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Research article

Insights into climate change dynamics: A tourism climate index-based evaluation of Gilgit-Baltistan, Pakistan

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ABSTRACT

The tourism industry is a significant contribution to the economy of many countries, including Pakistan. However, its activities often have a negative impact on the environment, particularly related to climate change. Notably, Pakistan ranks fifth among countries most affected by climate change, which requires a targeted analysis of the tourism sector to determine its potential impacts. Despite the critical nature of this issue, there is currently a lack of research that examines how climate change specifically impacts Pakistan's tourism industry. This study aims to address this gap by using the Tourism Climate Index (TCI) to assess the impact of climate change on the suitability of different tourism locations across the country. Our results show that popular tourist destinations such as Gilgit-Baltistan experience their peak season in the warmer third quarter (summer), which corresponds to the highest observed TCI values. This suggests that warmer temperatures could boost tourism activity and spending in these regions. Furthermore, our analysis shows that air temperature plays a crucial role in determining tourist comfort levels and significantly influences tourists' TCI values and sensory experiences. The results of this study show that the TCI methodology can be an effective tool for further research into the geographical impacts of climate change on tourism. By identifying necessary changes due to climatic changes, future studies could provide valuable insights into how the tourism industry can adapt to and reduce its environmental footprint.

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1. Introduction

Tourism is a cornerstone of economic development in many countries, offering societal benefits through revenue generation and employment opportunities [1]. Tourism employs approximately 319 million people globally, contributing 10.4 % of the World's Gross Domestic Product (GDP) [2]. This dynamic sector has experienced rapid growth, becoming a significant player in the global economy. For instance, the share of international tourism in global exports of goods and services has increased to 7 %, up from 6 % in 2016 [3].

The year 2017, designated as the International Year of Sustainable Tourism for Development, witnessed a surge in international tourist arrivals, with projections estimating a 3.3 % annual increase from 2010 to 2030, reaching 1.8 billion [4]**.** Emerging economies have seen their market share grow, expected to hit 57 % by 2030, up from 45 % in 2016 [5]. In 2019 alone, international tourist arrivals totaled 1.5 billion worldwide, marking a 4 % growth [6]. Additionally, following the COVID-19 pandemic, the tourism industry has begun to develop, recovering from significant downturns and adjusting to shifts in tourists behavior [7]. This resurgence is characterized by enhanced safety measures and a move towards more sustainable and improved travel experiences, which align with evolving tourism preferences [8,9].

However, the relationship between tourism and climate change is complex and bidirectional. Tourism is both sensitive to and a contributor to climate change, with tourist activities responsible for approximately 5 % of the global carbon dioxide (CO_2) emissions [10]. Environmental conditions significantly influence tourism, impacting the selection of destinations, the duration of stays, and the frequency of visits [11–13]. Adverse climate conditions can lead to decreased visits, economic downturns, and lower productivity during harsh seasons [9,14]. Consequently, destinations in countries severely affected by climate change often experience a decline in tourism [15], with developing and underdeveloped nations bearing the brunt of these impacts.

Pakistan, with its strategic location, diverse cultures, and rich history, is a sought-after tourist destination offering various tourism types, including eco-tourism, religious, adventure, and archaeological tourism [16,17]. Although contributing minimally to global greenhouse gas (GHG) emissions (0.8 % annually), Pakistan is highly vulnerable to climate change, ranking sixth among the countries most at risk [13,18]. In 2017, tourism contributed 2.9 % to the nation's GDP, providing over 1.4 million jobs, or 2.5 % of the total employment [19]. With its unique cultural sites and natural beauty, Pakistan holds significant potential for tourism development, especially northern region of country with its unique demographics and diverse climate are still unexplored region, which can also catalyze improvement in such underdeveloped areas in the country [16].

Given Pakistan's susceptibility to global climate change, it is crucial to assess the viability of its tourist sites using the Tourism Climate Index (TCI). The TCI, a widely used tool, evaluates a tourist's climate adaptability based on various factors, including

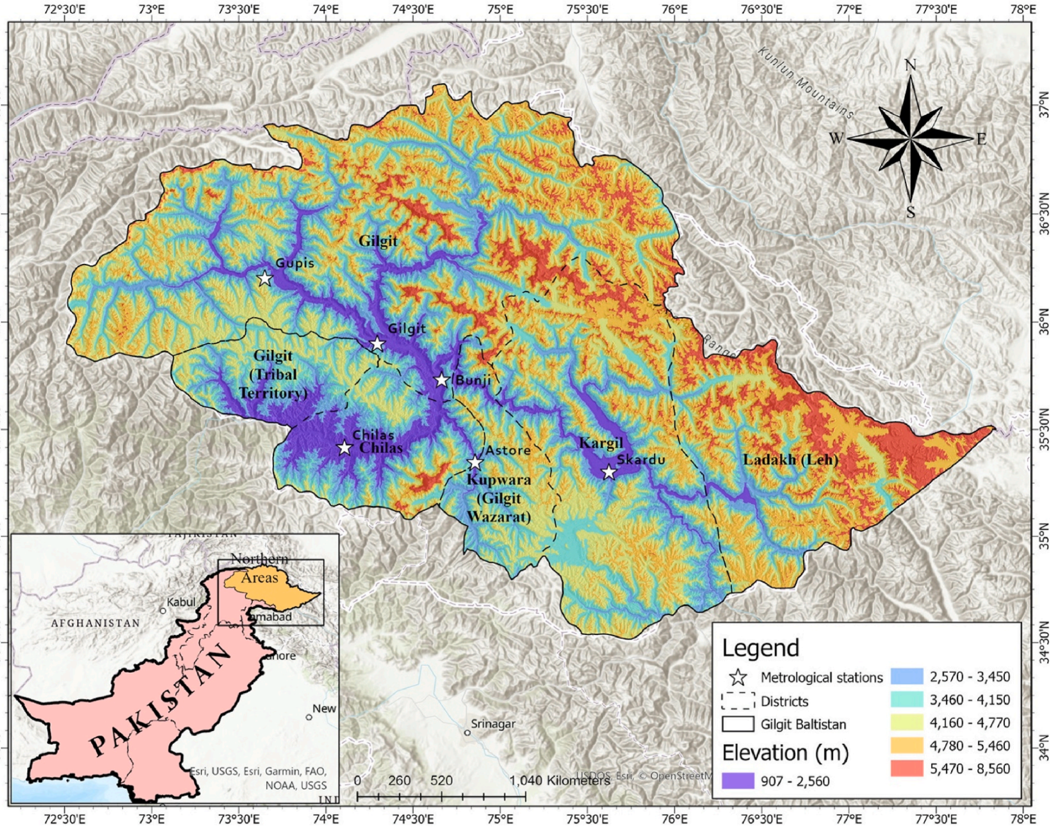

Fig. 1. Location of stations in the Gilgit-Baltistan Baltistan for which TCI was evaluated.

temperature, humidity, precipitation, sunshine duration, and wind intensity [20,21]. However, the application of TCI in Pakistan is limited due to scarce data available [19]. This study represents a pioneering effort to apply the TCI to one of Pakistan's climate-sensitive northern regions with high tourism potential [12].

Herein, we analyzed the effects of climate change on the tourist sector by calculating the TCI for Pakistan's most famous northern tourist areas, as well as forecasted the climate change effect on TCI under three different scenarios of three shared socioeconomic pathways (SSPs) such as SSP126, SSP370 and SSP585. This study will aid in projecting the trend and pattern of destination climate change due to quickly changing environmental conditions. Additionally, it will assess the influence of different TCI levels and the state of destinations tourism likely to be impacted by climate change. The information presented in this study will help analyze the susceptibility of tourism and the extent to which climatic variability affects this vital sector. Additionally, this study laid the groundwork for future research into applying the TCI to other regions of Pakistan.

