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HEALTH RISK APPRAISAL OF URBAN THERMAL ENVIRONMENT AND CHARACTERISTIC ANALYSIS ON VULNERABLE POPULATIONS

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Highlights

- The spatiotemporal evolution characteristics of Summer UHI effect were assessed.
- The impact of Summer UHI effect on residents' emotional health was evaluated.
- The characteristics of vulnerable age populations' genders, family state were analyzed.
- The findings serve as a reference for healthy and sustainable cities.

Abstract. Continuous global warming and frequent extreme high temperatures keep the urban climate health risk increasing, seriously threatening residents' emotional health. Therefore, analysis on spatial distribution of the health risk that the urban heat island (UHI) effect imposes on emotional health as well as basic research on the characteristics of vulnerable populations need to be conducted. This study, with Tianjin city as the case, analyzed data from Landsat remote-sensing images, meteorological stations, and digital maps, explored the influence of summer UHI effect on distress (a typical negative emotion factor) and its spatiotemporal evolution, and conducted difference analysis on the age groups, genders, family state, and distress levels of vulnerable populations. The results show: (1) During the period of 1992–2020, the level and area of UHI influence on residents' distress drastically increased–influence level elevated from level 2–4 to level 4–7, and high-level influence areas were concentrated in six districts of central Tianjin. (2) Influence of the UHI effect on distress varied in different age groups–generally dropping with fluctuations as residents got older, especially residents aged 50–59. (3) Men experienced a W-shaped pattern in distress and were more irritable and unsteady emotionally; while women were more sensitive to distress in the beginning, but they became more placid as temperature got higher. (4) Studies on family status show that couples living together showed sound heat resistance in the face of heat stress, while middle-aged and elderly people living alone or with children were relatively weak in adjusting to high ambient temperature.

Keywords: distress, environmental management, Tianjin, urban heat island, urban thermal environment, vulnerable population.

Introduction

With the advance of technology, human beings yield an increasing impact on climate. In detail, greenhouse gases, including carbon dioxide emitted from burning fossil fuels, lead to the continuous global warming; activities of human production and daily life affect the underlying surface, resulting in regional climate changes and higher probability of extreme events, such as heat wave, storm, flood, and forest fire. According to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (2013), global average temperature in the 21st century may grow by more than 1.5–2 °C (compared with 1850–1900), and the growth will not stop until 2100 (Blas et al., 2021; Liu et al., 2017a). In the meantime, UHI effect intensifies the heat waves in urban areas, yielding direct or indirect damages on people's mental and physical health. According to *China Report of the Lancet Countdown on Health and Climate Change* (Cai et al., 2021), the number of deaths related to heat waves in China in 2020 increased by about 92%. Continuous high-temperature days can cause "physiological sunstroke" and "emotional sunstroke" (Xu et al., 2011; Yu et al., 2020). High temperature would trigger a complex physiological mechanism called arousal. And long-term exposure to high temperature

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would excite sympathetic nerves, increase blood viscosity, and keep cardiovascular system running under high load. As a result, it would probably trigger heat cramps, respiratory diseases, and cardiovascular diseases (Astrom et al., 2020; Zheng et al., 2016). And high temperature also yields a significance impact on the emotional response part of hypothalamus, leading to emotional instability, abnormal behaviors, and endocrine disorder, which would further cause negative emotions like distress, nervousness, irritation and hostility (Basu et al., 2018; Feller et al., 2018)–Summer Seasonal Affective Disorder, or emotional sunstroke. Ding et al. surveyed residents in New South Wales of Australia and found that each 1 °C of temperature increase brought 0.2% more extremely painful emotions (Ding et al., 2016). Studies on the disease data and summer high temperature in Pearl River Delta, Yangtze River Delta, and Beijing-Tianjin-Hebei Region (Huang et al., 2020a; Wang et al., 2019) show that the incidence and patient number of emotional disorder caused by urban high temperature increased (Escobar et al., 2021). In addition, according to World Health Organization (WHO), the El Nino event from 1982 to 1983 increased the water surface temperature of the southern and central Pacific Ocean by 4–5 °C and raised the global incidence of mental disease by about 8% (Kovats, 2000). These studies prove that UHI affects residents' emotional health. Therefore, to prepare for intensified global warming in the future, it is imperative to probe into the relationship between the UHI effect and residents' emotional health, conduct a health risk assessment (HRA) in public urban areas in spatiotemporal scale, reduce the negative impact of climate change on residents' emotional health, and set up effective measures of environmental management.

The "sprawling" urban forms and intensifying urban population density leads to extensive UHI effect, affecting the urban environmental quality and resident health. Scholars in China and other countries have conducted a large number of studies on UHI effect, but early studies primarily focused on the spatiotemporal evolution features of UHI and their relationship to landscape patterns, lacking sufficient exploration on how UHI influences human health (Liu, et al., 2017b; Mirzaei & Haghighat, 2010). In recent years, with the advance of global warming, scholars worldwide have started to pay closer attention to such research directions. For example, Anderson et al. analyzed the death risk caused by heat waves in 43 cities in the United States (1987–2005) and found that the mortality of residents increased by 3.74% on days with heat waves (Anderson & Bell, 2011). However, these studies focus on pathology, and the relationship between high temperature and mortality and incidence of relevant diseases (Witt et al., 2015; Yin et al., 2018), rarely treating emotional health as a critical factor of how high-temperature environments affect residents' health (Wolf et al., 2014). Our research group found that negative emotions triggered by thermal environment mainly include distress, irritation, hostility, and nervousness, among which distress is the most obvious one, so this study chose distress as the research subject (Huang et al., 2020b).

In the extremely-high-temperature weather, faced with influence from urban micro-climate, ambient temperature, and human behaviors and activities, people may suffer from different doses of high-temperature, and be threatened by multiple diseases or even death–demonstrated as heat vulnerability in certain groups of people. Heat vulnerability refers to residents' uncomfortableness and inconvenience due to exposure to high temperature. The influence of the UHI effect on residents' emotional health is continuous and complicated, affected by multiple factors, including the physiological, social, and economic status of population with heat vulnerability (Chen et al., 2017; Valerie et al., 2018). To be specific, population with heat vulnerability includes infants, children, middle-aged and elderly people. Middle-aged and elderly people, in particular, due to their weakened physiological functions and ability to spontaneously adjust their body temperature, are more prone to the negative effects from high-temperature environments. That is why they are commonly categorized as population vulnerable to extremely high temperature (Hames et al., 2016). And infants and children, on the other hand, are not included as subjects of this study, due to their insufficient cognitive ability. At present, most heat-vulnerability studies are about the physiological status (age, gender, medical history, etc.) and socioeconomic status (level of education, income, vocation, etc.), lacking enough attention to their physiological and social features and emotional health (Hoyt et al., 2020). Hence, based on Erikson Stages of Psychosocial Development, this study was targeted at middle-aged and elderly at and over 40 years old, and chose three major factors–age, gender, and family status–to conduct difference analysis on distress.

