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Research Article

Monitoring the Interannual Spatiotemporal Changes in the Land Surface Thermal Environment in Both Urban and Rural Regions from 2003 to 2013 in China Based on Remote Sensing

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The thermal environment is closely related to human well-being. Diurnal and seasonal variations in surface urban heat islands (SUHIs) have been extensively studied. Nevertheless, interannual changes in SUHIs as well as in land surface temperatures (LSTs) in cities and their corresponding villages remain poorly understood, particularly using data from several continuous years to analyse change rates and corresponding significance levels. Using Aqua/Terra moderate resolution imaging spectroradiometer (MODIS) data for 2003–2013, we explored not only the interannual changes in annual and seasonal mean LSTs in rural and urban regions which were identified based on modified criteria, but also the SUHI intensities (SUHIIs) for these cities. The results showed that most of LSTs and SUHIIs did not change significantly ($p \geq 0.05$). Their changes exhibited clear spatiotemporal agglomeration and variation laws. The rural region LST change rates, which exhibited significant changes, were generally highest in the summer, with most of values of 0.1–0.5°C (yr^{-1}) during the daytime across China, except for the Xinjiang autonomous regions, and 0.1–0.2°C (yr^{-1}) during the night-time. The rates were lowest in the winter, with most of values of −0.4 to −0.1°C (yr^{-1}). The rates of daytime SUHIIs with significant changes were generally highest in the summer, with most of values of 0.1–0.3°C (yr^{-1}), and lowest in the winter, even with most of values of −0.4 to −0.1°C (yr^{-1}) in northern central China. During the night-time, most of rates were 0.0–0.1°C (yr^{-1}). In China, most of the changes in the surface thermal environment were harmful to humans at both large national and local urban scales. The changes could lower thermal comfort levels, harm human health, affect human reproduction rates and lives, and increase the energy consumed for refrigeration or heating, thereby increase emissions of greenhouse gases.

1. Introduction

The thermal environment can directly and indirectly affect human health, comfort and quality of life, energy use, air quality, occurrence and activity level of creatures, hydrology, soil physicochemical properties, etc. Changes in the thermal environment and effects of human activities on these changes are research hotspots, throughout China, which has experienced an extremely rapid and intense urbanization over the past few decades [1, 2]. Although the land surface temperatures (LSTs) derived by remote sensing are not identical to above-ground air temperatures, they are closely related [3, 4]. Remote sensing data can be acquired across a large area synchronously, accurately, economically, repeatedly, etc., in a fixed period. Therefore, certain previous studies have explored interannual spatiotemporal changes in the land surface thermal environment by remote sensing. To the best of our knowledge, only a few studies have analyzed the interannual changes in LSTs at a regional scale. The studies included the use of Terra/MODIS data from 2001 to 2013 to monitor annual change rates and corresponding significance levels in the arid Tianshan Mountains area, northwestern China [5], and Terra/MODIS or Landsat data from two or three nonconsecutive years to monitor changes in LSTs in the arid Xinjiang autonomous region, northwestern China [6], the Da Hinggan Mountains permafrost region with a humid cold climate, northeast China [7], and the Yangtze River Delta area [8]. The interannual variability and trends of surface urban heat islands (SUHIs) have been studied in certain studies [9, 10]. The adopted thermal infrared data were obtained from National Oceanic and Atmospheric Administration (NOAA)/advanced very high resolution radiometer (AVHRR), Terra/MODIS, Aqua/MODIS, or Landsat/thematic mapper (TM), enhanced thematic mapper (ETM)+, and thermal infrared sensor (TIRS) sensors [10, 11]. More than 28 indicators have been developed to monitor the intra-annual or interannual variations in daytime and night-time SUHIs (supporting material Table S1), and compare the variations at a single city, regional, continental, or global scale [10–13]. The methods can be classified as land cover driven approaches, land surface temperature (LST) pattern driven approaches, and combinations of the two approaches [4, 11–14]. The methods can also be divided into three broad classes: the LST as a proxy for a SUHI, LST differences between urban and reference areas, and nonparametric models [10]. Most of these studies of the interannual variability of SUHIs have focused on changes in LSTs or their spatial patterns [2, 15–18]. Only a few have explored the interannual variability of SUHIs by calculating the LST differences between urban and reference areas [2], or using the Gaussian fitting method [16, 19, 20]. Associated determinants have been extensively studied for diurnal and seasonal variations SUHIs [9, 10]. Nevertheless, the driving forces remain poorly understood for the interannual variations [9, 10]. Previous studies have mainly discussed the links between changes in LSTs and land use and land cover changes, particularly the urban expansion [15–18, 21]. In addition, relationships have been explored using correlation analysis or function fitting methods [2, 18] between LSTs and certain influence factors, such as the normalized difference vegetation index [2, 18], vegetation fraction [2], impervious surface fraction [2], population density [18], and night-time light intensity [18]. Moreover, certain studies have simply described possible reasons, such as restrictive development strategies and mitigation measures implemented in city centres [2, 18, 22, 23] and extensive new town development in less-populated urban fringes and suburban areas [18]. Nevertheless, certain issues still exist. First, the vast majority of studies only compared differences of LSTs or SUHIs over two or several days in different years, rather than calculating the change rates and corresponding significance levels based on continuous data for each year [5, 24]. Second, to the best of our knowledge, few studies have explored the interannual changes of LSTs across the entire urban regions and corresponding rural regions and further analyzed similarities, differences, and links between the two types of regions. This approach is quite different from monitoring the changes in LSTs across a large region. Third, certain disadvantages were associated with the use of previously proposed indicators compared to the monitoring indices of surface urban heat island intensities (SUHIIs) [10, 11]. For instance, certain studies defined SUHIIs as the differences in LSTs between a city or central city and its adjacent regions within a certain radius [12, 25–28]. Nonetheless, rapid urbanization usually occurs in areas surrounding cities, particularly large or mega cities in certain developing countries [29, 30]. Thus, biases can be introduced when monitoring SUHIIs. In addition, certain previous studies utilized differences in LSTs between cities or central cities and rural regions. In addition, rural regions were defined as zones within a certain distance from a city. However, the distance values in previous studies were too large for monitoring cities of different sizes [13, 31, 32]. The notable reason was that only regions that were sufficiently far enough away could be defined as reference villages. Therefore, fewer regions remained due to the dense distribution of cities in certain well-developed regions with dense populations. Moreover, certain studies have used the Gaussian fitting method [4, 20, 33], but this approach is only effective when the left field of the LST fits the Gaussian distribution after extraction of the background LST. However, this condition does not always exist [30]. For example, the method will fail when cold heat islands occur [25, 26] or when the outskirts or village regions have not been limited by the types of terrains [25–27, 32], waterbodies [32], or satellite towns. In addition, the impervious surface percentage should be considered when defining rural regions [32]. Fourth, certain studies used images from the middle resolution to explore the interannual changes in LSTs [7] or SUHIIs [2, 15, 17, 18]. However, acquiring data for the same days in different years was usually difficult due to long return periods, fickle weather conditions, etc. Moreover, the LSTs are instantaneous [34] and the reliability can also be affected by occasional factors. Moreover, the differences in background environmental conditions should be further considered because the spatiotemporal patterns of SUHIs greatly depend on these differences, such as the climate, vegetation activity, surface albedo, level of human activity, landscape pattern, etc [13, 32, 35, 36]. Thus, using Aqua/Terra MODIS data from 2003–2013, this study aimed to explore the interannual spatiotemporal changes in LSTs in 1449 urban and corresponding rural regions and SUHIIs for cities in five regions with different ecological contexts in China (Figure 1).

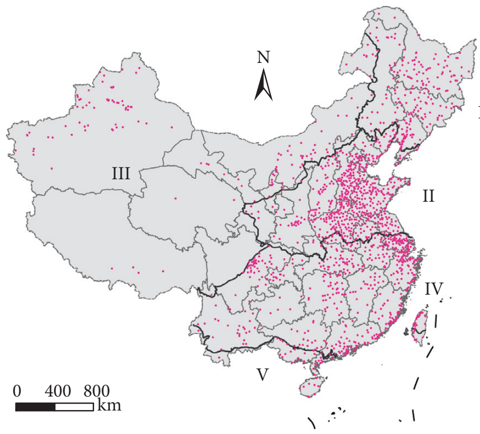


Figure 1: Locations of the 1449 cities selected for this study in the five environmental subareas.

2. Materials and Methods

2.1. Data. The ecological function recognition data were provided by the Data Sharing Infrastructure of Urban and Regional Ecological Science. China was divided into three first-level, 50 second-level, 206 third-level, and 1434 fourth-level ecological function regions based on their landforms, water and heat combinations, and vegetation characteristics.

Digital elevation data with a 1-km resolution were taken from the Cold and Arid Regions Sciences Data Center at Lanzhou. The monthly mean daytime and night-time LST MODIS/Aqua data with a 1 km resolution from 2003 to 2013 were downloaded from the Geospatial Cloud of Computer Network Information Centre, Chinese Academy of Sciences website. The Aqua satellite passed over the study area twice a day, at approximately 1 : 30 am and 1 : 30 pm, local time, during the daytime, and night-time, respectively. Land use data from 2000 to 2010, which had a 1-km resolution, were provided by the Data Centre for Resources and Environmental Sciences, Chinese Academy of Sciences. Data were primarily produced from the interpretation of Landsat TM/ETM + images [37]. The classification schemes included six first-level land use types: cropland, woodland, grassland, waterbody, built-up land, and unused land [37, 38]. In addition, there were 25 second-level land use types in the two data sets. The overall accuracy of classification was higher than 91.2% for each land use type [37]. The 500°m resolution impervious percentage data for 2010 were provided by the Beijing City Lab. Data were derived by the regression method, based on the normalized urban areas composite index (NUACI) [39]. The NUACI was generated based on the night-time light intensity, enhanced vegetation index, and normalized difference water index [39]. The accuracy of the impervious percentage data was high ($R^2 = 0.8079$, $R = 0.8908$, and root mean square error (RMSE) = 0.1176); the impervious percentage data referred to the extracted impervious data by the maximum likelihood method using ETM + data that were obtained by Landsat satellites [39].

