land

Article

Spatial–Temporal Characteristics of Human Thermal Comfort in Xinjiang: Based on the Universal Thermal Climate Index from 1981 to 2019

Jianwei Qi [1,2], Zhaoping Yang [1,2,*], Fang Han [1,2], Baoshi He [3] and Xuankai Ma [1,2]

1 Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China; qijianwei16@mails.ucas.ac.cn (J.Q.); hanfang@ms.xjb.ac.cn (F.H.); maxuankai20@mails.ucas.ac.cn (X.M.)
2 University of Chinese Academy of Sciences, Beijing 100049, China
3 Key Laboratory of Watershed Geographic Sciences, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing 210008, China; hebaoshi20@mails.ucas.ac.cn
* Correspondence: yangzp@ms.xjb.ac.cn

Abstract: Xinjiang is one of the world's most sensitive and vulnerable regions to climate change. However, little is known about the current status and changes in thermal comfort conditions in this area. Using the Universal Thermal Climate Index (UTCI) derived from the newly available high-resolution dataset HiTiSEA, the spatial–temporal pattern and changes thereof over annual and seasonal scales across Xinjiang from 1981 to 2019 were evaluated. The results reveal that the distribution and change of thermal comfort in Xinjiang have apparent regional heterogeneity and seasonal characteristics. Across all scales, 7 of 10 UTCI thermal stress categories were observed, from slight cold stress to strong heat stress. Annually, the mean UTCI is 3 °C and has significantly increased at 0.37 °C decade^{-1}. The mean number of comfortable days (CDs) is 114 days, with a range from 0 to 189 days. On the space scale, the Tarim Basin experiences the highest UTCI value, while the Ili River Valley, the north side of the Tianshan Mountains, and the peripheral areas of the Tarim Basin have a higher number of CDs. Seasonally, summer has the highest UTCI value, while winter is the lowest. The trend for all seasons is upward, and spring increases fastest. Results also indicate that air temperature has a positive correlation with climate comfort, and the influence of air temperature on climate comfort is most significant. Further research indicates that the range and intensity of population exposure to uncomfortable climates in Xinjiang have increased. The distribution and expansion of population exposure are similar to the population density. These findings contribute to a systematic understanding of the local climate environment and can be helpful for the assessment of the impact of climate change and optimize tourism development.

Keywords: thermal comfort; universal thermal climate index; Xinjiang; climate change; HiTiSEA; population exposure

check for updates

Citation: Qi, J.; Yang, Z.; Han, F.; He, B.; Ma, X. Spatial–Temporal Characteristics of Human Thermal Comfort in Xinjiang: Based on the Universal Thermal Climate Index from 1981 to 2019. *Land* **2023**, *12*, 1864. https://doi.org/10.3390/land12101864

Academic Editors: Hélder Da Silva Lopes, Paula Remoaldo, Vítor Patrício Rodrigues Ribeiro and Juliana Araújo Alves

Received: 8 September 2023
Revised: 28 September 2023
Accepted: 29 September 2023
Published: 30 September 2023

1. Introduction

According to the Sixth Assessment Report (AR6) by the Intergovernmental Panel on Climate Change (IPCC), the global surface temperature has been increasing at an unprecedented rate. Notably, the past decade (2011–2020) witnessed an average temperature rise of 1.09 °C above the pre-industrial era (1850–1900), and it was recorded that each of the previous three decades was warmer than any preceding decade since 1980 [1]. This human-induced climate change has caused widespread adverse impacts and related losses and damages to nature and people [2]. Thermal comfort, or climate comfort, refers to the meteorological conditions that can maintain the energy balance of heat exchange between the human body and the atmosphere, represents people's satisfaction with the thermal environment, and reflects people's perception of the environment [3,4]. Thermal comfort is an essential parameter to assess the comfort state of the human body under different climatic conditions from the perspective of meteorology, and it has an essential impact on human society in many fields, including architectural design [5], urban planning [6], human health [7], tourism and recreation [8]. Changes in climate factors such as air temperature, precipitation, wind speed, and radiation response to global warming can result in changes in climate comfort. Therefore, studying the changes in thermal comfort in the context of climate change is of great significance for understanding changes in living conditions, improving residents' quality of life, and providing a scientific basis for climate change adaptive measures.

The study of thermal comfort has a history of nearly 100 years, and multiple assessment models have been developed to evaluate bio-climatic conditions for human beings [9]. The early stage of the thermal comfort model was intuitive feelings, usually evaluated through the results of direct measurement using instruments [10]. These indicators are only a one-sided response to the environment and do not consider whether the human body feels comfortable. In 1923, Houghton proposed the effective temperature index (ET), marking the point at which thermal comfort research entered the stage of empirical models [11]. Empirical models are generally linear equations about air temperature, humidity, and wind speed, such as wind chill index (WCI) [12], wet bulb globe temperature (WBGT) [13], and temperature–humidity index (THI) [14]. These indicators are easy and straightforward to calculate and forecast and are widely used by the public. However, their simple formulation contains unreasonable calculations to reduce the accuracy of the results so that they cannot meet the basic requirement of the correspondence between the index value and the human thermo-physiological state. Their results are often not comparable and have obvious regional limitations in terms of time and space scales [15]. In the 1960s, the rapid development of biometeorology and computer technology made the mechanistic models based on the heat budget models gradually attract attention, including predicted mean vote (PMV) [16], perceived temperature (PT) [17], standard effective temperature (SET) [18], and physiological equivalent temperature (PET) [19]. However, although the abovementioned indices are appropriate for application in any assessment of the thermal environment, because of the persistent shortcomings of thermal physiology and heat exchange theory, they have not been used as a fundamental standard. In 2000, with the development of multidisciplinary integration, based on the latest scientific progress in human response-related thermos physiological modeling, UTCI was presented to the scientific community to address these shortfalls [20]. UTCI was proposed under the initiative of the World Meteorological Organization (WMO) Commission on Climatology, and it was jointly completed by 45 scientists from 23 countries in the fields of thermal physiology, mathematical modeling, occupational medicine, and meteorological data handling. UTCI is regarded as one of the most comprehensive indicators for evaluating thermal comfort, suitable for thermal assessments in all climates and seasons and on any scale. Additionally, UTCI depicted temporal variability of thermal conditions better than other indices because of sensitivity to slight changes in climatic variables [21–23].

Since its introduction, the UTCI has been widely used to assess human thermal comfort in different parts of the world in recent years [24]. In Europe, UTCI has revealed significant variations, with northern parts of Sweden and Finland reaching −80 °C during winter, while regions like Germany, the Netherlands, France, and certain parts of Spain are 20 °C in summer [25]. Furthermore, UTCI values across 32 major European cities have all shown a statistically significant increase ranging from 0.6 to 3.2 °C [26]. In Africa, Sarah found a wide range of thermal stress experienced, ranging from very strong cold stress to extreme heat stress in southern Africa. The study also noted a significant increase in UTCI with a rate of 0.28 °C decade^{-1} [27]. Similarly, research by Mohammed in North Africa and the Middle East found UTCI values ranging from 0 °C to 32 °C, with an increasing trend of 0.1 °C to 0.7 °C decade^{-1} [28]. In the Arctic, the average UTCI was found to be 0.025 °C, and it has shown a significant increase at a rate of 0.457 °C decade^{-1} during the summer [29]. In Russia, thermal stress ranges from extreme cold stress to moderate heat stress in summer, and the distribution and trend of thermal stress are primarily related to air temperature. In Asia, the average UTCI for South Asia is 2.4 °C, with a rate of increase at 0.27 °C decade^{-1} [30]. Aung et al. found that most parts of South Asia experience moderate thermal stress for over 100 days, with the UTCI displaying an upward trend in many areas. Afghanistan and Central India have experienced an increase of nearly 1 °C, while Pakistan saw a more significant rise of 1.5 °C [31]. Some studies use UTCI to analyze thermal comfort in China. Kong found that the spatial pattern of UTCI shows a correlation with latitude; UTCI decreases with increasing latitude for most of China, and the temporal variation of UTCI shows positive trends in northeastern China and negative trends in southwestern China [32]. Lei found a similar spatial pattern of UTCI that is distributed along a latitudinal direction and decreases from south to north [33]. Wu found that UTCI values decreased due to the increase of the latitude in China, and the comfort area in summer (69.5%) is more extensive than in winter (7.7%) [34]. In summer, UTCI increased with the largest increase rate of 0.053 °C/a in northwest China [35]. Some studies have focused on changes in UTCI in the Beijing–Tianjin–Hebei Urban Agglomeration [36], the Qinghai-Tibet Plateau [37], the Guangdong–Hong Kong–Macau Greater Bay, and other areas [38]. However, studies on thermal comfort in Xinjiang have received less attention, especially under a rapid climate change background.

