

局地气候分区框架下城市热岛时空分异特征 研究进展

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摘要: 局地气候分区(LCZ)框架自2012年提出以来,在城市热岛研究领域备受重视,但目前对LCZ框架下城市热岛(简称LCZ城市热岛)时空分异特征仍缺乏系统性总结。本文以统计和“荟萃分析”为手段,系统梳理了2012—2019年LCZ城市热岛研究在数据获取手段、时空格局和影响因素3个方面的进展,并对今后研究进行了初步展望。结果表明,迄今为止全球范围内已在超过130座城市开展了LCZ城市热岛研究,这些城市主要集中于中纬度(35°N~55°N)的亚洲和欧洲地区,且主要聚焦于以近地表气温表征的“冠层热岛”和以地表温度表征的“地表热岛”。具体而言:①在温度数据获取方面,站点观测(文献数量占比42.5%)、模型模拟(38.3%)与移动测量(19.2%)是获取气温的主要方法,其中模型模拟方法占比逐年升高。而卫星热红外遥感是获取地表温度的主要手段(86.5%)。②在时空格局方面,就全球而言,LCZ气温的类间极值差(均值为3.1 K)显著低于地表温度的类间极值差(9.8 K),且该极值差通常在夏季或冬季较大;冠层热岛与地表热岛均存在显著的“LCZ类内热岛”现象。③在影响因素方面,多数研究局限于定性分析地表结构、覆盖、材质和人类活动的影响,而普遍忽略了建筑布局与邻近LCZ类型等潜在因素的作用。本文将有利于从整体上更好地把握LCZ城市热岛的研究进展与今后的发展趋势。

关键词: 局地气候分区;城市热岛;近地表空气温度;地表温度;时空格局
DOI: 10.11821/dlxb202009004

1 引言

城市热岛效应对城市能源消耗、空气质量与人类健康等多方面影响深远,因而成为国内外众多学者广泛关注的议题^[1-7]。传统研究大多在“城—郊”二元划分(即将城市地表划分为城区和郊区2种类型)的框架下计算城市热岛强度并进一步探讨城郊热力差异^[8-10]。然而,“城—郊”二元划分方法忽略了城郊内部三维结构与地表材质等多方面的

收稿日期: 2019-11-27; 修订日期: 2020-06-07

基金项目: 国家自然科学基金项目(41671420); 江苏省杰出青年科学基金项目(BK20180009); 江苏省研究生培养创新工程(KYCX19_0036) [Foundation: National Natural Science Foundation of China, No.41671420; Jiangsu Provincial Natural Science Foundation for Outstanding Youth, No.BK20180009; Jiangsu Provincial Graduate Student Innovation Project, No.KYCX19_0036]

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差异,严重影响了城市热岛的准确评估,并进一步阻碍了全球范围内城市热岛的区域对比研究^[11]。在此背景下,局地气候分区(Local Climate Zones, LCZ)分类体系应运而生^[12]。

根据地表覆盖、地表结构、地表材质和人类活动等方面的差异,LCZ体系制定了10个量化指标,并利用这些指标将城市下垫面划分为17种基本类型,包括10种建筑类型(LCZ 1~10)和7种自然类型(LCZ A~G)(图1)。LCZ体系建议用不同类型LCZ间的温差($\Delta T_{LCZ X-LCZ Y}$,其中LCZ X与LCZ Y分别代表X类别与Y类别LCZ)定义并计算热岛强度,从而奠定了热岛强度区域乃至全球尺度准确对比的理论基础。早期,基于LCZ分区的城市热岛研究主要关注城市冠层的近地表气温(下文简称LCZ冠层热岛)^[13-15]。随着LCZ遥感制图的发展,尤其伴随着能够快速获取地表温度的卫星热红外遥感反演技术的不断成熟,基于LCZ分区的城市地表热岛(下文简称LCZ地表热岛)研究受到广泛关注^[16-19]。