2.2. Methods

2.2.1. Regionalization of the Background Environment in China. China was divided into five regions based on ecological function recognition results at the first, second, and third levels (Figure 1) to analyse potentially different influence factors of the SUHII in each region and to predict SUHIIs. Region I largely corresponded to the vast majority of northeastern China, which exhibits climatic zones that range from cold temperate to midtemperate zones. The region is affected by monsoons and has four distinct seasons—warm and rainy summers and cold and dry winters with long periods of melting ice and snow. The climate of region II is similar to that of region I. However, the winters are warmer and shorter than those in region I. Region III is the only zone that is not affected by monsoons in China and has a typical arid temperate climate, with a mean annual precipitation (MAP) below 400 mm. Region III suffers cold winters and hot or warm summers. The vast majority of region IV belongs to the subtropical zone, while the remainder belongs to the tropical zone. The aforementioned region has a typical rainy and hot temperate climate, with a MAP exceeding 800 mm and evergreen vegetation.

2.2.2. Definition of Urban and Rural Regions. Urban land polygons were first aggregated at a distance of 1 km, which was sufficient to include most adjacent and scattered urban land polygons in the urban class and was able to distinguish main city zones and satellite cities or two closely adjacent cities that should be considered separately according to standard perceptions. Cities with areas larger than 6 km^2 in 2010 were considered, which included the vast majority of cities in the eastern regions in China; the latter were cities with the highest population densities and most well-developed economies. The urban regions only considered pixels that belonged to cities in both 2000 and 2010. The corresponding rural zones were defined as the buffer zones of cities in 2010, with buffer distances between 5 and 10 km [25] and impervious percentages below 5% [31]; however, the rural zones did not include waterbodies, regions with slopes exceeding 7.5° or elevations that were 50 m greater than or less than the maximum or minimum elevations of the urban zones, respectively [13, 31, 40]. We observed that 99.70% of the cities in China were located in plain regions with slopes that were lower than 7.5° in 2010.

2.2.3. Calculation of the Interannual Spatiotemporal Changes in LSTs and SUHIIs. First, mean daytime and night-time LSTs in the 1449 urban and corresponding rural regions and SUHIIs for these cities were calculated in each of the four seasons and the whole year for each year. The seasons were defined based on definitions of the meteorological seasons [41]. The winter lasted from December to February, spring lasted from March to May, summer lasted from June to August, and autumn lasted from September to November. Then, linear trend analysis was conducted to calculate the change rates and corresponding significance levels. In addition, the mean values and standard deviations were calculated for the LSTs or SUHIIs in each region and period. Finally, significant differences in the LSTs or SUHIIs among the five environmental regions were determined using nonparametric tests of k independent samples.

3. Results and Discussion

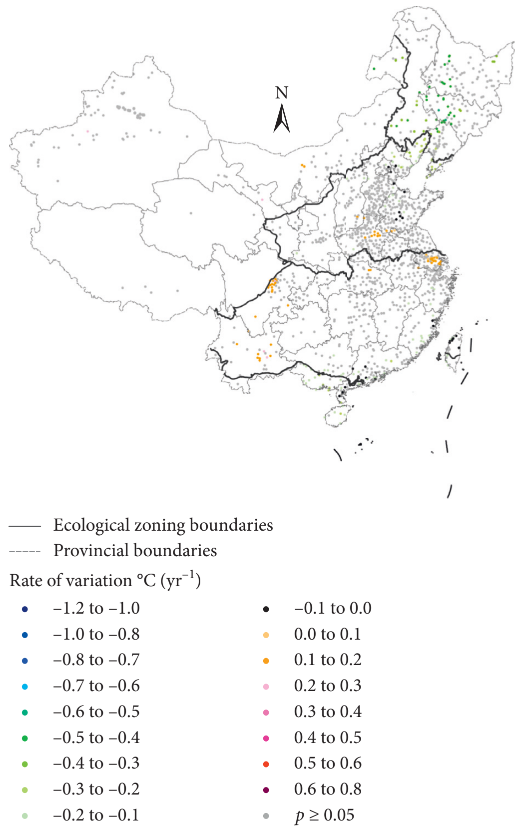
3.1. Changes in the LSTs in the Rural Regions. The LSTs in the vast majority of rural regions did not change significantly from 2003 to 2013 for the five environmental regions of China ($p \geq 0.05$), as indicated by grey points in Figure 2. Nevertheless, significant changes were still observed in a certain proportion (Figure S1). The changes indicated notable spatiotemporal agglomeration and variation laws. The later implied that similar changes occurred in adjacent locations or periods, while different changes were observed in different locations or periods. These results were consistent with those from a previous study [42] and were mainly due to the different general atmospheric circulations in the different regions [42].

From a regional comparison aspect, the lowest spatial heterogeneity in the LST change rates in rural regions with significant variations was observed in the autumn during both the daytime and night-time, as shown in Figure 3. The labeled A–E represent results of the mean comparison among regions, based on nonparametric tests of k independent samples; significant differences only occurred in rural LSTs among the five environmental regions as indicated by the different labels. In addition, the highest change rates were observed in region IV while lowest rates occurred in region I during both the daytime and night-time in the winter, spring, and whole year. In the summer, the order was region I > IV = V > II = III during the daytime and region III > I > II > IV during the night-time. All of the regional mean rates were positive in the summer.

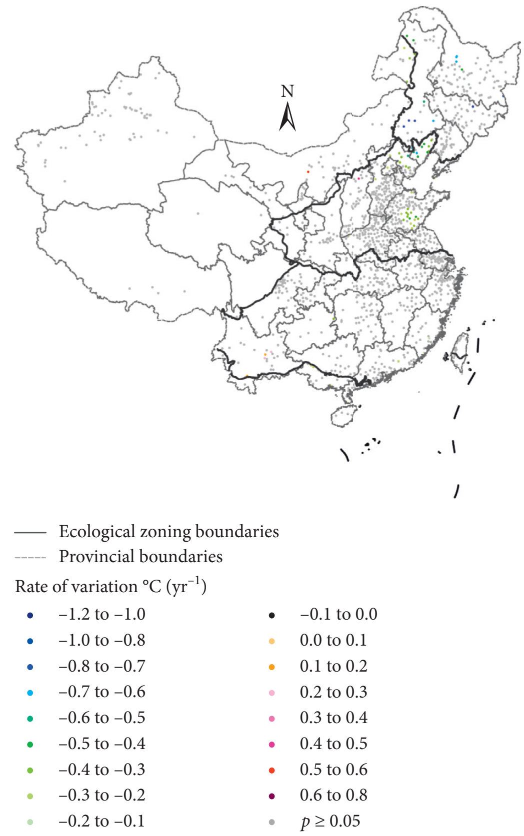
Limited by the number of samples, comparisons of the mean rates in different periods for the same region were difficult to perform. However, distinct seasonal variation laws could be observed for changes in the LSTs in rural regions of most of the regions in China during both the daytime and night-time. The rates were usually highest in the summer, lower in the spring and autumn, and lowest in the winter. In China, the annual mean rates of the daytime and night-time LSTs with significant changes ($p < 0.05$) were -0.13 ± 0.20 and -0.11 ± 0.06°C (yr^{-1}), respectively. During both the daytime and nigh-time, the lower rates occurred in northeastern China (mostly region I), with rates of −0.5 to −0.3 and −0.3 and −0.1°C (yr^{-1}) in most cases, respectively. During the daytime, negative change rates were also observed in southern China, southeastern coastal regions, northeastern China and eastern central northern China (region II). Most of the rates were −0.3 to −0.1°C (yr^{-1}). Positive changes were concentrated in the Yangtze River Delta, Sichuan Basin, Huang-Huai area, and northeastern Yunan Province; most of rates were 0.1–0.2°C (yr^{-1}). During the night-time, additional negative change rates were observed in North China Plain and areas surrounding region I. Most of the rates were −0.2 to 0.0°C (yr^{-1}). Positive changes were concentrated in the Sichuan Basin. Most of rates were 0.1-0.2°C (yr^{-1}). During the summer daytime, the higher rates of LSTs with significant changes in rural regions occurred in northeastern Yunan Province, and most of the rates were 0.3–0.5°C (yr^{-1}). The rates were lower in the Sichuan Basin, middle and low reaches of Yangtze River, and Huang-Huai area, and most of the rates were 0.1–0.3°C (yr^{-1}). The rates were lowest in the Xinjiang autonomous regions, and most of the rates were −0.3 to −0.1 (yr^{-1}). The highest rate was 0.53°C (yr^{-1}), and occurred in the western region of Panzhihua City in the Yunnan–Guizhou Plateau during the daytime in the summer. During the summer night-time, significant changes were largely located in northern, northeastern, and northwestern China. Most of the rates were 0.1–0.2°C (yr^{-1}), while the rates in northern northeastern China were 0.2–0.3°C (yr^{-1}). In contrast, winter LSTs in the rural regions primarily did not significantly change or exhibited significant negative changes that were concentrated in northeastern and northcentral regions. Most of the aforementioned rates were −0.4 to −0.1°C (yr^{-1}). Moreover, some of the rates were −0.8 to −0.4°C (yr^{-1}) and mainly occurred in northeastern China and surrounding regions. Both the increase in LSTs in the summer and decrease in the winter could result in lowering of the thermal comfort levels of the human body, harming human health, affecting human reproduction rates and lives, or increasing the energy consumed for refrigeration or heating, and emission of greenhouse gases. In the autumn, the rates with significant changes were primarily negative during the daytime and night-time, most of them were −0.4 to −0.1°C (yr^{-1}). During the daytime, the changes were mainly located in the southern China, southeastern coastal regions, and central southern northeastern China. During the night-time, the changes mainly occurred in the North China Plain and in a few cities in the Northeast Plain and Sichuan Basin. In the spring, certain rural regions suffered significant negative changes in daytime LSTs with lower rates in central southern northeastern China. Most of the aforementioned rates were −1.0 to −0.5°C (yr^{-1}), while the lowest rate was −1.06°C (yr^{-1}), which occurred in Gongzhuling, Jinlin Province, the Northeast China Plain, during the daytime in the spring. The changes were harmful to humans due to the humid cold climate in that region.