As one of the most arid areas in the world, Xinjiang is a typical eco-fragile area and is one of the most sensitive and vulnerable regions to climate change [39]. The climate in Xinjiang has experienced significant warming and moistening, and such a 'warming–wetting' trend has occurred since the mid-1980s [40,41]. The increase in air temperature in Xinjiang is more rapid than in China and the entire globe [42]. Climate change is exerting various impacts on its ecology [43], environment [44], and economy [45,46]. As the core region of the "Silk Road Economic Belt", Xinjiang has experienced rapid economic and population development in recent years. In 2020, the total population of Xinjiang was 25.85 million. Compared to the population in 2010, Xinjiang's population growth rate ranked 4th nationwide, and the population in Xinjiang is expected to continue to grow steadily. However, compared to the national average, Xinjiang has a lower level of economic development and weaker capacity to adapt to climate change. The primary industries, such as agriculture, play a significant role in its economy, and there is a greater exposure to thermal stress. Therefore, studying the status and changes in the comfort conditions of Xinjiang in the context of climate warming is of great significance for the future sustainable development of China.

The limited and sparsely distributed meteorological stations in Xinjiang may hamper the use of UTCI due to a lack of available requisite input variables from ground-based meteorological stations. Hence, this study uses a newly developed high-resolution dataset derived from ERA5 reanalysis data to calculate the UTCI in Xinjiang. In this study, there are two primary objectives. The first one is to investigate the spatial–temporal variation of UTCI and the number of comfortable days (CDs) in Xinjiang, focusing on exploring the spatial distribution pattern and temporal change trend. The second one is to examine the relationship between the climate variables and thermal comfort and find how the population changes with thermal uncomfortable conditions in Xinjiang.

2. Study Area and Research Methods

2.1. Study Area

Xinjiang Uygur Autonomous Region (73.66°–96.38° E, 34.42°–49.17° N), located at the northwest border of China, is the largest administrative province (166.49 × 10^6 ha), accounting for one-sixth territorial area of China. The topography of Xinjiang is known as "two basins sandwiched by three mountains". The three mountains from north to south are the Altay Mountains, the Tianshan Mountains, and the Kunlun Mountains, and the two basins are the Junggar Basin and the Tarim Basin, forming a unique mountain-basin system. Figure 1 shows the location and the topography of Xinjiang. Located deep in the hinterland of the Eurasia continent, the climate of Xinjiang is typical of a temperate continental climate, with a wide air temperature range, low precipitation, strong winds, and low humidity. The annual average air temperature of Xinjiang ranges from 5 °C to 13 °C, and the mean annual total precipitation ranges from 90 mm to 250 mm. The economy and population in Xinjiang have witnessed rapid development in recent years. The population in Xinjiang increased from 18.5×10^6 in 2000 to 25.9×10^6 in 2022. The gross domestic product (GDP) of 2022 in Xinjiang is 13 times the GDP of 2000, higher than the annual growth rate of GDP in China.

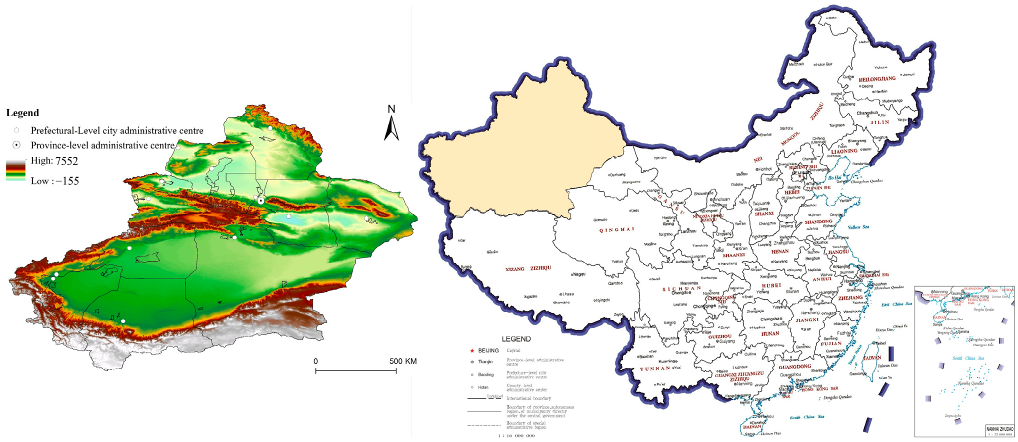

Figure 1. The location of the study area (map approval number: GS (2019) 1686).

2.2. Data

The UTCI data were collected from a high-spatial-resolution dataset of human thermal stress indices over South and East Asia (HiTiSEA) for the period 1981–2019 [47]. This dataset was derived using climate variables including air temperature, humidity, wind speed, direct solar radiation, and shortwave and longwave radiation fluxes from the ERA5-Land and ERA5 reanalysis data from the European Center for Medium-Range Forecasts (ECMWF) within the Copernicus Climate Change Service (C3S). The dataset was downloaded as NetCDF files from the website of Scientific Data (https://springernature.figshare.com/collections/A_High-spatial-resolution_Dataset_of_Human_Thermal_Stress_Indices_over_South_and_East_Asia/5196296, assessed on 1 May 2023), with the temporal resolution of day and the horizontal resolution of $0.1° \times 0.1°$. Compared to the existing thermal index dataset ERA5-HEAT [48] and HiTIC-Monthly [49], the HiTiSEA database has the advantages of higher spatial resolution, with a comprehensive validation based on thousands of weather stations [30]. The climate data, including 2 m temperature, relative humidity, and 10 m wind speed, are sourced from the ERA5-Land dataset. The population data from 1990 to 2015 is sourced from the "Kilometer grid dataset of China's historical population spatial distribution" by the National Tibetan Plateau Data Center [50].

2.3. Method

2.3.1. The UTCI and Comfort Level

The UTCI is a six-degree polynomial equation based on the theory of thermo-physiological exchange. The output is an equivalent temperature (°C), delineated as stress levels (Table 1), representing the air temperature of a reference outdoor environment that would elicit in the human body the same physiological response as the actual outdoor environment [51]. The reference environment includes a walking speed of 4 km/h (equivalent to a metabolic rate of 2.3 MET), a 10 m wind speed of 0.5 m/s, T_{mrt} equal to T_a, relative humidity (RH) of 50 % for $T_a \leq 29$ °C, and vapor pressure of 20 hPa for Ta > 29 °C. The thermal stress assessment scale (Table 1) was derived from the modeled physiological and psychological response. The calculation formula is shown in Equation (1).

$$UTCI = T_a + O_{ffset}\ (T_a, T_{mrt}, V_a, T_d) = f(T_a, T_{mrt}, V_a, T_d) \quad (1)$$

Table 1. Assessment scale of UTCI.

UTCI Range (°C)	Stress Category
UTCI $\geq$ 46	Extreme heat stress
38 $\leq$ UTCI < 46	Very strong heat stress
32 $\leq$ UTCI < 38	Strong heat stress
26 $\leq$ UTCI < 32	Moderate heat stress
9 $\leq$ UTCI < 26	No thermal stress
0 $\leq$ UTCI < 9	Slight cold stress
−13 $\leq$ UTCI < 0	Moderate cold stress
−27 $\leq$ UTCI < −13	Strong cold stress
−40 $\leq$ UTCI $\leq$ −27	Very strong cold stress
UTCI < −40	Extreme cold stress

2.3.2. Trend Analysis

The study used the Theil-Sen trend estimation and the Modified Manne–Kendall (MMK) test to analyze the trends and significance of the UTCI and comfortable days from 1981 to 2019 in Xinjiang. The changes in UTCI and CDs are determined using the Theil-Sen estimation, and the significance of these changes is assessed using the MMK test. Theil-Sen trend estimation is a non-parametric statistical technique used to estimate the trend or slope in a dataset over time [52]. The calculation formula is as follows:

$$\beta = Median\left(\frac{x_j - x_i}{j - i}\right), \forall j > i \quad (2)$$

β is the slope estimate, x_j and x_i represents data points of time series data, j and i represents indices of data points; when $\beta > 0$, the indicator follows an upward trend; when $\beta < 0$, the indicator shows a downward trend; when $\beta = 0$, there is no change in trend. MMK test is a non-parametric statistical method used to detect trends or monotonic trends in time series data [53]. The test uses Z-statistics; a positive Z value indicates an increase, while a negative value indicates a decrease. We use the R package "modifiedmk" package [54] to implement the analysis described above.

