accuracy than simplified empirical indices. However, their numerous input variables and intensive computational costs greatly restrict their practical application in routine meteorological forecasting over extensive high-altitude areas in Northwest China. The main features of these typical apparent-temperature indices are summarized in **Table 1**.

Table 1. Intercomparison of typical calculation indices for apparent temperature in meteorological applications.

Index Type	Representative Method	Input Parameters	Applicable Scenarios	Simulation Accuracy	Computational Complexity
Single/Dual-Factor Simple Empirical Index	THI (Thom, 1959)	Air temperature, relative humidity	Indoor and plain areas with hot and humid summers in southern China	Low; neglects wind speed and solar radiation	Extremely low; calculated directly via linear formula
	WCI (Siple & Passel, 1945)	Air temperature, 10 m wind speed	Low-temperature and windy environments in winter and spring over northern and high-altitude plateau regions (Urumqi)	High accuracy in low-temperature conditions; invalid in warm seasons	Extremely low
Three-Factor Empirical Index	AT (Steadman, 1994)	Air temperature, relative humidity, wind speed	General conventional meteorological services nationwide (Wuhan, Golmud)	Moderate; lacks solar radiation correction	Low; piecewise empirical formula
Multi-Factor Regional Empirical Model	Localized formulas (Lü, 1997; Liu et al., 2020)	Air temperature, humidity, wind speed, cloud cover, seasonal clothing coefficient, solar altitude angle	Regional daily outdoor forecasting (North China, coastal cities)	Medium-high; optimized via localized parameter adaptation	Moderate; contains piecewise functions and trigonometric operations
Indoor Mechanistic Model	PMV (Fanger, 1970)	Air temperature, humidity, wind speed, radiant temperature, metabolic rate, clothing thermal resistance	Indoor buildings and small-scale enclosed spaces	High; precise for indoor thermal environment simulation	High; requires iterative thermal balance solution
Global Comprehensive Mechanistic Index	UTCI (Bröde et al., 2012)	Full meteorological factors, graded human activity intensity	Global climatic zones with extreme hot and cold environments	Highest; universal adaptability across all regions	Extremely high; embedded complex physiological iteration algorithms

3. Research Progress of Apparent Temperature Simulation in Northwest China

Most conventional apparent temperature formulas are originally developed for humid plain regions of eastern China or temperate climatic zones worldwide, and their direct application to Northwest China causes prominent simulation biases. To address this issue, domestic researchers have performed localized optimization of empirical parameters, threshold criteria, and computational procedures based on classical frameworks, including the Lü's apparent temperature scheme, human thermal balance equations, and wind chill mechanistic formulas, combined with *in-situ* meteorological observations across Northwest China. A series of regionally adapted apparent temperature algorithms have been established, and representative localized achievements are summarized as follows.

Proposed by Lü (1997) and widely adopted in Chinese operational meteorology, the generalized apparent temperature framework is expressed as:

$$T_G = T_a + T_u + T_r - T_v \quad (3)$$

where T_G is the apparent temperature (˚C), T_a is the ambient observed air temperature (˚C), T_u denotes the humidity correction term (˚C), T_r represents the solar radiation warming correction term (˚C), and T_v is the wind-induced cooling correction term (˚C). Proposed by Lü (1997), this formula integrates four core meteorological factors and performs well in humid plain areas of central and eastern China. However, the radiation intensity, humidity thresholds, and wind chill characteristics in arid and high-altitude Northwest China differ substantially from those in eastern humid regions. Accordingly, targeted coefficient recalibration and threshold optimization have been conducted to develop region-specific computational schemes for Northwest China.

Focusing on the local human climatic adaptability of Yinchuan, Sun and Wang (2005) optimized the empirical parameters of the generalized apparent temperature model for arid environments. They innovatively established two sets of radiation correction schemes for sunlit and shaded conditions, and determined the critical humidity threshold (23˚C air temperature and 57% relative humidity) for high-altitude arid zones. The wind cooling correction was further refined based on the wind calibration algorithm proposed by Xu and Zhu (2000). The optimized model can output multi-scale apparent temperature products, including daily maximum, daily minimum, and hourly values, which fully meet the operational forecasting demands of meteorological stations in Ningxia. This study first incorporated regional human physiological adaptability into apparent temperature modeling for Northwest China, demonstrating that local residents in Yinchuan exhibit stronger cold tolerance and higher heat sensitivity. The model compensates for the deficiency of universal schemes that ignore regional human thermal adaptability and has been fully operationalized for meteorological services in the Ningxia arid plain.