3.2. Changes in the LSTs in the Urban Regions. The LSTs can increase notably in newly developed urban regions. Nevertheless, this study focused only on land parcels that had always belonged to urban lands during the study period. The spatiotemporal change laws of LSTs in urban regions were always closely related to those in corresponding rural regions (Figure 4). We speculated that the variations in LSTs in urban regions were derived not only from general atmospheric circulations at a large scale, but also from human activities.

The regional comparison findings for the change rates of LSTs with significant variations in the urban regions were similar to those in rural regions (Figure 5), but were more complicated due to effects of both natural and human factors. In general, the laws were notably different in the



(a)



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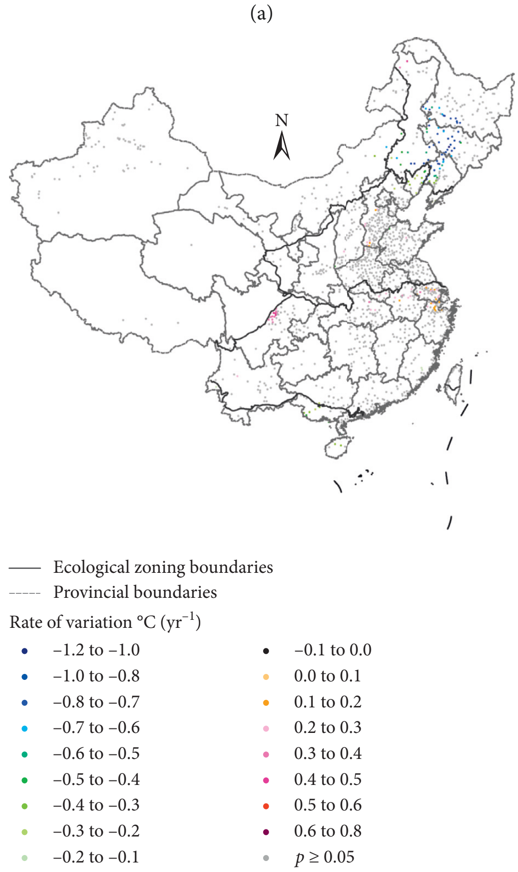

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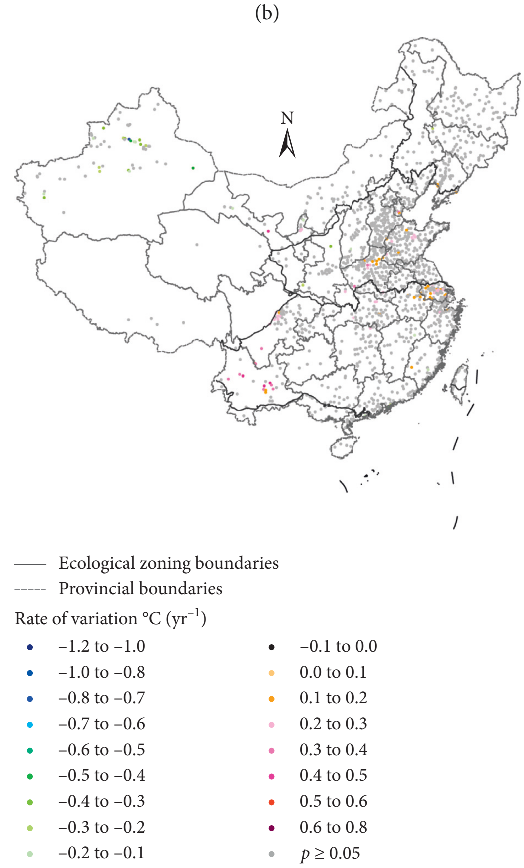

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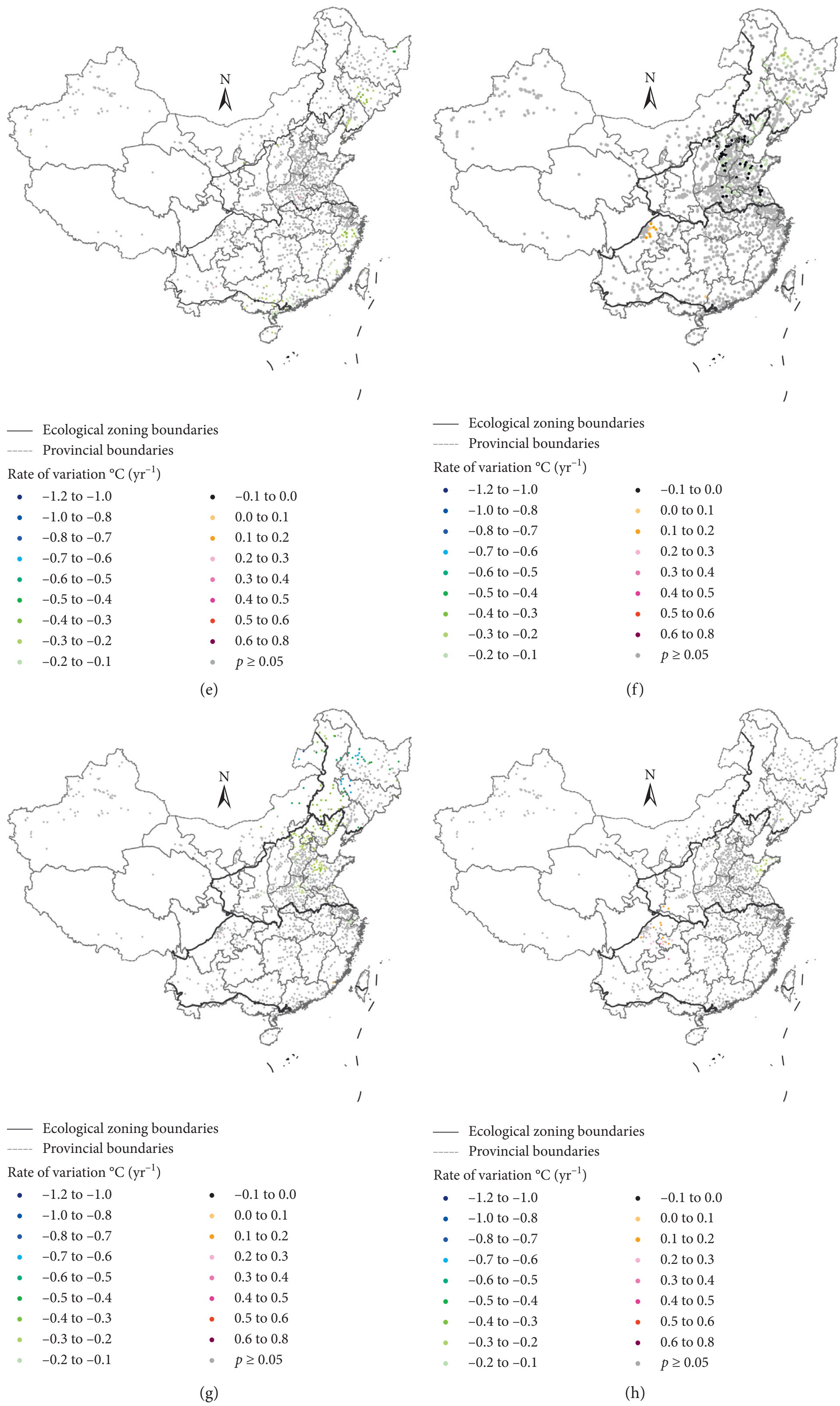