2.3.3. Correlation Analysis

This study aims to employ correlation analysis to investigate the relationships between the UTCI, the number of comfortable days, and various meteorological factors to determine the extent of influence exerted by meteorological elements on thermal comfort. Correlation analysis is a statistical method used to assess the degree of association between two or more variables. It helps us understand whether these variables are, to some extent, interrelated and the strength and direction of this association. We use the Pearson correlation method to analyze the relationship between the UTCI, comfortable days, and climate indicators quantitatively. The formula for the correlation coefficient is as follows:

$$r = \frac{\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \overline{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \overline{y})^2}} \quad (3)$$

where $\overline{x}$ represents the average UTCI and the number of CDs and $\overline{y}$ is the average of a given climate variable.

2.3.4. Population Exposure

In this article, we define population exposure as the size of the population exposed to uncomfortable climate conditions. Following the method adopted by Li et al. [55], we assessed population exposure as the product of population times the yearly number of uncomfortable days (unit: person per day), as follows:

$$PE_{ij} = P_{ij} \times UCDs_{ij} \quad (4)$$

PE_{ij} is the population exposure of Grid j in the i-th year, P_{ij} is the population size of Grid j in the i-th year, $UCDs_{ij}$ is the number of UCDs of Grid j in the i-th year. The definition of UCDs is the days that have thermal stress (UTCI > 26 °C or UTCI < 9 °C). We ultimately analyzed 25 years of population exposure in Xinjiang from 1990 to 2015.

3. Results

3.1. UTCIs

3.1.1. Spatial Patterns of UTCI

To better understand the mean state of thermal comfort in Xinjiang, we initially examined the distribution of climatologically averaged UTCI (1981–2019). As shown in Figure 2, daily mean UTCI values averaged over annual and seasonal scales for 1981–2019 reveal that Xinjiang experienced seven of the ten UTCI thermal comfort categories: strong and moderate heat stress, no thermal stress, very strong, strong, moderate, and slight cold stress. The distribution of UTCI shows a noticeable spatial heterogeneity, primarily influenced by the natural geographical conditions.

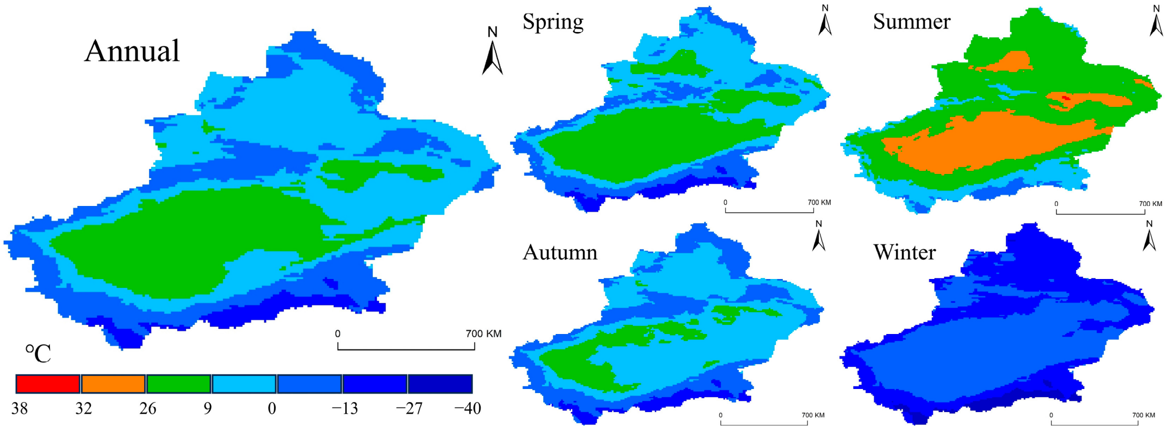

Figure 2. The mean annual and seasonal spatial distribution of UTCI for 1981–2019.

Regarding the annual UTCI, Xinjiang's UTCI ranges from −19 to 16 °C, with an average of 3 °C, indicating that Xinjiang is generally perceived as having a slight cold stress. As shown in Table 2, most areas exhibited "slight cold stress" reached 42.53%, primarily located in the Junggar Basin and the surrounding areas of the Tarim Basin. "No thermal stress" was mainly in the Tarim Basin and the Turpan–Kumul Basin and reached 27.61%, while "moderate cold stress" was mainly in the Altay Mountains, the Tianshan Mountains, and the part of the Kunlun Mountains and reached 25.51%. It indicates that the Tarim Basin and the Turpan–Kumul Basin have a more comfortable climate than other regions of Xinjiang. Because of the high altitude and glacial distribution, the UTCI showing "strong cold stress" in the high mountain area in Kunlun Mountain accounts for 4.35%. This area is the most uncomfortable.

Table 2. The percentage of thermal stress categories of Xinjiang for 1981–2019.

Percentage (%)	Very Strong Cold Stress	Strong Cold Stress	Moderate Cold Stress	Slight Cold Stress	No Thermal Stress	Moderate Heat Stress	Strong Heat Stress
Annual	0	4.35	25.51	42.53	27.61	0	0
Spring	0	4.69	17.46	36.77	41.08	0	0
Summer	0	0	2.72	12.95	56.68	27.57	0.08
Autumn	0	4.67	29.01	52.52	13.8	0	0
winter	4.17	41.99	53.84	0	0	0	0

The seasonal distribution of UTCI over Xinjiang reveals distinct climatic features. In spring, UTCI ranges from −22 to 18 °C (from "no thermal stress" to "strong cold stress") with an average value of 4.8 °C. Most of the areas are under "no thermal stress". In summer, UTCI ranges from −4 to 33 °C (from "strong heat stress" to "moderate cold stress") with an average value of 18.9 °C; most of the areas are under "no thermal stress", and 27.65% of areas are under heat stress, and 15.67% areas are under cold stress. In autumn, UTCI ranges from −19 to 15 °C (from "no thermal stress" to "strong cold stress") with an average value of 2.1 °C; most of the areas are under "slight cold stress". In winter, UTCI ranges from −35 to −1 °C (from "moderate cold stress" to "very strong cold stress"), with an average value of −13.5 °C; most of the areas are under "moderate cold stress". The "no thermal stress" areas for the four seasons, spring, summer, autumn, and winter, are 41.08%, 56.68%, 13.8%, and 0%, respectively. This implies that in Xinjiang, the climate is most comfortable during summer, followed by spring and autumn, with the least comfortable climate during winter.

3.1.2. Long Term Changes

As shown in Figure 3a, the average annual UTCI in Xinjiang from 1981 to 2019 displays a significant upward trend. The result of Theil-Sen trend estimation is 0.037, indicating an upward trend in Xinjiang's UTCI, with an average increase of 0.37 per decade. The *p*-value from the MMK test is less than 0.001, demonstrating that this trend is statistically highly significant. The mean annual UTCI value is 3.093 °C, with the highest value occurring in 2007 at 4.241 °C and the lowest in 1984 at 1.598 °C.

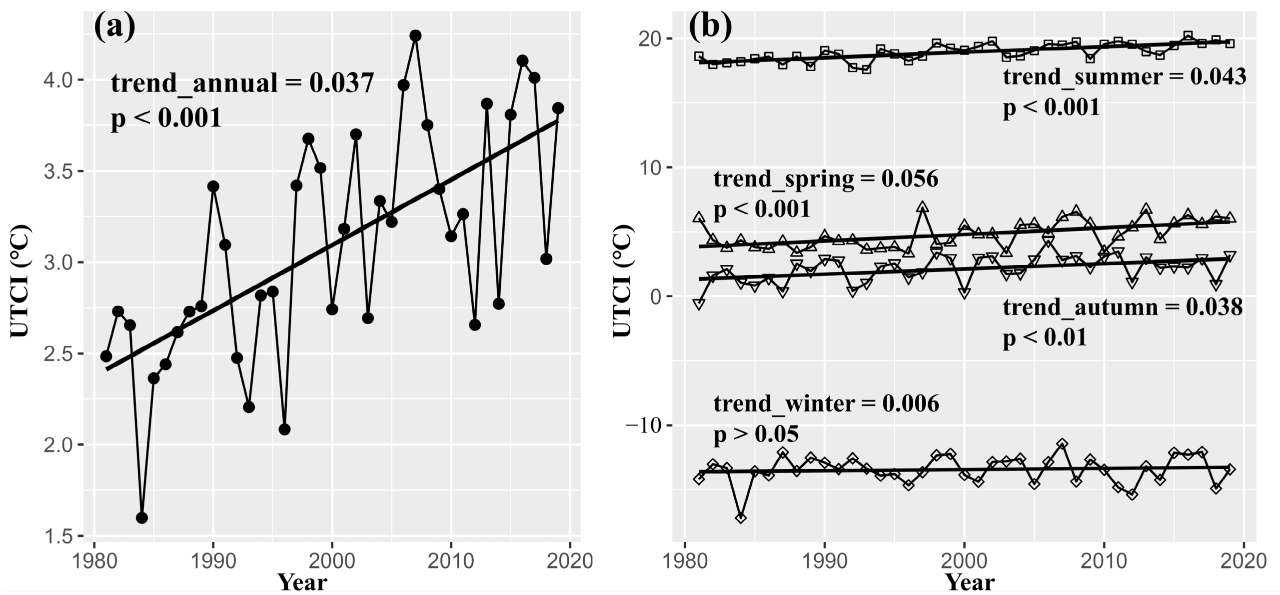

Figure 3. Trends of UTCI in Xinjiang for (**a**) annual and (**b**) seasonal during 1981–2019.