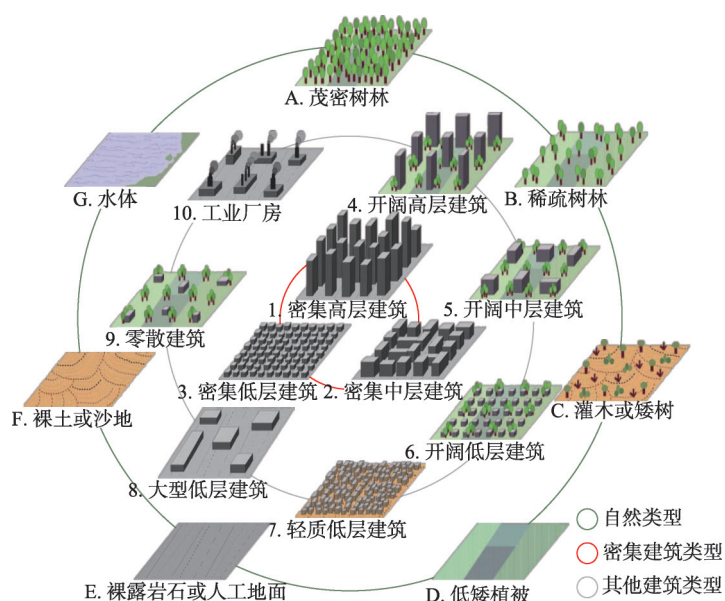


图1 LCZ体系的基本类型(据Stewart^[12]改绘)

Fig. 1 Standard types of the LCZ scheme (modified from Stewart^[12])

LCZ体系极大地促进了城市热岛研究的快速发展^[20]。然而,目前对LCZ框架下城市冠层和地表热岛时空分异特征仍缺乏系统性总结,主要体现在:①数据获取手段缺乏概括,特别是对新方法、新技术的应用情况尚未进行充分梳理。②时空格局缺乏深入分析,LCZ类别之间(简称“类间”)和类别内部(简称“类内”)在冠层和地表热岛时空分异特征的比较未受到充分关注。③影响因素缺乏详细归纳,尤其是一些潜在因素仍未引起足够重视。这些问题的存在,使得目前该领域的发展仍不够有序,同时也严重影响了对LCZ城市热岛研究领域的整体认知,进而阻碍了LCZ框架下区域乃至全球尺度下城市热岛的对比研究。

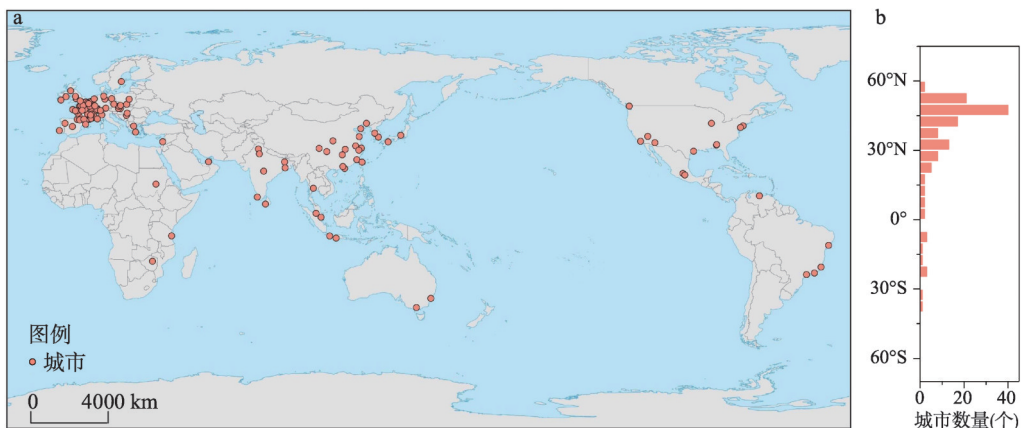
在理清LCZ发展脉络的基础上,本文以统计和“荟萃分析”(Meta-Analysis)为手段,通过整理与LCZ城市热岛有关的调查研究,综述LCZ城市热岛在数据获取手段、时空格局和影响因素3个方面的研究进展,进而深入探讨现有研究的不足并力图提出应对策略,以期为今后研究提供新思路。