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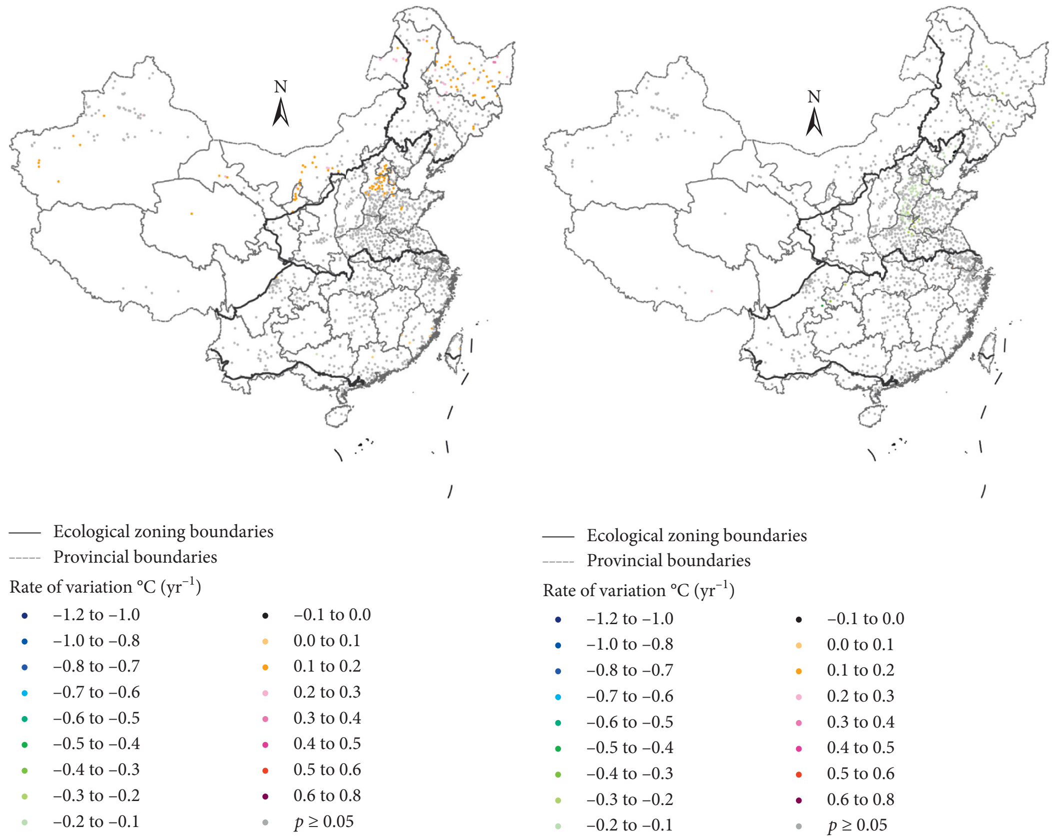
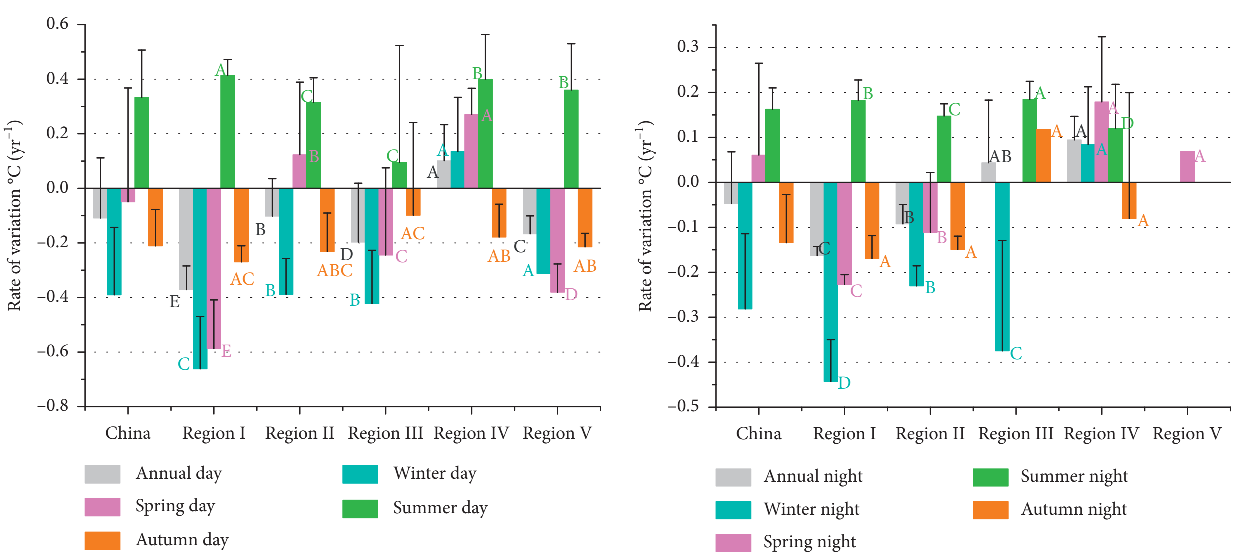


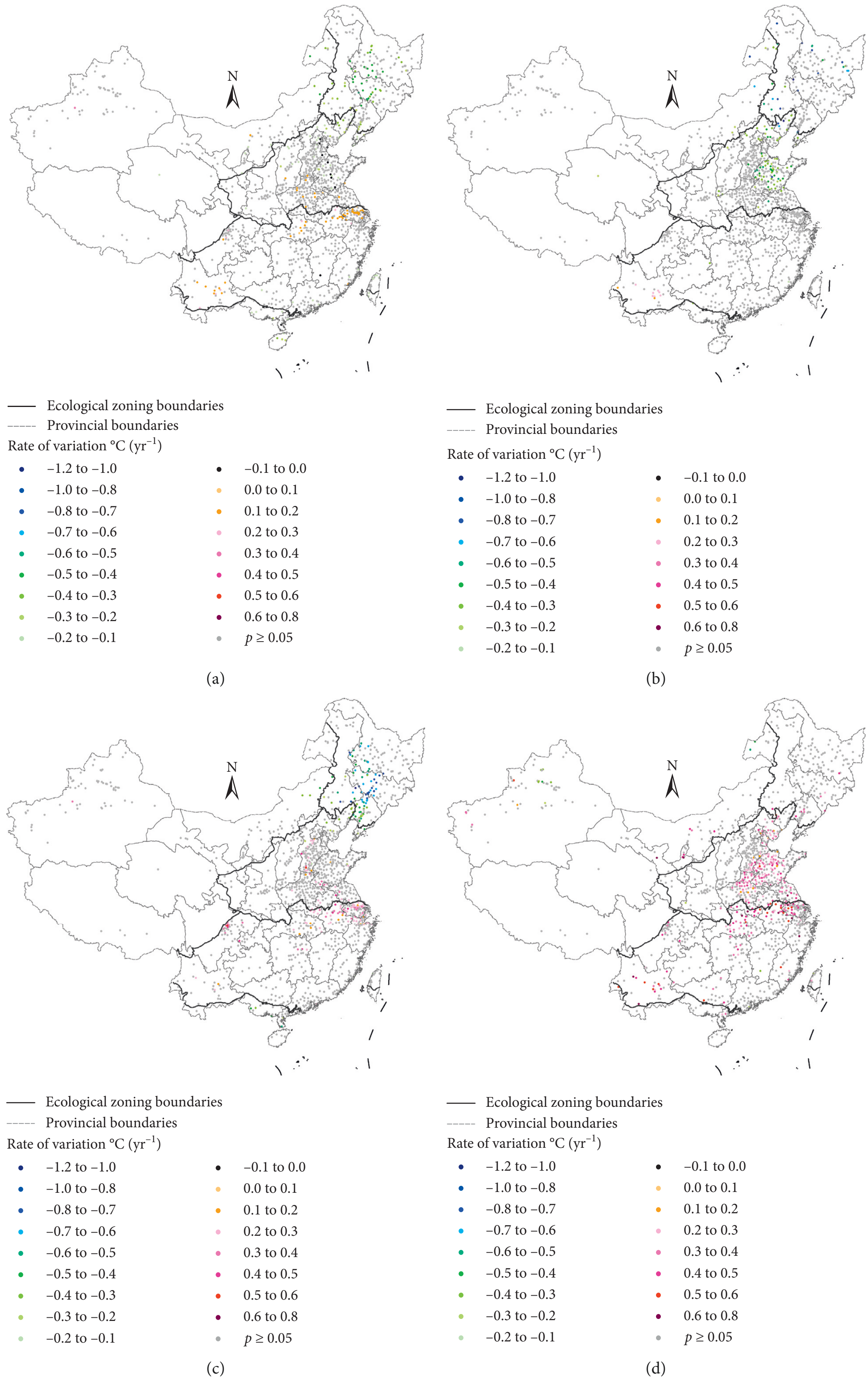
(i) (j)

Figure 2: Spatial distribution of the annual and seasonal change rates of LSTs in rural regions during the daytime and night-time from 2003 to 2013 in the five environmental regions of China: (a–e) the results during the whole year, winter, spring, summer, and autumn daytime, respectively; (f–j) corresponding values during night-time. (a) Annual day. (b) Winter day. (c) Spring day. (d) Summer day. (e) Autumn day. (f) Annual night. (g) Winter night. (h) Spring night. (i) Summer night. (j) Autumn night.



(a) (b)

Figure 3: Statistics of the variation rates of mean LSTs in rural regions that significantly changed in the whole year and four seasons during the daytime and night-time from 2003 to 2013 in the five environmental regions, China (A–E represent the mean comparison results among regions, using nonparametric tests of *k* independent samples; significant differences only existed in rural LSTs among the five environmental regions when the label letters were the same).



