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Key Points:
- The contribution of urbanization to regional warming is robust in homogenized SAT data and ERA5 reanalysis using different methods
- The spatial scale dependence of urbanization warming is investigated; the contribution of urbanization warming decreases when the scale increases
- Urbanization contribution exhibits distinct seasonal variation based on the uncertainty assessment

Supporting Information:
- Supporting Information S1

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A New Evaluation of the Role of Urbanization to Warming at Various Spatial Scales: Evidence From the Guangdong-Hong Kong-Macau Region, China

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Abstract The urbanization impacts on surface air temperature (SAT) change in the Guangdong-Hong Kong-Macau region (GHMR) from 1979 to 2018 are examined using homogeneous surface observations, reanalysis, and remote sensing. Results show that the warming due to urbanization tends to be smaller or insignificant as the spatial scale increases. The urbanization contribution to the local warming can reach as high as 50% in the center of each metropolis, remains high (~25%) in the Greater Bay Area (GBA), and decreases to about 10% in the whole GHMR. The warming in GHMR is nearly uniform throughout the day, and therefore, the observed trend of the diurnal temperature range (DTR) is not statistically significant. However, the urbanization contribution exhibits distinct seasonal variations, large in summer and autumn while smaller in winter and spring.

Plain Language Summary The Guangdong-Hong Kong-Macau region (GHMR), especially the Greater Bay Area (GBA), is a region typical of China's economic development and rapid urbanization. To precisely assess how much the urbanization contributes to the regional warming, we comprehensively evaluate the urbanization warming and its uncertainties in GHMR by using more careful processed and assessed data (observations, reanalysis, and remote sensing) and different analysis methods. The results show that the warming due to urbanization tends to be smaller as the spatial scale increases: The contribution to the local warming can reach as high as 50% in the metropolis, remains high (~25%) in GBA, and decreases to about 10% in GHMR. In addition, this paper systematically discusses the uncertainty in urbanization contribution detection, which was often neglected in the past detection. Based on the significance tests, urbanization warming is nearly uniform throughout the day, while it exhibits distinct seasonal variation. Our study also has important implications for understanding the influences of human activities on regional climate change for other regions experiencing rapid urbanization processes.

1. Introduction

As urbanization increases rapidly across the globe, the urbanization contribution to climate warming has been increasingly discussed. For the global average surface air temperature (SAT) change, studies indicated that the impact of urbanization on the contribution to the large-scale warming is of secondary importance and is an order of magnitude smaller than the climate warming itself (Intergovernmental Panel on Climate Change, Trenberth et al., 2007; Hartmann et al., 2013; Jones et al., 1990; Q. X. Li, Sun, et al., 2020; Parker, 2004). However, there are significant differences (from less than 5% to more than 40% of the total warming in China), and these lead to uncertainties in the urbanization contribution to national and regional warming over China (Jones et al., 2008; Q. X. Li et al., 2004; Ren et al., 2008; Yan et al., 2009; X. Yang et al., 2011, 2013; Ye et al., 2018; F. Wang et al., 2015; K. C. Wang et al., 2017), due to the use of different data sources and processing methods, such as the use of model data to assess the impact of urbanization on site records (Koopmans et al., 2015; Van Weverberg et al., 2008), as well as different aspects of urbanization, such as the classification of urbanization level (Oke et al., 2017; Tysa et al., 2019). Therefore, accurate detection