In general, this study, with Tianjin city as the case, analyzed data from Landsat remote-sensing images, meteorological stations, and digital maps via platforms like ArcGIS, MATLAB, and SPSS, to explore the influence of summer UHI effect and its spatiotemporal evolution. Moreover, this study chose distress as the symbol of negative emotions to construct a theoretical model of relationship between UHI intensity and residents' distress level and to carry out difference analyses on the age groups, genders, family state, and distress levels of these vulnerable populations. The purpose was to draw a warning map of emotional health risks in spatiotemporal scale, run a health impact appraisal on urban thermal environment, identify high-risk populations and areas, so as to improve residents' emotional health and to offer better solutions for comprehensive environmental administration.

1. Material and methods

1.1. Overview of study area

Tianjin city (38°33′–40°15′N and 116°42′–118°03′E), economic center of the Bohai Economic Rim, neighbors the Yan Mountains in the north and the Bohai Sea in the east. As of 2020, Tianjin's permanent population had reached 15.6183 million, population density 1,328 persons / km^2, and the urbanization rate of permanent population 84%. The city enjoys profuse land resources–of the total land area, 40.7% is cultivated land, 18.33% is urban, town, and rural land, and industrial and mining land, 2.76% is land for transportation, and 26.43% is water area. In the study area, Hexi District has the most parks–17 parks, covering about 151.44 hectares, while other Districts all have no more than 10 parks, except for Nankai District which has 8 parks, covering the largest area–332.82 hectares. In the past half a century, mean temperature in Tianjin showed an obvious upward trend–annual mean temperature increased by around 1.9 °C, and the average warming rate was significantly higher than other cities in China (Li et al., 2020; Zhao et al., 2020). The maximum monthly average temperature surpassed 29 °C, and the peak temperature reached up to 41.7 °C. Tianjin, as one of the fastest urbanizing cities in China, has been experiencing not only an intensified urban thermal environment as the urban population and land use scale expand, but also higher resident health risks (Guo et al., 2009). This study chose 10 districts in Tianjin with a total area of 2,311.7 km^2 as study subjects (Figure 1), including Heping District, Hongqiao District, Hebei District, Nankai District, Hexi District, Hedong District, Jinnan District, Dongli District, Beichen District, and Xiqing District.

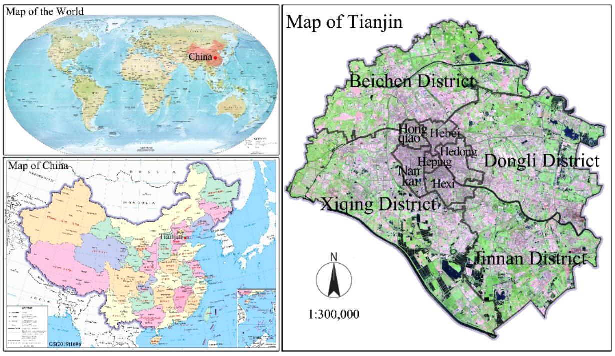

Figure 1. Overview of study areas

1.2. Data collection

This study selected Landsat images from the years 1992, 2001, 2011, and 2020. Images were collected at about 10:30am in July and August of each sampling year, with no cloud coverage, low wind velocity, high spatiotemporal resolution, and sound imaging conditions in the study areas. Weather data were collected from a total of 183 meteorological stations in Tianjin and Beijing–a megacity nearby. These stations were selected because they were only minimally impacted by the surrounding artificial structures, hardened pavements, and other factors, thus ensuring data accuracy. In addition, this study applied the population profiles, including ages, genders, and family state from Tianjin Statistical Yearbook 2020 (Tianjin, 2020).

Temperature data were collected from small WS-30 handheld weather stations 1.5 m above ground. Such stations are ±0.3 °C in accuracy, ±3% in humidity, ±0.3 m/s in wind velocity, and automatically record data every 1 minute after data are stabilized–quick in response, high in accuracy, and suitable for outdoor urban environments. The thermosensitive resistance principle was applied in recording temperature–as temperature varies, the resistance value changes accordingly. Questionnaire surveys were conducted in the designated 17 locations where weather stations were placed, mainly in the empty space in the center of residential districts, squares, and parks.

Between the hours of 8:00–12:00 and 14:00–17:00 on July 28 to August 27, 2019, a total of 992 questionnaires were handed out, and 417 were retrieved. At 9:00 and during the period of 13:00–17:00 on July 31 to August 14, 2020, a total of 1,326 questionnaires were handed out, and 563 retrieved. After filtering out invalid questionnaires, including blank ones, unfinished ones, and those filled out by subjects under 40 years old, a total of 379 and 552 questionnaires were confirmed valid respectively, which were combined (931 in total) to establish a basic database. On such basis, a form of temperature-emotion relationship was created by objectively rating the outdoor environment via field survey and examination, and rating the thermal environment via collecting the background information of questionnaire respondents.

1.3. Data processing

1.3.1. Inversion of land surface temperature

This study used Landsat satellite images for land surface temperature (LST) retrieval, and applied atmospheric correction method–first estimate the influence of atmosphere on surface thermal radiation, then subtract it from the total thermal radiation received from satellite sensors (Kos et al., 2020; Yue & Liu, 2018), to obtain surface brightness temperature which was then converted into relevant LST. The formula is as Eq. (1):

$$T_S = 1231.08 / \ln(774.89 / (L_\lambda - 0.78 - 0.9(1-\varepsilon)1.37) + 1), \quad (1)$$

where: L_λ is the thermal infrared radiant luminance received by satellite sensors; ε is the surface radiant emittance. While calculating ε, surface coverage can be categorized into three types – water body, urban and town area, and natural surface (Sobrino et al., 2004; Qin et al., 2003), and the formula for the surface radiant emittance of each type is as Eqs (2)–(4):

$$\varepsilon_w = 0.995; \quad (2)$$

$$\varepsilon_b = 0.9589 + 0.086 P_v - 0.0671 P_v^2; \quad (3)$$

$$\varepsilon_s = 0.9625 + 0.0641 P_v - 0.0461 P_v^2, \quad (4)$$

where: P_v is the vegetation coverage and can be calculated by Eq. (5):

$$P_v = (N - 0.05) / 0.02, \quad (5)$$

where: N refers to the Normalized Vegetation Index (NDVI) of the entire study area.