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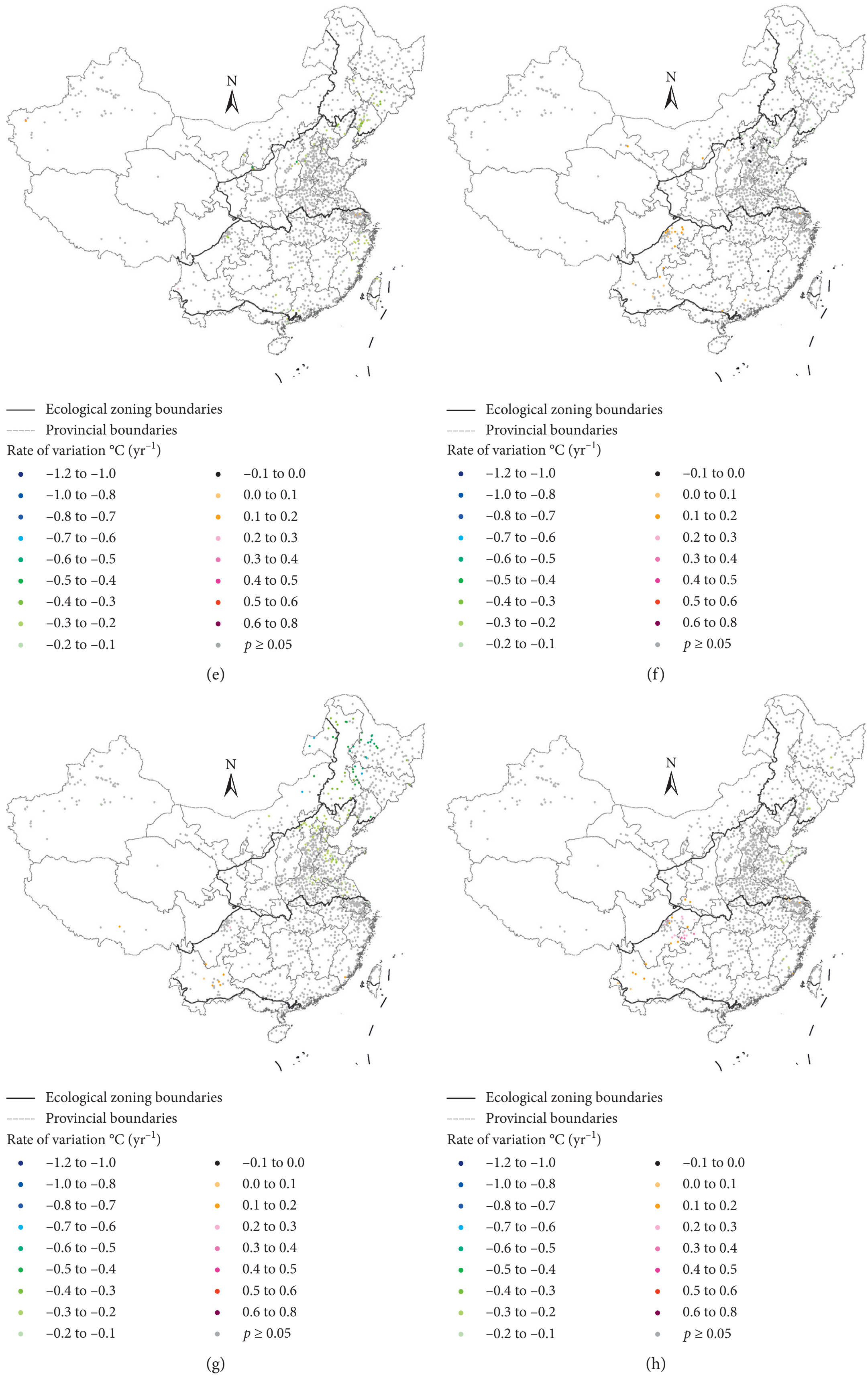

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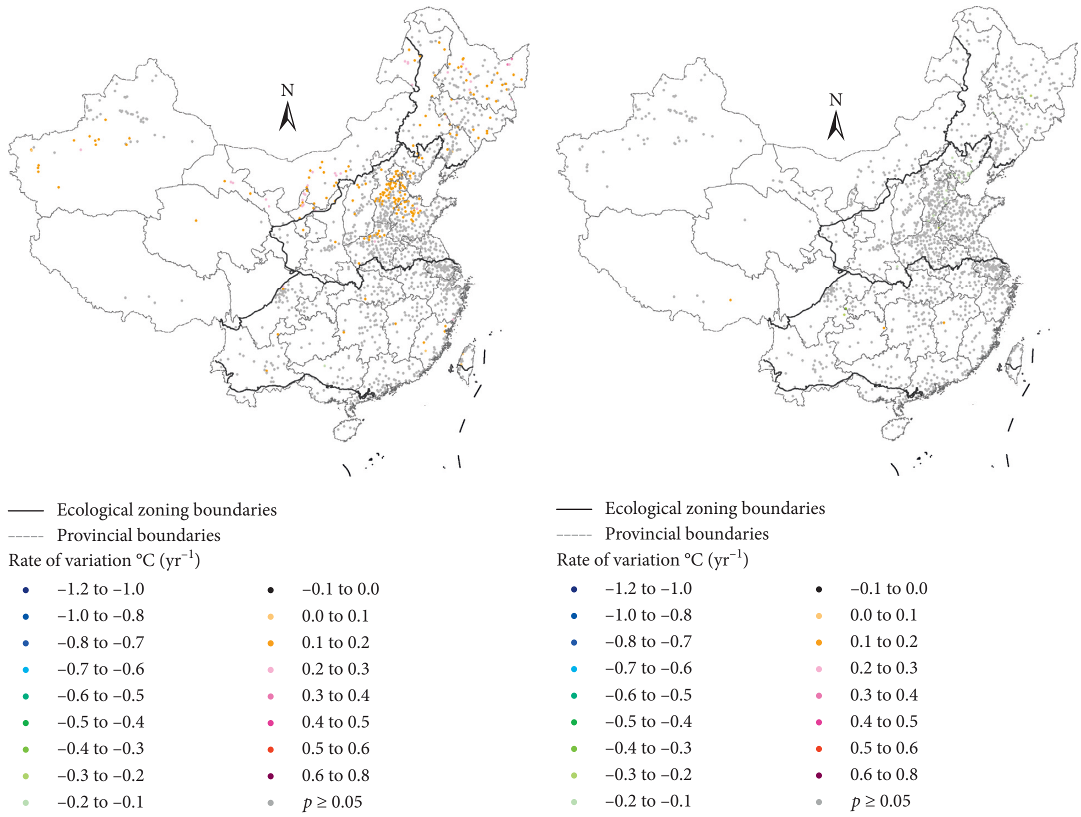
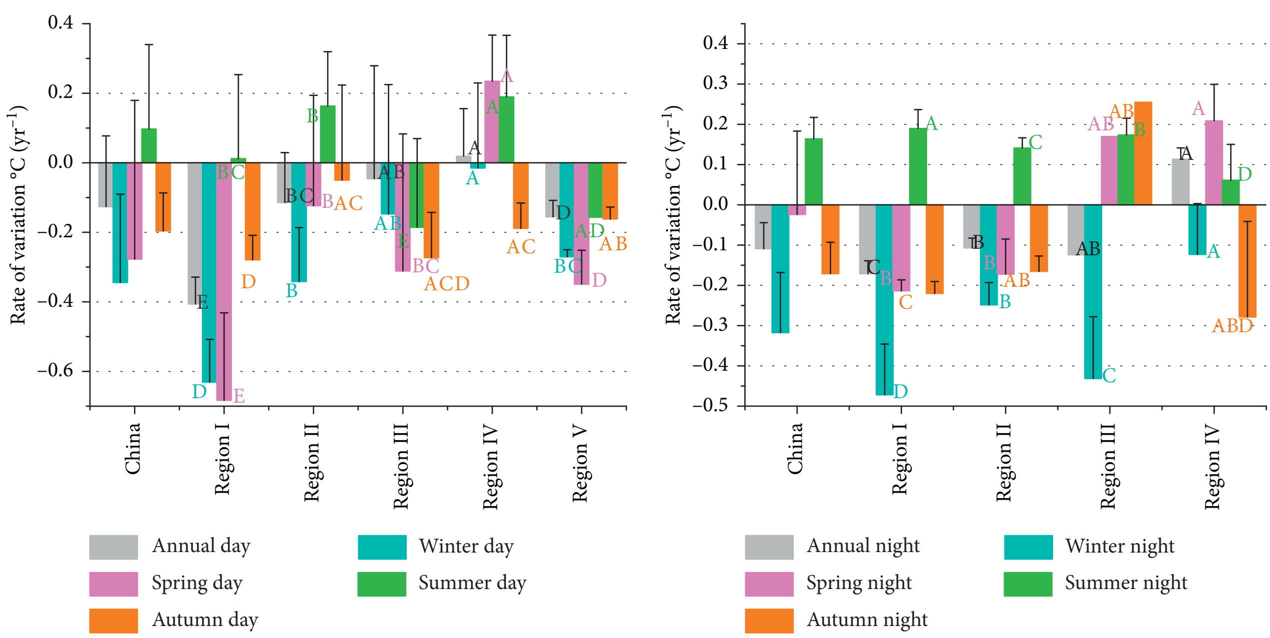


(i) (j)

Figure 4: Spatial distribution of the annual and seasonal change rates of LSTs in urban regions during the daytime and night-time from 2003 to 2013 in the five environmental regions of China: (a–e) the results during the whole year, winter, spring, summer, and autumn daytime, respectively; (f–j) corresponding values during night-time. (a) Annual day. (b) Winter day. (c) Spring day. (d) Summer day. (e) Autumn day. (f) Annual night. (g) Winter night. (h) Spring night. (i) Summer night. (j) Autumn night.



