Science of the Total Environment 589 (2017) 200–211

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Urbanization and the thermal environment of Chinese and US-American cities

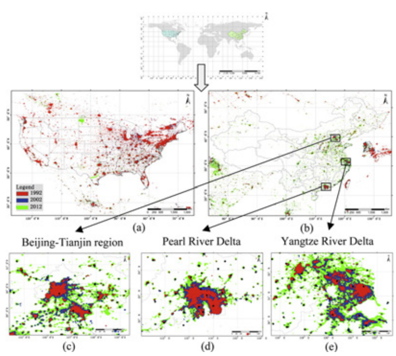
Danlu Cai [a,*], Klaus Fraedrich [b], Yanning Guan [a,*], Shan Guo [a], Chunyan Zhang [a]

[a] Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Beijing, China
[b] Max-Planck-Institute for Meteorology, Hamburg, Germany

HIGHLIGHTS

- Urbanization modifies light intensities and surface temperatures.
- Light intensities increase with urban area.
- Temperature tendencies indicate decrease at daytime (increasing at nighttime).
- High light intensity regions show less seasonal variability in temperature tendency.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 26 May 2016
Received in revised form 27 January 2017
Accepted 17 February 2017
Available online 2 March 2017

Editor: Dr. D. Barcelo

Keywords:
Surface thermal environment
Urbanization
Light intensity
City size
MODIS daytime/nighttime temperature tendency

ABSTRACT

Urbanization induced change of the thermal environment of cities is analyzed using MODIS LST and DMSP/OLS nighttime light data sets (2001 – 2012) to a) extend previous studies on individual megacities to a city size spectrum; b) investigate the heterogeneous surface thermal environment associated with the urbanization processes in terms of nighttime light intensity and city size; and c) provide insights in predicting how urban ecosystems will respond to urbanization for both a developing and a developed country (China and US-America), and on global scale. The following results are obtained: i) Nighttime light intensities of both countries (and globally) increase with increasing city size. ii) City size dependent annual or seasonal mean temperature tendencies show the urban effect by decreasing daytime and increasing nighttime mean temperatures (particularly in China) while variability can be related to climate fluctuations. iii) Daytime/nighttime seasonal warming tendencies (inferred from regional downscaling within city clusters) show the high light intensity regions to be stable while in low light intensity regions fluctuations prevail.

© 2017 Elsevier B.V. All rights reserved.

1. Introduction

The global urbanization process, where human population, material demands of production, human consumption and urban waste discharge expand and become more intense, has recently emerged as a sustainability challenge in an increasingly urbanized world (Alberti

* Corresponding authors.
E-mail addresses: caidl@radi.ac.cn (D. Cai), guanyn@radi.ac.cn (Y. Guan).

http://dx.doi.org/10.1016/j.scitotenv.2017.02.148
0048-9697/© 2017 Elsevier B.V. All rights reserved.

2005; Johnson 2001; Montgomery 2008; Pataki et al. 2006; Ren 2015). Whereas in 1900 a mere 10% of the global population were urban dwellers, that percentage now exceeds 50% and will rise even more to approach the 80% urbanization level of most industrialized nations today (Grimm et al. 2008). That is, global urban population is projected to increase by 2.7 billion in 2050, nearly doubling today's urban population of 3.4 billion (UN 2010). In addition, urban surface climate is generally characterized by higher surface air temperature, weaker mean wind speed, and lower relative humidity compared with its surrounding suburbs and countryside (Landsberg 1981; Oke 1987).

Although global and regional climate changes are known to have an impact on altering the urban surface climate, the urbanization/anthropogenic induced change in surface parameters, including increased atmospheric greenhouse gas concentration, aerosol emissions, and land use and land cover change, is a major component for the formation and evolution of urban climates (Grimm et al. 2008; Ren 2015; Wu and Yang 2013). Kalnay and Cai (2003) estimated urbanization and other land-use changes accounting for half of the observed reduction in the diurnal temperature range and an increase in mean air temperatures in the United States during the past century. The best-documented example of anthropogenic climate modification is the urban heat island effect (Landsberg 1981; Oke 1987), which affects not only local and regional climate, but also water resources, air quality, human health, and biodiversity and ecosystem functioning (Platt et al. 1994). Thus, research on the effects of global/regional urbanization on urban surface thermal environment may provide insights in predicting how urban ecosystems will respond to urban climate change (Carreiro and Tripler 2005).

Research on global/regional urbanization requires the definition of urban land use, which can be different depending on the questions being addressed (Schneider and Woodcock 2008, see also http://blogs.worldbank.org/sustainablecities/what- does-urban-mean): i) socio-demographic definitions involve administrative boundaries, population size or density, and economic indicators (Utzinger and Keiser 2006); and ii) physical definitions use the presence of human-made structures and materials (Mertes et al. 2015; Taubenböck et al. 2014). Unlike traditional socio-demographic research, employing remote sensing techniques to analyze physical human-made structures and materials in urban surface environment is a relatively recent field of research (Small et al. 2011), and has potential to obtain more comprehensive characteristics relating to urban dynamics and associated environmental consequences during the urbanization processes (Ma et al. 2012).

Nighttime light signals derived from the Defense Meteorological Satellite Program's Operational Linescan System (DMSP/OLS) provide striking remotely sensed data to analyze spatiotemporal changes in global urbanization processes (Elvidge et al. 1997; Small and Elvidge 2011; Small et al. 2005; Sutton 2003). Most previous studies have attempted to quantify the correlation between night lighting areas and urbanization variables, including urban expansion (Huang et al. 2016; Zhang et al. 2015), population growth (Ghosh et al. 2010; Sutton et al. 2001; Zhang and Seto 2011), gross domestic product (Doll et al. 2006; Henderson et al. 2012; Sutton and Costanza 2002), and electric power consumption (Amaral et al. 2005). However, to our knowledge, few studies have been concerned with the quantitative relationship among global, regional DMSP/OLS nighttime light signals and remote sensing based urbanization-related surface thermal changes, particularly on a basis of a city size spectrum analysis (details see Section 2).

Unlike using station and simulation data covering socio-demographic areas, remote sensing based technique of physical human-made nighttime light area is used in this study to define urbanization based land use (or city size) and thus to analyze the interrelationship, change tendency and variability of city size, light intensity and urban surface air temperature. It will help enhance our understanding of the spatiotemporal characteristics of urbanization and urban surface thermal environment in global and regional scale. After introducing the remote sensing-based DMSP/OLS nighttime light signals and surface air temperature datasets, methods of analysis are presented (Section 2). Global, countrywide and regional comparison of urban thermal environment and its relation to city size and nighttime light intensity is discussed (Section 3), followed by a concluding summary (Section 4).

2. Data and methods of analysis

Small et al. (2011) indicate that the idea of defining a city as a discrete entity with fixed administrative boundaries may be fundamentally flawed, because human settlement patterns and, more generally, land surface modification can be represented as continuous spatial variation in intensity of development or degree of modification. In this study, spatiotemporal changes of urbanization obtained from global DMSP/OLS nighttime stable lights products (1992, 2002 and 2012, acquired from NOAA National Geophysical Data Center) with the brightness range DN of 0 to 63 at the spatial resolution of 30 arc-seconds (~1 km) are used. To reduce the effects of over-glow, usually caused by anthropogenic activities in undeveloped areas that were not taken into account in statistical data of urban development (Elvidge et al. 1997; Small et al. 2005), only spatially contiguous lighted pixel units (subscript 'i') with $DN_i \geq 12$ are discussed below as cities (detailed descriptions of data quality control and threshold choosing see Small et al. (2011)). The area of each pixel within spatially contiguous lighted areas, $a(j)$, is defined as a_i. Thus a city (numbered by 'j') is characterized by its size, $size(j)$. Its light intensity and its light variability are deduced from the spatially contiguous lighted area with brightness $DN_i \geq 12$. Thus, j corresponds to the sequence of spatially contiguous areas exceeding the brightness threshold and i corresponds to the number of pixels in each of these areas. That is

$$City\ size(j) = \sum_i a_i(j)$$

$$Light\ intensity(\mathrm{j}) = \left(\sum_i DN_i\right)/size(j) \quad \text{and}$$

$$Light\ variability(j) = std(DN_i)$$

The city size spectrum analysis provided in this study is inspired by the power-law or Zipf's law which implies that small occurrences are extremely common, whereas large instances are extremely rare (Adamic 2000). That holds for huge city samples in a global and subcontinental scale analyses, and it will circumvent limitations of previous studies with their inconsistencies, including differences of time period, regional span and analysis method (see Sections 3.1 to 3.3).

Twelve years of land surface temperature (LST) data of Moderate Resolution Imaging Spectroradiometer (MODIS, MOD11C3) is analyzed provided monthly at 0.05° spatial resolution as a gridded level-3 product for daytime and nighttime to calculate temperature tendencies from 2001 to 2012. To be comparable, the DMSP/OLS nighttime stable light products are resampled according to the spatial resolution of MODIS LST data. Intra-annual seasonality and annual mean temperatures are calculated before a simple linear regression model (against year) is used to obtain the temperature change trend/slope. Inter-annual temperature change tendencies of spring (March to May), summer (June to August), autumn (September to November), winter (December to February) and annual mean of the surface air temperature are evaluated by F-$test$ with all significance levels at the P-value <0.05 level (unless noted otherwise).