1.3.2. Sample analysis

SPSS software was utilized to draw a box plot of sample temperature data, and the data distribution is shown in Figure 2. The results show that the sample data covered 31–48 °C and were evenly distributed in spatial terms. Interquartile range (IQR) was 4, which took up 25% of range, proving that temperature samples were not concentrated within a single interval, but rather scattered in various intervals, which in turn guaranteed enough samples in each interval. At the same time, median fell at 39.5 °C and mode 35.5 °C, demonstrating that samples covered most weather conditions with temperature over 35 °C. Basic descriptive analysis proved that samples were suitable for studying the influence of urban thermal environment on residents' distress.

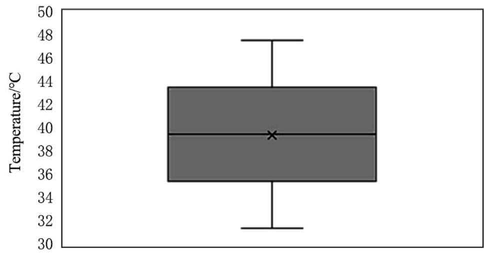

Figure 2. Coverage interval of sample temperatures

Next, to visualize the frequency distribution, the dataset of temperatures was divided into multiple temperature intervals every 1 °C. In eight intervals–25–26 °C, 26–27 °C, 27–28 °C, 29–30 °C, 30–31 °C, 48–49 °C, 49–50 °C, and 50–51 °C, the frequency was always less than 16, and relative frequency less than 1%, which shows that these temperature intervals, due to insufficient sample quantity, were not symbolic enough to represent relevant typical emotions. To compare the emotional health risks of different temperatures, control groups of low-and middle-temperatures were formed and experimented. To summarize, the temperature interval this study selected for analysis was 31–48 °C.

1.3.3. Appraisal of the UHI's influence on distress

As the UHI effects pick up intensity, it elevates the ambient temperature of the city, and influences residents' distress. So, the prerequisite for assessing environmental health risks is to accurately separate and evaluate the UHI's influence on distress. Based on the 931 valid questionnaire, weather data from handheld weather stations, as well as relevant research (Berry et al., 2010; Noelke et al., 2016), this study applied the CFtool, the curve-fitting function of MATLAB, to analyze curvilinear regressions and establish a theoretical relational model between instantaneous temperature and distress, thereby screening out the most fitted equation (Figure 3a).

Based on the relational model between instantaneous temperature and distress, this study selected the hourly data of summer temperature fields from weather stations and 14-day heat waves, to calculate the hourly distress

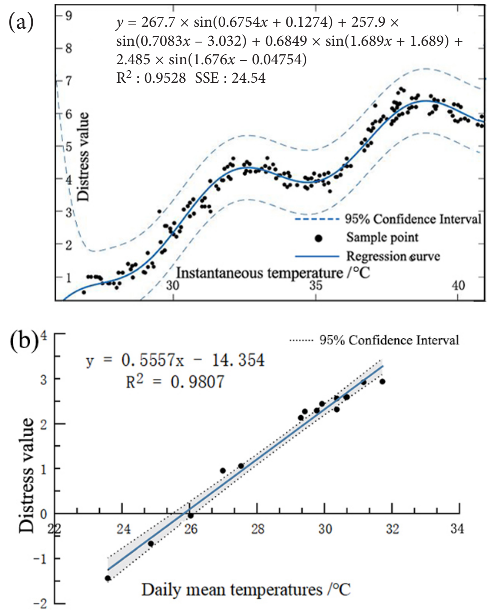

Figure 3. Analysis of the relationship between temperature and distress: a) Theoretical relationship between transient temperature and distress; b) Relation curve between daily mean temperature and distress factors

value between 08:00 and 17:00, to further attain intraday average distress value. Next, with the average hourly temperature during 08:00–17:00 as the daytime mean temperature, this study fitted a linear equation about daytime mean temperature and average distress value (Figure 3b). In a word, based on the environmental stress theory and the relation equation between ambient temperature and emotion, this study extrapolated the regression equation in line with statistical test, to analyze how urban summer high temperature affects residents' distress.

This study set the daily mean temperature of 27.5 °C as the threshold of the UHI's effect on distress in Tianjin, to assess the emotional health risks that summer daily mean temperatures, combined with heat island warming, had on distress. Based on the response relational model between high temperatures and distress (Figure 4), the influence of the UHI on distress was graded into 10 levels (Table 1). Levels 1 and 2 represent low-level influence, levels 3 and 4 middle-level influence, levels 5 through 7 high-level influence, and levels 8 through 10 extreme-high-level influence (Noelke et al., 2016; Denissen et al., 2018; Qi et al., 2015).

Table 1. Grading of influence of high temperature on distress

Level	Temperature/°C	Emotional changes
1	<30	Comfortable
2	30–31	Emotionally stable
3	31–32	Mildly uncomfortable
4	32–33	Uncomfortable and uneasy
5	33–34	Be in a bad mental state, feel restless and anxious
6	34–35	Be in a bad mental state, feel restless and anxious

End of Table 1

Level	Temperature/°C	Emotional changes
7	35–36	Be moody, bad-tempered, and irritable
8	36–36.5	Start to feel agitated and damage things
9	36.5–37	Start to feel agitated and damage things
10	>37	Feel extremely agitated and prone to violence

2. Results and discussion

2.1. Feature analysis of spatiotemporal evolution of urban thermal field

Summer urban thermal fields are mainly comprised of basic summer high temperatures and UHI warming. In this study, satellite images from Landsat 5, 7, and 8 were utilized for air temperature regression, and a regression equation was formulated based on data from weather stations in Tianjin and Beijing, in order to figure out the spatiotemporal distribution of UHIs in Tianjin during the period of 1992–2020 (Figure 4). Air temperatures were graded–low-temperature area: ≤27 °C; middle-temperature area: 27–28 °C; sub-high-temperature area: 28–30 °C; high-temperature area: 30–32 °C; and extreme-high-temperature area: 32–34 °C (Table 2).