2. Materials and methods

2.1. Study area

Gilgit-Baltistan, formerly known as the Northern Areas, stands as a top-level administrative subdivision within Pakistan (Fig. 1). Covers an area of 72,971 square kilometers and offers diverse landscapes, including the Himalayan, Hindu Kush, Karakoram and Pamir mountain ranges [22,23]. With around 1,582 square kilometers of lush forests, the region is ecologically very rich and important. The choice of Gilgit-Baltistan as a study area is justified by its special geography and its prominence as a tourist destination. Gilgit-Baltistan is located in the middle of the Himalayan and Karakoram Mountain ranges and is an example of the challenges faced by mountain tourism regions worldwide when climate change and tourism development intersect. Recent research highlights the vulnerability of mountain areas to environmental change and emphasizes the need for sustainable tourism practices [24]. The lessons learned from our study in Gilgit-Baltistan are therefore promising for similar regions struggling with comparable environmental and socio-economic dynamics. By demonstrating the broader relevance of our findings, we aim to contribute to global efforts to strengthen climate resilience and promote sustainable tourism development in different geographical contexts.

To gauge the climatic nuances and comfort levels in the Gilgit-Baltistan area thoroughly, our study concentrated on six key locations strategically chosen within major population centers of the region. These locations include Astore, Bunji, Chillas, Gilgit-Baltistan, Gupis, and Skardu. Each of these locales represents a microcosm of the broader Gilgit-Baltistan-Baltistan region, showcasing unique environmental characteristics and offering valuable insights into the intricacies of the local climate.

The selection of these specific locations aligns with the aim of capturing a comprehensive understanding of climatic variations within Gilgit-Baltistan-Baltistan. The geographical diversity among these key population centers enables a nuanced analysis of the region's climate, encompassing variations in altitude, topography, and ecological features.

For a visual representation of these chosen locations and their spatial arrangement, please refer to Fig. 1. This figure provides a graphical layout, clearly depicting the distribution of the study areas across the Gilgit-Baltistan-Baltistan region.

2.2. TCI index

TCI index is based on 5 sub-indices: 1) CID - daytime comfort index that considers maximum daily temperature and minimum daily humidity; 2) CIA - daily comfort index that takes into account average daily temperature and humidity; 3) R - rainfall rating, 4) S - daylight hours rating, 5) W - rating that takes into account average wind speed. TCI is calculated based on these sub-indices according to Equation (1):

$$TCI = 2(4CID + CIA + 2R + 2S + W) \tag{1}$$

The CIA and CID sub-indices can take values from −3 to 5, while the others range from 0 to 5. The final TCI value can take values from −30 to 100.

In Mieczkowski's pioneer study (1985), the CID and CIA indices were derived graphically using a modified nomogram of effective temperatures. The assessment of tourists' satisfaction with thermal environmental conditions employed the ASHRAE method [25]. Furthermore, we applied the most recent calculation algorithm based on ANSI/ASHRAE Standard 55–2020, utilizing the pythermal comfort library's set_tmp function [26] in the Python 3 programming language.

In addition to temperature and air humidity, the calculation of the indices incorporated several constants: mean radiant temperature set equal to air temperature (dry bulb air temperature); metabolic rate set at 1 to represent normal metabolic rate; clothing set at 0.5, indicative of a summer outfit; and a minimum wind speed of 0.1, as the wind factor is considered in a separate subindex. The conversion of effective temperature to CID and CIA scores followed the scale provided by Mieczkowski (1985). Subsequently, the scores for the R and S subindices were determined based on tables from the same publication.

Notably, while considering wind speed, the W index also accounts for air temperature. Mieczkowski proposed three scales to estimate the effect of wind at different temperature ranges and modified a nomogram to account for the effect of wind chill in cold climates. We adopted these proposed scales in our work and reconstructed the nomogram using the thin spline method, based on 280 manually traced points from the published graph. All calculations were grounded in average monthly meteorological indices. Finally, the TCI forecast under potential climate change conditions was derived from projected climate indices.

2.3. Climatic data

The TCI calculation relied on data from six meteorological stations within Gilgit-Baltistan-Baltistan, an administratively defined region in Pakistan. The Pakistan Meteorological Department (https://www.pmd.gov.pk) facilitated data provision, encompassing monthly temperature averages, relative humidity, wind speed, and precipitation from 1991 to 2021. Unfortunately, the obtained data lacked monthly maximum daily temperature and minimum daily humidity, critical for complete TCI computation. To address this gap and data omissions at some stations, we supplemented the dataset with information retrieved from the ERA5 climate reanalysis [27]. The temporal coverage of the initial climate station data is illustrated in Fig. 2.

Utilizing the ERA5-Land hourly dataset spanning from 1950 to the present (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land), we incorporated climate variables such as "2m dew point temperature", "2m temperature", "Total precipitation", "10m u-component of wind" and "10m v-component of wind" for the entire target area from 1991 to 2021.

Given that the raw reanalysis data lacked the "relative humidity" variable, we calculated it using the dew point temperature and 2m temperature. The formulas from the Integrated Forecast System (IFS) description of the ERA5 reanalysis [28]. Guided this computation, where relative humidity (RH) was expressed as the ratio of partial pressure of water vapor at dew point temperature Td (e *(Td)*) to the saturation partial pressure of water vapor over a plane of liquid water/ice at temperature T ($e_{sat}(T)$) according to the Equation (2):

$$RH = \frac{e(T_d)}{e_{sat}(T)} \tag{2}$$

where the saturation water vapor pressure *esat(T)* is expressed with the teen's formula:

$$e_{sat}(T) = a_1\, exp\left(a_3\left(\frac{T - T_0}{T - a_4}\right)\right) \tag{3}$$

where T is air temperature and with the parameters set according to Ref. [29] for saturation over water ($a_1 = 611.21$ Pa, $a_3 = 17.502$ and $a_4 = 32.19$ K) and to the AERKi formula of [30] for saturation over ice ($a_1 = 611.21$ Pa, $a_3 = 22.587$ and $a4 = -0.7$ K), with $T_0 = 273.16$ K.

To address the aggregate state of water or the presence of a mixed phase, the saturation vapor pressure was defined considering water and ice, and a mixed phase function (Equation (4)) was applied.

$$e_{sat}(T) = \alpha e_{sat(w)}(T) + (1 - \alpha)e_{sat(i)}(T) \tag{4}$$

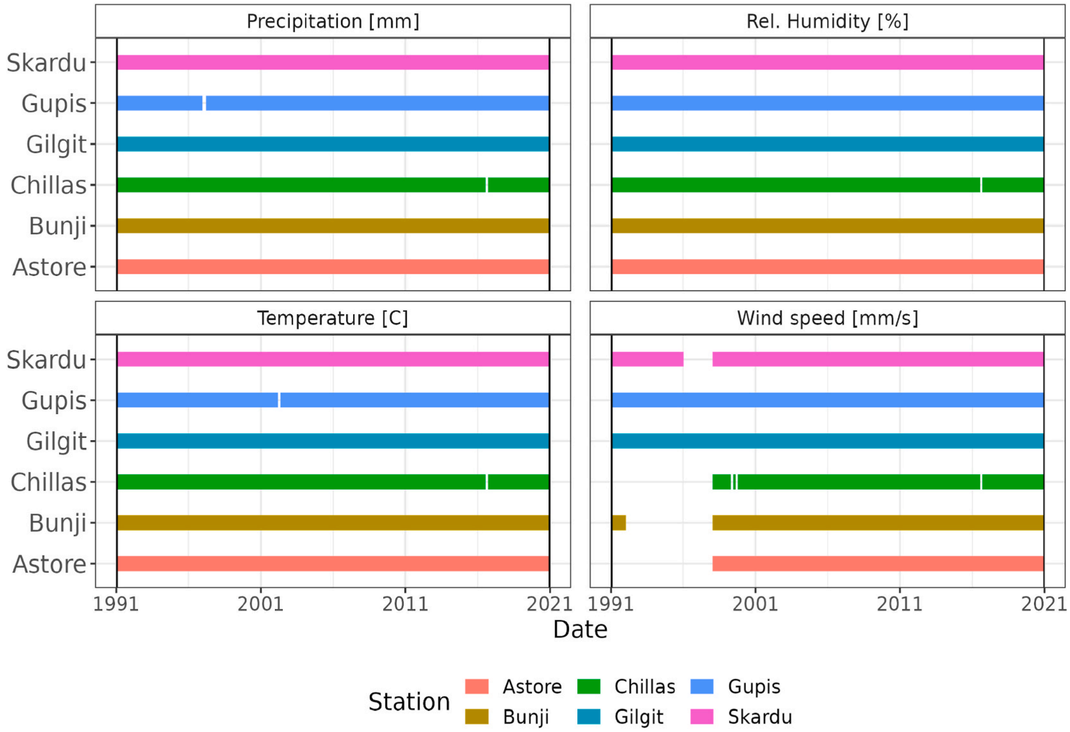

Fig. 2. Climate station data coverage for current climate assessment. The gaps showing the missing values from ground-based datasets.

where $e_{sat(w)}$ *(T)* and $e_{sat(i)}$ *(T)* are the saturation partial pressures of water vapors concerning water and ice, respectively, given by Teten's formula (eq. (3)), and α is the mixed phase function given by equitation 5:

$$\alpha = 0 \qquad T \le T_{ice}$$
$$\alpha = \left(\frac{T - T_{ice}}{T_0 - T_{ice}}\right) \qquad T_{ice} < T < T_0 \tag{5}$$
$$\alpha = 0 \qquad T \ge T_0$$

T_{ice} and T_0 represent the threshold temperatures between which a mixed phase can exist and are chosen as $T_{ice} = 250.16$ K and $T_0 = 273.16$ K.