2 LCZ发展脉络及研究现状

LCZ体系提出之前,国内外学者已尝试发展了多种分类体系或城市气候图(Urban Climate Map)^[21-22],来研究以城市热岛为代表的城市气候。然而,多数分类体系和城市气候图局限于少数特定的城市^[23-24]。为此,在前期研究基础上^[25],Oke等学者尝试提出一种适应于全球的城市地表分区体系。历经城市气候带(Urban Climate Zones, UCZ)体系初步探索阶段^[26-27]与热气候区(Thermal Climate Zones, TCZ)体系过渡阶段^[28-29],LCZ体系雏形得以形成^[30-31],并在之后得到最终确定^[12]。与之前Oke提出的一系列体系相比,LCZ体系普适性更强。这主要体现在:一方面类型更加标准化,各类型高度抽象化地表真实形态,以适应不同城市复杂地表;另一方面分类指标更加完善,各指标对城市热环境具有高敏感性,而且指标值的参考范围由全球大量城市实地调查研究得到。

自LCZ体系提出以来,全球范围内已有超过130座城市在LCZ框架下进行了城市热岛研究,这些城市大部分集中在北半球中纬度地区(35°N~55°N)(图2)。从大洲看,目前LCZ城市热岛研究仍主要集中于欧洲与亚洲城市(图3)。其中,欧洲城市最早开展相关研究,亚洲城市紧随其后,且随着时间推移,亚洲城市的文献数量在2019年已大幅超越欧洲;对北美洲和南美洲城市的研究相对较晚,文献数量也相对较少;对大洋洲和非洲城市的研究直到2018年才出现。

围绕LCZ城市热岛的学术活动和研究项目也相继开展。学术活动方面,Remote Sensing期刊早在2015年即为LCZ城市热岛研究设立了专刊^[32]。ICUC(2015年和2018年)^[33]、PLEA(2017年和2018年)^[34]以及JURSE(2017年和2019年)^[35]等国际会议均多次设立有关LCZ城市热岛理论与应用的专门议题。此外,在中国香港和成都、爱尔兰都柏林与法国图卢兹等多座城市也专门开展了LCZ研讨会^①。研究项目方面,逐渐涌现了诸多基于LCZ分类框架的项目,如WUDAPT项目^[36]、URBAN-PATH项目^[37]、MapUCE项目^[38]与URBAN-FLUXES项目^[39]等。这些项目都旨在进一步促进城市气候理论与应用研究。特别地,在LCZ框架指导下,URBAN-PATH项目联合构建了塞尔维亚诺维萨德和匈牙利塞格德的气象监测网,专门用来研究以城市热岛为代表的城市气候。



注:该图基于自然资源部标准地图服务网站下载的审图号为GS(2016)1665号的标准地图制作,底图无修改。

图2 LCZ体系框架下开展热岛研究城市的全球分布(a)及纬度分布(b)

Fig. 2 Global (a) and latitudinal (b) distributions of the cities where LCZ-based urban heat island has been investigated

① 资料来源:<http://www.wudapt.org/outreach/events/>和<https://jzxy.swjtu.edu.cn/info/1032/4703.htm>。

3 基于LCZ的城市热岛分析文献综述

首先,在Google Scholar、ISI Web of Knowledge、中国知网(CNKI)等主流数据库中锁定2012年至2019年10月1日引用Stewart等^[12]的所有文献,以标题、摘要或关键词中至少有一项包含“local climate zone”或“LCZ”等近似表达为基本筛选标准,初步得到与LCZ相关的文献。其次,逐篇浏览摘要,筛选出以研究城市热岛为主题的文献。最后,删除会议摘要等,保留期刊论文和会议论文,最终共得到文献107篇。需要特别说明的是,限于数据可获得性,本文可能遗漏部分硕士、博士学位论文等资料。

统计结果表明,目前LCZ城市热岛研究主要关注以近地表空气温度(下文简称气温)表征的城市冠层热岛和以地表温度表征的城市地表热岛研究两类(图4)。由于LCZ最初旨在反映城市不同气象站点间气温的特征差异,因此LCZ冠层热岛研究开展得相对较早,且持续受到城市气候学家的关注。尤其在2018年,LCZ冠层热岛的文献数量激增。在2019年1—9月,冠层热岛研究的文献数量仍保持较高水平,预计文献数量将持续增长。相比于LCZ冠层热岛,LCZ地表热岛的研究起始时间相对较晚(始于2014年)。但是随着LCZ遥感制图的兴起以及卫星红外遥感获取大范围地表温度的便利性^[40],LCZ地表热岛文献数量亦呈现高速增长趋势,目前已成为新的研究热点(图4)。特别地,在2019年1—9月份,相关文献数量已接近2018年全年文献数量的3倍。