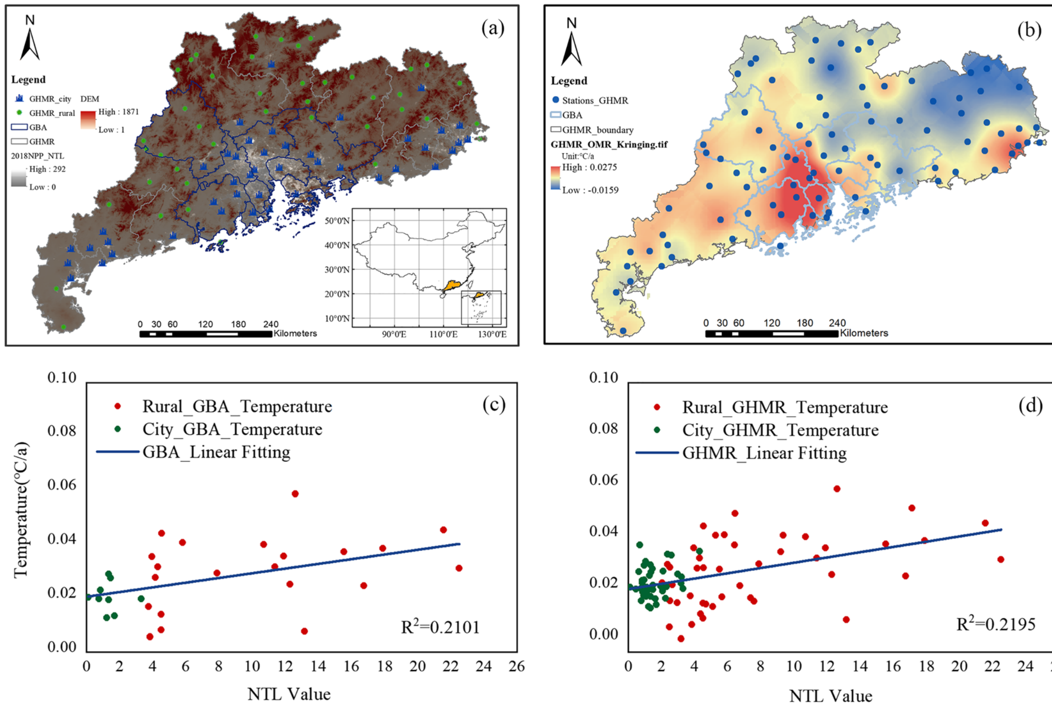

Figure 1. (a) Digital elevation model (DEM) information, spatial distribution of climate observation stations, and the degree of urbanization (expressed by NPP_NTL) in Guangdong, Hong Kong, and Macau (the quantities color scale shows the DEM value, and the gray scale shows the NPP_NTL value). (b) The urbanization effect on the GHMR detected by the observation minus reanalysis (OMR) method during the period of 1979–2018 period, and the relationship between the urbanization trends and the NTL values in GBA (c) and GHMR (d).

and extraction of the contribution of urbanization to the climate warming remain an important subject of study.

The Guangdong-Hong Kong-Macau region (GHMR, Figure 1a), especially the Greater Bay Area (GBA), is a typical region of China's economic development and most rapid urbanization. Thus, the urbanization effect on climate change in this region has been of great concern to scientists and the public (J. Y. Huang et al., 2004; Jiang et al., 2019; Q. X. Li et al., 2004; Luo & Lau, 2017; Ye et al., 2018; Zhou et al., 2004). Since there are no sufficient rural stations that can be used as a climate reference in this region, especially in the recent past, it is difficult in studying the contribution of urbanization to the warming and its uncertainty. Consequently, it has brought certain obstacles to quantitatively assess the urbanization impacts on people's daily life and health issues (Y. J. Yang et al., 2020; Yim et al., 2019).

This paper will adopt different methods to systematically evaluate and compare the contribution of climate warming caused by urbanization at different spatial scales in this area (Metropolises, the GBA, and the whole GHMR area) and estimate the level of uncertainty based on different data. Our purpose is to provide scientific support for the regional climate change rules and the decision making within government departments in response to climate change. Section 2 briefly introduces data and analysis methods used in this paper. Section 3 provides the analysis results of local urbanization warming contributions in all areas of the GHMR, the GBA, and Guangzhou and Shenzhen. Section 4 makes a systematic discussion on the analysis results and their uncertainties. Section 5 draws brief conclusions and proposes future research directions.

2. Data and Methods

2.1. Data and Regions

Our study focuses on the GHMR in China, including Guangdong province, Hong Kong, and Macau, a total of 88 climate observation stations. Considering the differences due to the unbalanced economic development in the GHMR region, the analysis in this paper also specifically takes into account the regional effect on the GBA (Figure 1a).

The observational SAT data include the monthly mean of daily maximum, daily minimum, and daily average temperatures. The time span of observations is from January 1965 to December 2018. The reanalysis SAT is widely used to evaluate the urbanization effects due to their not assimilating surface observations like National Center for Atmospheric Research/National Centers for Environmental Prediction (NCAR/NCEP) (Kalnay & Cai, 2003) and NCEP/DOE (J. Wang et al., 2018; X. Yang et al., 2011; Zhou et al., 2004) or assimilating them in small weight like ERA-Interim (Goddard & Tett, 2019). The reanalysis used in this paper is derived from the ERA5 (the data selection rules are same with those in the ERA-Interim) of the European Centre for Medium-Range Weather Forecasts (ECMWF; Hersbach et al., 2020), and the time coverage is from January 1979 to December 2018 (see Texts S1 and S2 and Figures S1 and S2 in the supporting information (SI)). We adopt Moderate Resolution Imaging Spectroradiometer (MODIS) Land Cover Type Yearly L3 Global 500 m SIN Grid product MCD12Q1 data and 2018 NPP-VIIRS nighttime light (NTL) remote sensing image data to characterize the degree of urbanization (Figure 1a) (see the detailed data (Text S3) and method (Text S4) in the SI).

2.2. Quantification of Urbanization and Uncertainty Assessment

All the stations are first divided into urban and rural stations based on the NTL (see the Text S5 in the SI) in study regions, and then a regional weighted average series is calculated for the SAT time series with weightings from the loading of the first Principal Component Analysis (PCA) mode; thus, the regional temperature series would provide a good representation of regional temperature change as it will reduce impacts from several problematic stations (Q. X. Li et al., 2004; and see the Text S5 in the SI). The urbanization impact separation process is carried out as follows: (1) The difference between the regional average SAT series of all stations and the regional average SAT series of nonurban (rural) stations represents the urbanization impact of the region and is recorded as all minus rural (AMR); (2) 2 m temperature data from ERA5 are interpolated to the SAT series for each observational site using an inverse distance interpolation (IDW) method, and then the difference between the observation and the reanalysis series is calculated as the impact of urbanization in this region, which is recorded it as OMR (see Text S6 in the SI).