The partial pressure of water vapor at dew point temperature T_d ($e(T_d)$) is calculated by formula 2 using the values of a1, a3 и a4 for liquid water and T = T_d (dew point temperature).

Wind speed was calculated as the vector sum of "10m u-component of wind" and "10m v-component of wind" using Equation (6).

$$windspeed = \sqrt{u^2 + v^2} \tag{6}$$

Monthly averages of maximum daily temperatures and minimum daily humidity were derived from hourly values. For missing values in the initial climatic station data, a simple linear regression was employed for imputation, building models based on comparable data from the ERA5 dataset, incorporating month and station as independent variables [31].

Finally, we computed average values of all necessary variables by month for the entire study period (1991–2021), establishing them as the climatic norm for the current climate and forming the basis for TCI estimation.

To assess the dynamics of TCI under potential climate change scenarios, we used the climate projections of the CHELSA 2.1 project [32]. We used data from three forecasting algorithms: GFDL-ESM4 (Geophysical Fluid Dynamics Laboratory- Earth System Model v4) [33], IPSL-CM6A-Lr (Institute Pierre-Simon Laplace - Coupled Model Intercomparison Project v6 – Low resolution) [34], MPI-ESM1.2-HR (Max Planck Institute - Earth System Model v1.2 – Higher Resolution) [35], here after termed as model 1, model 2 and model 3, respectively. Each model applied to three Shared Socioeconomic Pathways (SSP): SSP126, SSP370, SSP585. In this case, SSP126 represents the scenario of sustainable human development (optimistic scenario). SSP370 is a pessimistic scenario with significant regional economic development and sustainability heterogeneity. SSP585 also represents a pessimistic scenario with extensive economic development due to fossil fuel consumption growth. The CHELSA project provides forecasts for three time periods in the future with central years: 1995 (nominally current climate), 2025, 2055, and 2085. The available projection variables are monthly mean air temperature, maximum daily air temperature, and precipitation. An initial evaluation of the current climate data showed that the air temperature values (mean and maximum) in the CHELSA dataset are underestimated relative to observations at the climate stations. In this case, we suggested the presence of some stable bias in the CHELSA data, possibly related to a correction for site altitude.

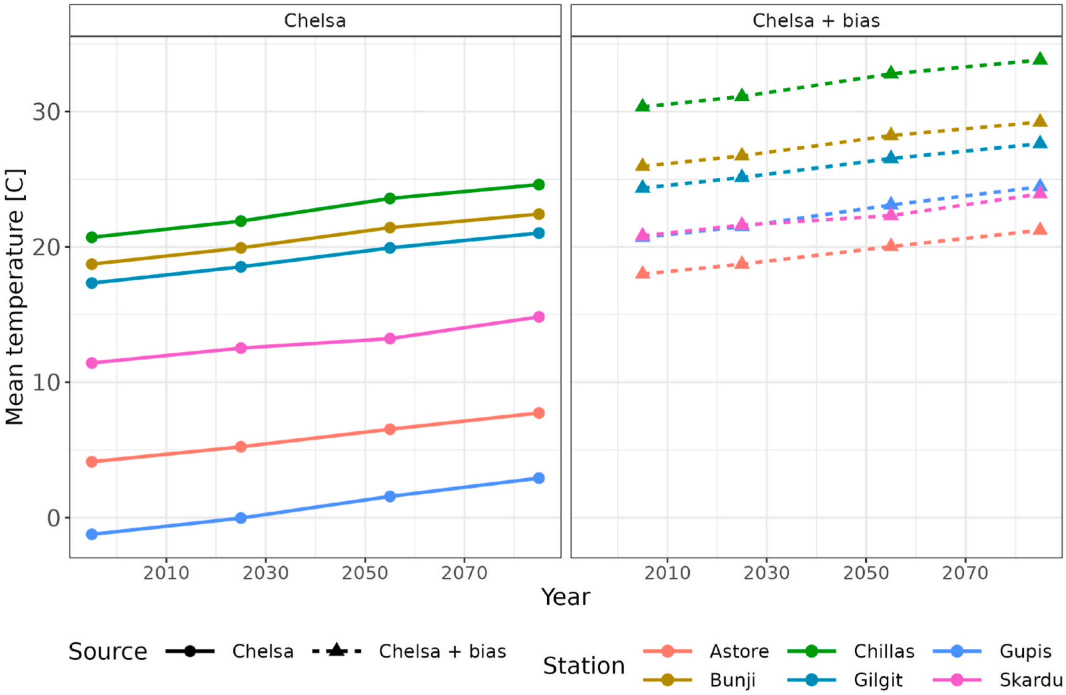

Fig. 3. Example of average air temperature values in June according to the CHELSA dataset.

To remove this bias, we found the difference between the station readings and the CHELSA estimate of the current climate and subtracted this difference from all predicted future climate values. In this way, we kept the trend of changes relative to observations at the climate stations. An example of this transformation is shown in Fig. 3.

Fig. 3 indicated the mean air temperature values for June (The CHELSA dataset) using the algorithm model 1, ssp340 (on the left), and the equivalent value after incorporating the constant bias, which indicates the difference between the estimate and the actual observations (right). The air temperature measured at the climate station coincides numerically with the first column of points in the right panel.

Future climate projections did not contain values of average and minimum relative humidity [15]; in a similar situation, they replaced the missing variables with values of the current climate, as if they remained constant in the future. We assumed humidity usually correlates with temperature and precipitation, so it would be more plausible to estimate future values based on regression models that account for this correlation. Models were trained on contemporary climate data (dataset of climate stations). Dependent variables are average daily or minimum relative humidity. Independent variables are air temperature, precipitation, station, and month of the year. Predicted values were obtained as model predictions based on known future variables. Since wind speed did not exhibit a pronounced correlation with the available predictive variables, we used the current climate values unchanged.

Basic data manipulations, including spatial data and regression model fitting, were performed using the R programming language using the packages sf [36], terra, and tidyverse [37]. The duration of daylight hours was calculated based on the geographical location of the stations using the geosphere package [38].

3. Results

3.1. *Climatic norm of the current climate*

Upon imputing missing data, we generated a continuous series of monthly averages encompassing mean and maximum air temperature, mean and minimum air humidity, precipitation sum, wind speed, and duration of daylight hours (Fig. 4). Subsequently, the averaged values over the 30-year period (1991–2021) were adopted as the current climatic norm.

As per the climatic norm, mean and minimum temperatures exhibited a summer peak in July across all stations. Chillas station recorded the highest mean daily and maximum daily temperatures in July, reaching 32.9 °C and 38.6 °C, respectively. In contrast, Astore station reported the lowest values, registering at 21.0 °C and 25.5 °C, respectively. The climatic norm highlighted January as the month with the lowest annual temperatures, featuring negative mean daily temperatures at Astore, Gupis, and Skardu stations, with values of −2.25 °C, −0.71 °C, and −2.32 °C, respectively. Interestingly, other stations did not experience mean daily temperatures below freezing throughout the year. Negative monthly maximum daily temperatures were specifically observed at Astore and Skardu stations in January, with values of −0.692 °C and −0.740 °C, respectively. Overall, these conditions are favorable for tourists to experience the natural beauty under good climatic conditions. Astore and Skardu appeared to be best possible choices in terms of temperature to spend summer season, while these places experience lower temperatures in winter season.