Targeting the extremely arid, low-cloud, and high-insolation climatic characteristics of Golmud, Shi (2011) simplified the radiation correction module and constructed a lightweight apparent temperature formula:

$$T_G = T_A + T_R + 0.55(1 - f) - T_V \quad (4)$$

where T_G is the apparent temperature (˚C), T_A is the *in-situ* air temperature (˚C), T_R is the solar radiation warming correction (˚C), f is the dimensionless relative humidity ranging from 0 to 1, and T_V represents the wind-induced cooling correction (˚C). In this model, the original humidity correction term is simplified as 0.55 $(1 - f)$, and fixed wind cooling values corresponding to different wind speed gradients are quantified, which avoids iterative calculation of complex radiation coefficients and greatly reduces the computational threshold for grassroots meteorological stations. By eliminating sophisticated subdivision parameters of cloud cover and clothing coefficients, this lightweight model is highly adaptable to the data-sparse conditions of desert areas in Northwest China and has become a representative simplified scheme for arid desert apparent temperature simulation.

Based on long-term meteorological observations from 1971 to 2000 in Jiuquan, Shen et al. (2002) developed a segmented apparent temperature model divided into high-temperature, normal-temperature, and low-temperature intervals. Diurnal temperature range was introduced as a key correction factor for hot conditions, and a ten-grade human thermal perception classification criterion was established. This segmented framework is specifically optimized for the distinct seasonal climatic features of the Hexi Corridor, including strong spring winds, dry and hot summers, and severely cold winters. Compared with conventional single-formula models, the segmented algorithm significantly improves the simulation accuracy of apparent temperature under extreme hot and cold weather, providing an effective modeling reference for meteorological forecasting in Gobi-oasis ecotones.

Considering the unique wind direction differentiation in northern Xinjiang river valleys (northwesterly cold winds and southeasterly dry-hot winds), Yang (2002) implemented dual corrections to the classical wind chill formula of Rees (1993). First, seasonal denominator coefficients were calibrated separately for winter and summer to mitigate the underestimation of wind chill cooling under low-temperature and high-wind conditions. Second, a wind-direction correction term $V^{1/3}$ was added to eliminate the artificial cold bias induced by southeasterly dry-hot winds. Furthermore, seasonal empirical correction equations for radiation and humidity were constructed, with refined gradient corrections for solar warming corresponding to light, medium, and dark clothing across four seasons. Supporting graded clothing indices, cold hazard indices, and heat hazard indices, this integrated mechanism-empirical hybrid model realizes full-chain operational forecasting and serves as a typical optimized scheme for frigid and arid cities in Northwest China.

Adopting the human thermal balance equation proposed by Xu and Zhu (2000), Luo et al. (2012) conducted a comprehensive climatic suitability evaluation across Qinghai Province. Incorporating air temperature, relative humidity, and wind speed, the study established a plateau-specific human thermal classification standard, dividing apparent temperature into six grades: extremely cold, cold, cool, slightly cool, comfortable, and hot. The spatiotemporal thresholds of human thermal perception in river valleys, lake basins, and pastoral areas at different altitudes of Qinghai were quantitatively clarified. Notably, this study proposed a ten-day-scale tourism suitability assessment based on apparent temperature variations, confirming annual comfortable periods in the Huangshui and Yellow River valleys and year-round unsuitable tourism conditions in high-altitude pastoral areas of southern Qinghai. This work fills the research gap of apparent temperature application for tourism meteorology in high-altitude alpine regions.

4. Existing Limitations and Future Perspectives

Previous regional studies have proposed fixed linear wind cooling gradients: a 1.2˚C cooling per wind speed grade for humid plains in Henan Province (Li et al., 2007) and a 3.0˚C cooling per grade for semi-arid regions in Inner Mongolia (Hu et al., 2010). These fixed empirical coefficients are only applicable to the average climatic backgrounds of their respective study areas. The discrepancies in results across different regions also indicate that the wind-induced cooling effect is not universally constant, and its relationship with local climatic conditions remains to be further clarified.