The trend estimation and its significance at 5% level is calculated using the restricted maximum likelihood (REML) method (Diggle et al., 1994; Trenberth et al., 2007; Hartmann et al., 2013). Following Karl et al. (2015), the data uncertainty (by perturbing the time series by its the standard deviation) and fitting uncertainty are combined to assess the total uncertainty of the SAT trends for urbanization warming. The fitting uncertainty is quantified using effective sampling size determined by Lag-1 autocorrelation of time series considered (B. Huang et al., 2020; Q. X. Li, Sun, et al., 2020).

3. Results

3.1. The Warming Trend in GHMR and Its Correlation With the Urbanization Indicator

From Table 1, we can easily get the temperature trends of several Metropolises, the GBA, and the GHMR from 1979 to 2018. The annual average SAT trend is 0.410°C/10a in Guangzhou and 0.311°C/10a in Shenzhen, which is greater than the regional average warming trend (compared to GBA and GHMR). However, the rate of temperature warming in Hong Kong and Macau is significantly lower than the regional average warming level. The warming trend of Macau does not even pass the significance test at the 5% level. For the whole GHMR, the average temperature has significantly increased in the 40 years, and its linear trend is 0.248°C/10a; for the GBA where urbanization is more concentrated, the average temperature trend is 0.278°C/10a. It is worth noting that the temperature trend in this region is similar to the global average (0.274 ± 0.040°C/10a) (Q. X. Li, Dong, & Jones, 2020) but still slightly lower than the national average for China (0.379 ± 0.044°C/10a) (Q. X. Li et al.,) because the GHMR is located in the lower latitude region of China and the air temperature is regulated by the ocean in certain degree.

Figure 1b shows the spatial distribution of the effect of urbanization on temperature based on the OMR method for all stations in the GHMR region interpolated with the ordinary Kriging and the relationship between the degree of urbanization (represented by the NTL) and the SAT trends for 1979–2018 in GBA (Figure 1c) and GHMR (Figure 1d). Unlike the result from Jones et al. (2008), the more significant

Table 1
*Comparison of the Trends and Urbanization Contribution of Different Annual Temperature in the Metropolises, GBA, and GHMR From 1979 to 2018 (OMR = Obs—ERA5; AMR = All_Obs—Rural_Obs) (Unit: °C/10a. Trend: Mean ± 1.96 * Stand Error)*

		Obs							
		All	Rural	City	ERA5	OMR	Contribution	AMR	Contribution
MEAN	Guangzhou	—	0.230 ± 0.050	0.410 ± 0.094	0.207 ± 0.096	0.203 ± 0.045	49.50%	0.180 ± 0.049	43.90%
	Shenzhen	—	0.202 ± 0.069	0.311 ± 0.110	0.234 ± 0.086	0.077 ± 0.051	24.80%	0.109 ± 0.045	35.10%
	Hong Kong	—	—	0.220 ± 0.082	0.228 ± 0.082	−0.009 ± 0.035	−3.60%	—	—
	Macau	—	—	0.095 ± 0.096	0.211 ± 0.086	−0.116 ± 0.043	−122.10%	—	—
	GBA	0.278 ± 0.100	0.206 ± 0.102	0.310 ± 0.098	0.201 ± 0.096	0.076 ± 0.020	27.70%	—	—
	GHMR	0.248 ± 0.094	0.220 ± 0.090	0.276 ± 0.100	0.229 ± 0.090	0.019 ± 0.016	7.66%	0.028 ± 0.014	11.29%
MAX	GBA	0.292 ± 0.118	—	0.320 ± 0.118	—			—	—
	GHMR	0.288 ± 0.112	0.269 ± 0.118	0.306 ± 0.118	—			0.019 ± 0.020	6.60%
MIN	GBA	0.321 ± 0.096	—	0.361 ± 0.096	—			—	—
	GHMR	0.279 ± 0.094	0.243 ± 0.094	0.316 ± 0.096	—			0.036 ± 0.018	12.90%
DTR	GBA	0.007 ± 0.080	—	0.014 ± 0.073	—			—	—
	GHMR	0.029 ± 0.088	0.031 ± 0.102	0.026 ± 0.073	—			−0.002 ± 0.018	−6.90%

Note. The trends are statistically significant at the 5% level.

urbanization effects are always seen in the larger cities, so this would likely be related to the urbanization of the surrounding areas near the observation stations in China (Figure 1b). It should be pointed out that the OMR value in several stations is negative (the negative OMR value in eight stations even passed the significant test at 5% level) and that urbanization in this region may have a certain contribution to the warming of local SAT (Figure 1b). As shown in Figures 1c and 1d, as the NTL increases, the trend of temperature warming of the stations (cities) generally increases, or the higher the NTL of the station is, the greater the SAT increases. It is a common feature that the warming of urban stations is higher than that of rural stations. However, the feature may have a large randomness and uncertainty (Figures 1c and 1d). No matter whether for the whole of GHMR or the GBA, the fitting is not ideal since R^2 is about 0.2 only. Due to the uneven distribution and sparse rural stations in the GBA and more than two thirds of the weather stations in the core area are all urban stations (Figure 1a), only the OMR method is used to analyze the urbanization contribution in the GBA.