Air humidity displayed an inverse relationship with temperature. The lowest daily mean and minimal humidity occurred in June–July across the observed stations. Chillas station reported the lowest daily mean humidity at this time, measuring 15.7 %, while Bunji station recorded the highest at 31.8 %. The distribution of minimum daily humidity varied among stations, with Chillas

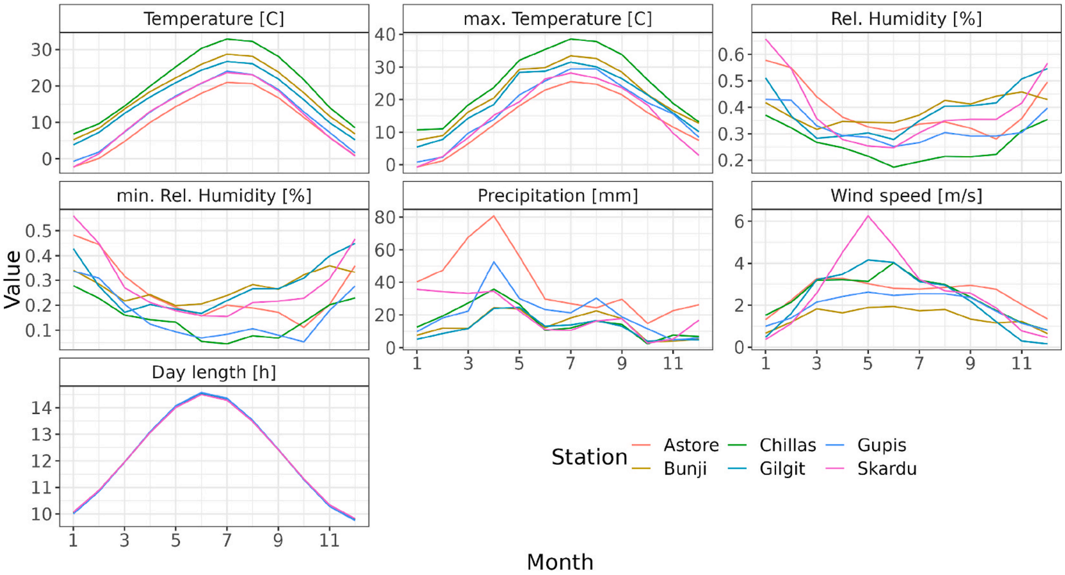

Fig. 4. Monthly mean climatic norms values (period from 1991 to 2021) for the six climatic stations considered in the study.

experiencing the lowest values (2.8 %) in July and Gupis observing the minimum air humidity (4.1 %) in October. Maximum humidity values were observed in January, with mean daily humidity ranging from 36.7 % (Chillas) to 65.4 % (Skardu), and minimum daily humidity at the same stations measuring 27.3 % and 55.5 %.

Monthly precipitation totals peaked in April, ranging from 23.9 mm (Gilgit-Baltistan) to 79.1 mm (Astore), while the lowest amounts occurred from September to January, with Chillas station reporting a minimum of 2.91 mm in September. Based on these climatic averages, Gilgit-Baltistan appears to be less vulnerable to rainfall, showcasing better choice for tourists in April, whereas the Astore area experiences higher average rainfall.

Wind speed displays a distinct seasonal pattern in our study area. The windiest period occurs from April to June, defining a notable feature of the region's climate with peak summer temperatures. Spring emerges as a season characterized by the highest precipitation levels and the most vigorous winds. During this timeframe, average daily wind speeds vary, ranging from 1.63 m/s in Bunji to 6.25 m/s in Skardu. Conversely, the winter months, particularly from December to January, exhibit the lowest average wind speeds. Chillas station recorded maximum wind speeds of 1.52 m/s during this period, while Skardu and Gilgit-Baltistan observed minimums of 0.46 m/s and 0.48 m/s, respectively. The duration of daylight hours in the study area varied from a minimum of 9.75 h in December to a maximum of 14.6 h in June. Skardu experiences high wind speeds during May, making it less suitable for tourism activities during this period. In contrast, other locations in the region exhibit more moderate wind speeds, which do not suspect to pose significant challenges for tourists.

3.2. TCI in the current climate

Based on the prepared current climate data (climatological normal for the period 1991–2021), we calculated all TCI subindices (Fig. 5). As per the results, the CIA (daily comfort index), accounting for average daily temperature and humidity, displayed seasonality across all stations. There was a general tendency for an increase during the summer, except for Chillas and Bunji, where the index showed a monotonic increase in spring, reaching a plateau of maximum rating score (5 points). The timing of the maximum score varied, with Gilgit-Baltistan peaking from May to August and Astore station reaching it only in July. Chillas and Bunji stations exhibited bimodal dynamics with two peaks in April and September for Chillas and May and August for Bunji. Both stations experienced a local minimum in July, dropping scores to 3 and 4, respectively. This decline in CIA was attributed to high air temperatures, particularly in stations with the highest July mean daily temperatures and high mean daily humidity for Bunji, causing discomfort at an average daily temperature of 28.1 °C.

In January, Skardu station recorded a minimum CIA score of 0. Notably, both CID and this index allowed negative values up to 3. Considering maximum daily temperature and minimum humidity, the CID index (daytime comfort index) exhibited a more pronounced tendency toward bimodality. The CID curve had a single summer peak only for Astore and Skardu, while other stations showed two 5-point peaks each, shifted to spring and autumn. In June, the index dropped to 4 at Gupis station, three at Bunji and Gilgit-Baltistan, and one at Chillas station. Like CIA, the primary reason for the summer CID drop was discomfort due to high air temperatures.

The sunshine index, rating the duration of daylight hours, was consistently high for all stations (4.5–5 points), with minimum values expected in the December–January winter period.

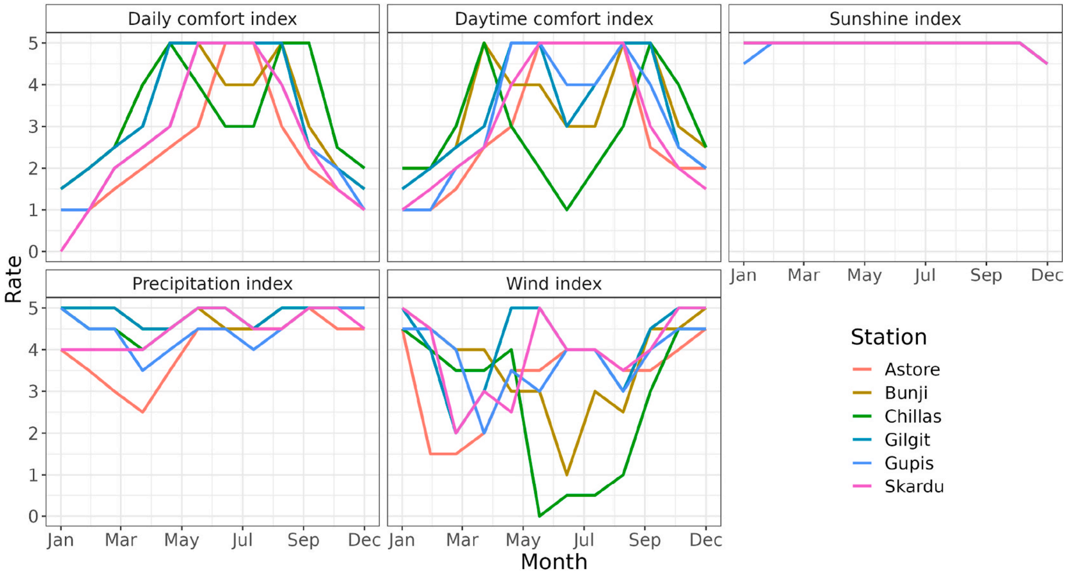

Fig. 5. Annual dynamics of TCI sub-indices: CIA - daily comfort index, CID - daytime comfort index, S - daylight hours rating (Sunshine index), R – rainfall (precipitation) index, W - average wind speed rating.