LCZ城市冠层和地表热岛研究的主要内容是评估不同局地气候分区的温度差异。研究过程通常涵盖如下3个步骤:①获取温度数据;②基于LCZ框架分析城市不同区域的温度差异,估算城市热岛强度,并分析城市热岛的时空格局特征规律;③探讨影响城市热岛时空分异特征的因素。下文将依次从温度数据获取、时空格局、影响因素3个方面进行综述。

3.1 温度数据获取手段综述

在研究LCZ冠层和地表热岛前,分别需要获取气温与地表温度数据,这两类温度数据的获取手段存在较大差异。

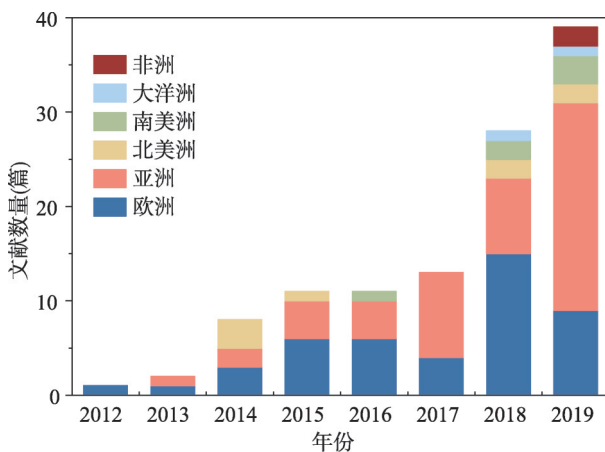


图3 2012—2019年LCZ热岛研究文献数量逐年变化情况
Fig. 3 Comparison of literature number related to the LCZ-based UHI by year (2012-2019)

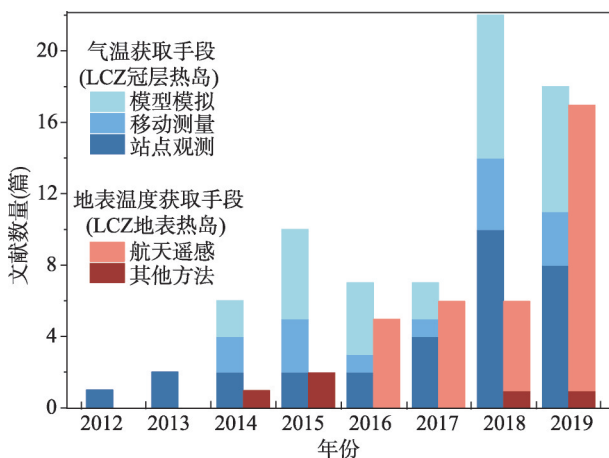


图4 采用不同温度获取手段的LCZ冠层和地表热岛文献数量逐年变化情况对比

Fig. 4 Comparison of literature number that applies different approaches to obtain temperatures for LCZ-based UHI studies

气温数据主要通过“站点观测”“移动测量”和“模型模拟”3种方法获取(图4)。

①“站点观测”方法最为常用(文献数量占42.5%),通常直接从城市气象站点获得气温观测资料,亦有少数研究在重点区域布置固定的小型气象站来收集气温资料。这种传统方法的优势在于其简便性,且历史数据通常较为丰富^[41-44]。但在大多数城市,站点数量较少,这使得单个或某几个站点的观测结果难以代表单个LCZ区域内的整体平均气温^[45]。特别地,在建筑密集的区域,如LCZ 1~3(均为密集建筑)等,观测站点往往非常缺乏,这导致其所对应LCZ的气温数据更加难以获取。

②“移动测量”通常指利用车载测温仪器来自动采集行车路线上气温数据的一类方法。该方法通过灵活增加测量线路或位点,“加密”站点观测的单点数据,从而成为固定站点观测的重要补充^[46-47](文献数量占19.2%)。然而,该方法耗时费力,且仅能获取某些时刻的气温数据,因此亦存在一定局限性。