3.2. The Urbanization Contribution to the Annual SAT Changes

3.2.1. Urbanization Contribution at Local Scale

As shown in Table 1, the annual SAT anomalies of Guangzhou and Shenzhen since the 1979 have a warming trend in the observations from the central city station, in the reanalysis and even in the observations from the surrounding rural station. It can also be seen from Table 1 that the warming trends obtained by OMR and AMR methods are slightly different, but their urbanization impacts are broadly similar. The similar urbanization impact indicates the robustness of the results from the perspective of methodology. For example, the urbanization contribution from the OMR method is 0.203°C/10a (approximately 49.5% of the total warming) in Guangzhou. The difference between Guangzhou city station and its nearby rural (average of the trends of Yingde Station and Fogang Station), namely, the Urban Minus Rural (UMR) method, is about 0.18°C/10a (about 43.9% of warming).

In contrast, for the two cities of Hong Kong and Macau, although temperature series of the observations and the reanalysis data show a trend of increasing temperature (Table 1), the OMR difference among observations from Hong Kong Observatory Station, observations at Macau Station, and the ERA5 reanalysis at Macau Station and Hong Kong Station is much smaller. Furthermore, the difference quantifying urbanization contribution is insignificant at Hong Kong Station. The warming trend of the observation series of the Macau Station is much lower than that in ERA5, resulting in the urbanization contribution of −122.1% by OMR method. It seems that the reanalysis data would be less representative for this city since the reanalysis does not have the fine coastline/island detail). In addition, the observation data for Macau Station show that its temperature trend does not pass the 5% significance test, so it is not statistically significant for studying urbanization warming. The low warming trend may be due to two reasons: (1) Urbanization for both cities (Hong Kong and Macau) is in a mature stage during the period of 1979–2018, and the warming effects in these two cities are lower (Jones et al., 2008). (2) The urbanization warming may be partly canceled by the heat exchange via sea-land Breeze Circulation or regulated by the maritime climate (Memon et al., 2011; Oke et al., 2017).

3.2.2. Urbanization Contribution at Regional Scales of GBA and the Whole GHMR

Figure 1b shows the urbanization effect on the GHMR detected by the OMR method in the past 40 years. For the GHMR, the results from the OMR and AMR methods are very consistent with each other (Table 1). Our analysis indicates that the trend of the average SAT is 0.278°C/10a, and the annual average urbanization contribution is 0.077°C/10a (approximately 27.7% of warming) by the OMR method and 0.031°C/10a (11.29%) by the AMR method. Both are lower than the values of 55.7% given by Chen et al. (2013). The main reason for the higher urbanization contribution in Chen et al. (2013) is that they used the UMR method for the regional urbanization contribution. Therefore, in terms of average temperature, the warming trend of the GBA is greater than that of the GHMR (ALL), and its urbanization warming contribution (OMR) is also significantly greater than that of GHMR.

As shown in Table 1, it is clear that the warming trends of maximum and minimum temperatures in the GBA are greater than those in the GHMR. However, the linear trends of their diurnal temperature range (DTR) in both the GBA and the GHMR do not pass the significance test. The urbanization contribution of daily minimum temperature warming is 0.036°C/10a (approximately 12.90% of warming). The urbanization contribution of daily maximum temperature warming in GHMR estimated using the AMR method is 0.019°C/10a (approximately 6.60% of warming), and the warming contribution of annual average DTR is −0.002°C/10a, both do not pass the 5% significance test.

Based on the analysis in Table 1, it is clear that the linear trends of the annual mean temperature, maximum temperature, and minimum temperature in the GBA are greater than those in the GHMR. For the GBA region, the urbanization contribution of the annual mean minimum temperature warming is greater than that of the annual mean maximum temperature, which is consistent with previous studies (Chen et al., 2011; Shi et al., 2019). For the annual mean DTR in the GHMR, both the trend and the urbanization contribution do not pass the significance test at 5% level, which suggests that the warming in GHMR area is symmetrically uniform for both maximum and minimum temperatures.

3.3. Seasonal Variation in the Urbanization Contribution

Our analyses indicate that the linear trends of the daily mean temperature in the four seasons in the GBA are greater than those in the GHMR. The urbanization contributions to the warming in the four seasons in the GBA are greater than those in GHMR as well. Moreover, the temperatures in spring, summer, and autumn have significant warming trends but not in winter due to their larger uncertainties (see Text S7 and Table S1 in the SI).