As shown in Figure 3b, the UTCI in Xinjiang from 1981 to 2019 exhibits an upward trend in all seasons. The upward trend in spring and summer is higher than in other seasons, while the upward trend in winter is insignificant. Ranked by Theil-Sen trend estimation results, the order is spring (0.056) > summer (0.043) > autumn (0.038) > winter (0.006). This indicates that UTCI warms faster in summer and slower in winter. Regarding the *p*-values from the MMK test, the results for summer and spring are highly significant, while the result for winter is insignificant. Xinjiang's UTCI generally reflects an upward trajectory, aligning with the region's rising temperatures driven by climate change [56]. Notably, the most pronounced increases are observed during summer and spring.

3.2. Comfortable Days

3.2.1. Number of Comfortable Days

As shown in Figure 4, we define the "no thermal stress" days as CDs and count the annual and seasonal CDs in Xinjiang from 1981 to 2019. In general, the distribution of CDs in Xinjiang exhibits remarkable spatial heterogeneity, and the number of CDs ranges from 0 to 189 days, with an average of 114 days. It indicates that from the climate suitability perspective, Xinjiang is acceptable and comfortable for living or traveling for over a third of the year. The regions with a higher number of CDs are mainly distributed in the Ili River Valley, both sides of the Tianshan Mountains, and the peripheral areas of the Tarim Basin, except for the eastern part. The oases surrounding the Junggar and the Tarim Basin are also urban distribution and population-dense areas in Xinjiang [57]. However, it is very uncomfortable in the mountain regions, particularly the Kunlun Mountains. The number of CDs in this area is fewer than 20 days. This indicates that the topography greatly affects the number of CDs in Xinjiang.

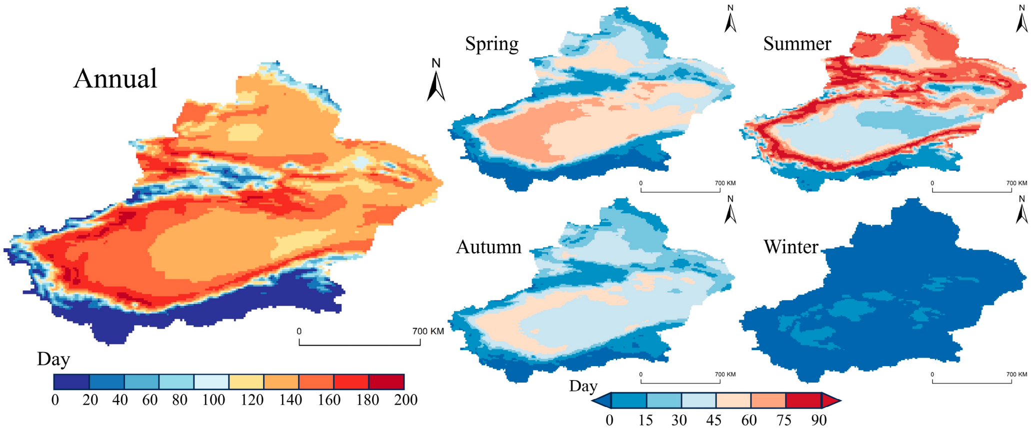

Figure 4. The mean annual and seasonal spatial distribution of CDs for 1981–2019.

For the seasonal number of CDs in Xinjiang, we found that the spring and autumn have similar distribution characteristics. There are more CDs in the western part of the Tarim Basin, reaching up to 70 days in the spring and 57 days in the autumn. The distribution of summer is more complex than that of spring and autumn. In summer, the distribution of CDs has a circular distribution. The number of CDs near Kunlun Mountain is still 0 days, and most of the Tarim Basin, the Turpan–Kumul Basin, and the southwestern part of the Junggar Basin are less than 45 days. During winter, almost all areas in Xinjiang are extremely cold and lack CDs, except for a few areas in the Tarim Basin with less than 15 CDs. The average number of CDs in each season is as follows: summer (53 d) > spring (34 d) > autumn (26 d) > winter (0 d), indicating that summer has a favorable climate during the year from the perspectives of comfort and safety.

3.2.2. Long Term Changes

Since analyzing the overall change in Xinjiang's CDs reveals minimal variation, we conduct our analysis by examining the changes in CDs across different regions within Xinjiang. Figure 5 shows the spatial distribution of the trends in the number of CDs in Xinjiang from 1981 to 2019. We found that the eastern Tarim Basin, Junggar Basin, and Kunlun Mountain in Xinjiang are experiencing a declining trend in CDs. In most areas, the number of CDs is decreasing by 2 days per decade, with the Hami region experiencing the most significant decline, with a decrease of 5 days per decade. The Altai Mountain region, Tianshan Mountain region, Ili River Valley, western Tarim Basin, and the south edge areas of the Tarim Basin are showing an increasing trend in the number of CDs, with an increase at most 8 days per decade. These regions have become more suitable for living and tourism in the past 40 years.

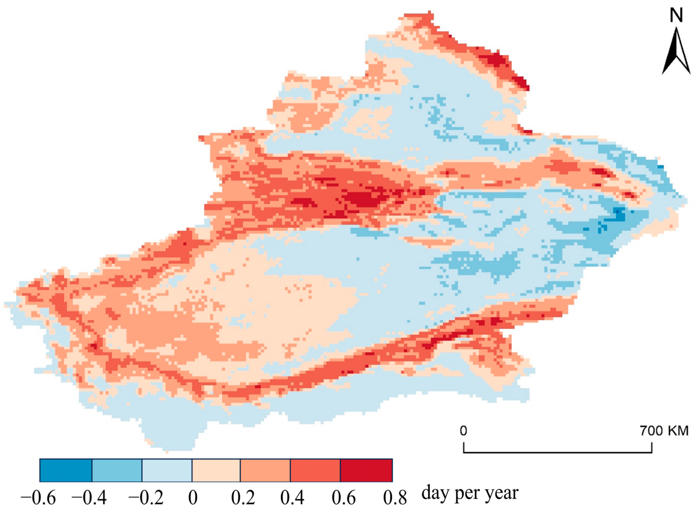

Figure 5. Spatial distribution of CDs trends in Xinjiang during 1981–2019.

3.3. Contributions of Meteorological Elements to UTCI Changes

Factors influencing the UTCI variations include air temperature, relative humidity, and wind speed. The relationship between meteorological elements and thermal comfort was analyzed based on the ERA5-Land dataset. Figure 6 shows the interannual changes in Xinjiang's annual air temperature, relative humidity, and wind speed from 1981 to 2019, with averages of 6.996 °C, 43.002%, and 1.370 m/s, respectively. The air temperature rose significantly from 1981 to 2019 (p < 0.001), with a rate of 0.365 °C decade^{-1} and a total increase of 1.123 °C. The relative humidity shows a decreasing trend (p < 0.01), with an average decline of 0.779% per decade, resulting in a total decrease of 1.606%. The wind speed fluctuated greatly, but the change was insignificant (p > 0.05), indicating that the air temperature increase and the relative humidity decrease were the main climate change characteristics in Xinjiang.

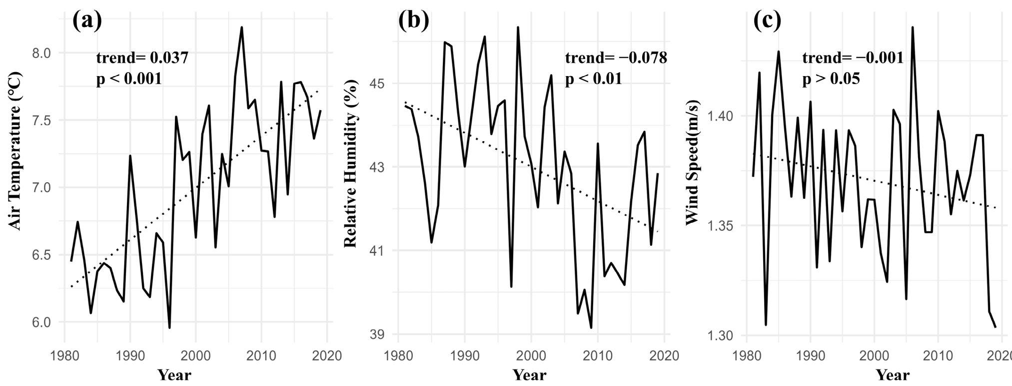

Figure 6. Changes in the average air temperature (**a**), relative humidity (**b**), and wind speed (**c**) in Xinjiang during 1981–2019.