Scale dependent analysis (Section 3) includes a city unit (city size spectrum analysis, see Section 3.1–3.3) and a pixel unit (see Section 3.4). Among, brightness DN, daytime and nighttime temperatures and their related tendencies are recorded as pixel units. City size, light intensity, light variability and related city size based averaged temperature tendencies for both daytime and nighttime are calculated in terms of city units. Therefore, besides urbanization and heterogeneous surface thermal environment on individual megacities (Section 3.4), this study extends the analyses to a city size spectrum both for China and America and on global scale, which to our knowledge, is new.

3. Scale dependent spatial heterogeneity of the surface thermal environment

The geographical setting in Fig. 1 displays the space, landscape and intensity change of nighttime lighted area and their related variations of urbanization process: i) Accurate information related to the spatio-temporal extent and dynamics of urban surface energy fluxes is especially necessary for China (see Fig. 1a–b) which, in the past decades, experienced rapid urban development (Frolking et al. 2013). In the two decades (1992–2012), the land used for urban construction in China has expanded in all directions from the original core function zone (highlighted in Fig. 1c–e, detailed statistics see Table 1), while no obvious urban area expanding pattern in the main city zone of America could be found. ii) There is a green patch (2012) that looks like a big city near Williston, North Dakota, America, although there is mostly grass and no big city in that part of North Dakota. In fact, those lights could not be detected six years ago before the oil boom based on fracking technology started (details see Krulwich (2013)). Note that there is also another large light trend of shale gas production in south Texas and a very large area of non-urban light in China on the loess plateau north of Xi'an (pers. communication by reviewer). iii) Possible distinctions between China and US-America with respect to urbanization

Table 1
City size comparison for three major city clusters in China: spatially contiguous lighted areas in 2012 (with DSMP/OLS $DN \geq 12$ are classified as city boundaries).

Pixel number (>12)	1992	2002	2012
Beijing-Tianjin Region	13,719	22,327	44,023
Pearl River Delta	16,167	21,593	31,795
Yangtze River Delta	18,881	38,512	78,286

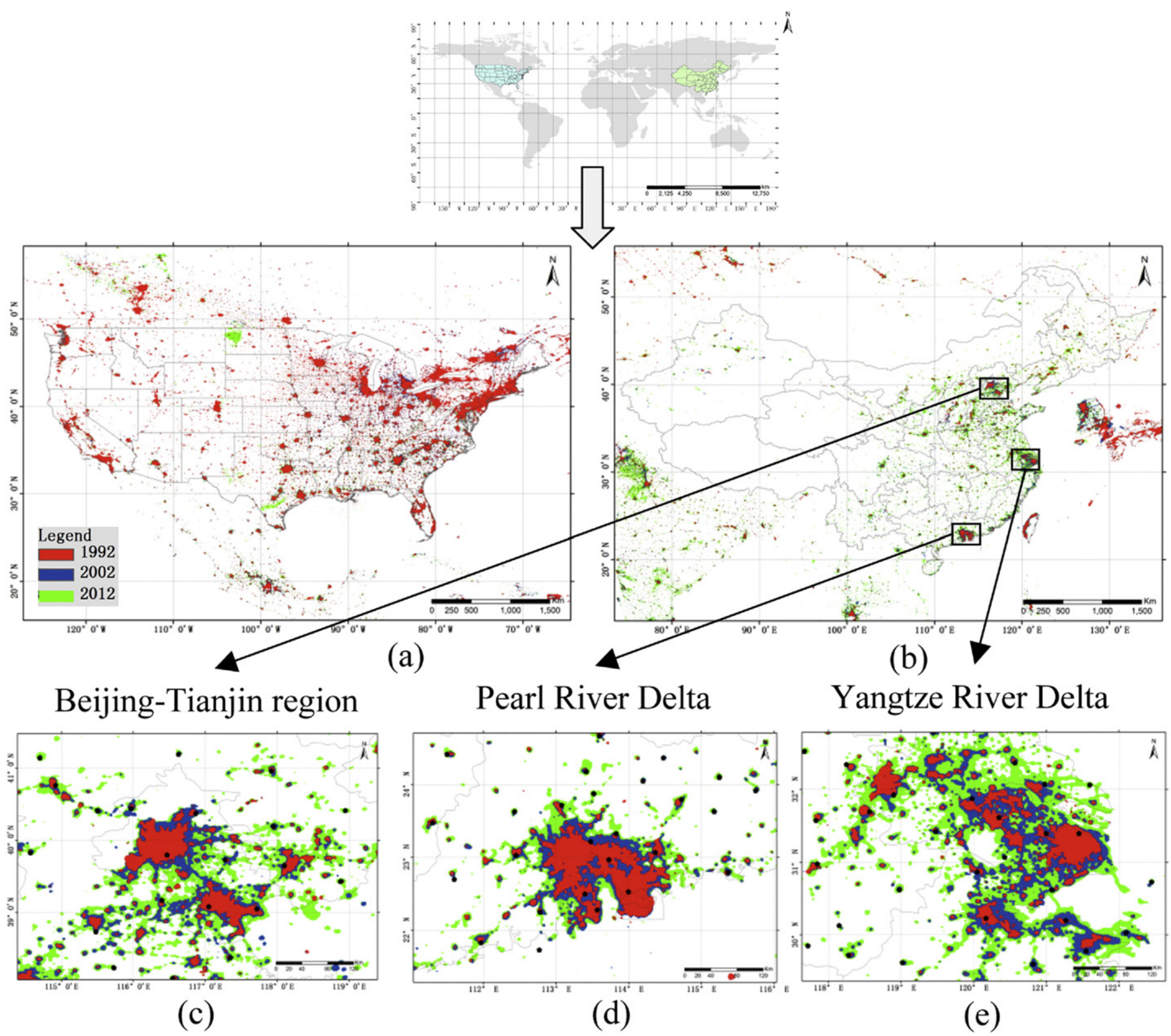


Fig. 1. Geographical setting of spatiotemporal city size changes of 1992 (red), 2002 (blue) and 2012 (green) using DSMP/OLS nighttime light data for a) America, b) China, and for three major city clusters in China of c) Beijing-Tianjin region; d) Pearl River Delta; and e) Yangtze River Delta. Spatially contiguous lighted areas with $DN \geq 12$ are classified as cities (detailed descriptions of data quality control and threshold selection see Small et al. (2011)).

may provide insight for understanding of urban climates in countries undergoing a more stable compared to a rapidly changing development. City clusters of Beijing-Tianjin, Pearl River Delta, Yangtze River Delta, New York, Los Angeles and San Francisco and their related spatial averaged summer surface temperature time series are displayed geographically and statistically (Fig. 2), showing a decreasing (increasing) warming tendency in daytime Beijing-Tianjin, Pearl River Delta and San Francisco (others) city clusters, and a increasing warming tendency in nighttime city cluster, except for San Francisco with *slope ~ −0.01*. For detailed spatial temperature changes see Section 3.4.

3.1. City size and light intensity

The satellite-derived observations of spatially contiguous stable anthropogenic light in 2012 are used to indicate city boundaries or human habitation regions to calculate light intensity (accumulated brightness per area, see Section 2) and spatially averaged temperature tendencies (discussed in subsections below). Fig. 3 demonstrates the relationship between city size and light intensity on global scale, and for China and America: i) Like a power-law or Zipf's law implies that small occurrences are extremely common, whereas large instances are extremely rare (Adamic 2000), small size cities prevail in terms of number compared with megacities, and thus statistics interval of city size is binned into exponentially wider bins with a base of 2 km^2 to get a suitable display. ii) No obvious distinction could be found in statistics of the (*city size, light intensity/variability*)-diagram analyzing the global and the sub-continental scale of China and America. iii) Light intensity and variability increase with increasing city size subject, however, to small fluctuations. That is, high light intensity >*~40* exists in cities (city clusters) ranging from *16,384* to *32,768* km$^{\mathbf{2}}$. For huge cities/city clusters >*~32,768* km^2, light intensity is averaged/decreased to *~30*. Here the variability is measured in terms of standard deviations and coefficients of variation (ratio of regional standard deviation to regional mean) binned in area classes.