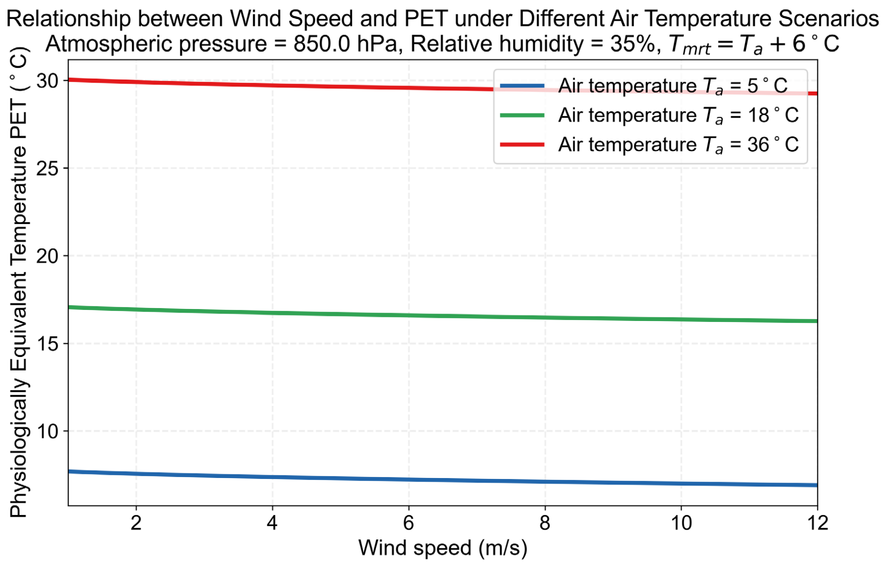

Figure 2. PET response curves under varying wind speed and air temperature.

The Physiologically Equivalent Temperature (PET) sensitivity analysis was programmatically implemented in Python with the pythermalcomfort library. Meteorological boundary conditions were extracted from the 1991-2020 long-term ground observation dataset of Golmud National Meteorological Station (36.42˚N, 94.90˚E, 2808 m above sea level), a representative monitoring site for the arid plateau area of Northwest China. All fixed environmental parameters were set consistently with **Figure 2**: atmospheric pressure = 850.0 hPa, relative humidity = 35%, and mean radiant temperature $T_{mrt} = T_a + 6^\circ$C. Three representative ambient temperature scenarios were established as 5˚C (cold season), 18˚C (mild transitional season) and 36˚C (extreme summer high temperature). Wind speed samples were collected at 1 m/s intervals within the range of 1 - 12 m/s; the horizontal axis in the figure starts at 2 m/s to optimize trend visualization. For each group of meteorological inputs, the Python code first solves the human energy balance equation following the standard PET algorithm, and then performs iterative calculation to acquire the equivalent air temperature of the reference indoor environment (wind speed 0.1 m/s, relative humidity 50%, $T_{mrt} = T_a$), which yields identical physiological responses of core temperature and skin temperature. The results show that PET declines monotonically with increasing wind speed under each constant ambient temperature. The wind cooling gradient differs evidently across temperature scenarios; the curve at 36˚C presents an extremely gentle slope, verifying that the cooling effect of wind is weak when ambient temperature exceeds 33˚C. In summary, wind cooling intensity is closely dependent on ambient air temperature, so a unified wind cooling gradient cannot be generalized for all thermal conditions, as listed in **Table 2**.

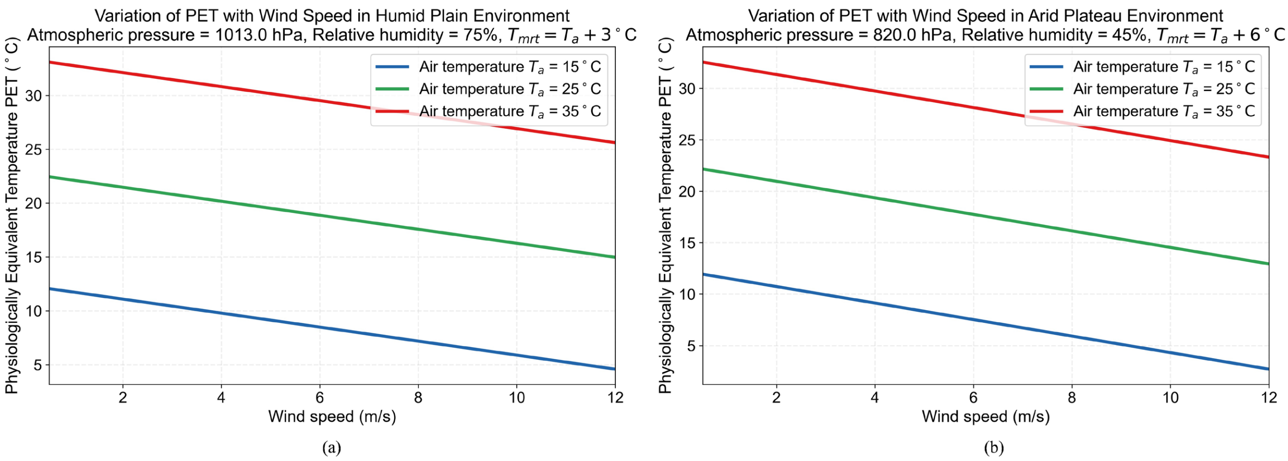

Figure 3. Comparative analysis of PET responses to wind speed in humid plain and arid plateau environments.