Comparing the annual variations of meteorological elements to the annual variations of the UTCI and the number of CDs. We found a positive correlation between the air temperature trends and the variations in the UTCI and the number of CDs. Specifically, the correlation coefficient between air temperature and UTCI is r = 0.927 (p < 0.001), while the correlation coefficient between air temperature and CDs is r = 0.520 (p < 0.001). The correlation between wind speed with UTCI and CDs has not undergone a significance test (p > 0.05). The correlation between relative humidity and the UTCI is insignificant, and there is a negative correlation between relative humidity and CDs (r = −0.471, p < 0.01).

The spatial correlation coefficients between UTCI and CDs with air temperature, relative humidity, and wind speed in Xinjiang from 1981 to 2019 have been analyzed, as depicted in Figure 7. It showed that there are significant spatial correlations between them, and there are differences between different elements in the relevant regions. We have observed a significant and strong positive correlation between air temperature and UTCI, and this correlation is even in the whole area. Air temperature also positively correlates with CDs in most areas of Xinjiang (81%), except for the eastern part of Xinjiang, particularly in the Turpan Basin. This is because these areas experience extremely high temperatures during the summer, which reduces the number of CDs with the increase in temperature. The relative humidity is negatively correlated with UTCI and CDs, with a larger region showing significant correlations with UTCI (54%) than with CDs (20%). The relationship between wind speed UTCI and CDs is rather complex. Among them, wind speed is negatively correlated with UTCI in 68% of the areas in Xinjiang and positively correlated in 32% of the areas. Wind speed is negatively correlated with CDs in 48% of the areas and positively correlated in 52%. Generally speaking, in Xinjiang, climate comfort is positively correlated with air temperature and negatively correlated with relative humidity and wind speed. The correlation with air temperature is the strongest and most significant, followed by relative humidity, indicating that air temperature is the most important factor affecting climate comfort in Xinjiang.

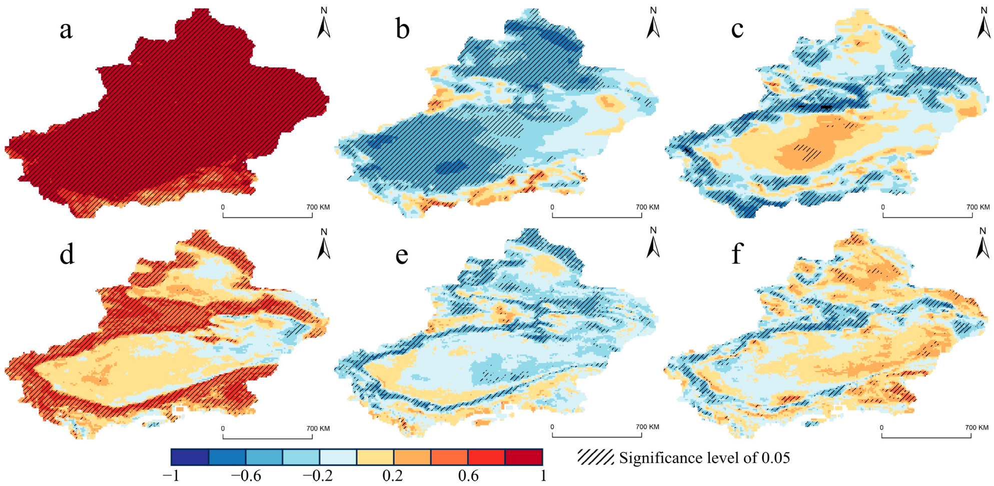

Figure 7. Spatial correlation coefficients between: (**a**) Air Temperature–UTCI; (**b**) Relative Humidity-UTCI; (**c**) Wind Speed-UTCI; (**d**) Air Temperature–CDs; (**e**) Relative Humidity-CDs; (**f**) Wind Speed-CDs in Xinjiang from 1981 to 2019.

3.4. Population Exposure

In order to estimate the number of people affected by climate change, we analyze the population under uncomfortable conditions. Figure 8 displays the population density maps of Xinjiang for 1990, 2000, 2010, and 2019. The population in Xinjiang is mainly concentrated in the northern slopes of the Tianshan Mountains, the Ili River Valley, and the western regions surrounding the Tarim Basin. It is distributed around major cities such as Urumqi, Ili, Kashi, and others. Population density is lower, and the high-density areas are relatively scattered. From an annual perspective, relatively high-density population areas in Xinjiang are increasing. For instance, areas with a population density exceeding 1000/km^2 grew from 0.03% in 1990 to 0.14% in 2019. Additionally, there is a trend of population concentration in Xinjiang, with the maximum population density increasing from 4753/km^2 in 1990 to 12,151/km^2 in 2019. It can be observed that both the population distribution areas and the population growth areas in Xinjiang show similarities with the distribution of UTCI and CDs. To some extent, thermal comfort has an impact on the distribution and changes in Xinjiang's population.

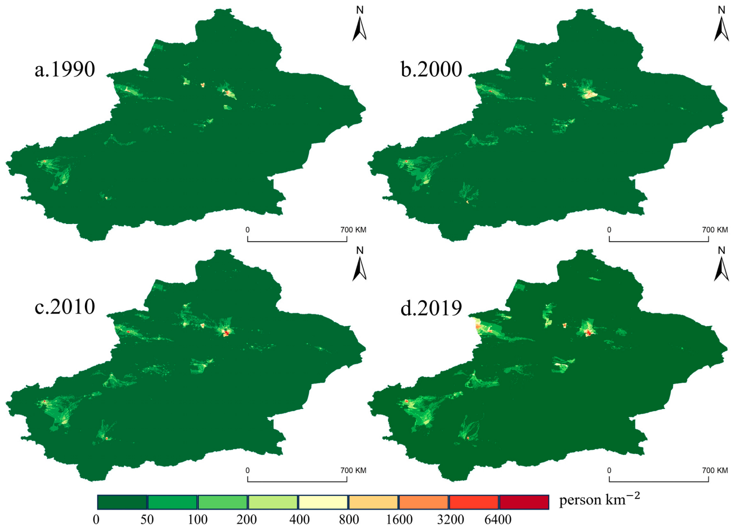

Figure 8. The distribution of population size in Xinjiang in 1990 (**a**), 2000 (**b**), 2010 (**c**), and 2019 (**d**).

Based on the long sequence of the uncomfortable days and population distribution data, the population exposure to an uncomforting climate was explored, and its temporal-spatial change pattern was shown in Figure 9. The high population exposure was mainly concentrated in high-density population areas, primarily centered around urban agglomeration in the North Slope of the Tianshan Mountains, the Ili River Valley, and the South-Western margin of Tarim Basin. The core cities include Urumqi, Karamay, Yining, Kashi, and Hotan. These cities served as high-exposure centers and, at the same time, exhibited the largest growth from 1990 to 2015. The average population exposure for the years 1990, 2000, 2010, and 2019 are 1998, 2548, 2944, and 3540 person-day, respectively. In 1990, the area of population exposure of more than 3000 people covered 17.09% in total, which stretched to 20.98%, 22.19%, and 23.89% in 2000, 2010, and 2019. Due to the rapid population growth in Xinjiang, the population exposure rate in Xinjiang from 1990 to 2015 has also been increasing rapidly. The range and intensity of population exposure in Xinjiang have both increased over time. Consequently, the surge in population exposure in Xinjiang heightens environmental and health risks for its residents. The urgent need for immediate action to adapt to the increasing population exposure at both regional and local scales may be necessary.

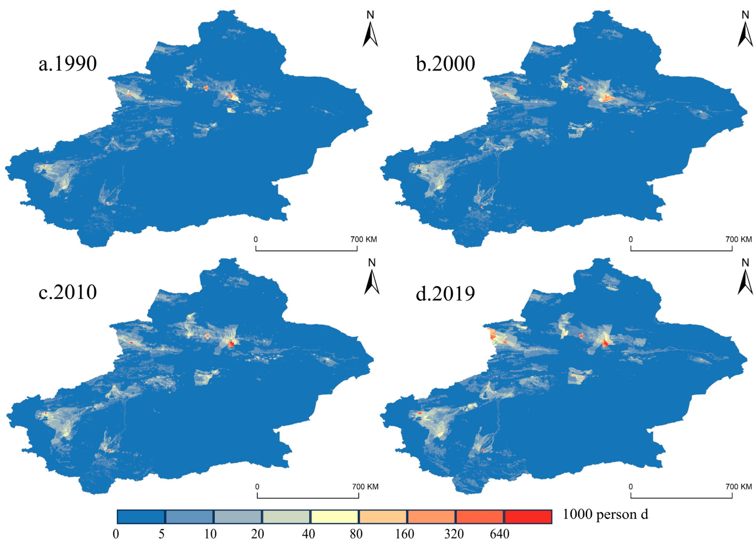

Figure 9. The population exposure under uncomfortable thermal conditions in 1990 (**a**), 2000 (**b**), 2010 (**c**), and 2019 (**d**).