3.2. City size and temperature change

The Urban Heat Island effect suggests that land surface is replaced by anthropogenic material overlays, which lead to changes in urban thermal characteristics, especially in megacities. The possible distinct influences of urbanization on the urban warming effect are analyzed comparing a near stable (America) and a more rapidly changing

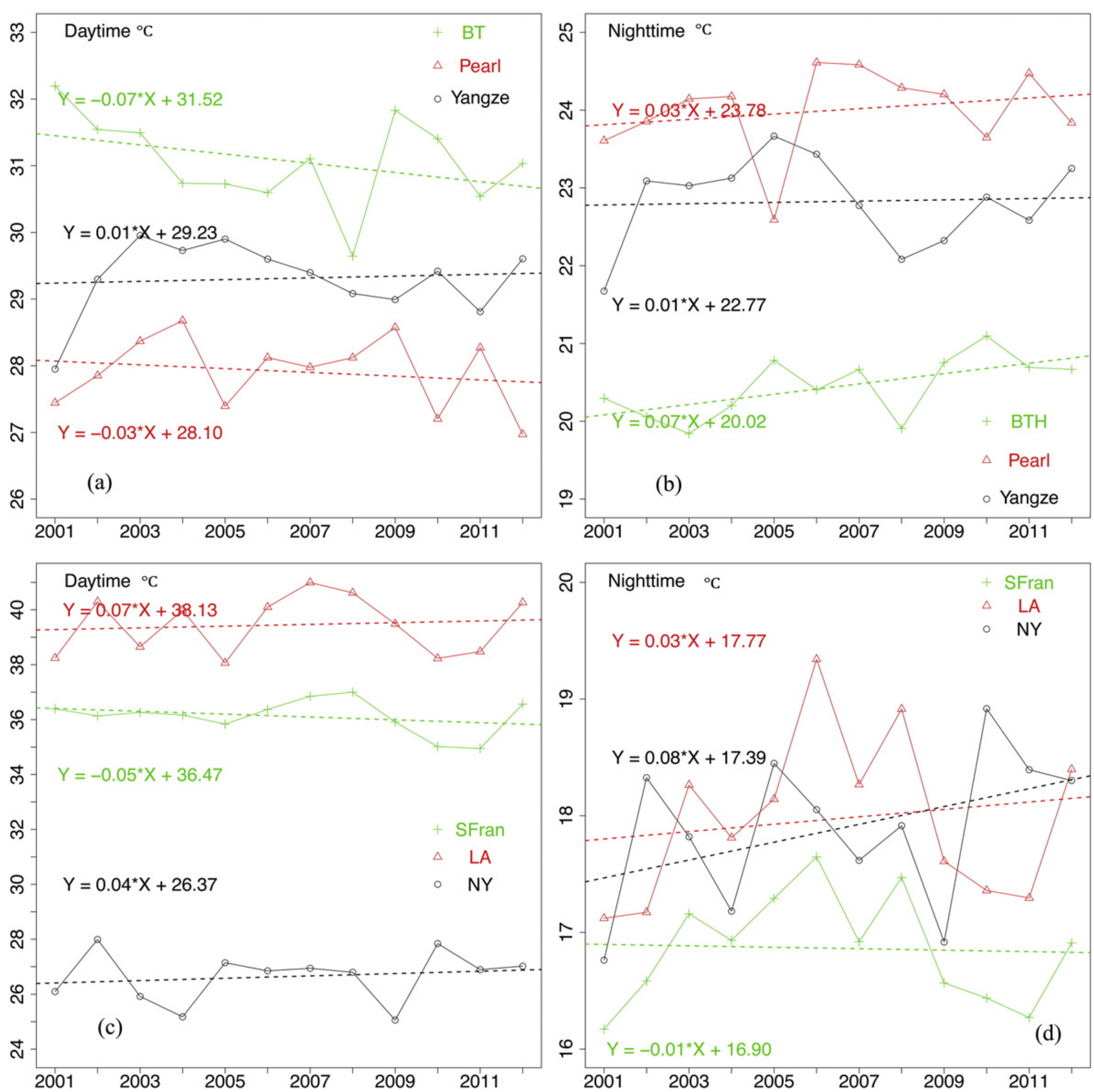


Fig. 2. Time series comparison of several American and Chinese city clusters of surface temperature for day- and night-time (a–b) Beijing-Tianjin (BT), Pearl River Delta (Pearl) and Yangze River Delta and for daytime and nighttime (c–d) San Francisco (SFran), Los Angeles (LA) and New York (NY).

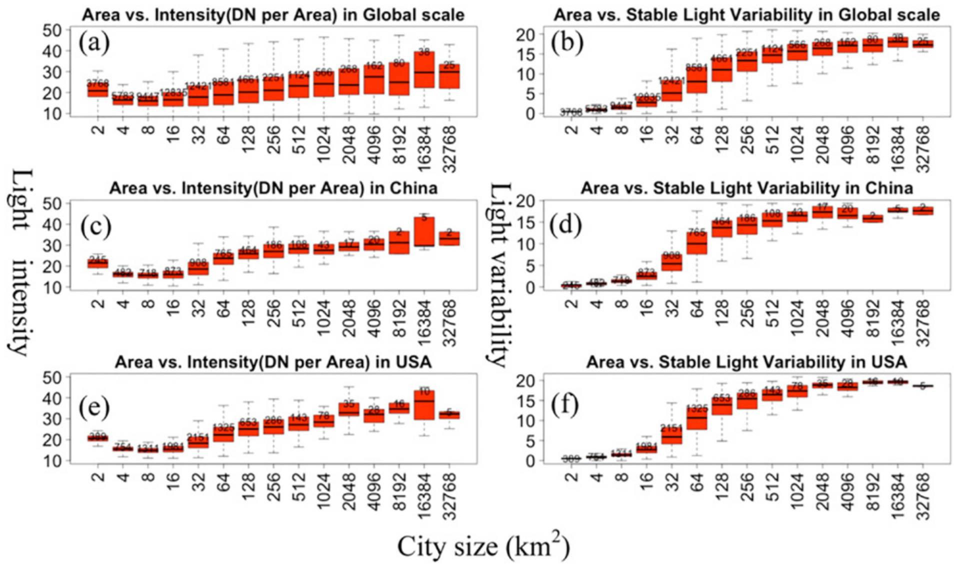


Fig. 3. City size dependent analyses of nighttime light a) intensity (accumulated brightness per city) and b) variability (standard deviation of nighttime light intensity of the global); c) intensity and d) variability in China; and e) intensity and f) variability in America. City sizes are binned into exponentially wider bins to circumvent the situation that few numbers of cities appear in large city size ranges (city size unit: km^2).

developing country (China). First we observe that, from 1992 to 2012 (see Fig. 1) the urban constructions in China have expanded in all directions but no obvious expansion pattern could be identified for America. For the subsequent comparison between city sizes extracted from 2012 nighttime light data and their related MODIS LST tendencies (2001–2012) on both global and on country scale, the following results are noted (Fig. 4):

1) For MODIS daytime annual mean tendency, globally (in China and in US-America), 56.63% (24.79% and 72.22%) cities are undergoing statistically significant warming in the daytime annual mean tendency. While for nighttime annual mean tendency, a hundred percent of the whole city size is found showing a warming tendency. That is, cities are more likely to show urban warming rates with temperature decreasing in the daytime and an increasing in the nighttime which is comparable with previous results that urbanization may weaken (strengthen) urban warming rates in the daytime (nighttime) as shown by Kalnay and Cai (2003) and Ren (2015).
2) For MODIS daytime annual mean tendency, the increasing rates of mean (averaged median) are 0.30 (0.33), −1.02 (−0.53) and 0.80 (0.94) °C/decade for global scale, China and America, respectively. And for nighttime annual mean tendency, the increasing rates in terms of mean (averaged median) are 1.02 (0.71), 0.37 (0.84) and 0.47 (0.67) °C/decade for global scale, China and America, respectively. The most obvious difference between mean and median, daytime and nighttime temperatures occurs in China which may be related to the fact that the large and significant urbanization-induced warming has contributed to changes in climate change

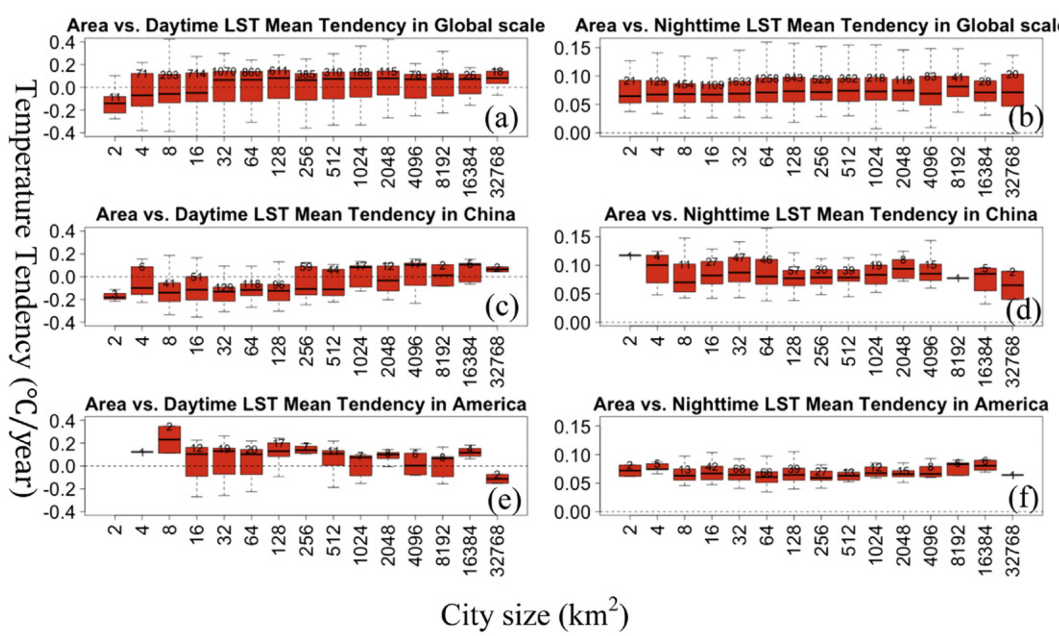


Fig. 4. City size dependent analyses of MODIS daytime and nighttime annual averaged land surface temperature tendencies (2001–2012): a–b) on global scale, c–d) in China, and e–f) in America. City sizes are binned into exponentially wider bins to circumvent the situation that few numbers of cities appear in large city size ranges (city size unit: km^2, tendency (2001–2012) unit: °C/year).

induced extreme temperatures in China (Ren and Zhou 2014; Zhou and Ren 2012).