(a) (b)

Figure 5: Statistics of the variation rates of mean LSTs in urban regions that significantly changed in the whole year and four seasons during the daytime and night-time from 2003 to 2013 in the five environmental regions of China (A–E represent the mean comparison results among regions, using nonparametric tests of k independent samples; significant differences only existed in rural LSTs among the five environmental regions when the label letters were the same).

summer compared to those in other seasons or that in the whole year. The lowest rates were observed in region I except during the night-time in the spring and summer and during the daytime in the summer. The highest rates occurred in region IV in the winter, spring, and whole year. In the summer, all of the regional mean rates were positive during the daytime and night-time, and the order was region I > III > II > IV during the night-time.

During the daytime, the largest differences occurred in the summer between the spatiotemporal variations in LSTs in urban regions and corresponding rural regions. Not only was there a clear increase in the number of cities whose LSTs significantly changed with positive rates, but the change rates also notably increased. The largest change was observed in Simao City in the southern Yunnan–Guizhou Plateau during the daytime in the summer, with a rate of 0.73°C (yr^{-1}), which was 0.20°C (yr^{-1}) higher than the highest change rate in rural regions. In the spring, the change rates in urban regions were also higher than those in rural regions, particularly for certain cities in the middle and lower reaches of the Yangtze River. The lowest change rate was observed in Baicheng City in the western Songnen Plain during the daytime in the winter, which was −1.18°C (yr^{-1}). The abovementioned changes were harmful to humans in most cases in China. During the night-time, a certain degree of differences existed for the change laws of LSTs between urban and corresponding rural regions. The main change types were as follows. First, LSTs did not change significantly in rural regions but changed significantly in urban regions with positive rates, such as the change rates in the northern central Yunnan Province at the scale of the whole year, winter and spring. Second, LSTs changed significantly with negative rates in the rural regions but did not change significantly in urban regions, such as in northeastern and northern China in the autumn, or in Jiaodong Peninsula in the spring. Third, the magnitudes of these negative changes decreased, such as that occurred in northeastern and northern China in the whole year. Finally, the rates increased for positive significant changes, such as in certain regions in the northern China in the summer. Both the change rates and spatial scopes of LSTs could be affected by human activities in the four seasons during the night-time, although the effects were less pronounced than those during daytime. The LSTs could decrease in urban regions if effective measures were taken [2, 18, 21]. Nevertheless, the effects of human activities on LST changes were positive in urban regions in most of the cases, particularly during the night-time.

3.3. Changes in the SUHIIs. The SUHIIs in the vast majority or most of rural regions did not change significantly from 2003 to 2013 in the five environmental regions of China in the whole year and four seasons (Figure 6). Nevertheless, significant changes were still observed in a certain proportion (Figure S5). During the night-time, the proportion with significant changes in the SUHIIs for the cities was distinctly larger than that in the LSTs in both the urban and rural regions. This result indicated that the change degree of effects of human activities was notably more profound than that of natural factors during the study period in China. The change rates of SUHIIs that had significantly changed also exhibited notable spatiotemporal agglomeration and variation laws. However, the regularity of SUHIIs changes was lower than the changes of LSTs in rural and urban regions. That was probably mainly because the intensities and types of human activities exhibited clear spatiotemporal agglomeration and variation laws as well. However, the regularity of human activities was lower than that of natural factors.

In the winter, the change rates of daytime SUHIIs with significant variations showed a distinct spatial heterogeneity (Figure 7). The regional order was region V > IV > I = II > III. All of the regional mean rates were negative except in region V. Nevertheless, all of the rates were positive in the summer. The lowest values occurred in region I and II. The spatial heterogeneity degree was lowest in the spring, autumn, and whole year. The rates were significantly higher in region I in the spring. During the night-time, a clear spatial heterogeneity also existed, except in the autumn. The change rates were significantly lower in region I at the whole year scale, and highest in region III in the winter. The regional order was region III > II > IV > I in the spring, while in the summer, the order was region II > IV = III > I. All of the regional mean rates were positive during the night-time, except in region I in the summer.

The change rates of the annual mean daytime and night-time SUHIIs in China that had significantly changed were 0.03 ± 0.11 and 0.05 ± 0.03°C (yr^{-1}), respectively. The cities with significant positive changes were mainly concentrated in certain regions of Anhui and Jiangsu Provinces in the middle and lower reaches of the Yangtze River during the daytime and in central northern China during the night-time. Most of rates were most 0.0–0.2°C (yr^{-1}). During the daytime, the interannual variations in the SUHIIs exhibited clear seasonal laws. In the summer, not only the change rates but, in general, also the spatial scopes with significant changes were generally notably the highest. The highest rate was 0.78°C (yr^{-1}), which occurred in Simao City in the southern Yunnan–Guizhou Plateau during the daytime in the summer. In the spring, the change rates were generally lower and primarily positive. In the autumn, the rates were generally further lower and even negative in the vast majority of cities with significant changes in SUHIIs occurring in central northern China. The change rates were generally lowest in the winter. In addition, the lowest rate was −0.77°C (yr^{-1}), which occurred in the Wulatezhong Banner in central northern Inner Mongolia during the daytime in the winter. These results were consistent with those from previous studies, in which it had been observed that the intensities or areas of SUHIs were largest in the summer, smaller in the spring and autumn, and smallest in the winter with cold island effects in the temperate region [24, 27, 33]. In addition, we observed that the effects of human activities on LSTs in urban regions were not only the most notable in the summer for a single year but also strengthened as time passed. The latter could further increase the highest values of SUHIIs and LSTs in the summer or decrease the lowest

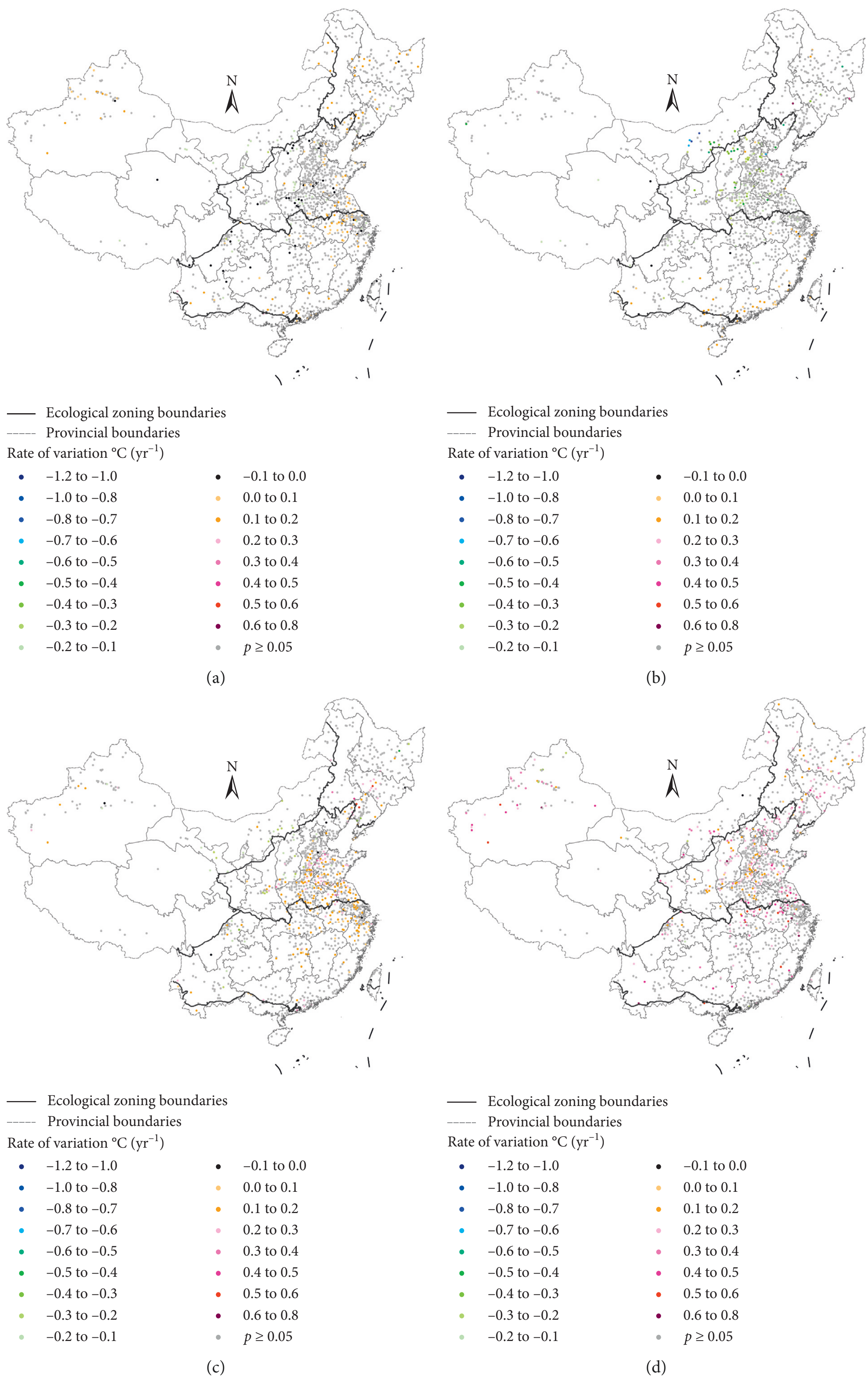
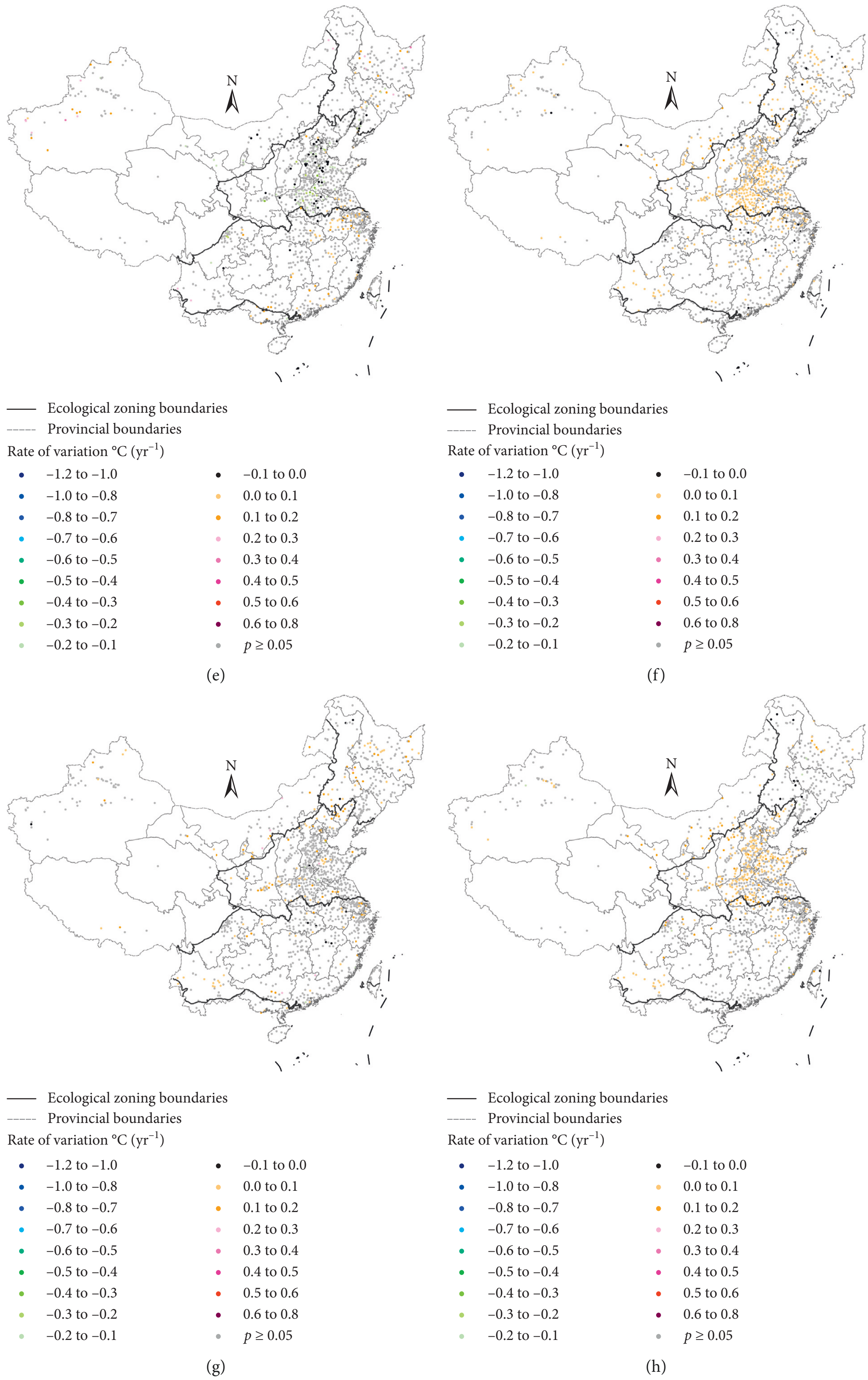