For mean temperature, for the entire region of GHMR, the urbanization contributions estimated by OMR and AMR methods are similar in terms of magnitude. The exceptional case is that the summer temperature trend (0.121°C/10a) from the reanalysis is much higher than that from the rural stations (0.087°C/10a). The estimation by the AMR method shows that the urbanization contribution to the warming of summer temperatures reaches 32%. However, the urbanization contribution in the other three seasons is less than 10%. The urbanization contribution in summer and autumn seasons passes the 5% significance test, while not in spring and winter seasons. In contrast, the estimation by the OMR method shows that only the urbanization contribution (about 8%) in spring passes the 5% significance test. For the GBA, the results using the OMR method are as follows: The urbanization contribution is 0.058°C/10a (approximately 36.5%, which is the largest contribution) in summer, and the urbanization contribution in the other three seasons of spring, autumn and winter is less than 26%. The urbanization contribution in all four seasons has passed the significance test at 5% level.

We adopted the AMR method to analyze the impact of urbanization on the daily maximum (representing daytime temperature) and daily minimum temperature (representing nighttime temperature) for the four seasons for GHMR; since there is no monthly average maximum and minimum temperature data in ERA5, the OMR method is not applicable. For the average maximum temperature, the warming caused by urbanization in summer and autumn has the most significant contribution but it is less than 16%. For the average minimum temperature, the warming caused by urbanization in spring and summer has the

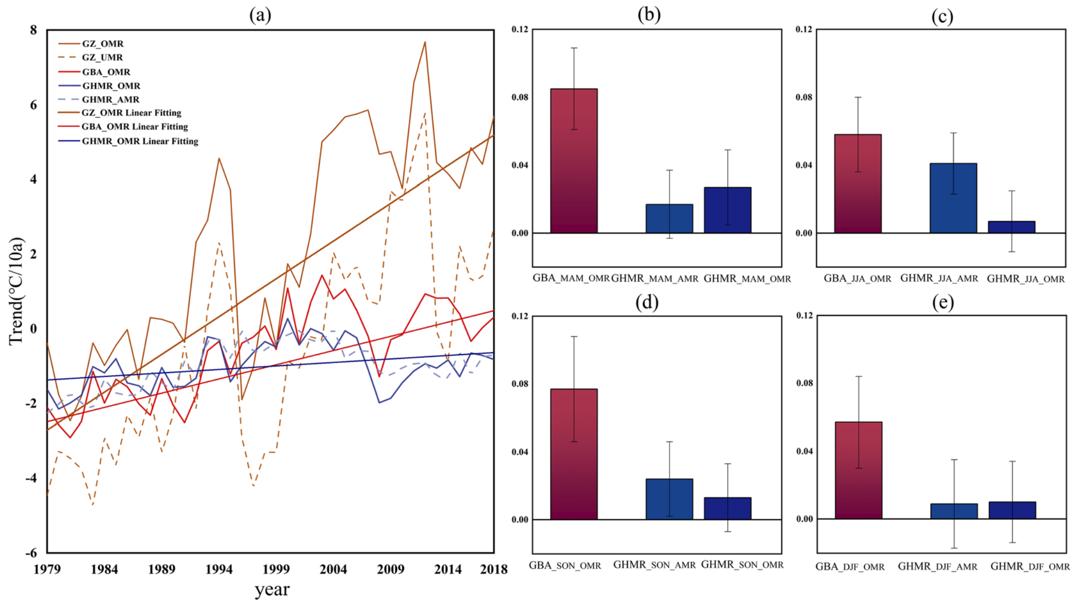

Figure 2. Comparison of annual average temperature trends in Guangzhou, the GBA and the GHMR regions (a) and the contribution of urbanization warming of the four seasons in GBA and GHMR regions: MAM (b), JJA (c), SON (d), and DJF (e). Note: GZ, Guangzhou; FG, Fogang; YD, Yingde; SZ, Shenzhen; HK, Hong Kong; MA, Macau. Trend: Mean ± 1.96 * stand error.

most significant contribution, 13.5% and 23.4%, respectively. For the mean DTR, the urbanization contribution to spring warming is negative (−0.04°C/10a; about −15.3%). The above results have passed the 5% significance test.

The urbanization contributions in other seasons are not significant. For the maximum and minimum temperature in the entire GHMR (Table S1 in the SI), the urbanization contribution in summer is the strongest, followed by autumn, which shows that urbanization has significantly increased the daytime and nighttime temperatures in urban areas in summer and autumn, but it has not significantly increased in spring and winter. This has led to the seasonal variations being more significant.

4. Discussion

4.1. Relationship Between Urbanization Contribution and Spatial Scales

Through the above research, it has been found that as the urbanization degree in the study area becomes higher, the temperature increase is larger. By comparing the urbanization effects on the annual SAT of Guangzhou, the GBA, and the GHMR from 1979 to 2018, it is found that the urbanization contribution to the total warming decreases when the spatial scale enlarges (Figure 2a).