3) Previous studies (focusing on megacities) are extended to a city size spectrum. Comparing annual averaged daytime temperature trends on global scale, China and America show differences between small to moderate size and mega- cities. On global scale (China), city size less than ~*30* km^2 (~*200* km^2) mainly shows a cooling tendency in daytime temperature, while most of the cities in America show a warming tendency independent from city size. However, no obvious difference between small and mega cities could be found in annual averaged nighttime temperature tendency. Mackey et al. (2012) demonstrate that albedo increases produced greater cooling than

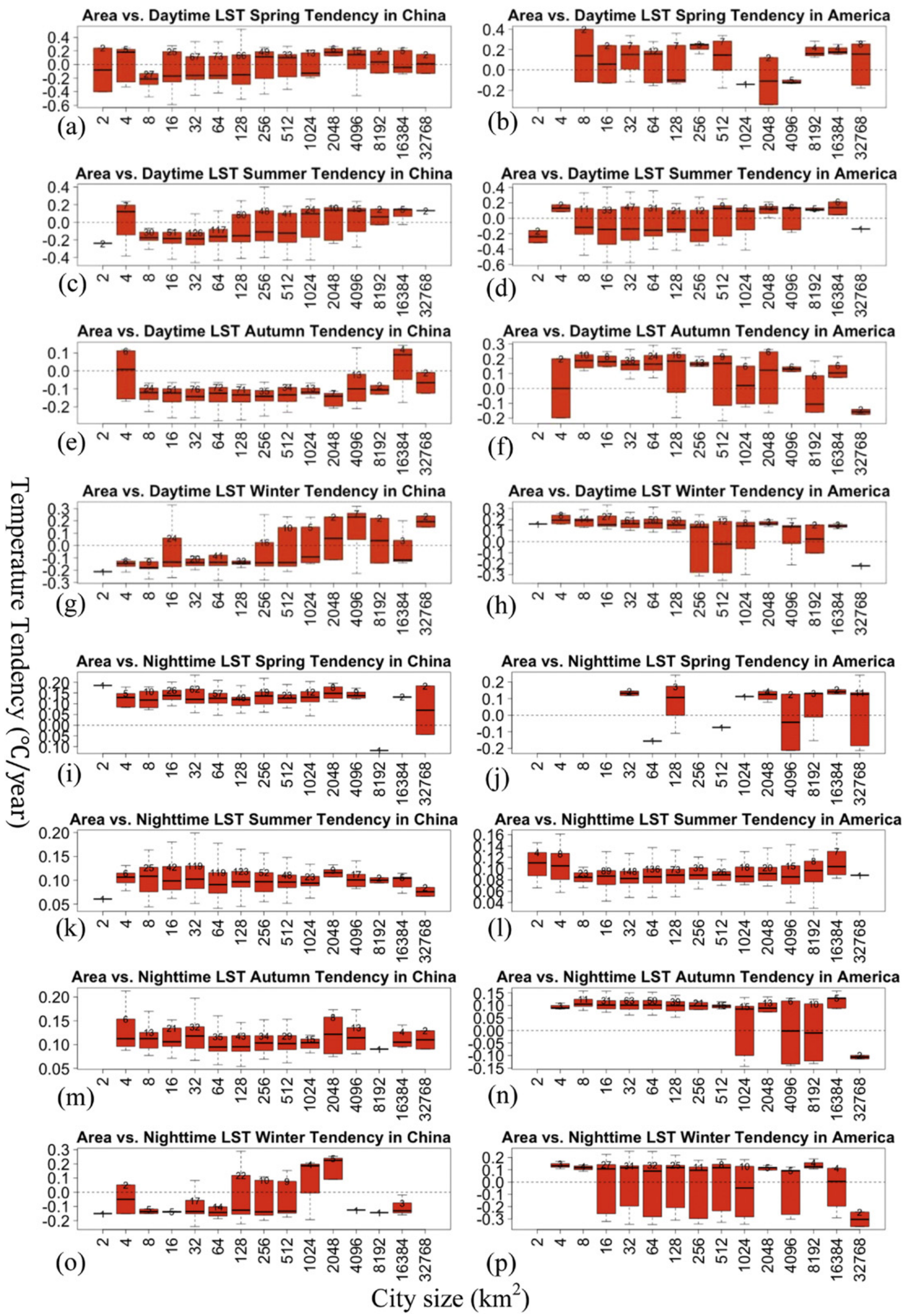


Fig. 5. City size dependent analyses of MODIS daytime seasonal averaged land surface temperature tendencies (2001–2012) in China and US-America: a–b) spring, c–d) summer, e–f) autumn and g–h) winter; and of MODIS nighttime tendencies: i–j) spring, k–l) summer, m–n) autumn and o–p) winter. City sizes are binned into exponentially wider bins to circumvent the situation that few numbers of cities appear in large city size ranges (city size unit: km^2, tendency (2001–2012) unit: °C/year).

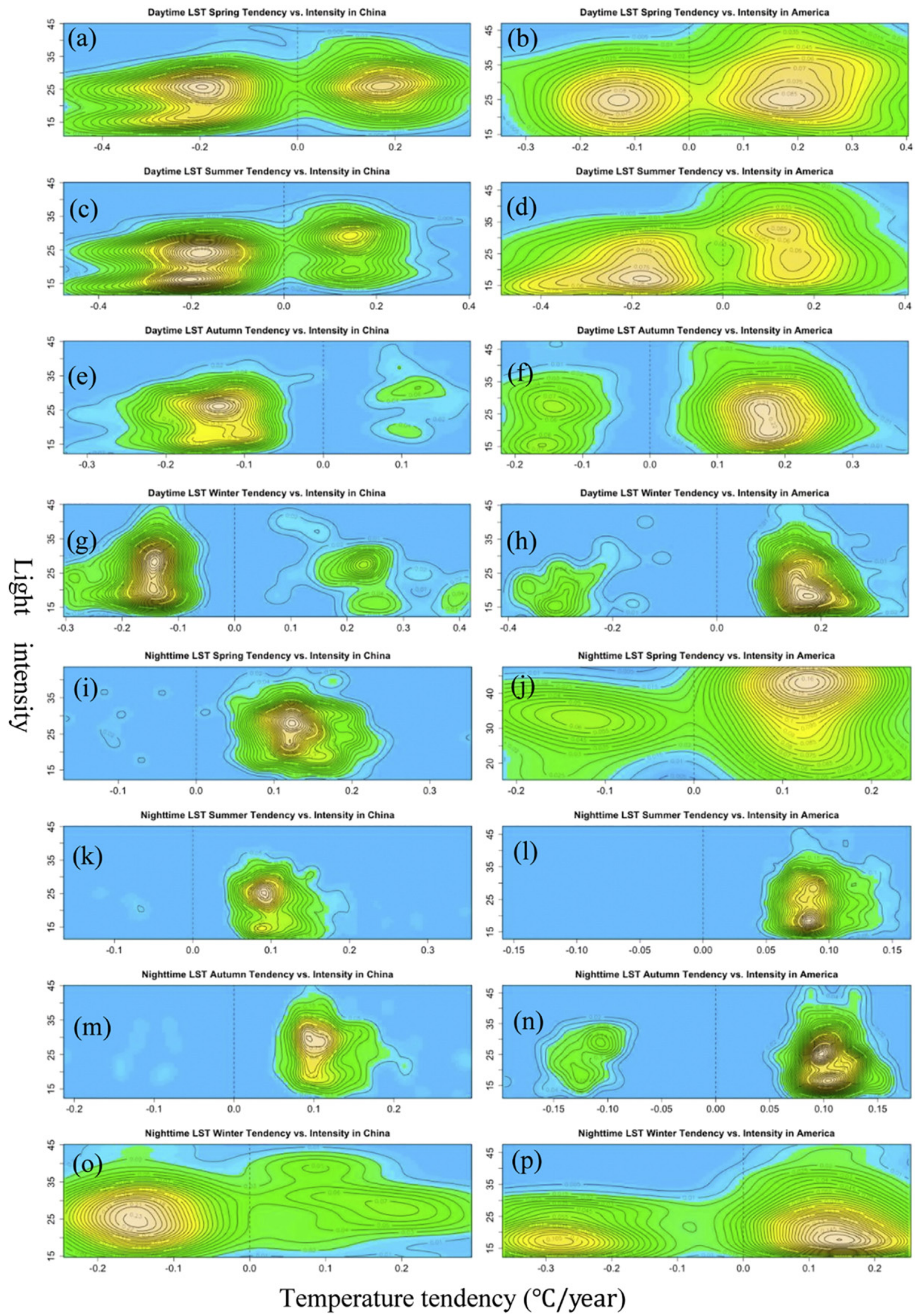


Fig. 6. Density distributions of (*light intensity, temperature tendency*)-diagram in daytime China and US-America of a–b) spring, c–d) summer, e–f) autumn and g–h) winter; and in nighttime China and US-America of i–j) spring, k–l) summer, m–n) autumn and o–p) winter (tendency (2001–2012) unit: °C/year).