The results show that in 1992, middle-temperature areas assumed the highest proportion, while high-temperature areas were concentrated in six districts of central Tianjin–Heping District, Hongqiao District, Hebei District, Nankai District, Hexi District, and Hedong District of Tianjin city. The reason was that in central Tianjin–packed with high-density low-rise buildings and a substantial population–urban heating elements were high in number but slow in cooling rate, resulting in an ambient warming. During 2001–2011, sub-high-temperature areas expanded from central Tianjin to the city's outskirts, raising proportion up from 54.6% to 80%. Small yet high-density patches were scattered in high-temperature areas, expanding outwards. Rapid urbanization pushed the construction in cities and towns outwards, jumping out of the original monocentric model. At the same time, green space spots were scattered evenly in the central urban area, easing up the thermal environment in central Tianjin to some degree. In 2020, high-temperature areas expanded drastically, making up 37%, with spatial features being concentrated in central urban areas, and clustered in groups in the outskirts. Urban vegetation coverage dropped, impervious water surfaces increased in number, and plot ratio of buildings also climbed up, thereby obstructing the urban ventilation corridors and exacerbating the urban thermal environment. All in all, during the period of 1992–2002, as urbanization rates picked up, middle- and low-temperature areas gradually disappeared, while sub-high- and high-temperature areas expanded from central urban areas to outskirts. Artificial structures in urban areas increased in quantity, while urban blue and green space was insufficient. As a result, the city's ability to alleviate the UHI effect was weakened, affecting urban residents' emotional health.

2.2. Analysis of the UHI's influence on distress

Based on the criteria of assessing the UHI's risk of elevating emotional distress, a spatiotemporal distribution map of the UHI's influence on distress in Tianjin in four periods during 1992–2020 (Figure 5) and a table of content of different distress levels (Table 2) were created. In general, the rapid urbanization gave birth to a series of warming effects that low-level influence area dropped drastically. The UHI's influence on residents' distress in Tianjin elevated in level, a high-level influence area expanded by the year from the central urban area to the outskirts; and the influence level increased from levels 2–4 to levels 4–7.

Results show that in 1992, distress influence was mainly graded as ranging from levels 2–4, and the level 5 influence area was small in area, concentrated in the central urban area while scattered like small patches in outskirts in a radial pattern. The reason was that early urbanization was conducted in the central urban area, aggregating heat, exacerbating the UHI effect, and affecting residents' distress. During 2001–2011, the influence area of level 2 shrank and was gradually fragmented compared with the year 1992 itself, but levels 3–5 influence areas showed an obvious trend of expansion from being concentrated in central urban areas like patches while sprawling to the outskirts. Industrialization and the intensified thermal environment in the outskirts and the surrounding city further triggered distress. In 2020, the area of level 4–7 areas increased generally. To be more specific, the level

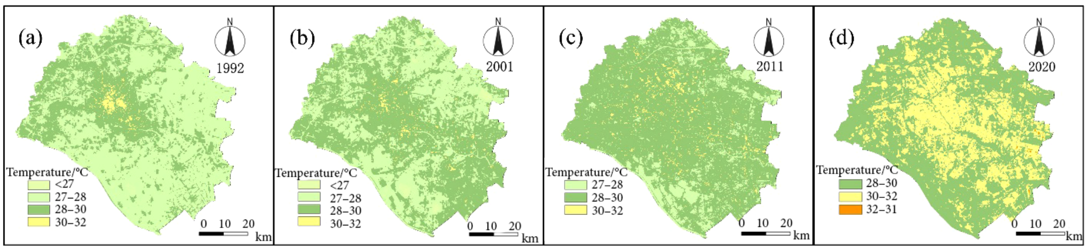

Figure 4. Level distribution of UHI's influence on high temperature from 1992 to 2020:
a) represent 1992; b) represent 2001; c) represent 2011; d) represent 2020

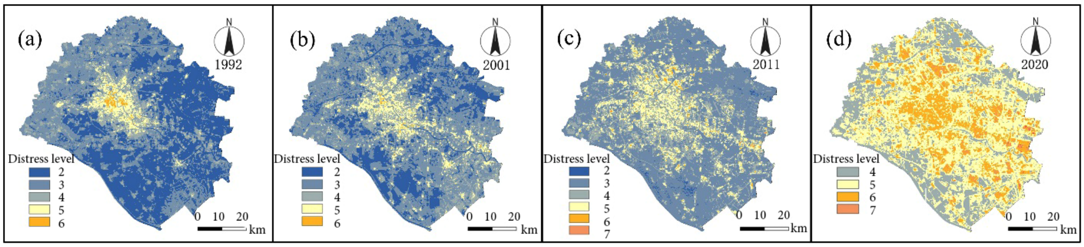

Figure 5. Distribution of the different levels of UHI influence on distress from 1992 to 2020: a) represent 1992; b) represent 2001; c) represent 2011; d) represent 2020

Table 2. Area of the UHI's influence on distress

Year \ Level		2	3	4	5	6	7
1992	Area/km^2	968.751	904.478	313.490	111.803	13.024	–
	Ratio/%	41.90	39.12	13.56	4.83	0.56	–
2001	Area/km^2	504.936	1174.474	444.044	180.396	7.691	–
	Ratio/%	21.84	50.80	19.20	7.80	0.33	–
2011	Area/km^2	17.599	1278.623	660.624	326.718	26.749	1.264
	Ratio/%	0.76	55.31	28.57	14.13	1.15	0.05
2020	Area/km^2	–	–	596.498	1233.511	436.546	42.453
	Ratio/%	–	–	25.80	53.35	18.88	1.83

5 influence area stood out and expanded by 48.5% compared with 1992, characterized by being concentrated in a central urban area and scattered like large patches in the outskirts, showing an upward trend in terms of influence on distress.