As shown in **Figure 3**, the wind cooling effect shown in the schematic diagram presents a nonlinear curve, which reflects the relationship between wind speed and thermal perception under real atmospheric conditions. In contrast, the PET sensitivity simulation shows an approximately linear trend. This simulation keeps humidity, mean radiant temperature and other meteorological factors constant. Within the conventional near-surface wind speed range of 1 - 12 m/s, the nonlinear characteristic of wind-induced cooling on PET is negligible, resulting in an approximate linear response. The discrepancy arises from different boundary conditions: the schematic represents real atmospheric environments with variable meteorological factors, while the PET result derives from controlled idealized experiments.

Table 2. Parameter configuration for PET simulations in arid plateau and humid plain environments.

Parameter Index	Plateau Arid Environment (Represented by Golmud)	Humid Plain Environment (Eastern China Plain)
Atmospheric Pressure	820 hPa	1013 hPa
Relative Humidity	45% (arid)	75% (humid)
Mean Radiant Temperature Difference T_{mrt}- T_a	+6˚C (strong solar radiation over plateau)	+3˚C (weak radiation over plain)
Air Temperature Gradient	15˚C, 25˚C, 35˚C	15˚C, 25˚C, 35˚C
Wind Speed Range	0.5 - 12 m/s	0.5 - 12 m/s

Several limitations remain in current regional apparent temperature modeling for Northwest China. First, unified humidity thresholds and wind correction coefficients are adopted across the entire region, without considering the spatial differentiation of hydrothermal conditions along altitude gradients. Second, the empirical models are solely calibrated by meteorological observational data and lack validation against *in-situ* human subjective thermal perception measurements. Third, local climatic factors, such as cloud cover and topographic circulation, are not fully incorporated, restricting model applicability in complex mountainous and valley terrain.

Future studies should conduct multi-altitude field thermal perception experiments to optimize segmented thresholds and correction coefficients based on *in-situ* human comfort observations. Refined radiation correction schemes should be established for diverse weather conditions, and topographic modulation effects on local wind fields and apparent temperature should be parameterized to improve model performance over complex plateau terrain.

Furthermore, existing localized empirical formulas developed for Golmud and Xinjiang are regionally restricted and cannot be universally applied across Northwest China, while mainstream mechanistic models lack targeted calibration for arid plateau environments. Future research should develop a unified regional apparent temperature correction framework incorporating altitude, atmospheric pressure, and solar radiation parameters based on multi-altitude field observations and human thermal perception samples. Integrated datasets from ground stations, remote sensing retrievals, and numerical models can be utilized to support block-scale refined simulation. Improved radiation correction schemes for varied weather conditions and localized topographic and land-cover parameters should be incorporated to enhance simulation accuracy.

On this basis, interdisciplinary applications, including climate change impact assessment and plateau population health risk evaluation, can be further promoted. Comparative analysis of apparent temperature formation mechanisms across the Loess Plateau, inland basins, and alpine plateaus will help continuously improve the model adaptability for complex northwestern terrain and provide scientific support for regional meteorological services and human living environment optimization.

5. Conclusion

Globally and domestically, apparent temperature simulation methods have evolved from simple empirical statistical schemes to multi-factor physically based mechanistic models, with continuously improved indicator systems and expanding application scenarios covering diversified meteorological service industries. Research on apparent temperature in Northwest China has achieved phased progress, forming a methodological system dominated by operational empirical indices and supplemented by gradually optimized mechanistic models. Relevant achievements have effectively supported tourism climatic comfort evaluation, urban thermal environment analysis, and extreme temperature early warning services, promoting the development of regional meteorological industries.

Nevertheless, constrained by the unique arid plateau climate and uneven observational data distribution, current studies still suffer from several deficiencies, including poor regional adaptability of universal models, insufficient coverage of high-altitude and desert region research, limited original localized algorithms, and inadequate interdisciplinary exploration. Future efforts should focus on three key directions: model localization calibration, multi-scale refined simulation, and interdisciplinary integration, so as to comprehensively enhance the adaptability and service value of apparent temperature simulation for the complex climatic environment of Northwest China.

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Author Contributions

Conceptualization, Yang, M. and Yang, Y.; writing—original draft preparation, Yang, Y., Zhang, L. and Yang, M.; writing—review and editing, Xie, K., Wu, R., Yang, M. and Lu, E.; resources, all authors. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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