the NDVI increases. Observation of aerial images confirmed that typical instances of efforts to increase albedo, such as reflective roofs, produced stronger cooling than common instances of efforts to change NDVI, such as greening roofs, planting street trees and providing green spaces (Mackey et al. 2012). In China, small to moderate size cities experienced rapid urban development in terms of land cover type changes (attribution changes): vegetated land surface is replaced by anthropogenic material overlays; in megacities, however, land cover type has remained unchanged and kept its attribution in the reconstruction process. In US-America, no obvious patterns of urban area expansion/brand-new cities could be found since 1972 (see Fig. 1). Thus the ratio of land cover type changes (from vegetated land surface to anthropogenic material overlays) may be the reason.

Similar comparisons between city sizes and their related seasonal MODIS LST tendencies in China and America (Fig. 5) demonstrate that daytime cooling tendency (in small cities) occurs in China, while in US-America it could only be found in summer, and the daytime warming tendency, which is observed in the other three seasons, is independent of city size. The nighttime warming in China (US-America) accounts for 97.56% (66.67%), 97.15% (99.68%), 95.31% (81.82%) and 30.00% (63.01%) of the whole city size, with the increasing rates in terms of averaged median are 1.13 (0.60), 0.97 (0.91), 1.06 (0.70) and −0.81 (0.63) °C/decade in spring, summer, autumn and winter, respectively. That is, for the whole China (America), the magnitudes of the warming rates vary from season to season: spring > autumn > summer > winter (summer > autumn > spring > winter). The seasonal warming rate

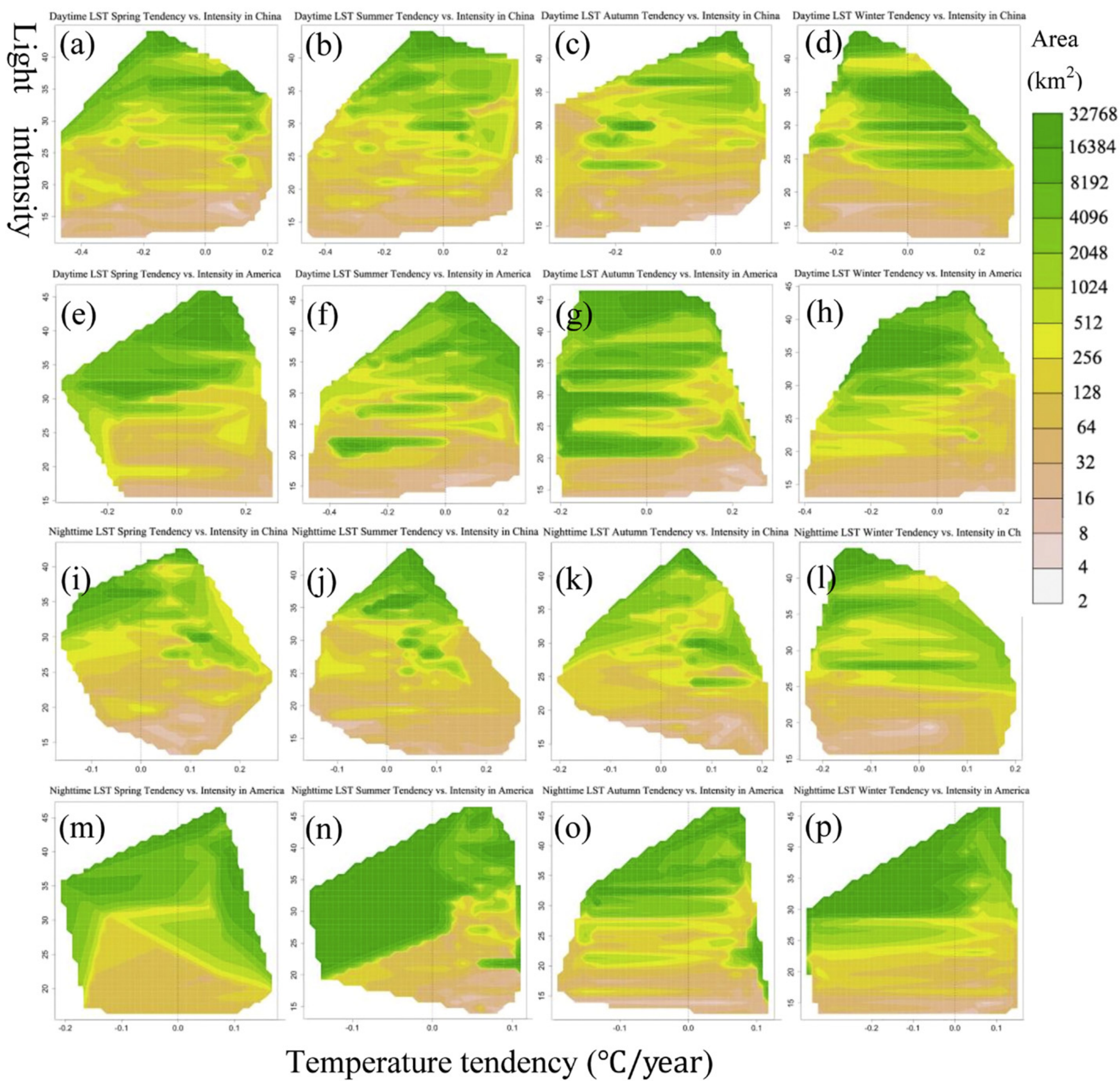


Fig. 7. City size information embedded in the (*light intensity, temperature tendency*)-diagram for daytime China: a) spring, b) summer, c) autumn and d) winter, versus for daytime US-America of e) spring, f) summer, g) autumn and h) winter; and for nighttime China: i) spring, j) summer, k) autumn and l) winter, versus for nighttime US-America of m) spring, n) summer, o) autumn and p) winter (tendency (2001–2012) unit: °C/year).

order in US-America is comparable with previous results based on one of the megacities in China (Yangtze River Delta, Du et al. (2007)).

3.3. Urban thermal environment: relation to city size and light intensity

Seasonal urban surface states in the (*temperature tendency, light intensity*)-diagram are presented as frequency (number of cities) distribution (Fig. 6), and the city size information embedded in the diagram is shown in Fig. 7. Both figures are used to demonstrate how the urban thermal environment responds to the change of city size and light intensity. The following results are noted.

i) A bimodal frequency distribution of city unit is aligned near *light intensity ~ 25* but separated by the zero temperature change line, separating warming and cooling tendencies, which is particularly pronounced for daytime temperature tendency based statistics. But for nighttime temperature tendency based statistics, a unimodal frequency distribution of city unit occurs in spring, summer and autumn in China and in summer in US-America, associated only with a warming tendency.

ii) The frequency distribution covers *light intensity* from *~15* to *45*, cities with similar light intensity show both warming and cooling. Regions with high light intensity generally correspond to fully developed urban areas with near total outdoor illumination, less brightly observations may correspond to lower built area density with dimmed outdoor lights throughout or to a small number of discrete lighted areas with somewhat brighter lighting (Small et al. 2011). Therefore, no linear relationship shows between seasonal urban temperature tendency and light intensity, particularly in daytime.

iii) Compared with daytime and nighttime temperature tendencies in US-America, the situation, mentioned in previous research (Kalnay and Cai 2003; Ren 2015), that daytime urban warming rates decline while nighttime urban warming rates increase is more pronounced in China. This, to a certain extent, may be related to anthropogenic air pollution within cities. Furthermore, greater concentration of aerosols in the middle to lower troposphere will also affect precipitation in urban areas by modifying the microphysical processes of clouds (Rosenfeld et al. 2008; Van Den Heever and Cotton 2007).