③“模型模拟”方法无需经过实地调查,只需输入各类地表参数,便可利用气候模型模拟获得长时间、大范围的气温数据,因而近年来逐渐受到更多关注^[48-51](文献数量占38.3%)(图4)。然而,也正是因为输入参数较多,该方法的数据处理过程较为复杂,模型模拟结果难以逼近气温时空变化的真实情景^[52]。需要说明的是,由于LCZ的适宜空间尺度(几百米至几千米)通常介于气象学中的微尺度和中尺度之间^[53],因此目前采用的气候模型既包括小尺度模型,如ENVI-met^[54-55]、TEB^[56]与MUKLIMO_3^[57-58]与UrbClim^[59]等,也包括中尺度模型,如WRF^[60-62]等。

地表温度数据主要通过“航天遥感”获取,也包括少量其他获取方法,例如“航空遥感”和“模型模拟”等(图4)。

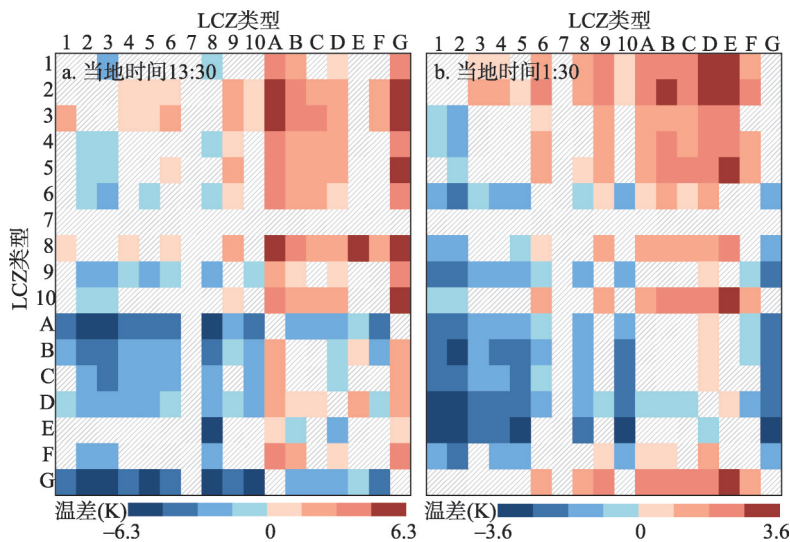
①“航天遥感”是指利用卫星热红外遥感影像反演地表温度进行LCZ热岛研究的方法。一般而言,卫星遥感的地表温度空间分辨率相对较低,但由于大多遥感影像数据可免费获取且覆盖范围广,因而得到广泛应用(文献数量占比86.5%)。目前所应用的地表温度数据主要由如下卫星传感器获得:TIRS(Landsat 8)、ASTER和MODIS。这3类传感器在时空分辨率上各有优缺点:TIRS影像的空间分辨率(100 m)相对较高,但其重访周期较长(16 d),且通常仅能获取上午时刻的地表温度^[63];ASTER影像空间分辨率(90 m)亦相对较高,还可获得夜晚时分LCZ的地表温度,但其重访周期同样较长^[64]。MODIS虽然能够获得每天4个时刻的地表温度数据,但其空间分辨率(1 km)较低,难以应用于LCZ面积较小的区域^[65-66]。

②“航空遥感”是指基于机载热红外遥感反演直接获得地表温度的方法,而“模型模拟”获得地表温度的方法与其模拟气温类似,即利用城市气候模型来模拟。尽管“航空遥感”能够获得较高空间分辨率的LCZ地表温度数据,但其成本相对高昂。相应地,“模型模拟”虽然相对便捷,但模拟结果的精度难以保证。因而这两种方法的研究文献数量占比较少(13.5%)。

3.2 热岛时空格局特征综述

城市热岛时空格局一般是基于城市热岛强度进行定量分析。Stewart等学者建议用LCZ间的温差表征城市热岛强度,即LCZ X均温与LCZ Y均温的差值($\Delta T_{LCZ X-LCZ Y}$)^[12]。目前,大部分研究的重点是不同类型LCZ的温差,即“类间热岛”(即X、Y不同)。少数研究在计算每类LCZ的均温时,发现分布在城市不同区域的不同类别LCZ间亦存在较大温差,形成“类内热岛”(即X、Y相同)。因此下文将分别总结“类间热岛”和“类内热岛”时空格局的总体特征。