Figure 6: Continued.



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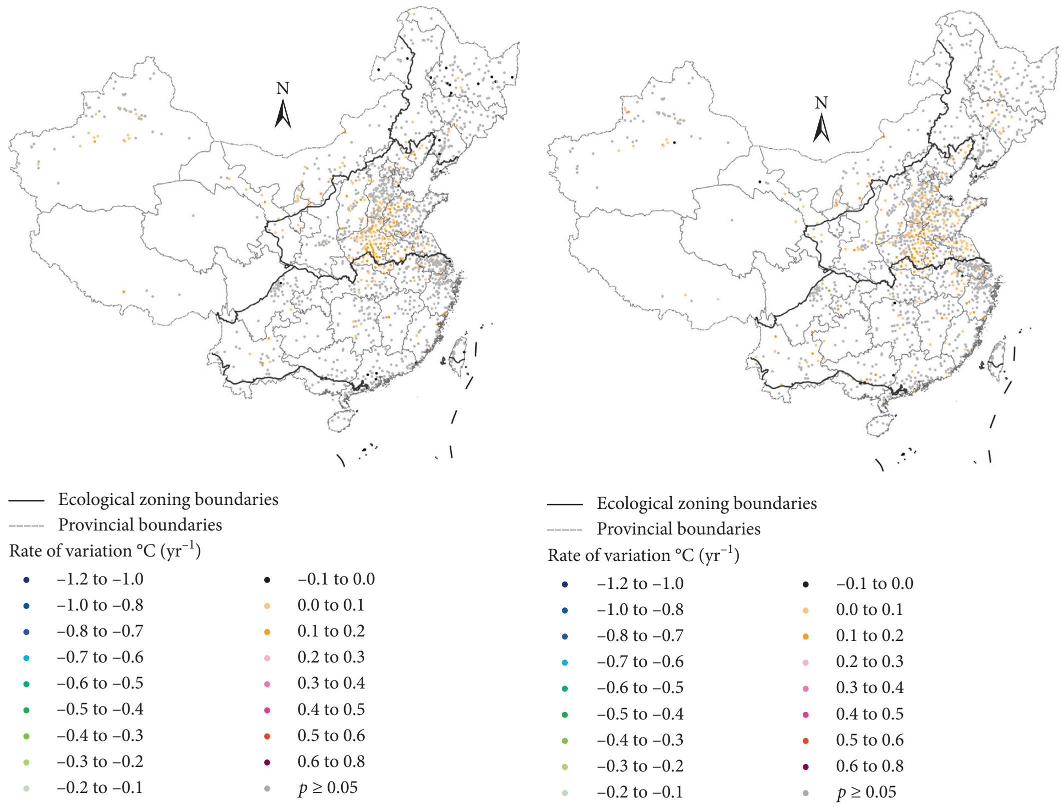
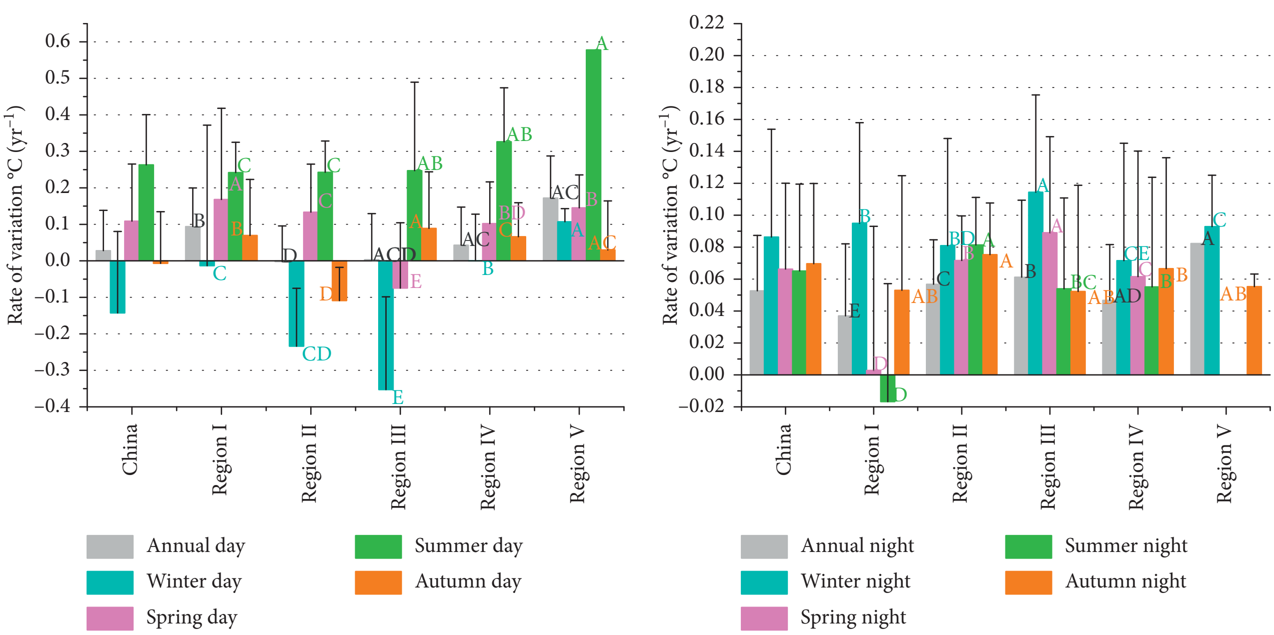


(i) (j)

FIGURE 6: Spatial distribution of the annual and seasonal change rates of SUHIIs during the daytime and night-time from 2003 to 2013 in the five environmental regions of China: (a–e) the results during the whole year, winter, spring, summer, and autumn daytime, respectively; (f–j) corresponding values during night-time. (a) Annual day. (b) Winter day. (c) Spring day. (d) Summer day. (e) Autumn day. (f) Annual night. (g) Winter night. (h) Spring night. (i) Summer night. (j) Autumn night.