Projecting the spatial information (Fig. 7, smoothed frequencies) onto the (*temperature tendency, light intensity*)-diagram (Fig. 6) leads to a bivariate frequency density distribution which represents city size dependent countrywide statistics of the urban thermal environment; the following results are noted:

i) In China, the daytime spring and summer reveal bimodality of (*temperature tendency, light intensity*)-regimes characterized by warming or cooling tendencies (*~±0.2, ~25*) for moderate size cities; in daytime of autumn and winter the density peak of cooling tendency (*~−0.15, ~25*) corresponds with moderate size to mega-cities. The nighttime warming density peak (*~0.1, ~25*) in China, except winter, corresponds with moderate size to mega- cities as well.

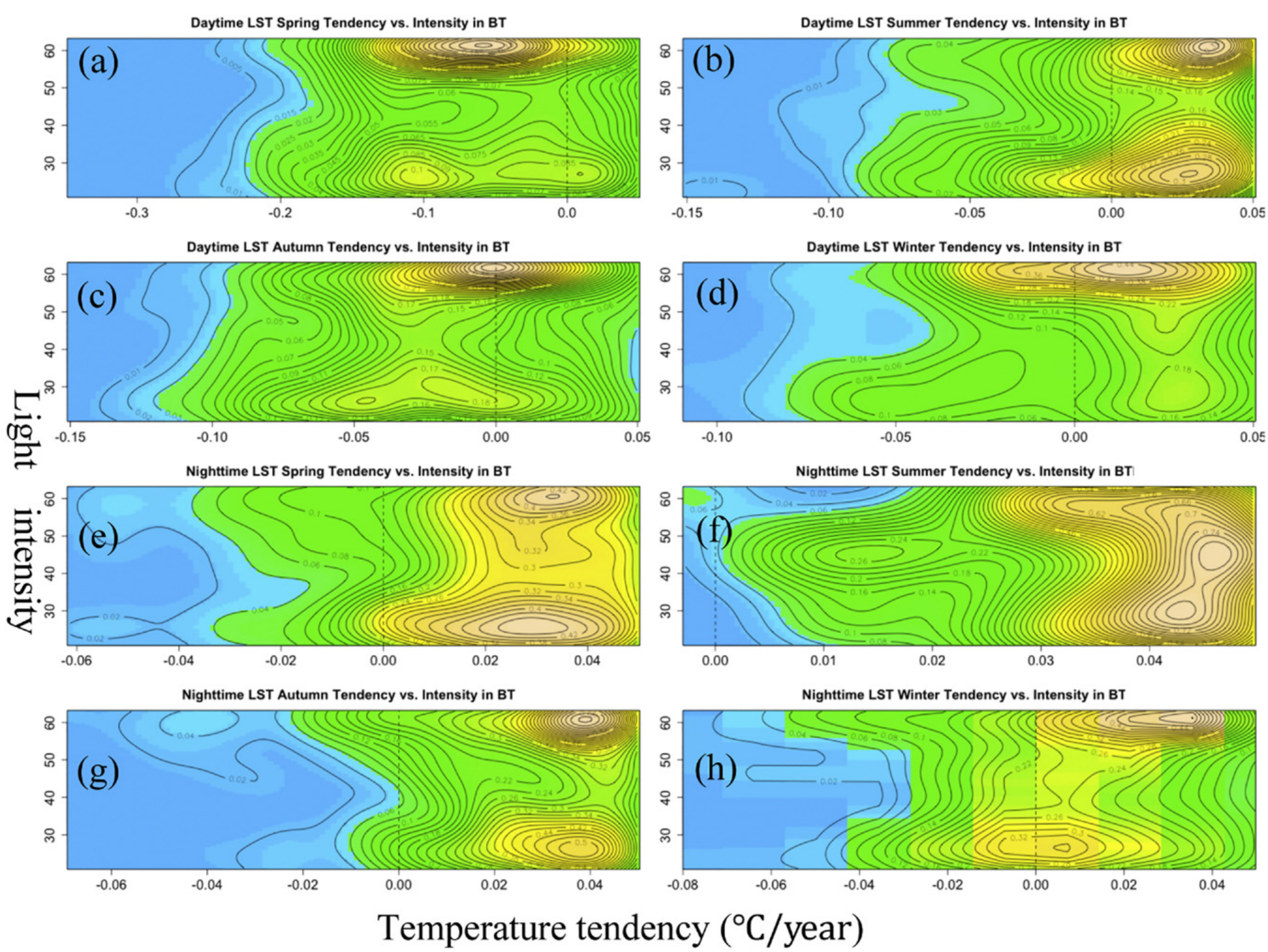


Fig. 8. Seasonal density distribution comparison of (*light intensity* versus *temperature tendency*)-diagram in daytime Beijing-Tianjin (BT) city cluster of a) spring, b) summer, c) autumn and d) winter; and in nighttime of e) spring, f) summer, g) autumn and h) winter (tendency (2001–2012) unit: °C/year).

ii) Comparing China with US-America, daytime spring and summer bimodal regimes show a similar density distribution, while there is a 'mirror' like difference of temperature tendency peak (that is, cooling in China and warming in US-America) appearing in daytime autumn and winter. The density peak of daytime warming tendency *(~0.2, ~25)* in autumn and winter corresponds with megacities in US-America. The nighttime warming density peak in US-America shifts from megacities in spring to moderate size cities in the other three seasons. That is, most cities in US-America, particularly for moderate to mega-cities, are mainly characterized by urban warming both in day- and nighttime.

iii) The area information embedded in the daytime and nighttime (*temperature tendency, light intensity*) diagram shows slight fluctuations existing in a general tendency that city size is positively related to light intensity but no linear relationship lies between city size and temperature tendency. City areas of US-America embedded in the nighttime (*temperature tendency, light intensity*)-diagram are more smoothly distributed (Figs. 7m-p) indicating a more uniform/balanced development of megacities with respect to light intensity.

3.4. Regional application: a downscaling analysis

China has been experiencing intensive urbanization since the 1980s, particularly in the eastern part (Wu and Yang 2013). Single cities have expanded to form distinctive city clusters, and the most obvious examples are the Beijing-Tianjin (~40°N), Pearl River Delta (~20°N) and Yangtze River Delta (~30°N) city clusters (Fig. 1). For the three city clusters (of regional scale) the urban surface states are highlighted seasonally and presented as frequency (number of pixels) distribution in the (*temperature tendency, light intensity*)-diagram (Figs. 8 to 10) to estimate the effect of urbanization on surface air temperature change, to detect the seasonal variation of urban warming in different regions, and to analyze the impact of urbanization on daytime and nighttime temperatures.

The following results are noticed: i) Pearl River Delta and Yangtze River Delta city clusters show a more uniform/balanced development with respect to light intensity (the frequency peak at light intensity *~55* and *~50*) compared with a bimodality frequency distribution associated with high and low light intensity peaks separated at light intensity *~40* in Beijing-Tianjin city clusters. ii) In the Beijing-Tianjin city cluster, the daytime summer and winter and the nighttime four seasons indicate a warming tendency. In the Pearl River Delta city cluster, daytime summer and nighttime spring, summer and autumn show a warming tendency and a general warming tendency, except nighttime winter, is found in the Yangtze River Delta city clusters. iii) The most obvious warming is in nighttime autumn Beijing-Tianjin cluster with the density peak *~0.4* °C/decade. In addition, an opposite temperature tendency shows up for the three city clusters in nighttime winter, with a warming tendency in Beijing-Tianjin cluster compared with cooling tendencies in Pearl River Delta and Yangtze River Delta city clusters.