4. Discussion

4.1. Comparison of the Results of Related Studies

This research is the first case study on thermal comfort conditions in Xinjiang using the UTCI index. And we have applied the latest high-resolution UTCI dataset HiTiSEA. In comparison to the UTCI dataset ERA5-HEAT (0.25° × 0.25°), the HiTiSEA (0.1° × 0.1°) dataset applied in this study has a higher spatial resolution. It provides more details on studying the spatial distribution of UTCI. As seen in Figure 10, the spatial contrast of ERA5-HEAT (b) UTCI distribution near the Tianshan Mountains is blurred, while the HiTiSEA (c) UTCI provides clearer boundaries of the Tianshan Mountains. Therefore, HiTiSEA provides us with more accurate information for our analysis of UTCI, making our related analyses more precise. Therefore, the assessment of the UTCI index in East Asia and South Asia is recommended using the HiTiSEA dataset.

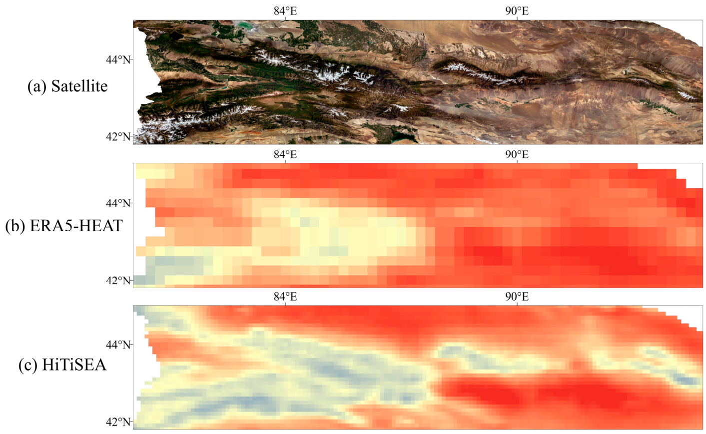

Figure 10. The satellite image (**a**), the distribution of UTCI from ERA5-HEAT (**b**) and HiTiSEA (**c**) for the region of Tianshan Mountains on 22 June 2019.

Currently, only one Chinese paper focuses on climate comfort in Xinjiang, which is based on the combination of THI, ICL, and CCI indices [58]. Similar to its research findings, the climate comfort is slightly cold and relatively comfortable in Xinjiang and has generally improved towards a warmer level. Jinkui Wu et al. analyze the variation of UTCI of Kashi during 1979–2018, a major city in southern Xinjiang. The findings reveal that the Kashi shares a similar stress with Xinjiang, with thermal perception at the coolish level and moderate cold stress. The increase rate of the UTCI in Kashi (0.31 °C/decade) is lower than the overall average for Xinjiang (0.37 °C/decade) [59]. Di Zeng et al. analyzed China–Pakistan Economic Corridor's (CPEC) spatial–temporal pattern of UTCI during 1979–2018, which covers the part area of southwest Xinjiang. Most areas of CEPC exhibit "moderate heat stress", and autumn has the most CDs, which differs from Xinjiang. Moreover, the increased rate of UTCI in CPEC (0.33 °C/10a) is slower than in Xinjiang [60,61].

In comparison to research using the UTCI for climate comfort in China, we found that the most widely distributed thermal stress in China is Moderate cold stress (35.43%), while in Xinjiang, the most widely distributed thermal stress is Slight cold stress (42.53%). In both Xinjiang and China average, the distribution of UTCI in the spring and autumn is like the annual pattern. Summer offers the highest proportion of "No thermal stress", while winter exhibits the lowest [32,62]. The growth trend of the UTCI in Xinjiang is higher than the China average growth rate (0.22 °C decade^{-1}) [37]. The relevant research indicates that the rate of temperature increase in Xinjiang is higher than the China average. This suggests that influenced by temperature changes, the increase of the UTCI in Xinjiang is also higher than the national average in the context of climate change. The UTCI in summer has been increasing in all regions of China; Northern Xinjiang has the second largest increase rate where the average UTCI increase rate is 0.047 °C/a, consistent with the results of the summer UTCI growth rate presented in this article (0.043 °C/a) [35].

4.2. Implications for Tourism Development

Climate comfort is a vital tourism resource and a significant limiting factor for tourism development. The comfort level and length of the comfort period have important practical significance for tourism development [61]. As suggested by Ge et al. [62], regions with large diurnal climate variability, such as Xinjiang, should give more detailed information for tourists to make decisions and for the relevant government departments and tourism enterprises to formulate policies and plans. Our results indicate that, overall, the tourism climate is not an advantage for tourism in Xinjiang. The annual average climate comfort is slightly on the cooler side, and there are significant seasonal variations. Specifically, the summer has universal and sufficient climate resources, but they are inadequate for winter throughout the whole region. Studies by Kong and others [63] show that northern Xinjiang is an ideal destination for "Bsunbird" tourism throughout summer. In the summer, except for the Tarim Basin and Turpan Basin interior areas, almost the entire season in other parts of Xinjiang is characterized by CDs. The summer provides the best time for tourists to be outside, and a favorable climate can be integrated with other tourism resources in the design of tourism products, such as hiking and mountaineering. According to the results of Lei Hua et al., the number of top tourist attractions with the best climate comfort level is relatively high in spring and autumn in China, so Xinjiang's tourist attractions have a greater opportunity to attract visitors [33]. In the spring, except for the northern regions of the Junggar Basin and mountainous areas, the number of CDs exceeds 45 days, allowing areas such as Yining and Urumqi to develop spring skiing, while places like Kashi and Turpan can develop folk-custom tourism. In autumn, cities like Aksu and Hotan, located in the northern and western parts of the Tarim Basin, can develop tourism activities that combine the sightseeing of golden Populus euphratica leaf and Taklamakan Desert.

Based on the trends in UTCI and CD changes, we have observed the increasing UTCI and the lengthening of CDs in Xinjiang. In this context, climate change potentially benefits the health and well-being of the residents of Xinjiang, as well as fosters opportunities for the development of tourism in this region.

4.3. Limitations of the Study

Some limitations should be addressed in the future. Firstly, this study focuses exclusively on climate comfort in Xinjiang, with a relatively limited spatial scope, which imposes certain constraints on the spatial scale of the research. Furthermore, although the UTCI is a widely used bioclimatic index in climatology research and has yielded results in studies across various climate category regions worldwide, it still has some deficiencies. Notably, in the UTCI-clothing model, the thresholds of the UTCI mainly depend on the individuals of European and American backgrounds and may not be consistent with Chinese or Asians on this point, which may bring some error to calculation results. In the future, the studies should modify the model and adjust the classification standard according to the local climate conditions and people's character. In addition, this study only considers the daily average UTCI and does not consider the maximum and minimum values of the UTCI, ignoring the daily UTCI fluctuations and extreme conditions. Last, it is worth knowing the changes in the regional climate comfort pattern under future climate scenarios using the latest CMIP6 climate models extension of the present study.

5. Conclusions

This research is the first study to use the UTCI to evaluate thermal comfort's spatial and temporal characteristics in Xinjiang. Based on a newly developed high-resolution dataset HiTiSEA, the distribution and trends of UTCI and CDs during 1981–2019 are comprehensively assessed, and an in-depth study on the relationship between thermal comfort conditions with meteorological elements and population is conducted. The key findings of this study are the following:

(1) From 1981 to 2019, the mean annual UTCI over Xinjiang was 3 °C and has significantly increased at a rate of 0.37 °C decade^{-1}. This indicates that the thermal stress

over Xinjiang is "slight cold stress" and is changing in a good direction under the background of global warming. On the annual and seasonal scales, 7 of the 10 UTCI thermal stress categories were experienced, ranging from very strong cold stress to strong heat stress. The ranking of climate comfort level by season is summer > spring > autumn > winter. The growth rate by season is spring > summer > autumn > winter, suggesting the climate conditions in summer are the best while winter's is the worst. Spatially, the distribution of UTCI is influenced by topography and exhibits characteristics where the basin is higher than the mountainous areas.