(a) (b)

FIGURE 7: The statistical of variation rates of mean city SUHIIs that changed significantly throughout the year and during four seasons during the daytime and night-time from 2003 to 2013 in the five environmental regions of China (A–E represent the mean comparison results among regions, using nonparametric tests of k independent samples; significant differences only existed in rural LSTs among the five environmental regions when the label letters were the same).

values of SUHIIs and LSTs in the winter in across several regions. Clearly, this phenomenon could decrease the thermal comfort in the summer and winter, increase the energy consumed for refrigeration or heating, and increase emissions of greenhouse gases in most cases. In addition, the aforementioned had large potential effects on air pollution in central northern China in the winter. The seasonal fluctuations in SUHIIs during the night-time were notably smaller than those during daytime. The changing rates almost unchanged during the night-time, and most of them were 0.0–0.1 or 0.1–0.2°C (yr^{-1}) for certain cities, which supported previous studies. In the aforementioned studies, SUHIIs exhibited smaller and more complex seasonal fluctuations during the night-time than in the daytime [2]. The differences between daytime and night-time not only were observed in the change laws for a single year but were also present in those for several many years; an accumulative effect clearly existed.

3.4. Uncertainties and Limitations. Although MODIS LST data have been validated and have been found to be highly accurate in many cases, and as a result, have been widely accepted and used, certain uncertainties and issues remain, particularly related to urban environments and rural areas with complex terrains or vegetation types caused by the highly complicated spatial heterogeneity in landscape components, higher air pollution levels in cities, and well-known anisotropy issues [25]. Moreover, aiming at eliminating the effects of interference factors, seasonal or annual composite data based on observed daily values were used in this study instead of instantaneous data. However, MODIS data for even more years in the future, or the comprehensive use of the multisource images, should be adopted [2, 10]. In addition, the associated determinants of SUHIIs need to be explored at various scales and dimensions, particularly for the cities with typical spatiotemporal changes laws. The associated determinants may include land use and land cover types, surface biophysical conditions, landscape components and configurations, intensities of human activities, meteorological conditions, geographical locations, policy factors, etc. [9]. In addition, air temperatures have a more direct influence on human comfort and health. Although air temperatures are closely related to LSTs, these two variables cannot satisfactorily represent one another in urban environments [3, 14, 43]. Researchers should work cooperatively to further explore air temperature prediction methods in urban environments and to conduct comparative studies of SUHIs and UHIs.

4. Conclusions

We studied interannual spatiotemporal changes in the LSTs in 1449 urban and corresponding rural regions and changes in SUHIIs for these cities from 2003 to 2013 in five environmental regions with different ecological contexts in China. Certain important conclusions can be summarized as follows:

(1) Most of LSTs in urban and rural regions and SUHIIs for cities did not change significantly. Their changes had clear spatiotemporal agglomeration and variation laws.

(2) In general, the changes in LSTs in rural regions exhibited distinct seasonal variations in most regions of China during both the daytime and night-time. The rates with significant changes were usually highest in the summer, and most of them were 0.1–0.5°C (yr^{-1}) in China except for Xinjiang Province, which had negative rates during the daytime, and most of the rates with significant changes were 0.1–0.2°C (yr^{-1}) during night-time. The rates with significant changes were lowest in the winter, and most of them were −0.4 to −0.1°C (yr^{-1}).

(3) The spatiotemporal change laws of LSTs in urban regions were closely related to those in corresponding rural regions. During the daytime, the differences were the largest in the summer. Not only was there a notable increase in the number of cities whose mean LST values significantly changed with positive rates, but the change rates also clearly increased. During the night-time, human activities resulted in increased LSTs in the four seasons.

(4) During the daytime, the interannual variations in SUHIIs exhibited clear seasonal change laws. In the summer, not only the change rates but also the spatial scopes with significant variations were clearly the largest. The next highest rates occurred in the spring, in which the change rates were mainly positive, followed by the rates in the autumn. The variations were smallest in the winter, when the change rates in northcentral China were even negative. During the night-time, the variations in SUHIIs exhibited fewer seasonal fluctuations. The change rates remained almost unchanged, and most of them were 0.0–0.1°C (yr^{-1}).

Data Availability

The digital elevation data were taken from http://westdc.westgis.ac.cn/data/92bb3089-cc0c-46d2-908d-aae810ef064e. The LST data were downloaded from http://www.gscloud.cn/. The land use data were provided by http://www.resdc.cn/. The impervious percentage data were provided by https://www.beijingcitylab.com/. The other data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

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

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Supplementary Materials

The following supporting information is available as part of the online article. Figure S1: the percentages of reference rural regions whose annual and seasonal variation rates of mean LSTs significantly changed during both the daytime and night-time from 2003 to 2013 in the five environmental regions of China. Figure S2: the percentages of reference rural regions whose annual and seasonal variation rates of mean LSTs significantly positively changed during both the daytime and night-time from 2003 to 2013 in the five environmental regions of China. Figure S3: the percentages of urban regions whose annual and seasonal variation rates of mean LSTs significantly changed during both the daytime and night-time from 2003 to 2013 in the five environmental regions of China. Figure S4: the percentages of urban regions whose annual and seasonal variation rates of mean LSTs significantly positively changed during both the daytime and night-time from 2003 to 2013 in the five environmental regions of China. Figure S5: the percentages of cities whose annual and seasonal variation rates of mean SUHIIs significantly changed during both the daytime and night-time from 2003 to 2013 in the five environmental regions of China. Figure S6: the percentages of cities whose annual and seasonal variation rates of mean SUHIIs significantly positively changed during the daytime and night-time, and differences between the daytime and night-time rates from 2003 to 2013 in the five environmental regions of China. Table S1: typical monitoring indicators of SUHIIs. (*Supplementary Materials*)

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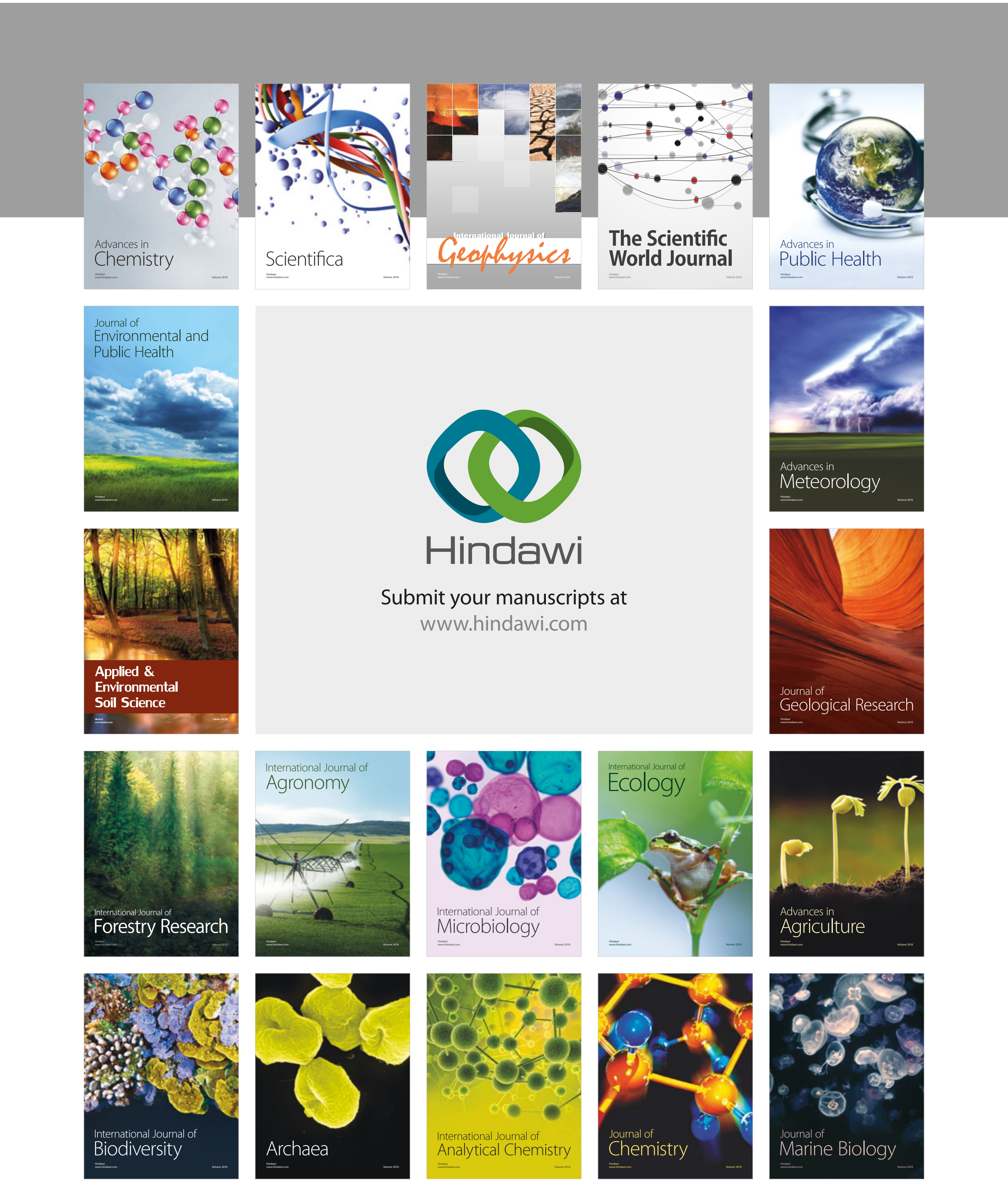

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