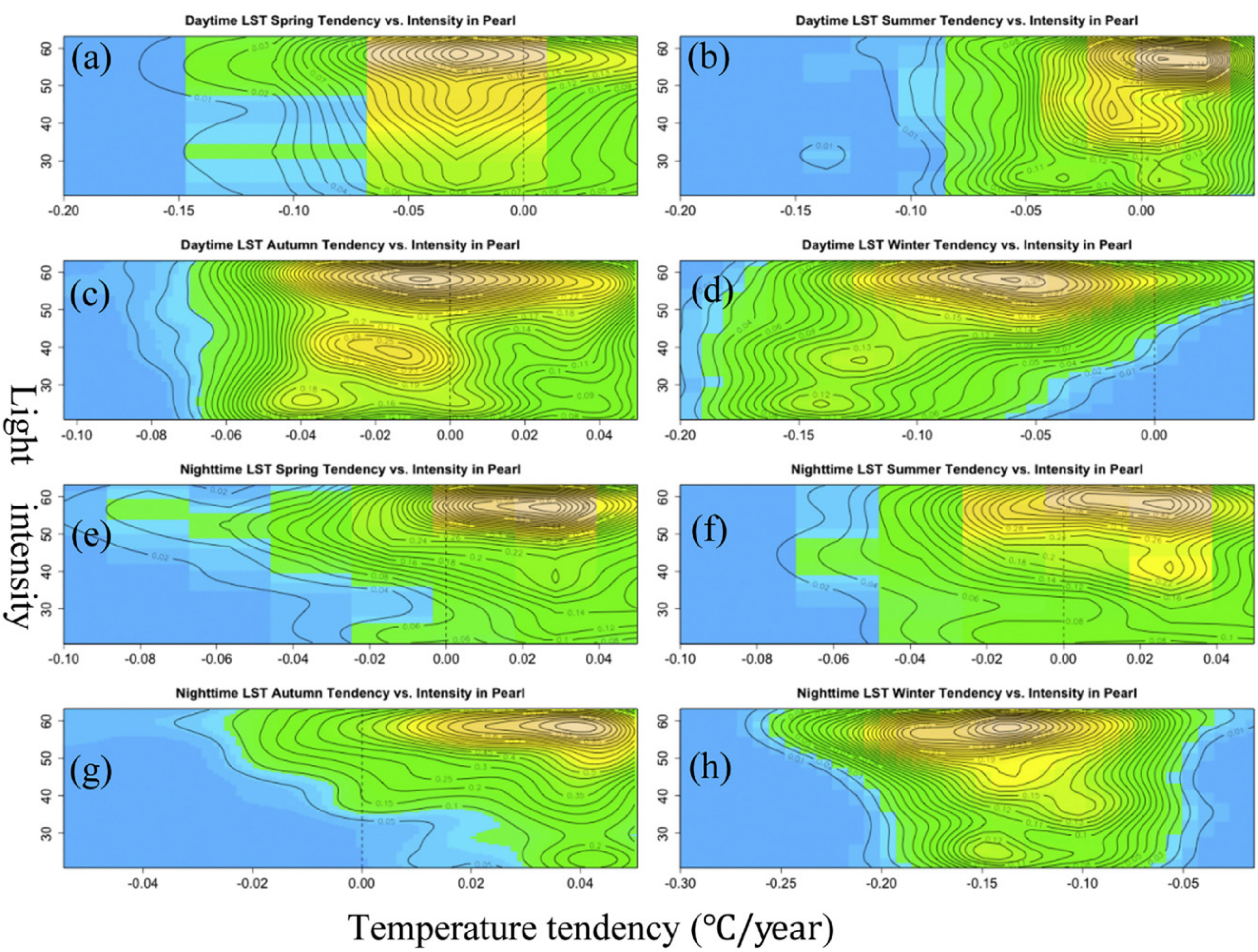


Fig. 9. Seasonal density distribution comparison of (*light intensity, temperature tendency*)-diagram in daytime Pearl River Delta city cluster of a) spring, b) summer, c) autumn and d) winter; and in nighttime of e) spring, f) summer, g) autumn and h) winter (tendency (2001–2012) unit: °C/year).

iv) High light intensity regions within city clusters reveal a more stable warming tendency in both daytime and nighttime compared with seasonal variability characterized by low light intensity regions.

4. Summary and conclusion

The urbanization induced change is a major component for the formation and evolution of urban climates (Grimm et al. 2008; Ren 2015; Wu and Yang 2013), which affects not only the climates on local and regional scale, but also water resources, air quality, human health, biodiversity and ecosystem functioning (Platt et al. 1994). There are numerous studies focusing on the impact of urbanization on the surface air temperature change in individual megacities (see Table 1 in Wu and Yang (2013)). However, considerable inconsistencies exist, including differences of time period, regional extent and methods of analysis. With DMSP/OLS nighttime lights (2012) and MODIS LST documented for 2001–2012 and analyzed on global and subcontinental scale (China and US-America), this study investigates spatial heterogeneities of the urban surface environment associated with the urbanization processes in terms of light intensity and city size spectrum to provide insights in predicting how urban ecosystems will respond to urbanization on global scale, and for developing and developed countries. City unit based (i–iii) and pixel unit based (iv) main conclusions are as follows.

i) Although the spatiotemporal extent and dynamics of urban surface energy fluxes in China has experienced rapid urban development in the past decades, no obvious distinction could be found in the relationship between city size and light intensity/variability comparing statistics on global scale, and for China and US-America. That is, in the city size and light intensity relationship, the general tendency of light intensity clearly increases with increasing city size while small countrywide-to-global fluctuations exist.

ii) Unlike a linear relationship, city size dependent annual or seasonal mean temperature tendency could be found in daytime global and developing countrywide (China) statistics. Small to moderate size cities globally and China show cooling tendencies or fluctuations in daytime urban surface temperature, while except summer, no remarkable city size dependent temperature tendencies are found in US-America. In addition, China indicates more obvious temperature tendency fluctuations, which may relate to the fact that the large and significant urbanization-induced warming has contributed to changes in extreme temperature in China.

iii) Density statistics in the (*temperature tendency, light intensity*)-diagram confirm that a bimodal frequency distribution of light intensity associated with warming and cooling tendencies is particularly pronounced for daytime urban surface temperature. But the nighttime statistics reveals a seasonal uni-modal frequency distribution of light intensity associated with a warming tendency both in China, where it is more intense, and US-America. That is, cities are more likely to show urban effect in terms of a temperature decrease in the daytime and an increase in the nighttime, particularly for a developing country like China.

iv) Regional downscaling analysis on pixel scale of the Beijing-

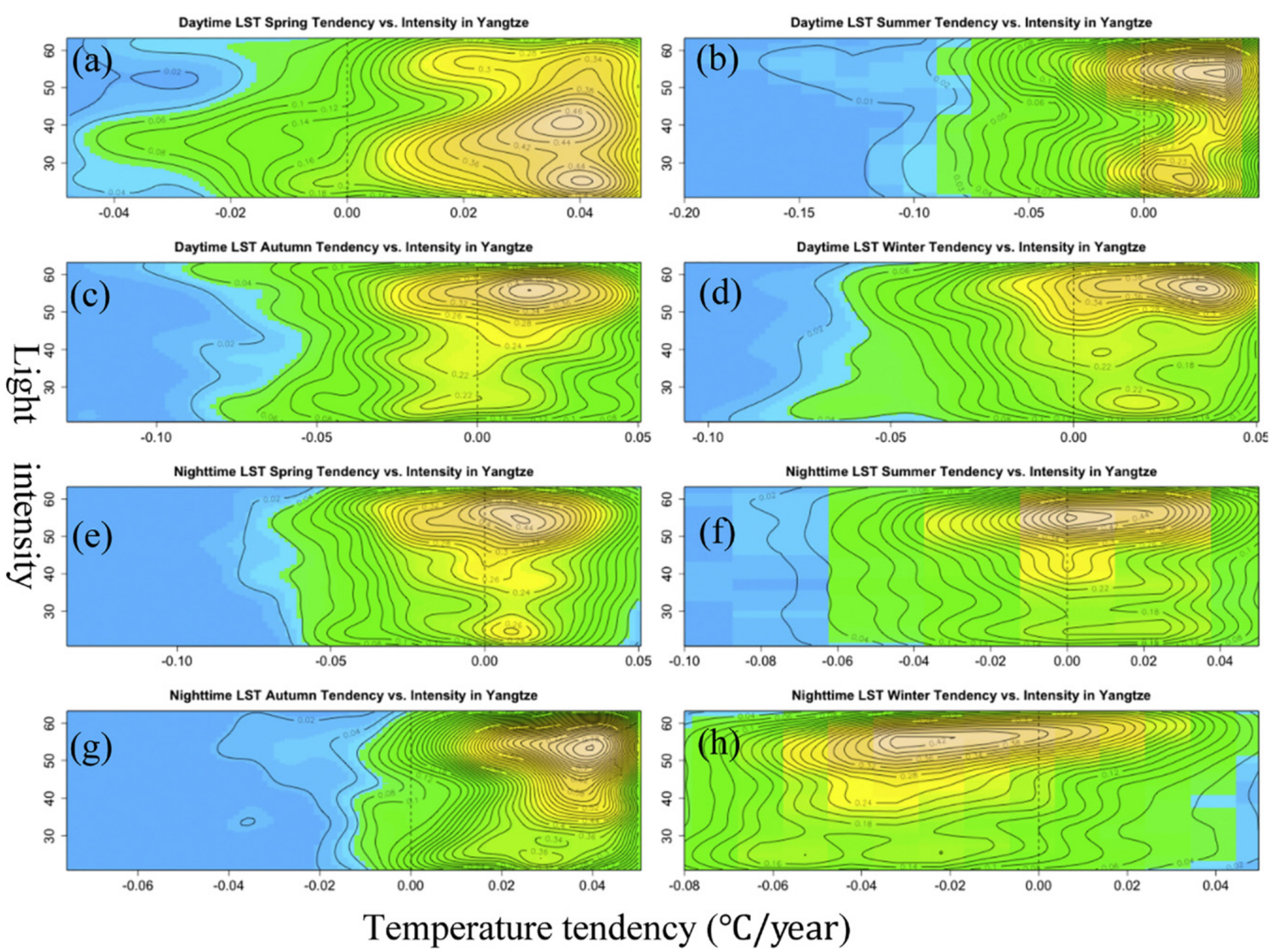


Fig. 10. Seasonal density distribution comparison of (*light intensity, temperature tendency*)-diagram in daytime Yangtze River Delta city cluster of a) spring, b) summer, c) autumn and d) winter; and in nighttime of e) spring, f) summer, g) autumn and h) winter (tendency (2001–2012) unit: °C/year).