(2) The mean annual number of CDs is 114 days, with the range of 0 to 189 days. The highest number of CDs were observed in the Ili River Valley, both sides of the Tianshan Mountains, and the peripheral areas of the Tarim Basin, which exceeded 180 days. The lowest CD number was recorded in the Kunlun Mountains, with CDs of fewer than 20 days. Seasonal analysis shows that in spring and autumn, relatively large CD values occur in the western part of the Tarim Basin with 70 days. During summer, high CD values have a circular distribution around the basin (>75 days). During winter, regions are extremely cold and lack CDs. The change of CDs shows an increasing trend of 0–8 d/decade^{-1} in the Altai Mountains region, Tianshan Mountain region, Ili River Valley, and western Tarim Basin. Other region shows a decreasing trend of 0–6 day.

(3) For the related climate variables, air temperature and climate comfort are positively correlated in Xinjiang, and relative humidity and wind speed were negatively correlated. Compared to other variables, air temperature is the most crucial factor affecting climate comfort in Xinjiang.

(4) In the last 30 years, the range and intensity of population exposure to uncomfortable climate in Xinjiang have increased. The high population exposure was mainly concentrated around urban agglomeration in the North Slope of the Tianshan Mountains, the Ili River Valley, and the South-Western margin of Tarim Basin, with significant exposure area and population expansion.

Author Contributions: Writing—original draft preparation, J.Q.; writing—review and editing, J.Q. and F.H.; visualization, J.Q. and X.M.; methodology, J.Q. and B.H.; supervision, Z.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Second Tibetan Plateau Scientific Expedition and Research Program (STEP) [Grant No. 2019QZKK0401; No. 2019QZKK1004].

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Masson-Delmotte, V.; Zhai, P.; Pirani, A.; Connors, S.L.; Péan, C.; Berger, S.; Caud, N.; Chen, Y.; Goldfarb, L.; Gomis, M. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2021; Volume 2.
2. Pörtner, H.-O.; Roberts, D.C.; Adams, H.; Adler, C.; Aldunce, P.; Ali, E.; Begum, R.A.; Betts, R.; Kerr, R.B.; Biesbroek, R. *Climate Change 2022: Impacts, Adaptation and Vulnerability*; IPCC: Geneva, Switzerland, 2022.
3. Parsons, K. *Human Thermal Environments: The Effects of Hot, Moderate, and Cold Environments on Human Health, Comfort and Performance*; CRC Press: Boca Raton, FL, USA, 2007.
4. Wu, J.; Liu, C.; Wang, H. Analysis of Spatio-temporal patterns and related factors of thermal comfort in subtropical coastal cities based on local climate zones. *Build. Environ.* **2022**, *207*, 108568. [CrossRef]
5. Rupp, R.F.; Vásquez, N.G.; Lamberts, R. A review of human thermal comfort in the built environment. *Energy Build.* **2015**, *105*, 178–205. [CrossRef]
6. Chen, L.; Wen, Y.; Zhang, L.; Xiang, W.-N. Studies of thermal comfort and space use in an urban park square in cool and cold seasons in Shanghai. *Build. Environ.* **2015**, *94*, 644–653. [CrossRef]

7. Pantavou, K.; Theoharatos, G.; Mavrakis, A.; Santamouris, M. Evaluating thermal comfort conditions and health responses during an extremely hot summer in Athens. *Build. Environ.* **2011**, *46*, 339–344. [CrossRef]
8. Li, Y.; Zhang, S.H.; Han, J.T.; Zhao, Y.; Han, Q.; Wu, L.Y.; Wang, X.; Qiu, Z.Y.; Zou, T.Q.; Fan, C. A study of the temporal and spatial variations in the suitability of the environment in Chinese cities for tourism and in strategies for optimizing the environment. *Int. J. Digit. Earth* **2022**, *15*, 527–552. [CrossRef]
9. Potchter, O.; Cohen, P.; Lin, T.-P.; Matzarakis, A. Outdoor human thermal perception in various climates: A comprehensive review of approaches, methods and quantification. *Sci. Total Environ.* **2018**, *631–632*, 390–406. [CrossRef]
10. Hill, L.; Griffith, O.W.; Flack, M. The Measurement of the Rate of Heat-Loss at Body Temperature by Convection, Radiation, and Evaporation. *Philos. Trans. R. Soc. Lond. Ser. B Contain. Pap. A Biol. Character* **1916**, *207*, 183–220.
11. HOUGHTEN, F.C. Determining lines of equal comfort. *ASHVE Trans.* **1923**, *29*, 163–176.
12. Siple, P.A.; Passel, C.F. Measurements of dry atmospheric cooling in subfreezing temperatures. *Proc. Am. Philos. Soc.* **1945**, *89*, 177–199. [CrossRef]
13. Yaglou, C.; Minaed, D. Control of heat casualties at military training centers. *Arch. Indust. Health* **1957**, *16*, 302–316.
14. Thom, E.C. The discomfort index. *Weatherwise* **1959**, *12*, 57–61. [CrossRef]
15. Jendritzky, G.; de Dear, R.; Havenith, G. UTCI—why another thermal index? *Int. J. Biometeorol.* **2012**, *56*, 421–428. [CrossRef] [PubMed]
16. Gagge, A.P.; Fobelets, A.; Berglund, L. A standard predictive index of human response to the thermal environment. *ASHRAE Trans.* **1986**, *92*, 709–731.
17. Staiger, H.; Laschewski, G.; Grätz, A. The perceived temperature–a versatile index for the assessment of the human thermal environment. Part A: Scientific basics. *Int. J. Biometeorol.* **2012**, *56*, 165–176. [CrossRef] [PubMed]
18. Gonzalez, R.; Nishi, Y.; Gagge, A. Experimental evaluation of standard effective temperature a new biometeorological index of man's thermal discomfort. *Int. J. Biometeorol.* **1974**, *18*, 1–15. [CrossRef]
19. Höppe, P. The physiological equivalent temperature–a universal index for the biometeorological assessment of the thermal environment. *Int. J. Biometeorol.* **1999**, *43*, 71–75. [CrossRef]
20. Błażejczyk, K. UTCI—10 years of applications. *Int. J. Biometeorol.* **2021**, *65*, 1461–1462. [CrossRef]
21. Blazejczyk, K.; Epstein, Y.; Jendritzky, G.; Staiger, H.; Tinz, B. Comparison of UTCI to selected thermal indices. *Int. J. Biometeorol.* **2012**, *56*, 515–535. [CrossRef]
22. Błażejczyk, K. New climatological and physiological model of the Human Heat Balance outdoor (MENEX) and its applications in bioclimatological studies in different scales. *Zesz. Inst. Geogr. Przestrz. Zagospod. PAN* **1994**, *28*, 27–58.
23. Zare, S.; Hasheminejad, N.; Shirvan, H.E.; Hemmatjo, R.; Sarebanzadeh, K.; Ahmadi, S. Comparing Universal Thermal Climate Index (UTCI) with selected thermal indices/environmental parameters during 12 months of the year. *Weather. Clim. Extrem.* **2018**, *19*, 49–57. [CrossRef]
24. Krüger, E.L. Literature review on UTCI applications. In *Applications of the Universal Thermal Climate Index UTCI in Biometeorology: Latest Developments and Case Studies*; Springer: Cham, Switzerland, 2021; pp. 23–65.
25. Doshi, S.C.; Lohmann, G.; Rimbu, N.; Ionita, M. Spatiotemporal trend analysis of climate indices for the European continent. *J. Water Clim. Chang.* **2023**, *14*, 3112–3130. [CrossRef]
26. Antonescu, B.; Mărmureanu, L.; Vasilescu, J.; Marin, C.; Andrei, S.; Boldeanu, M.; Ene, D.; Ţilea, A. A 41-year bioclimatology of thermal stress in Europe. *Int. J. Climatol.* **2021**, *41*, 3934–3952. [CrossRef]
27. Roffe, S.J.; van der Walt, A.J.; Fitchett, J.M. Spatiotemporal characteristics of human thermal comfort across southern Africa: An analysis of the Universal Thermal Climate Index (UTCI) for 1971–2021. *Int. J. Climatol.* **2023**, *43*, 2930–2952. [CrossRef]
28. Hamed, M.M.; Kyaw, A.K.; Nashwan, M.S.; Shahid, S. Spatiotemporal changes in Universal Thermal Climate Index in the Middle East and North Africa. *Atmos. Res.* **2023**, *295*, 107008. [CrossRef]
29. Huang, Y.; Zhang, X.; Zhang, D.; Zhang, L.; Zhang, W.; Ren, C.; Pan, T.; Chu, Z.; Chen, Y. Spatial-temporal characteristics of Arctic summer climate comfort level in the context of regional tourism resources from 1979 to 2019. *Sustainability* **2021**, *13*, 13056. [CrossRef]
30. Ullah, S.; You, Q.; Wang, G.; Ullah, W.; Sachindra, D.A.; Yan, Y.; Bhatti, A.S.; Abbas, A.; Jan, M.A. Characteristics of human thermal stress in South Asia during 1981–2019. *Environ. Res. Lett.* **2022**, *17*, 104018. [CrossRef]
31. Kyaw, A.K.; Hamed, M.M.; Shahid, S. Spatiotemporal changes in Universal Thermal Climate Index over South Asia. *Atmos. Res.* **2023**, *292*, 106838. [CrossRef]
32. Kong, Q.; Zheng, J.; Wang, X. Spatial pattern and temporal variation in thermal comfort in China from 1979 to 2014. *Resour. Sci.* **2016**, *38*, 1129–1139.
33. Hua, L.; Zhang, H.; Liu, X.; Yang, X.; Duan, H.; Wu, T.; Nastos, P. Climate comfort evaluation of national 5a touristattractions in the mainland of China based on universal thermal climate index. *Adv. Meteorol.* **2020**, *2020*, 4256164. [CrossRef]
34. Wu, F.; Yang, X.; Shen, Z. Regional and seasonal variations of outdoor thermal comfort in China from 1966 to 2016. *Sci. Total Environ.* **2019**, *665*, 1003–1016. [CrossRef]
35. Hui-Jiao, L.; Hong-Yun, M.; Mi, Z. Analysis of the variation characteristics of human thermal comfort in summer of China from 1980 to 2019 based on UTCI. *Adv. Clim. Change Res.* **2022**, *18*, 58.
36. Huang, J.; Shen, S.; Zhao, M.; Cheng, C. Assessment of summer regional outdoor heat stress and regional comfort in the Beijing-Tianjin-Hebei agglomeration over the last 40 years. *GeoHealth* **2023**, *7*, e2022GH000725. [CrossRef] [PubMed]