2.3. Analysis of the features of vulnerable populations

2.3.1. Age

Scholars in China and other countries have historically focused on how people of different age groups adjust to high temperatures (Applegate et al., 1981). This study categorized middle-aged and elderly into 5 age groups (40–49-year-old, 50–59-year-old, 60–69-year-old, 70–79-year-old, and ≥80-year-old) to explore how the UHI affected their distress. The variation trend of distress incidence among all age groups is shown in Figure 6. The results show that the UHI's effect on distress differed among the various age groups. As people got older, their response to the effect generally dropped with fluctuations. To be specific, aging had a significant negative correlation with the UHI's influence on distress for residents who were in the 40–49-year-old, 50–59-year-old, and 60–69-year-old groups. For residents in the 50–59-year-old group, the influence experienced an intensified downward trend–9.6%. The reason is: as people get older, their physical and psychological stress response dwindles while average heat resistance enhances; on the other hand, as people accumulate more life experience, they become calmer and more able to adjust to the changes in the surrounding environment, thereby less prone to distress triggered by the external environment. However, in the age group of 70–79-year-old, the trend went the other way around and climbed up a little bit, the reason of which awaits further exploration in the future (Itani et al., 2020; Lin & Hu, 2000).

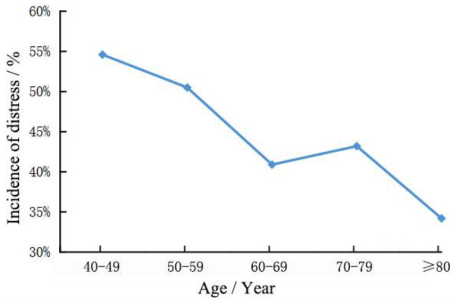

Figure 6. Variation trend of distress of middle-aged and elderly

2.3.2. Gender

At present, most studies on the relationship between high temperature and residents' emotional health cover the difference in gender. Therefore, this study, differentiates between men and women when exploring how the UHI influences the distress of middle-aged and elderly (Lee & Parpart, 2018; Tawatsupa et al., 2010). Generally speaking, as shown in Figure 7a, as distress levels elevated, both men and women's influence level dropped significantly. In detail, men's distress influence experienced a W-shaped pattern, with distress incidences under both low-level and high-level influences higher than those of women, and with levels 3–5 influence showing a fluctuated trend. In other words, under extremely high temperatures, men, as compared with women, were weaker in their heat resistance, more irritable and unsteady emotionally; meanwhile, women were more prone to the influence of distress at levels 2–4, and more sensitive to distress at the beginning, but they became less agitated as temperatures were higher.

According to the map of gender difference in emotional health risks of distress in various administrative districts of Tianjin (Figure 7b), high-level influence areas were concentrated in six districts of central Tianjin–Heping District, Hongqiao District, Hebei District, Nankai District, Hexi District, and Hedong District of Tianjin city, accounting for a bigger proportion (51.7% higher) than those in four around-central city districts on average. To be specific, Nankai District and Hexi District were the most influenced–1.9 times that of four around-city districts. Women were generally more influenced than men, and women in the six districts of central Tianjin were more influenced than women in the four around-city districts. The first reason was that there were more women than men in each district, and there were more women in the six districts of central Tianjin than in the four around-city districts; second, in the six districts of central Tianjin, as the city's cultural and economic center, suffered from traffic congestion, environmental degradation, and severe heat stress in downtown caused by high population density and clustering of intensive building complexes (Kyriakopoulos et al., 2020), which further intensified the UHI's influence on distress.

2.3.3. Family status

Facing constant high temperatures, the middle-aged and elderly of different family statuses were influenced by distress differently. As shown in Figure 8a, as distress levels elevated, the degree of influence that distress yielded on people of different family statuses dropped in general. More specifically, for people living alone, the influence decreased significantly with fluctuations at levels 3–5, and they were more prone to being impacted by changes in thermal environment. Faced with heat stress, couples who live together showed sound heat resistance, and only 15% of them suffered from distress at levels 4–7. In the meantime, people living alone and people living with children were weaker in adjusting to high ambient temperatures, more prone to heat stress, and respectively 32% and 28.1% of them showed symptoms of distress at levels 4–7.

According to the map of family status difference in emotional health risks of distress in various administrative districts of Tianjin (Figure 8b), people in the six districts of central Tianjin were more influenced by distress (2.4 times) than those in the four around-city districts; middle-aged and elderly living with children were the most influenced group–respectively 2.3 and 1.8 times more influenced than people living alone and

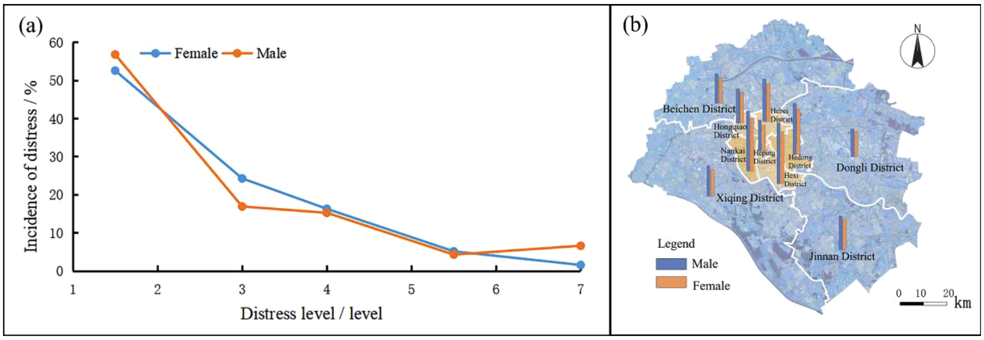

Figure 7. Gender differences and spatial characteristics of distress: a) Distribution of distress influence levels of different genders; b) Map of gender difference in emotional health risks of distress