For rapidly developing cities such as Guangzhou and Shenzhen, the warming caused by urbanization can reach up to 50%. In the rapidly urbanized area like the GBA, the warming caused by urbanization can reach about 20% to 35% of the total. For GHMR, the urbanization contribution is greater in some seasons (may exceed 10%). Overall, they do not exceed 10%. This would be related to the decrease of the urbanization rate when the spatial scale becomes larger. Also, it is very consistent with the conclusion of the previous IPCC scientific evaluation reports (Trenberth et al., 2007; Hartmann et al., 2013; Jones et al., 1990; Parker, 2004) and previous studies (Q. X. Li et al., 2004; F. Wang et al., 2015). Since the GBA in southern China is one of the most developed regions and one of the most important new engines of economic development, our conclusions may provide a reference for the detection and mitigation of the impacts of climate change in other similar regions over China.

4.2. Uncertainties of Urbanization Contribution

As mentioned in section 3, urbanization impacts on regional warming may differ due to using different methods and different data, which are termed as "broad uncertainties" by Chu et al. (2016). In other studies (Koopmans et al., 2015; Van Weverberg et al., 2008), the authors also discussed a high-resolution mesoscale modeling study acting as an alternative method, especially for the study area like GBA with no detailed high-quality observational data, which deserve trying in future investigation. Here we analyze the uncertainty of the urbanization warming trends detected by the OMR or AMR methods from the perspective of the statistical significance: When the trend is statistically significant, we conclude that urbanization impact on the local/regional warming is real. Otherwise, the urbanization has no significant effect in this region or city. Obviously, there are two situations where the impact of urbanization is considered as significant: First, the warming trend of the study area is significant, and the urbanization warming (by the OMR or UMR/AMR) is also significant, for example, the OMR and UMR series of Guangzhou and Shenzhen in Table 1. Second, the warming trend of the study area is significant, and the urbanization contribution is significant by one method and larger than 10% by the other method. Based on these standards, we can obtain the following conclusions for the GHMR region: (1) The urbanization contribution for the cities (Hong Kong and Macau) highly affected by maritime climate is insignificant; (2) the urbanization contribution of DTR in the GHMR is insignificant; and (3) the urbanization contribution is significant in spring and summer, insignificant in winter, and significant in annual average.

5. Conclusions

In this paper, two commonly used urbanization detection methods are adopted to analyze the urbanization impacts on SAT changes from 1979 to 2018 at different spatial scales by using homogenized in situ observational data, reanalysis, and satellite remote sensing data. The main conclusions are as follows:

The contribution of urbanization in GHMR to temperature trends decreases as the spatial scales increase. Urbanization has the highest impact on the temperature of two most important Metropolises of Guangzhou and Shenzhen since 1979, with a contribution of 43.9% and 35.1%, respectively. The urbanization contribution to the warming in the GBA is about 10–25%, and the contribution of urbanization to the warming in GHMR is only 10%. For the annual and monthly mean temperature, ERA5 reanalysis data show a good representation of the "nonurbanization" Land Surface Air Temperature (LSAT) change in GHMR, showing that the urbanization signals in the annual mean warming are clear in GBA and GHMR regions. In particularly, the warming of urban stations is greater than that of nonurban stations, and the urbanization contribution is higher in cities than in the rural areas. In general, our present work provides a scientific reference for accurately assessing and mitigating the regional climate change in high-density urban areas and surrounding areas at different spatial scales. The findings reported here have important implications for understanding the influences of human activities on regional climate change for other regions experiencing rapid urbanization processes.

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Data Availability Statement

Air temperature observational data can be registered and obtained from the NMIC (at http://data.cma.cn/en). Original ERA5 reanalysis data are available from ECMWF (at https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels-monthly-means?tab=form). The land cover data (The Terra and Aqua combined Moderate Resolution Imaging Spectroradiometer (MODIS) Land Cover Type (MCD12Q1) Version 6 data product) are available from the NASA (at https://ladsweb.modaps.eosdis.nasa.gov/search/order/1/MCD12Q1-6). The nighttime light (NTL) data, the Chinese population spatial distribution kilometer grid data set, and the DEM (Digital Elevation Models) data for the work in this paper can be downloaded from this site (https://doi.org/10.6084/m9.figshare.12949574.v1).

References

Chen, J., Li, Q. L., Niu, J., & Sun, L. Q. (2011). Regional climate change and local urbanization effects on weather variables in Southeast China. *Stochastic Environmental Research and Risk Assessment*, *25*(4), 555–565. https://doi.org/10.1007/s00477-010-0421-0

Chen, J. L., Du, Y. D., & Sun, W. G. (2013). Impact of urbanization on air temperature change in Pearl River Delta. *Advances in Climate Change Research*, *9*, 123–131. https://doi.org/10.3969/j.issn.1673-1719.2013.02.007

Chu, P., Jiang, Z. H., Li, Q. X., & Dong, L. P. (2016). Analysis of the effect of uncertainty in urban and rural classification on urbanization impact assessment. *Transactions of Atmospheric Sciences*, *39*, 661–671. https://doi.org/10.13878/j.cnki.dqkxxb.20130303003

Diggle, P. J., Heagerty, P. J., Liang, K., & Zeger, S. L. (1994). *Analysis of longitudinal data*. Oxford: Oxford University Press.