The wind speed rating was the most variable parameter, differing significantly in magnitude and annual change dynamics for different stations. Chillas and Bunji stations notably experienced a significant decrease in ratings during the summer period to scores of 0 and 1, respectively. For other stations, the W index ranged from 3 to 5 in the summer period.

Based on the established sub-indices for each station, monthly average TCI values for the current climate were calculated. The index dynamics are shown in Fig. 6. To qualitatively describe comfort conditions, the 100-point scale was mapped into five categories: unfavorable, acceptable, good, very good, and excellent.

Four out of six stations, namely Astore, Gilgit-Baltistan, Gupis, and Skardu, were marked by a summer TCI peak, with values remaining within the highest excellent category. The longest duration of the excellent period was noted at Gilgit-Baltistan and Gupis stations (6 months from May to October). Gilgit-Baltistan station-maintained values above 'good' throughout the year, while Gupis station's TCI dropped to 'acceptable' in January and February. At these stations, there was a slight decrease in absolute TCI values around June but no change in the category.

At Skardu and Astore stations, a continuous summer period of excellent grades lasted 5 and 4 months (from May to September and June to September), respectively. A winter period with an acceptable TCI score starting in January and lasting 2 and 4 months, respectively, was observed at both stations.

Bunji and Chillas stations exhibited bimodal TCI dynamics. At Chillas, TCI increased from February, peaked in March and April, then decreased to an acceptable value in June. The second period with the highest TCI score occurred from October to November. Similar patterns were observed at Bunji station. However, in summer, the minimum did not drop below the 'very good' threshold. Both stations maintained sufficiently high TCI values in winter, with December values not falling below 'good.' Moreover, values in March–February remained at the 'good' level. Overall, the summer season is considered excellent in terms of climatic conditions (TCI) for tourists, except in Chillas, where relatively higher daily temperatures negatively affect tourists' thermal comfort. According to the calculated TSI, as shown in Fig. 6, Skardu and Gilgit rank highest among other stations during the summer, demonstrating their superior suitability for tourism during this period.

Table 1 presents the total duration of periods with different TCI values for all stations.

Recently, Pakistan ranked 101 out of 119 countries on the 2024 Tour and Travel Development Index (TTDI), showing a four-point improvement. Despite this little progress, significant challenges and opportunities persist that require concerted efforts from government officials and policymakers to improve the tourism industry. The tourism sector plays a critical role in regional development and contributes significantly to GDP. In 2022, the tourism accounted for 5.9 % of the GDP and employed 4.2 million people [40]. However, the growth of the tourism industry is heavily influenced by factors such as strategic planning, security, hygiene, transportation, infrastructure development, and sustainability; where climatic conditions like temperature, rainfall, and wind speed are fundamental in attracting tourists [41,42]. Thus, at two stations, Bunji and Gilgit-Baltistan, the climate remains attractive enough for tourism all year round. Considering the non-overlapping ranges of excellent and very good marks of different stations based on the cited TCI's scale, our study area exhibited a suitable region's climate for year-round provision of tourist activity.

3.3. TCI regarding climate change projections

To evaluate the impact of potential climate change, we calculated the TCI based on the CHELSA 2.1 climate forecast. Fig. 7 shows nine scenarios (3 SSP for three forecast models) of potential monthly change in TCI on a five-point scale at Gilgit-Baltistan station.

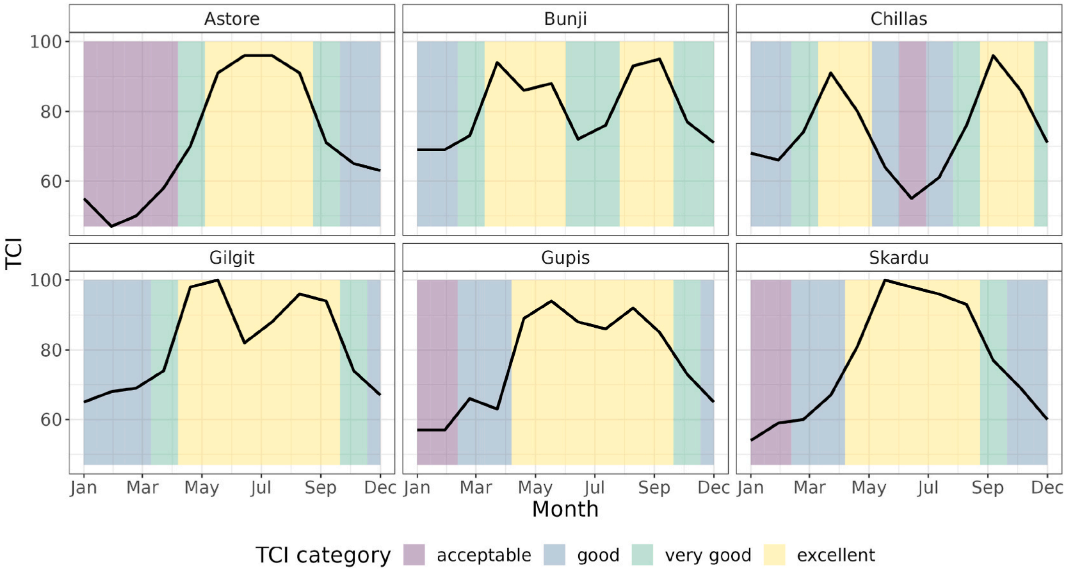

Fig. 6. Annual dynamics of the current climate TCI at the 6 stations considered in the study.

Table 1
The number of months with different categories of TCI ratings at the stations.

Station	Number of Months				
	Acceptable	Good	Very good	Excellent	Ideal
Astore	4	2	2	4	8
Bunji	0	2	5	5	12
Chillas	1	4	3	4	11
Gilgit-Baltistan	0	4	2	6	12
Gupis	2	3	1	6	10
Skardu	2	4	1	5	10

*Descriptive rating of tourist comfort index (TCI) value, i.e., Acceptable (50–59 %), Good (60–69 %), Very good (70–79 %, Excellent (80–89 %), and Ideal (90–99 %) quality of grades [39].

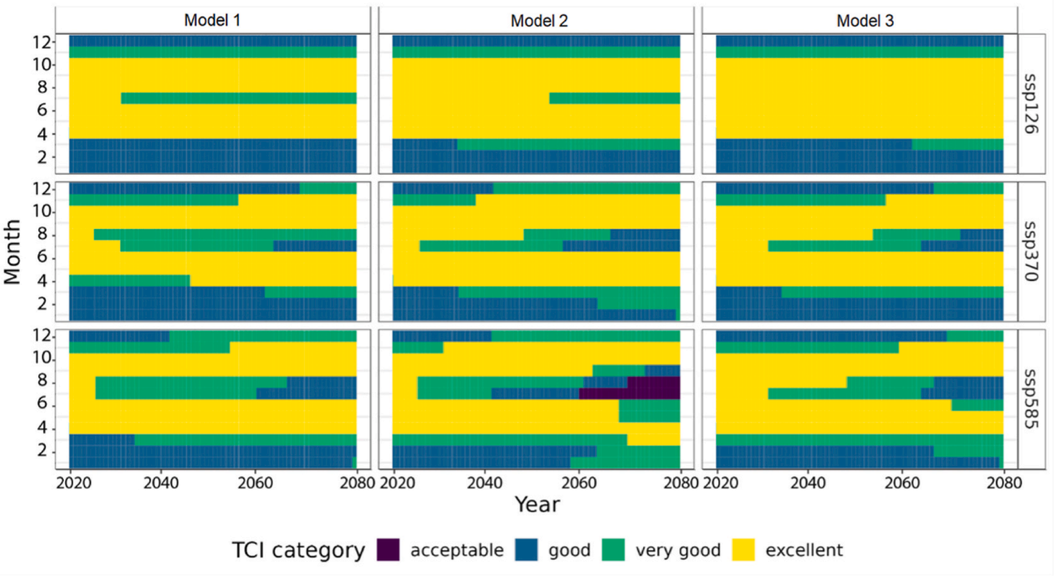

Fig. 7. Forecast of changes in the monthly TCI categories at Gilgit-Baltistan station according to CHELSA 2.1 climate data modeled under three SSP scenarios (SSP126, SSP370, SSP585) with three climate models: Model 1 (GFDL-ESM4), Model 2 (IPSL-CM6A-Lr), and Model 3 (MPI-ESM1.2-HR). SSP126 depicts an optimistic sustainable future, SSP370 a pessimistic scenario with uneven regional development, and SSP585 a high fossil fuel dependency scenario.