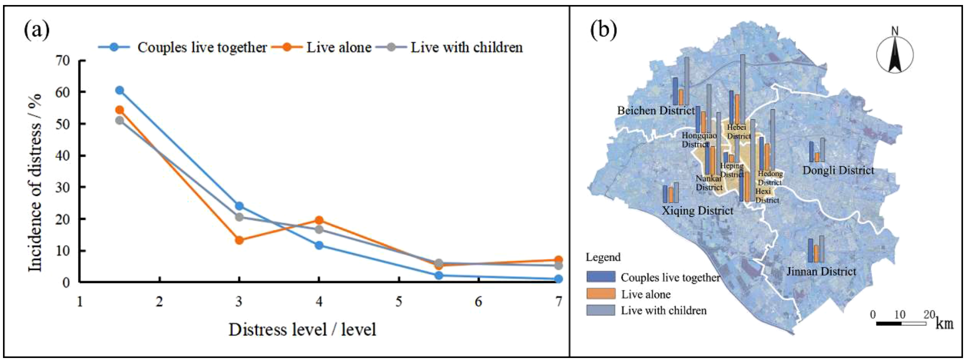

Figure 8. Family status differences and spatial characteristics of distress: a) Distribution of distress influence levels of different family statuses; b) Map of family status difference in emotional health risks of distress

couples who lived together, which was even more obvious in the six districts of central Tianjin. The reason for this is that currently in China, middle-aged and elderly who live with their children or help take care of offspring suffer from high life stress, serious generation gaps and conflicts, housing shortage in central urban areas, and many other problems, thus being more prone to distress. In the meantime, the UHI effect in the central urban area is intensified by factors like rapid urbanization, high population density, industrial agglomeration, and artificial heat emission, resulting in a severe thermal environment in summer where residents feel uncomfortable, and thus adding to the emotional health risks of distress (Stankuniene et al., 2020; Streimikiene et al., 2020).

2.3.4. Analysis on distress and built environment features

As shown in Figure 9, in each of the six districts of central Tianjin, local climate zones (LCZ) are distinct, buildings are mostly low-rise and mid-rise with intensive buildings accounting for 21.95%. Outside the outer ring, land is covered by high-density vegetations or fields. Built environment, on the other hand, share the same variation trend with the influence of vulnerable population from downtown to the suburbs. In detail, in the LCZs of six districts of central Tianjin, intensive buildings were clustered, and residents suffered from more obvious distress. Meanwhile, in the four round-city districts–Xiqing District, Beichen District, Jinnan District, and Dongli District, land was covered by vegetations and fields, and residents were less distressful due to the cooling and psychological adjustment from green space. In the meantime, in the six districts of central Tianjin, women, and those who live with children were less prone to distress, mainly because of the urban architectural layout–buildings were mostly clustered, small-sized, with relatively small living area per capita, roads and streets are narrow, and parks and green spaces are small in number. In a word, residents faced greater threat from thermal environment, leading to more obvious emotional health risk (Kanteraki et al., 2020; Kyriakopoulos, 2021).

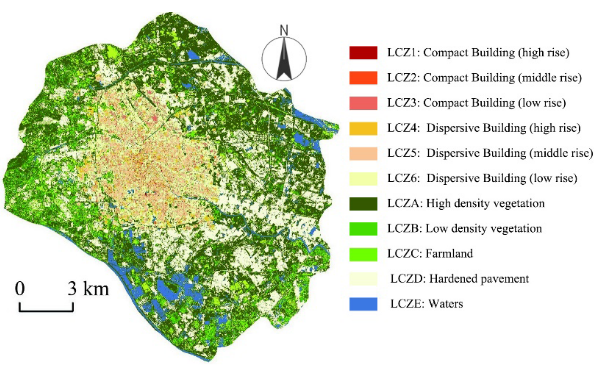

Figure 9. Distribution of LCZ in Tianjin

Conclusions

Since the 21st century, heat waves caused by global warming have been significantly more frequent, intense, and long-lasting. Given the two major challenges awaiting China in the next decades (population ageing and continuous urbanization), Chinese people may be more vulnerable facing extreme high temperatures, especially in terms of emotional health. This study used remote-sensing images from four periods between 1992–2020 for temperature inversion and summarized the characteristics of spatiotemporal changes in urban thermal fields, to assess the emotional health risks of distress that the UHI imposes on residents, and run difference analysis between distress and factors like age, gender, and family status of vulnerable populations. Here are the results:

(1) During the period from 1992–2020, the level and area of the UHI's influence on residents' distress showed a significant upward trend, with influence levels climbing from levels 2–4 to levels 4–7, and with high-level influence areas concentrated in six districts of central Tianjin–Heping District, Hongqiao District, Hebei District, Nankai District, Hexi District, and Hedong District of Tianjin city.

(2) The UHI's influence on distress varied among different age groups. As residents got older, the influence dropped, with fluctuations most obvious in those aged 50–59-year-old.

(3) Men experienced a W-shaped development in distress and were more irritable and unsteady emotionally; meanwhile, women were more sensitive to distress in the beginning, but they became more complacent as temperatures increased.

(4) Studies on family status show that couples living together showed sound heat resistance in the face of heat stress; while middle-aged and elderly living alone or with children were relatively weak in adjusting to high environment temperature.

This study is targeted at the emotional factor of distress and based on the difference in spatiotemporal distribution of the UHI's influence on emotional health at the city scale, but without middle- and small-scale explorations. In the future, more targeted and refined studies are planned in order to dig deeper into the mechanism of how the UHI influences irritation, hostility, nervousness, and other negative emotions prone to thermal environment; to analyze the difference in how urban internal landscapes (park, square, etc.) influence residents' emotional health via typical actual cases; to perfect the appraisal system for emotional health risks, with the purpose of offering decision-making guidance on comprehensively administering urban thermal environments, thus facilitating the progress of environmental protection.

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References

Anderson, G. B., & Bell, M. L. (2011). Heat waves in the United States: Mortality risk during heat waves and effect modification by heat wave characteristics in 43 U.S. communities. *Environmental Health Perspectives*, *119*(2), 210–218. https://doi.org/10.1289/ehp.119-a81

Applegate, W. B., Runyan, J. W., Brasfield, L., Williams, M. L., Konigsberg, C., & Fouche, C. (1981). Analysis of the 1980 heat wave in Memphis. *Journal of the American Geriatrics Society*, *29*(8), 337–342. https://doi.org/10.1111/j.1532-5415.1981.tb01238.x

Astrom, D. O., Astrom, C., Forsberg, B., Vicedo-Cabrera, A. M., Gasparrini, A., Oudin, A., & Sundquist, K. (2020). Heat wave–related mortality in Sweden: A case-crossover study investigating effect modification by neighbourhood deprivation. *Scandinavian Journal of Public Health*, *48*(4), 428–435. https://doi.org/10.1177/1403494818801615