Goddard, I. L. M., & Tett, S. F. B. (2019). How much has urbanisation affected United Kingdom temperatures? *Atmospheric Science Letters*, *20*, e896. https://doi.org/10.1002/asl.896

Hartmann, D. L., Klein Tank, A. M. G., Rusticucci, M., Alexander, L. V., Brönnimann, S., Charabi, Y., et al. (2013). Observations: Atmosphere and surface. In T. F. Stocker et al. (Eds.), *Climate change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the Intergovernmental Panel on Climate Change* (pp. 159–254). Cambridge, UK and New York, NY, USA: Cambridge University Press.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, *146*(730), 1999–2049. https://doi.org/10.1002/qj.3803

Huang, B., L'Heureux, M., Hu, Z. Z., Yin, X., & Zhang, H. M. (2020). How significant was the 1877–78 El Nino? *Journal of Climate*, *33*, 4853–4869. https://doi.org/10.1175/JCLI-D-19-0650.1

Huang, J. Y., Liu, X. N., & Li, Q. X. (2004). The study of relationship between heat island effect and population in cities over South China. *Journal of Tropical Meteorology*, *20*(6), 713–722. https://doi.org/10.16032/j.issn.1004-4965.2004.06.012

Jiang, S. J., Lee, X. H., Wang, J. K., & Wang, K. C. (2019). Amplified urban heat islands during heat wave periods. *Journal of Geophysical Research: Atmospheres*, *124*, 7797–7812. https://doi.org/10.1029/2018JD030230

Jones, P. D., Groisman, P. Y., Coughlan, M., Plummer, N., Wang, W. Y., & Karl, T. R. (1990). Assessment of urbanization effects in time series of surface air temperature over land. *Nature*, *347*(6289), 169–172. https://doi.org/10.1038/347169a0

Jones, P. D., Lister, D. H., & Li, Q. X. (2008). Urbanization effects in large-scale temperature records, with an emphasis on China. *Journal of Geophysical Research*, *113*, D16122. https://doi.org/10.1029/2008JD009916

Kalnay, E., & Cai, M. (2003). Impact of urbanization and land use change on climate. *Nature*, *423*(6939), 528–531. https://doi.org/10.1038/nature01675

Karl, T. R., Arguez, A., Huang, B. Y., Lawrimore, J. H., McMahon, J. R., Menne, M. J., et al. (2015). Possible artifacts of data biases in the recent global surface warming hiatus. *Science*, *348*, 1469–1472. https://doi.org/10.1126/science.aaa5632

Koopmans, S., Theeuwes, N. E., Steeneveld, G. J., & Holtslag, A. A. M. (2015). Modelling the influence of urbanization on the 20th century temperature record of weather station De Bilt (The Netherlands). *International Journal of Climatology*, *35*(8), 1732–1748. https://doi.org/10.1002/joc.4087

Li, Q. X., Dong, W., & Jones, P. (2020). Continental scale surface air temperature variations: Experience derived from Chinese region. *Earth-Science Reviews*, *200*, 102998. https://doi.org/10.1016/j.earscirev.2019.102998

Li, Q. X., Sun, W., Huang, B., Dong, W., Wang, X. L., Zhai, P., & Jones, P. D. (2020). Consistency of global warming trends strengthened since 1880s. *Science Bulletin*, *65*, 1709–1712. https://doi.org/10.1016/j.scib.2020.06.009

Li, Q. X., Zhang, H., Liu, X., & Huang, J. (2004). Urban heat island effect on annual mean temperature during the last 50 years in China. *Theoretical and Applied Climatology*, *79*(3–4), 165–174. https://doi.org/10.1007/s00704-004-0065-4

Li, Q. X., Zhang, L., Xu, W., Zhou, T., Wang, J., Zhai, P., & Jones, P. (2017). Comparisons of time series of annual mean surface air temperature for China since the 1900s: Observation, model simulation and extended reanalysis. *Bulletin of the American Meteorological Society*, *98*, 699–711. https://doi.org/10.1175/BAMS-D-16-0092.1

Luo, M., & Lau, N. (2017). Heat waves in southern China: Synoptic behavior, long-term change, and urbanization effects. *Journal of Climate*, *30*, 703–720. https://doi.org/10.1175/JCLI-D-16-0269.1

Memon, R. A., Leung, D. Y., Liu, C., & Leung, M. K. (2011). Urban heat island and its effect on the cooling and heating demands in urban and suburban areas of Hong Kong. *Theoretical and Applied Climatology*, *103*(3–4), 441–450. https://doi.org/10.1007/s00704-010-0310-y

Oke, T. R., Mills, G., Christen, A., & Voogt, J. (2017). *Urban climates*. Cambridge: Cambridge University Press.