Under the ssp126 scenario, the TCI profile for Gilgit-Baltistan province remains stable until 2085, with a slight increase in the excellent period after 2060. However, both the GDFL and model 2 predict a decline in TCI to ‘very good’ in July after 2030 and 2060, respectively.

For ssp370 and ssp585, the predicted change involves transitioning from unimodal to bimodal annual TCI dynamics. All three algorithms project a division of the summer maximum into spring and autumn peaks, accompanied by a summer decrease in TCI, attributed to the predicted rise in summer temperatures. This shift is most prominent in the model 2 algorithm for the ssp585 scenario.

Stations Gupis and Skardu (Figs. 8 and 9, respectively) exhibit similar but less pronounced dynamics of predicted changes. For ssp126, no significant changes in TCI are predicted. However, for ssp370 and ssp585, a slight decrease in TCI in June and July to the ‘very good’ and ‘good’ categories is expected after around 2060.

Astore station exhibited the highest suitability for tourism in terms of the impact of climate change. In all forecasts except model 2 ssp585, the annual dynamics of TCI show a single summer maximum with an excellent score. In the projections for ssp370 and ssp585, this maximum period extends by 1–2 months after about 2050 (Fig-10).

Bunji and Chillas stations (Figs. 11 and 12) with bimodal annual TCI dynamics in the current climate experience a worsening trend for summer depression formation. The spring and fall peaks of maximum TCI shift to the beginning and end of the year with climate change, making the overall climate less comfortable due to rising summer temperatures.

Our results indicate that, based on projections, the climate of the Gilgit-Baltistan region in the next 100 years will remain suitable and relatively stable for tourism during the summer months. TCI ratings for all present and future stations never fall below the ‘acceptable’ category. Stations are expected to have periods of maximum comfort with TCI values exceeding 80 units (Fig. 13).

For ssp126, all three algorithms project no decrease in the excellent period’s duration; in some cases, this period may extend for 1–2 months. The maximum total duration of the optimal period is expected for Gilgit-Baltistan station, reaching up to 7 months. For

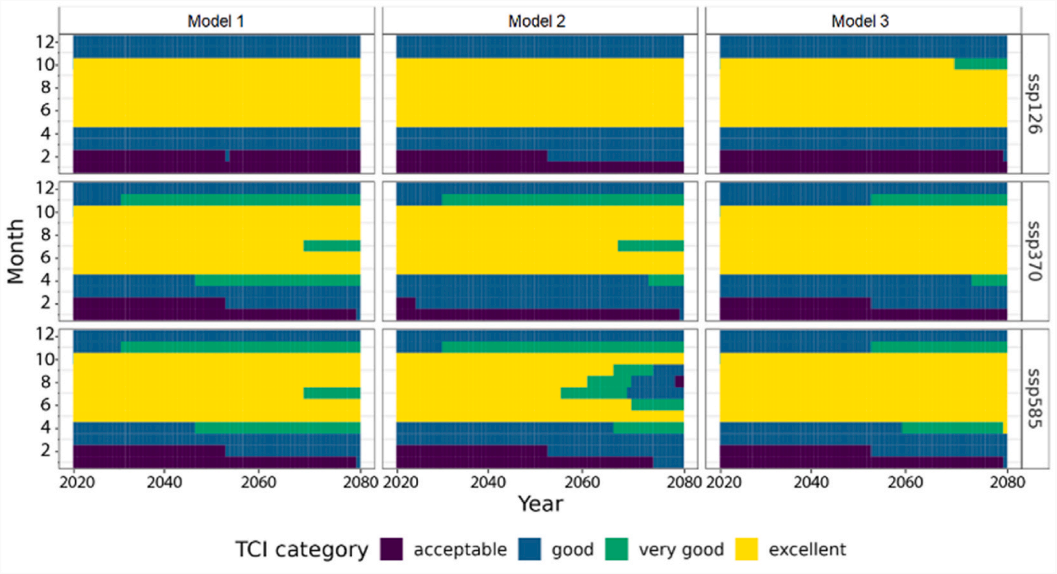

Fig. 8. Forecast of changes in the monthly TCI categories at Skardu station according to CHELSA 2.1 climate data modeled under three SSP scenarios (SSP126, SSP370, SSP585) with three climate models: Model 1 (GFDL-ESM4), Model 2 (IPSL-CM6A-Lr), and Model 3 (MPI-ESM1.2-HR).

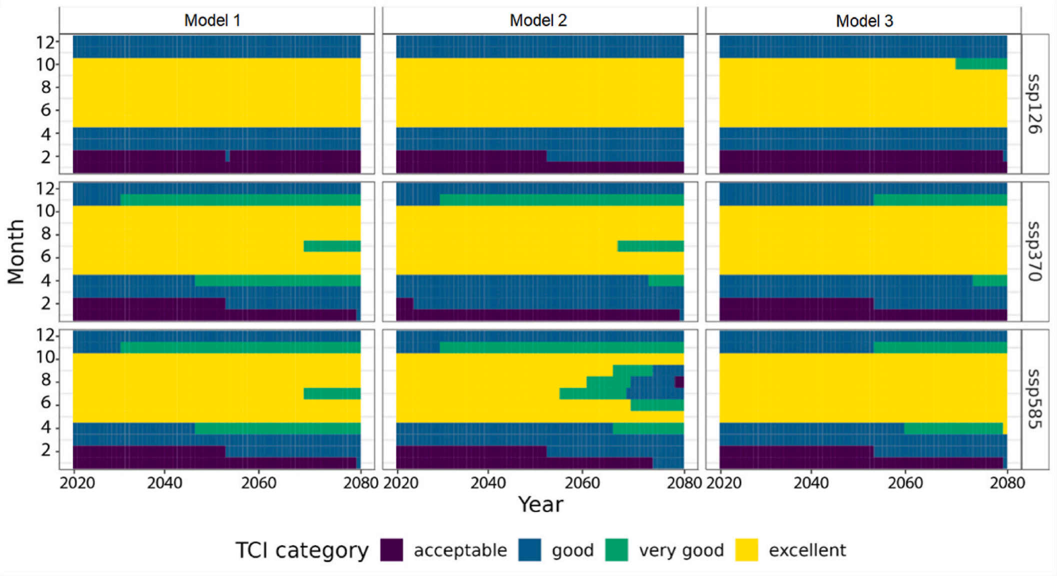

Fig. 9. Forecast of changes in the monthly TCI categories at the Gupis station according to CHELSA 2.1 climate data modeled under three SSP scenarios (SSP126, SSP370, SSP585) with three climate models: Model 1 (GFDL-ESM4), Model 2 (IPSL-CM6A-Lr), and Model 3 (MPI-ESM1.2-HR).

ssp370, we also do not anticipate a significant decrease in favorable months, except for Chillas station, where the number of excellent months may decrease from 4 to 3 by 2080. An average periodic increase in the optimal period of one month is expected for most other stations. The ssp585 forecast appears to be the most unstable. The expected number of optimum months may increase and decrease at different stations, with the model 2 algorithm offering the most pessimistic outlook. According to model 2, by 2080, a shortening of the favorable period is expected at most stations, with Skardu station experiencing the most significant changes, decreasing from five to 2 months.