Tianjin, Pearl River Delta and Yangtze River Delta city clusters indicates that Pearl River Delta and Yangtze River Delta city clusters show a more uniform/balanced development compared with Beijing-Tianjin city clusters, and that high light intensity regions within a city cluster show a more stable warming tendency compared with seasonal fluctuations in low light intensity regions.

Surface warming is attributed to natural climate change and anthropogenic forcing. The anthropogenic forcing mainly includes the emissions of green house gases and aerosols, as well as the land use and cover change (Parry et al. 2007). The urbanization is one of the extreme processes in the land use and land cover change (Pielke 2005). Since both green house gases and urbanization tend to increase the surface air temperature, it is quite difficult to estimate the relative contribution of either effect to the surface warming (Kalnay and Cai 2003). Thus further research on measures of multi-scale resilience and on the diagnostics of attributing the causes of change is required.

Acknowledgements

Support by the Chinese National Science Foundation (Grant No. 41501375), by the Max Planck Fellow Group (DC, KF) is acknowledged.

References

Adamic, L.A., 2000. Zipf, Power-Laws, and Pareto-A Ranking Tutorial. Xerox Palo Alto Research Center, Palo Alto, CA http://ginger.hpl.hp.com/shl/papers/ranking/ranking.html.

Alberti, M., 2005. The effects of urban patterns on ecosystem function. Int. Reg. Sci. Rev. 28, 168–192.

Amaral, S., Câmara, G., Monteiro, A.M.V., Quintanilha, J.A., Elvidge, C.D., 2005. Estimating population and energy consumption in Brazilian Amazonia using DMSP night-time satellite data. Comput. Environ. Urban. Syst. 29, 179–195.

Carreiro, M.M., Tripler, C.E., 2005. Forest remnants along urban-rural gradients: examining their potential for global change research. Ecosystems 8, 568–582.

Doll, C.N., Muller, J.-P., Morley, J.G., 2006. Mapping regional economic activity from night-time light satellite imagery. Ecol. Econ. 57, 75–92.

Du, Y., Xie, Z.Q., Zeng, Y., Shi, Y.F., Wu, J.G., 2007. Impact of urban expansion on regional temperature change in the Yangtze River Delta. J. Geogr. Sci. 17, 387–398.

Elvidge, C.D., Baugh, K.E., Kihn, E.A., Kroehl, H.W., Davis, E.R., 1997. Mapping city lights with nighttime data from the DMSP operational Linescan system. Photogramm. Eng. Remote. Sens. 63, 727–734.

Frolking, S., Milliman, T., Seto, K.C., Friedl, M.A., 2013. A global fingerprint of macro-scale changes in urban structure from 1999 to 2009. Environ. Res. Lett. 8, 024004.

Ghosh, T., Powell, R.L., Elvidge, C.D., Baugh, K.E., Sutton, P.C., Anderson, S., 2010. Shedding light on the global distribution of economic activity. The Open Geography Journal 3, 147–160.

Grimm, N.B., Faeth, S.H., Golubiewski, N.E., Redman, C.L., Wu, J., Bai, X., Briggs, J.M., 2008. Global change and the ecology of cities. Science 319, 756–760.

Henderson, J.V., Storeygard, A., Weil, D.N., 2012. Measuring economic growth from outer space. American Economic Review. vol. 102. American Economic Association, pp. 994–1028 2.

Huang, X.M., Schneider, A., Friedl, M.A., 2016. Mapping sub-pixel urban expansion in China using MODIS and DMSP/OLS nighttime lights. Remote Sens. Environ. 175, 92–108.

Johnson, M.P., 2001. Environmental impacts of urban sprawl: a survey of the literature and proposed research agenda. Environment and Planning A 33, 717–735.

Kalnay, E., Cai, M., 2003. Impact of urbanization and land-use change on climate. Nature 423, 528–531.

Krulwich, R., 2013. A Mysterious Patch of Light Shows Up in the North Dakota Dark. In. http://www.npr.org/sections/krulwich/2013/01/16/169511949/a-mysterious-patch-of-light-shows-up-in-the-north-dakota-dark.

Landsberg, H.E., 1981. The Urban Climate. Academic press.

Ma, T., Zhou, C., Pei, T., Haynie, S., Fan, J., 2012. Quantitative estimation of urbanization dynamics using time series of DMSP/OLS nighttime light data: a comparative case study from China's cities. Remote Sens. Environ. 124, 99–107.

Mackey, C.W., Lee, X., Smith, R.B., 2012. Remotely sensing the cooling effects of city scale efforts to reduce urban heat island. Build. Environ. 49, 348–358.

Mertes, C.M., Schneider, A., Sulla-Menashe, D., Tatem, A., Tan, B., 2015. Detecting change in urban areas at continental scales with MODIS data. Remote Sens. Environ. 158, 331–347.

Montgomery, M.R., 2008. The urban transformation of the developing world. Science 319, 761–764.

Oke, T.R., 1987. Boundary Layer Climates. Methuen, New York.

Parry, M., Canziani, O., Palutikof, J., Van der Linden, P., Hanson, C., 2007. Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change, 2007. Climate Change 2007: Working Group II: Impacts, Adaptation and Vulnerability.

Pataki, D., Alig, R., Fung, A., Golubiewski, N., Kennedy, C., McPherson, E., Nowak, D., Pouyat, R., Romero Lankao, P., 2006. Urban ecosystems and the North American carbon cycle. Glob. Chang. Biol. 12, 2092–2102.

Pielke, R.A., 2005. Land use and climate change. Science 310, 1625–1626.

Platt, R.H., Rowntree, R.A., Muick, P.C., 1994. The Ecological City: Preserving and Restoring Urban Biodiversity. Univ of Massachusetts Press.

Ren, G.Y., 2015. Urbanization as a major driver of urban climate change. Adv. Clim. Chang. Res. 1, 1–6.

Ren, G., Zhou, Y., 2014. Urbanization effect on trends of extreme temperature indices of national stations over Mainland China, 1961–2008. J. Clim. 27, 2340–2360.

Rosenfeld, D., Lohmann, U., Raga, G.B., O'Dowd, C.D., Kulmala, M., Fuzzi, S., Reissell, A., Andreae, M.O., 2008. Flood or drought: how do aerosols affect precipitation? Science 321, 1309–1313.

Schneider, A., Woodcock, C.E., 2008. Compact, dispersed, fragmented, extensive? A comparison of urban growth in twenty-five global cities using remotely sensed data, pattern metrics and census information. Urban Stud. 45, 659–692.

Small, C., Elvidge, C.D., 2011. Mapping decadal change in anthropogenic night light. Prog. Environ. Sci. 7, 353–358.

Small, C., Pozzi, F., Elvidge, C.D., 2005. Spatial analysis of global urban extent from DMSP-OLS night lights. Remote Sens. Environ. 96, 277–291.

Small, C., Elvidge, C.D., Balk, D., Montgomery, M., 2011. Spatial scaling of stable night lights. Remote Sens. Environ. 115, 269–280.

Sutton, P.C., 2003. A scale-adjusted measure of "urban sprawl" using nighttime satellite imagery. Remote Sens. Environ. 86, 353–369.

Sutton, P.C., Costanza, R., 2002. Global estimates of market and non-market values derived from nighttime satellite imagery, land cover, and ecosystem service valuation. Ecol. Econ. 41, 509–527.

Sutton, P., Roberts, D., Elvidge, C., Baugh, K., 2001. Census from heaven: an estimate of the global human population using night-time satellite imagery. Int. J. Remote Sens. 22, 3061–3076.

Taubenböck, H., Wiesner, M., Felbier, A., Marconcini, M., Esch, T., Dech, S., 2014. New dimensions of urban landscapes: the spatio-temporal evolution from a polynuclei area to a mega-region based on remote sensing data. Appl. Geogr. 47, 137–153.

UN, 2010. World Urbanization Prospects, 2009 Revision. United Nations, New York.

Utzinger, J., Keiser, J., 2006. Urbanization and tropical health—then and now. Ann. Trop. Med. Parasitol. 100, 517–533.

Van Den Heever, S.C., Cotton, W.R., 2007. Urban aerosol impacts on downwind convective storms. J. Appl. Meteorol. Climatol. 46, 828–850.

Wu, K., Yang, X., 2013. Urbanization and heterogeneous surface warming in eastern China. Chin. Sci. Bull. 58, 1363–1373.

Zhang, Q., Seto, K.C., 2011. Mapping urbanization dynamics at regional and global scales using multi-temporal DMSP/OLS nighttime light data. Remote Sens. Environ. 115, 2320–2329.

Zhang, X.Y., Li, P.J., Cai, C., 2015. Regional urban extent extraction using multi-sensor data and one-class classification. Remote Sens. 7, 7671–7694.

Zhou, Y., Ren, G., 2012. Change in extreme temperature event frequency over mainland China, 1961–2008. Clim. Res. 50, 125–139.