Basu, R., Gavin, L., Pearson, D., Ebisu, K., & Malig, B. (2018). Examining the association between apparent temperature and mental health-related emergency room visits in California. *American Journal of Epidemiology*, *187*(4), 726–735. https://doi.org/10.1093/aje/kwx295

Berry, H. L., Bowen, K., & Kjellstrom, T. (2010). Climate change and mental health: A causal pathways framework. *International Journal of Public Health*, *55*(2), 123–132. https://doi.org/10.1007/s00038-009-0112-0

Blas, I. D., Gonzalez, L., & Carranza, C. (2021). Integrated assessment models (IAMS) applied to climate change and energy transition. *DYNA*, *96*(3), 316–321. https://doi.org/10.6036/9922

Cai, W., Zhang, C., Suen, H. P., Ai, S., Bai, Y., Bao, J., Chen, B., Cheng, L., Cui, X., Dai, H., Di, Q., Dong, W., Dou, D., Fan, W., Fan, X., Gao, T., Geng, Y., Guan, D., Guo, Y., … Gong, P. (2021). The 2020 China report of the Lancet Countdown on health and climate change. *The Lancet Public Health*, *6*(1), 64–81. https://doi.org/10.1016/S2468-2667(20)30256-5

Chen, Q., Ding, M. J., Yang, X. C., & Hu, K. J. (2017). Spatially explicit assessment of heat health risks using multi-source data: A case study of the Yangtze River delta region. *Journal of Geo-information Science*, *19*(11), 1475–1484.

Denissen, J. J. A., Butalid, L., Penke, L., & Van Aken, M. A. G. (2008). The effects of weather on daily mood: A multilevel approach. *Emotion*, *8*(5), 662–667. https://doi.org/10.1037/a0013497

Ding, N., Berry, H. L., Bennett, C. M., & Scott, J. G. (2016). The importance of humidity in the relationship between heat and population mental health: Evidence from Australia. *PLOS ONE*, *11*(10), 1–15. https://doi.org/10.1371/journal.pone.0164190

Escobar, F. B., Velasco, C., Motoki, K., Byrne, D. V., & Wang, Q. J. (2021). The temperature of emotions. *PLOS ONE*, *16*(6), e0252408. https://doi.org/10.1371/journal.pone.0252408

Feller, S. C., Castillo, E. G., Greenberg, J. M., Abascal, P., Van Horn, R., & Wells, K. B. (2018). Emotional well-being and public health: Proposal for a model national initiative. *Public Health Reports*, *133*(2), 136–141. https://doi.org/10.1177/0033354918754540

Guo, J., Li, M. C., & Liu, D. Y. (2009). Effects of urbanization on air temperature of Tianjin in recent 40 years. *Ecology and Environmental Sciences*, *18*(1), 29–34. https://doi.org/10.16258/j.cnki.1674-5906.2009.01.028

Hames, E., Stoler, J., Emrich, C. T., Tewary, S., & Pandya, N. (2016). A GIS approach to identifying socially and medically vulnerable older adult populations in South Florida. *Gerontologist*, *57*(6), 1133–1141. https://doi.org/10.1093/geront/gnw106

Hoyt, M. A., Wang, W. T., Boggero, I. A., Eisenlohr-Moul, T. A., & Segerstrom, S. C. (2020). Emotional approach coping in older adults as predictor of physical and mental health. *Psychology and Aging*, *35*(4), 591–603. https://doi.org/10.1037/pag0000463

Huang, H. C., Deng, X., Yang, H. L., Li, S. M., & Li, M. Y. (2020a). Spatial evolution of the effects of urban heat island on residents' health. *Tehnički vjesnik*, *27*(5), 1427–1435. https://doi.org/10.17559/TV-20200503211912

Huang, X. J., Wang, B., Liu, M. M., Guo, Y. H., & Li, Y. Y. (2020b). Characteristics of urban extreme heat and assessment of social vulnerability in China. *Geographical Research*, *39*(7), 1534–1547. https://doi.org/10.11821/dlyj020190608

Intergovernmental Panel on Climate Change. (2013). *Working group I contribution to the IPCC fifth Assessment Report (AR5). Climate change 2013: The physical science basis.* http://www.climatechange2013.org/images/uploads/WGIAR5_WGI-12Doc2b_FinalDraft_All.pdf

Itani, M., Ghaddar, N., Ghali, K., & Laouadi, A. (2020). Bioheat modeling of elderly and young for prediction of physiological and thermal responses in heat-stressful conditions. *Journal of Thermal Biology*, *88*, 102533. https://doi.org/10.1016/j.jtherbio.2020.102533

Kanteraki, A. E., Kyriakopoulos, G. L., Zamparas, M., Kapsalis, V. C., Makridis, S. S., & Mihalakakou, G. (2020). Investigating thermal performance of residential buildings in Marmari region, South Evia, Greece. *Challenges*, *11*(1), 5. https://doi.org/10.3390/challe11010005

Kos, E., Pashynskyi, V., Klymenko, Y., & Pashynskyi, M. (2020). Analysis of methods for determining climate loads at a specified territory point by meteorological data. *Tehnički glasnik*, *14*(2), 206-211. https://doi.org/10.31803/tg-20191125075805

Kovats, R. S. (2000). El Nino and human health. *Bulletin of the World Health Organization*, *78*(9), 1127–1135.

Kyriakopoulos, G. L. (2021). Should low carbon energy technologies be envisaged in the context of sustainable energy systems? In *Low carbon energy technologies in sustainable energy systems* (pp. 357–389). Academic Press. https://doi.org/10.1016/B978-0-12-822897-5.00015-8

Kyriakopoulos, G., Ntanos, S., Anagnostopoulos, T., Tsotsolas, N., Salmon, I., & Ntalianis, K. (2020). Internet of things (IoT)-enabled elderly fall verification, exploiting temporal inference models in smart homes. *International Journal of Environmental Research and Public Health*, *17*(2), 408. https://doi.org/10.3390/ijerph17020408

Lee, J., & Parpart, J. L. (2018). Constructing gender identity through masculinity in CSR reports: The South Korean case. *Business Ethics-A European Review*, *27*(4), 309–323. https://doi.org/10.1111/beer.12191

Li, R., Guo, Y. X., Guo, C. C., Zhang, B., Zhang, W. J., Wang, Y. D., & Wang, Z. L. (2020). Evolution of annual and spring precipitation and air temperature in Tianjin coastal zone in recent 60 years. *Journal of Tianjin Normal University (Natural Science Edition)*, *40*(5), 44–53. https://doi.org/10.19638/j.issn1671-1114.20200507

Lin, Y. L., & Hu, Z. F. (2000). *Environmental psychology*. China Architecture & Building Press.