4. Discussion

The intricate relationship between climate change and the tourism industry is marked by positive and negative impacts. Within this

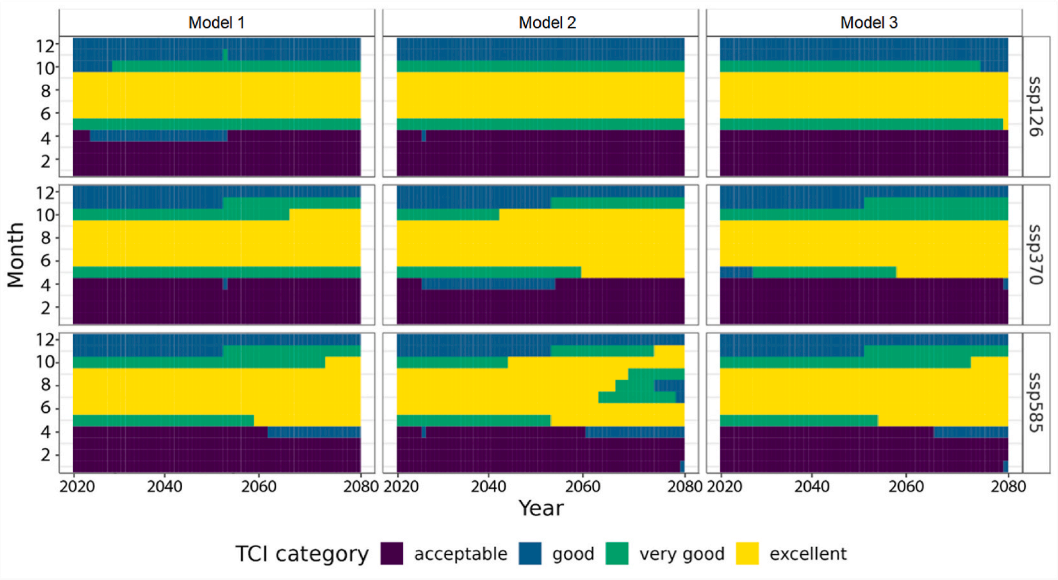

Fig. 10. Forecast of changes in the monthly TCI categories at Astore station according to CHELSA 2.1 climate data modeled under three SSP scenarios (SSP126, SSP370, SSP585) with three climate models: Model 1 (GFDL-ESM4), Model 2 (IPSL-CM6A-Lr), and Model 3 (MPI-ESM1.2-HR).

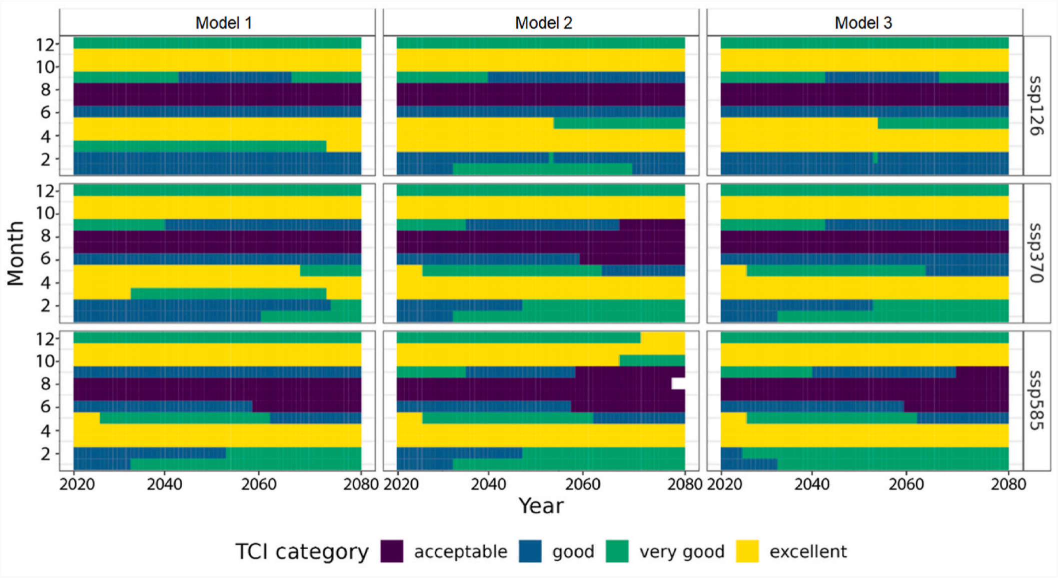

Fig. 11. Forecast of changes in the monthly TCI categories at Chillas station according to CHELSA 2.1 climate data modeled under three SSP scenarios (SSP126, SSP370, SSP585) with three climate models: Model 1 (GFDL-ESM4), Model 2 (IPSL-CM6A-Lr), and Model 3 (MPI-ESM1.2-HR).

complex dynamic, climate variables play a pivotal role in shaping tourist comfort and influencing destination choices, particularly in the context of ecotourism. To assess the current state of the tourism industry's adaptability to changing climate conditions, this study employed a suite of indices, including the Tourist Comfort Index (TCI), CIA, CID, S, R, and W, drawing on methodologies refined in previous studies [43–45]. Our findings underscore the profound impact of daily temperature and relative humidity on tourist comfort, highlighting how temperature extremes can adversely affect the overall tourism experience [46]. Aligning with prior research, our methodology affirms the significance of average mean temperature in influencing tourist preferences and destination choices. Notably, specific regions—Astore, Skardu, Gupis, Bunji, and Chillas experience diminished tourist comfort attributed to climate variability.

Our study confirms the far-reaching effects of climate change on the tourism industry. The central role of weather conditions at destinations in tourist satisfaction and choice makes the industry inherently vulnerable to the effects of climate change [47]. Consequently, sustainable tourism development strategies must proactively consider and address the multifaceted impact of climate

Fig. 12. Forecast of changes in the monthly TCI categories at Bunji station according to CHELSA 2.1 climate data modeled under three SSP scenarios (SSP126, SSP370, SSP585) with three climate models: Model 1 (GFDL-ESM4), Model 2 (IPSL-CM6A-Lr), and Model 3 (MPI-ESM1.2-HR).

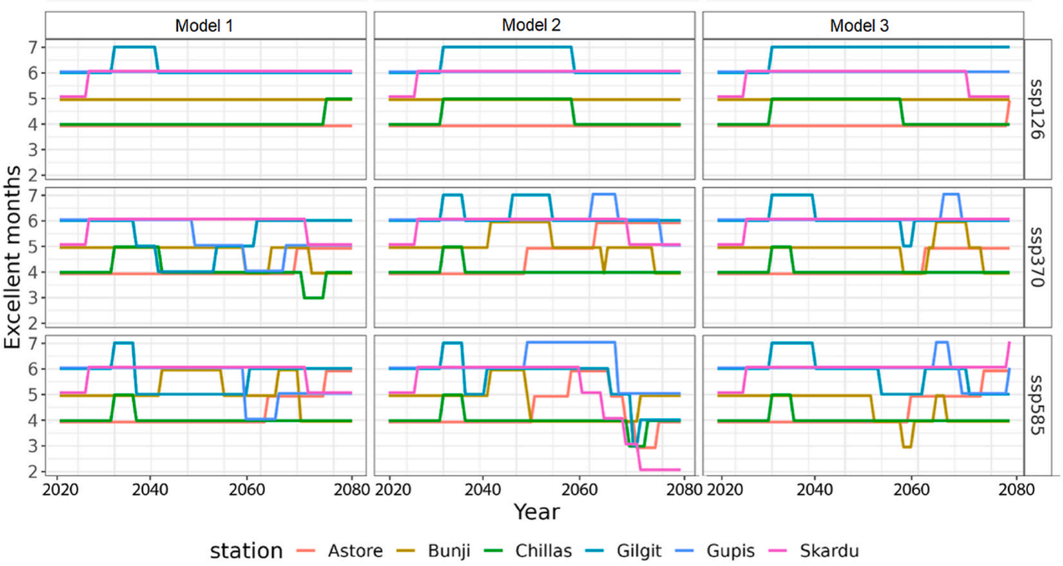

Fig. 13. Change in the number of months with the excellent TCI grade at all stations, considering projections of future climate changes modeled under three SSP scenarios (SSP126, SSP370, SSP585) with three climate models: Model 1 (GFDL-ESM4), Model 2 (IPSL-CM6A-Lr), and Model 3 (MPI-ESM1.2-HR).

change, implementing measures to mitigate potential negative consequences [48].

In addition, our study takes into account the different climatic zones in the area, which are influenced by different altitudes. The different sensitivities to future climate change at different altitudes reflect the unique ecosystems of the mountain regions [49]. The study highlights seasonal patterns and occasional fluctuations in climate variables such as temperature, precipitation and relative humidity in mountainous regions and highlights the vulnerability of these areas to extreme weather events that pose a threat to tourism infrastructure, esthetic beauty and cultural heritage [50].