37. Zhou, L.-Y.; Schmude, J.; Zhai, P.-M.; Wang, Q. Changes in thermal comfortable condition in the Qinghai-Tibet Plateau from 1979 to 2020. *Adv. Clim. Chang. Res.* **2022**, *13*, 666–675. [CrossRef]
38. Zhou, C.; Zhang, D.; Cao, Y.; Wang, Y.; Zhang, G. Spatio–temporal evolution and factors of climate comfort for urban human settlements in the Guangdong–Hong Kong–Macau Greater Bay Area. *Front. Environ. Sci.* **2022**, *10*, 1001064. [CrossRef]
39. Xu, Y.; Yang, J.; Chen, Y. NDVI-based vegetation responses to climate change in an arid area of China. *Theor. Appl. Climatol.* **2016**, *126*, 213–222. [CrossRef]
40. Yao, J.; Chen, Y.; Guan, X.; Zhao, Y.; Chen, J.; Mao, W. Recent climate and hydrological changes in a mountain–basin system in Xinjiang, China. *Earth-Sci. Rev.* **2022**, *226*, 103957. [CrossRef]
41. Yafeng, S.; Yongping, S.; Dongliang, L.; Guowei, Z.; Yongjian, D.; Ruji, H.; Ersi, K. Discussion on the present climate change from warm-dry to warm-wet in northwest china. *Quat. Sci.* **2003**, *23*, 152–164.
42. Li, B.; Chen, Y.; Shi, X. Why does the temperature rise faster in the arid region of northwest China? *J. Geophys. Res. Atmos.* **2012**, *117*. [CrossRef]
43. Fang, S.; Yan, J.; Che, M.; Zhu, Y.; Liu, Z.; Pei, H.; Zhang, H.; Xu, G.; Lin, X. Climate change and the ecological responses in Xinjiang, China: Model simulations and data analyses. *Quat. Int.* **2013**, *311*, 108–116. [CrossRef]
44. Hu, R.; Fan, Z.; Wang, Y.; Yang, Q.; Huang, Y. Assessment about the impact of climate change on environment in Xinjiang since recent 50 years. *Arid. Land Geogr.* **2001**, *24*, 97–103.
45. Li, N.; Lin, H.; Wang, T.; Li, Y.; Liu, Y.; Chen, X.; Hu, X. Impact of climate change on cotton growth and yields in Xinjiang, China. *Field Crop. Res.* **2020**, *247*, 107590. [CrossRef]
46. Shijin, W.; Xinggang, M.; Jia, X. A Review of the Impacts of Climate Change on Tourism in the Arid Areas: A Case Study of Xinjiang Uygur Autonomous Region in China. *Adv. Meteorol.* **2022**, *2022*, 8768542. [CrossRef]
47. Yan, Y.; Xu, Y.; Yue, S. A high-spatial-resolution dataset of human thermal stress indices over South and East Asia. *Sci. Data* **2021**, *8*, 229. [CrossRef] [PubMed]
48. Di Napoli, C.; Barnard, C.; Prudhomme, C.; Cloke, H.L.; Pappenberger, F. ERA5-HEAT: A global gridded historical dataset of human thermal comfort indices from climate reanalysis. *Geosci. Data J.* **2021**, *8*, 2–10. [CrossRef]
49. Zhang, H.; Luo, M.; Zhao, Y.; Lin, L.; Ge, E.; Yang, Y.; Ning, G.; Cong, J.; Zeng, Z.; Gui, K. HiTIC-Monthly: A monthly high spatial resolution (1 km) human thermal index collection over China during 2003–2020. *Earth Syst. Sci. Data* **2023**, *15*, 359–381. [CrossRef]
50. Wang Can, W.J. *Kilometer Grid Dataset of China's Historical Population Spatial Distribution (1990–2015)*; National Tibetan Plateau Data Center: Beijing, China, 2022. [CrossRef]
51. Fiala, D.; Havenith, G.; Brode, P.; Kampmann, B.; Jendritzky, G. UTCI-Fiala multi-node model of human heat transfer and temperature regulation. *Int. J. Biometeorol.* **2012**, *56*, 429–441. [CrossRef] [PubMed]
52. Sen, P.K. Estimates of the Regression Coefficient Based on Kendall's Tau. *J. Am. Stat. Assoc.* **1968**, *63*, 1379–1389. [CrossRef]
53. Hamed, K.H. Trend detection in hydrologic data: The Mann–Kendall trend test under the scaling hypothesis. *J. Hydrol.* **2008**, *349*, 350–363. [CrossRef]
54. Patakamuri, S.K.; O'Brien, N.; Patakamuri, M.S.K. Package 'modifiedmk'. 2020. Available online: https://cran.pau.edu.tr/web/packages/modifiedmk/modifiedmk.pdf (accessed on 1 June 2023).
55. Li, M.; Zhou, B.-B.; Gao, M.; Chen, Y.; Hao, M.; Hu, G.; Li, X. Spatiotemporal dynamics of global population and heat exposure (2020–2100): Based on improved SSP-consistent population projections. *Environ. Res. Lett.* **2022**, *17*, 094007. [CrossRef]
56. Li, Q.; Chen, Y.; Shen, Y.; Li, X.; Xu, J. Spatial and temporal trends of climate change in Xinjiang, China. *J. Geogr. Sci.* **2011**, *21*, 1007–1018. [CrossRef]
57. RUZI, T.; KASIMU, A.; Pengwen, G.; Mengchen, Z. Study on the spatiotemporal changes of Xinjiang urban expansion based on DMSP/OLS and NPP/VIIRS data. *J. China Agric. Univ.* **2020**, *25*, 156–165. [CrossRef]
58. Guan, J.; Li, D.; Xu, X.; Wang, Y.; Wang, X. Spatialtemporal pattern and evolution of tourism comfort period in Xinjiang in recent 40 years. *J. Southwest Univ.* **2022**, *44*, 185–197. [CrossRef]
59. Wu, J.K.; Jin, T.; Wu, Y.C.; Ding, Y.J.; Mu, Y.Q.; Zeng, D. The Variation of UTCI with the Background of Climate Change and Its Implications for Tourism in a Complicated Climate Region in Western China. *Sustainability* **2022**, *14*, 15047. [CrossRef]
60. Zeng, D.; Wu, J.; Mu, Y.; Deng, M.; Wei, Y.; Sun, W. Spatial-temporal pattern changes of UTCI in the China-Pakistan economic corridor in recent 40 years. *Atmosphere* **2020**, *11*, 858. [CrossRef]
61. Zeng, D.; Wu, J.; Mu, Y.; Li, H.; Deng, M.; Wei, Y.; Sun, W. An assessment of tourism climate comfort in the China–Pakistan economic corridor. *Sustainability* **2020**, *12*, 6981. [CrossRef]
62. Ge, Q.S.; Kong, Q.Q.; Xi, J.C.; Zheng, J.Y. Application of UTCI in China from tourism perspective. *Theor. Appl. Climatol.* **2017**, *128*, 551–561. [CrossRef]
63. Kong, Q.; Zheng, J.; Fowler, H.J.; Ge, Q.; Xi, J. Climate change and summer thermal comfort in China. *Theor. Appl. Climatol.* **2019**, *137*, 1077–1088. [CrossRef]