Liu, J., Shu, S. C., Lin, X. G., & Shi, Z. W. (2017a). A systematic review of research on anti-disaster capability in urban disaster. *Journal of Engineering Science and Technology Review*, *10*(5), 181–189. https://doi.org/10.25103/jestr.105.22

Liu, Y. X., Peng, J., & Wang, Y. L. (2017b). Relationship between urban heat island and landscape patterns: From city size and landscape composition to spatial configuration. *Chinese Journal of Ecology*, *37*(23), 7769–7780. https://doi.org/10.5846/stxb201610202142

Mirzaei, P. A., & Haghighat, F. (2010). Approaches to study Urban Heat Island-Abilities and limitations. *Building and Environment*, *45*(10), 2192–2201. https://doi.org/10.1016/j.buildenv.2010.04.001

Noelke, C., Mcgovern, M., Corsi, D. J., Jimenez, M. P., Stern, A., Wing, I. S., & Berkman, L. (2016). Increasing ambient temperature reduces emotional well-being. *Environmental Research*, *151*, 124–129. https://doi.org/10.1016/j.envres.2016.06.045

Qi, X., Hu, W. B., Page, A., & Tong, S. L. (2015). Associations between climate variability, unemployment and suicide in Australia: A multicity study. *BMC Psychiatry*, *15*, 114. https://doi.org/10.1186/s12888-015-0496-8

Qin, Z. H., Li, W. J., Zhang, M. H., Arnon, K., & Pedro, B. (2003). Estimating of the essential atmospheric parameters of Mono-window algorithm for land surface temperature retrieval from Landast TM6. *Remote Sensing for Natural Resources*, *15*(2), 37–43.

Sobrino, J. A., Jimenez-Munoz, J. C., & Paolini, L. (2004). Land surface temperature retrieval from LANDSAT TM 5. *Remote Sensing of Environment*, *90*(4), 434–440. https://doi.org/10.1016/j.rse.2004.02.003

Stankuniene, G., Streimikiene, D., & Kyriakopoulos, G. L. (2020). Systematic literature review on behavioral barriers of climate change mitigation in households. *Sustainability*, *12*(18), 7369. https://doi.org/10.3390/su12187369

Streimikiene, D., Lekavičius, V., Baležentis, T., Kyriakopoulos, G. L., & Abrhám, J. (2020). Climate change mitigation policies targeting households and addressing energy poverty in European Union. *Energies*, *13*(13), 3389. https://doi.org/10.3390/en13133389

Tawatsupa, B., Lim, L. Y., Kjellstrom, T., Seubsman, S. A., Sleigh, A., & Team, T. C. S. (2010). The association between overall health, psychological distress, and occupational heat stress among a large national cohort of 40,913 Thai workers. *Global Health Action*, *3*(1), 5034. https://doi.org/10.3402/gha.v3i0.5034

Tianjin, B. S. (2020). *Tianjin statistical yearbook* (in Chinese). China Statistical Publishing House.

Valerie, S., Palmer, K. I., Birchfield, P. S., & Spencer, P. S. (2018). Health of vulnerable populations. *Academic Medicine: Journal of the Association of American Medical Colleges*, *93*(9), 1263–1264. https://doi.org/10.1097/ACM.0000000000002324

Wang, P. Y., Tang, J. P., Sun, X. G., Liu, J. Y., & Juan, F. (2019). Spatiotemporal characteristics of heat waves over China in regional climate simulations within the CORDEX-EA project. *Climate Dynamics*, *52*(1–2), 799–818. https://doi.org/10.1007/s00382-018-4167-6

Witt, C., Schubert, J. A., Jehn, M., Holzgreve, A., Liebers, U., & Endlicher, W. (2015). The effects of climate change on patients with chronic lung disease. *Deutsches Arzteblatt International*, *112*, 51–52. https://doi.org/10.3238/arztebl.2015.0878

Wolf, T., McGregor, G., & Analitis, A. (2014). Performance assessment of a heat wave vulnerability index for Greater London, United Kingdom. *Weather and Climate Extremes*, *6*(1), 32–46. https://doi.org/10.1175/WCAS-D-13-00014.1

Xu, Y. Z., Zheng, Y. F., Yin, J. F., & Wu, R. J. (2011). Characteristics of high temperature and heat wave in Nanjing City and their impacts on human health. *Chinese Journal of Ecology*, *30*(12), 2815–2820. https://doi.org/10.13292/j.1000-4890.2011.0413

Yin, P., Chen, R. J., Wang, L. J., Liu C., Niu, Y., & Wang, W. D. (2018). The added effects of heatwaves on cause-specific mortality: A nationwide analysis in 272 Chinese cities. *Environment International*, *121*, 898–905. https://doi.org/10.1016/j.envint.2018.10.016

Yu, G. L., Chen, T. T., & Zhao, F. Q. (2020). The influence of air temperature and temperature variability on mental health. *Advances in Psychological Science*, *28*(8), 1282–1292. https://doi.org/10.3724/SP.J.1042.2020.01282

Yue, H., & Liu, Y. (2018). Comparison and analysis of land surface temperature retrieval algorithms based on Landsat 8 TIRS. *Science Technology and Engineering*, *18*(20), 200–205. https://doi.org/10.3969/j.issn.1671-1815.2018.20.028

Zhao, A. Z., Pei, T., Cao, S., Zhang, A. B., Fan, Q. Q., & Wang, J. J. (2020). Impacts of urbanization on vegetation growth and surface urban heat island intensity in the Beijing-Tianjin-Hebei. *China Environmental Science*, *40*(4), 1825–1833. https://doi.org/10.19674/j.cnki.issn1000-6923.2020.0206

Zheng, S., Wang, M. Z., Shang, K. Z., He, S. L., Yin, L., Li, T. S., & Wang, S. G. (2016). A case–crossover analysis of heat wave and hospital emergency department visits for cardiovascular diseases in 3 hospitals in Beijing. *Journal of Hygiene Research*, *45*(2), 246–251. https://doi.org/10.19813/j.cnki.weishengyanjiu.2016.02.012