In recent years, the complex connection between climate change and tourism has become increasingly important. Several studies have demonstrated the direct impact of global climate dynamics on travel behavior and destination sustainability [5] Understanding these impacts is critical to ensuring Gilgit-Baltistan's economic resilience, as the region copes with the impacts of climate change. Z. Mieczkowski initially created the Tourism Climate Index (TCI). (1985), who successfully correlated weather conditions with visitor satisfaction, provided a strong framework for assessing climate suitability for tourism. The goal of this research is to offer predictions about future climate scenarios and their potential consequences for the tourism sector in Gilgit-Baltistan using TCI. This is especially important given the findings [20], who demonstrate the usefulness of TCI in organizing and adjusting tourism plans in response to climate fluctuations.

Temperature emerges as a key climate variable affecting tourist flows (Fig. 3), with a non-linear relationship that varies from destination to destination and tourist perception [51]. Although the prediction indicates continued tourist interest in the designated study area due to the pleasant climate, it is imperative to recognize potential environmental changes due to climate change that require protective measures.

The intricate relationship between climate change and the tourism industry demands a deep understanding of dynamic factors [52–55]. The substantial impacts of climate change on tourism underscore the critical need for sustainable tourism strategies. Climate variables, including temperature, precipitation, humidity, and others, significantly influence tourist comfort and destination choices [56–58]. Implementing measures is essential to protect destinations and infrastructures from the adverse impacts of climate change, ensuring the long-term sustainability of the tourism industry [58].

Looking forward, understanding the influence of mountains on the climate of surrounding areas is crucial, particularly in terms of temperature and precipitation [56,57]. The topography of mountains affects air pressure, creating rain shadows and influencing precipitation patterns. Seasonality, determined by topography and atmosphere interaction, is vital in destination selection and tourism demand. Policymakers should consider these factors when developing sustainable tourism policies that balance the needs of tourists with environmental preservation [59].

To broaden the scope of our discoveries, we have conducted a more in-depth investigation of Gilgit-Baltistan as a case study. This region, with its climate patterns and dependence on tourism, serves as a useful example for studying the impacts of climate change using the Tourism Climate Index (TCI). This strategy can be extended to other areas worldwide, such as the Andean region, the European Alps, and the Himalayas in Nepal and Bhutan, all of which are vulnerable to the impacts of climate change [60]. Our research aims to highlight commonalities that not only focus on specific regional impacts, but also provide a global framework for tourism resilience. Our methods can be used by stakeholders in similar areas to improve local adaptive capacity and environmental sustainability, increasing the relevance and applicability of our findings at a global scale [61].

Weather conditions, especially temperature, have a significant impact on tourism, as tourists prefer warmer or cooler places to feel comfortable and enjoy themselves [62]. Climate variability such as heat waves, cold temperatures, droughts, storm surges, floods and heavy rainfall can affect the comfort and safety of tourists and destinations [22,63]. Therefore, understanding the interaction between topography, atmosphere and seasonal patterns can help to develop sustainable tourism policies and strategies that take climate variability and seasonality into account [64,65].

In summary, mountains are crucial in determining climatic conditions in surrounding areas, affecting tourism and destination accessibility [66,67]. Seasonality is a key factor in destination selection and seasonal tourism demand. Therefore, policymakers should consider the impact of climate fluctuations and seasonality in developing sustainable tourism policies that meet the needs of tourists while preserving the environment [68–70]. The CIA comfort index study explored the impact of seasonality, temperature, humidity, precipitation, and sunshine duration on tourist comfort in different destinations. The study found that seasonality increased in most areas during the summer, except in Chillas and Bunji, where the trend increased in spring and plateaued. The duration of seasonality also varied across destinations, which could be attributed to the heterogeneity of climatic variables [71]. Relative humidity significantly affected tourist performance and behavior, as increased humidity reduced climate conformity, significantly affecting international tourist flows. However, the effects of humidity were perceived differently by different tourists, and low precipitation and low humidity were desirable climatic conditions for visitors who chose a destination for comfort. Precipitation varied across the study areas, with Astore recording the highest precipitation and Chillas the lowest [72–74]. The precipitation pattern significantly impacted the tourist destination and comfort, with a negative impact on tourist comfort when precipitation exceeds the normal range. Wind speed affects the formation of weather and climate conditions, and horizontal and vertical air movements exist in the atmosphere. Wind gusts are common in mountainous regions, especially in high-altitude regions such as Gilgit-Baltistan-Baltistan. Cyclones or storms can significantly impact the number of tourists in a destination and hinder tourism in many goals [75]. The study also found differences in sunshine duration in the different study areas and between months, with longer periods of sunshine from May to October.

In Pakistan, the application of a Tourism Climate Index (TCI) could also be useful to determine the climatic suitability for tourism in different landscapes. By aggregating various bioclimatic parameters, this index could delineate the optimal seasons for tourist activities in regions ranging from the mountainous regions in the north to the coastal areas in the south [76].The research could reveal periods in which climatic conditions in various Pakistani regions are rated as marginal to excellent, similar to the results of other geographical studies. However, it is plausible that, as seen elsewhere, there may be a significant discrepancy between these favorable conditions and actual tourist arrivals. This discrepancy may indicate that potential visitors are uncertain about the best time to travel based on climatic comfort, or it may illustrate the influence of other factors on travel decisions. For Pakistani tourism authorities and operators, these findings represent a valuable opportunity [16]. By integrating the TCI into strategic planning, they could increase the attractiveness of destinations by informing and attracting tourists during climatically optimal times. This would include not only promoting these periods, but perhaps also adapting infrastructure and services to better accommodate tourists. Thus, the TCI could serve as a crucial tool in refining Pakistan's tourism strategy to synchronize visitor flows with the best possible weather conditions, potentially increasing both tourist satisfaction and the economic benefits of tourism.

This study highlights the importance of considering climatic factors such as temperature, humidity, precipitation, and sunshine duration when planning tourism activities at different destinations. Understanding the impacts of these environmental factors can help destinations develop appropriate strategies to mitigate negative impacts and improve tourists' experiences. Ecotourism can positively impact the country's economy by creating jobs, generating income, expanding infrastructure, and improving the livelihoods of local communities. Tourism revenues can also protect and conserve natural resources, raise awareness of climate change, and preserve the country's flora and fauna.

5. Conclusion

To summarize, this study has attempted to assess the reciprocal relationship between tourism and climate change in the northern regions of Pakistan. The findings highlight the sensitivity of the tourism industry to climate variability and emphasize the significant influence of weather conditions and esthetic appeal on tourists' preferences. The Tourism Climate Index (TCI) analysis shows that the selected study sites in Astore, Bunji, Chilas, Gilgit-Baltistan, Gupis and Skardu offer favorable climatic conditions, diverse landscapes, rich cultural experiences and variable climatic conditions, making them attractive destinations for tourists in the next century.

The study argues for collaboration between the tourism industry, economists and climate change experts and emphasizes the importance of mutually beneficial interaction. Rather than fighting each other, these actors should work together synergistically to harness the positive aspects of tourism while mitigating potential negative impacts on the regional and global climate, society and economy. The study encourages the incorporation of climate change mitigation strategies into current and future tourism-related projects and policies to promote sustainable practices for the long-term well-being of both the tourism industry and the environment.

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Data availability statement

On request, the authors will provide the data from this study.

CRediT authorship contribution statement

Nadeem Ullah: Writing – review & editing, Writing – original draft, Software, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Lin Chao:** Writing – review & editing, Conceptualization. **Tauheed Ullah Khan:** Writing – review & editing, Methodology, Formal analysis, Data curation, Conceptualization. **Wu Lun Sai:** Formal analysis, Data curation, Conceptualization. **Zhang Yazhuo:** Validation, Supervision, Project administration, Methodology, Funding acquisition. **Irshad Ahmad Khan:** Methodology, Formal analysis, Conceptualization. **Muhammad Azher Hassan:** Investigation, Formal analysis, Conceptualization. **YiKe Hu:** Writing – original draft, Validation, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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