Parker, D. E. (2004). Climate: Large-scale warming is not urban. *Nature*, *432*(7015), 290–290. https://doi.org/10.1038/432290a

Ren, G., Zhou, Y., Chu, Z., Zhou, J., Zhang, A., Guo, J., & Liu, X. (2008). Urbanization effects on observed surface air temperature trends in North China. *Journal of Climate*, *21*(6), 1333–1348. https://doi.org/10.1175/2007JCLI1348.1

Shi, J., Cui, L. L., Wang, J. B., Du, H. Q., & Wen, K. M. (2019). Changes in the temperature and precipitation extremes in China during 1961–2015. *Quaternary International*, *527*, 64–78. https://doi.org/10.1016/j.quaint.2018.08.008

Trenberth, K. E., Jones, P. D., Ambenje, P., Bojariu, R., Easterling, D., Klein Tank, A., et al. (2007). Observations: Surface and atmospheric climate change. In S. Solomon et al. (Eds.), *Climate change 2007: The physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change* (pp. 237–336). Cambridge, UK and New York, NY, USA: Cambridge University Press.

Tysa, S. K., Ren, G., Qin, Y., Zhang, P., Ren, Y., Jia, W., & Wen, K. (2019). Urbanization effect in regional temperature series based on a remote-sensing classification scheme of stations. *Journal of Geophysical Research: Atmospheres*, *124*, 10,646–10,661. https://doi.org/10.1029/2019JD030948

Van Weverberg, K., de Ridder, K., & Rompaey, A. (2008). Modelling the contribution of the Brussels heat island to a long temperature time series. *Journal of Applied Meteorology and Climatology*, *47*, 976–990. https://doi.org/10.1175/2007JAMC1482.1

Wang, F., Ge, Q., Wang, S., Li, Q. X., & Jones, P. D. (2015). A new estimation of urbanization's contribution to the warming trend in China. *Journal of Climate*, *28*, 8923–8938. https://doi.org/10.1175/JCLI-D-14-00427.1

Wang, J., Yan, Z., & Feng, J. (2018). Exaggerated effect of urbanization in the diurnal temperature range via "observation minus reanalysis" and the physical causes. *Journal of Geophysical Research: Atmospheres*, *123*, 7223–7237. https://doi.org/10.1029/2018JD028325

Wang, K. C., Jiang, S. J., Wang, J. K., Zhou, C. L., Wang, X. Y., & Lee, X. H. (2017). Comparing the diurnal and seasonal variabilities of atmospheric and surface urban heat islands based on the Beijing urban meteorological network. *Journal of Geophysical Research: Atmospheres*, *122*, 2131–2154. https://doi.org/10.1002/2016JD025304

Yan, Z., Li, Z., Li, Q., & Jones, P. (2009). Effects of site change and urbanisation in the Beijing temperature series 1977–2006. *International Journal of Climatology*, *30*(8), 1226–1234. https://doi.org/10.1002/joc.1971

Yang, X., Hou, Y., & Chen, B. (2011). Observed surface warming induced by urbanization in East China. *Journal of Geophysical Research*, *116*, D14113. https://doi.org/10.1029/2010JD015452

Yang, Y. J., Wu, B. W., Shi, C. E., Zhang, J. H., Li, Y. B., Tang, W. A., et al. (2013). Impacts of urbanization and station-relocation on surface air temperature series in Anhui Province, China. *Pure and Applied Geophysics*, *170*, 1969–1983. https://doi.org/10.1007/s00024-012-0619-9

Yang, Y. J., Zheng, Z. F., Yim, S. Y. L., Roth, M., Ren, G. Y., Gao, Z. Q., et al. (2020). $PM_{2.5}$ pollution modulates wintertime urban heat island intensity in the Beijing-Tianjin-Hebei Megalopolis, China. *Geophysical Research Letters*, *47*, e2019GL084288. https://doi.org/10.1029/2019GL084288

Ye, H., Huang, Z., Huang, L., Lin, L., & Luo, M. (2018). Effects of urbanization on increasing heat risks in South China. *International Journal of Climatology*, *38*, 5551–5562. https://doi.org/10.1002/joc.5747

10.1029/2020GL089152

Yim, S. H. L., Wang, M. Y., Gu, Y., Yang, Y., Dong, G. H., & Li, Q. (2019). Effect of urbanization on ozone and resultant health effects in the Pearl River Delta region of China. *Journal of Geophysical Research: Atmospheres*, *124*, 11,568–11,579. https://doi.org/10.1029/2019JD030562

Zhou, L. M., Dickinson, R. E., Tian, Y. H., Fang, J. Y., Li, Q. X., Kaufmann, R. K., et al. (2004). Evidence for a significant urbanization effect on climate in China. *Proceedings of the National Academy of Sciences of the United States of America*, *101*(26), 9540–9544. https://doi.org/10.1073/pnas.0400357101