3.2.1 类间热岛特征 在分析类间热岛时,通常采用“混淆矩阵”形式全面比较城市内不同类型LCZ间的温度差异(图5)。由于不同城市分布的LCZ类型不同,且部分文献中详细温度数据难以获取,因此本文主要提取既有文献中列出的温度最高值(T_{max})和最低值(T_{min})及其所对应的LCZ进行后续分析(详见表1和表2)。结果表明:类间的冠层热岛和地表热岛时空格局总体规律类似:无论在年际、季节、月和日内尺度上,建筑类型



注:斜纹方块表示对应行列的LCZ地表温度没有显著差异(K-S检验中显著性水平为0.05),数据来自Bechtel^[20]。

图5 由全球50座城市平均的LCZ类间地表温度差(行减去列)

Fig. 5 Land surface temperature difference between LCZs for 50 cities (row value minus column value) (Twill squares indicate no significant differences (significance level is 0.05 in K-S test) and the source data are from Bechtel^[20]).

LCZ的气温和地表温度均普遍高于自然类型LCZ,且在夏季或冬季温度的差异较其他季节更为显著^[67-69]。然而,类间冠层热岛和地表热岛的时空格局也存在一定的差异,主要体现在以下方面:①极值差显著不同:不同城市的气温极值差范围为0.9~6.1 K,而地表温度极值差范围为2.5~25.6 K。所有城市的气温极值差(均值为3.1 K)均显著低于地表温度极值差(均值为9.8 K)(图6)。产生此现象的主要原因在于相比气温,地表温度直接反映地表热量差异,且异质性更大^[67]。②极值分布的LCZ类型有所不同:对于冠层热岛,LCZ 1~3(均属于密集型建筑)通常具有最高气温,而LCZ D(低矮植被)和LCZ 9(零散建筑)气温一般最低。就地表热岛而言,LCZ 8(大型低层建筑)和LCZ 10(工业厂房)是出现最高地表温度的常见类型,而LCZ A(茂密树林)是出现最低地表温度的类型(图6)。此外,在分布有LCZ G(水体)的城市,LCZ G白天地表温度通常最低,夜晚地表温度最高^[70]。需要特别说明的是,在某些城市由于LCZ类型较少或背景气候较为特殊,出现温度极值的LCZ类型可能并非上述LCZ类型。例如,在美国芝加哥,LCZ 6(开阔低层建筑)达到气温最高值,主要原因在于该地区只划分出LCZ 3(密集低层建筑)和LCZ 6(开阔低层建筑)^[71]。

3.2.2 类内热岛特征 在城市内部不同的地理位置,通常会存在一定的温度差异。由LCZ定义可知,其划分侧重于对地表形态与材质等的刻画,而相对忽略了LCZ所在的地理位置差异。因此,即使划分为同一类型的LCZ,由于其在城市内部的地理位置不同,也可能存在一定温差。研究表明,分布在城市不同区域的单个LCZ之间均温存在显著区别,同时单个LCZ内部不同位点的温度也可能呈现较大差异,这些温差会导致类内热岛现象的出现^[113-116]。

与类间热岛类似,类内热岛也可从类内冠层热岛和类内地表热岛两方面分析。目前学界对类内冠层热岛的研究相对较多,而极少关注类内地表热岛。为数不多的研究表明:①类内冠层和地表热岛均未呈现普遍规律,亦没有鉴别出类内冠层和地表热岛强度显著较高或较低的特定LCZ,这可能是受城市所在地和测量时间的影响。例如,在

表1 不同城市LCZ气温极值情况(按大洲排列)

Tab. 1 The extreme values of the surface air temperature among LCZ types over various cities (ranked by continent)

| 城市(国家) | LCZ(T_{max}) | LCZ(T_{min}) | $T_{max}-T_{min}$ (K) | 计算天数(d) | 背景气候 [*] | 调查方法 | 数据源 |
|------------|------------------|------------------|-----------------------|---------|-------------------|------|---------------------|
| 安特卫普(比利时) | 2 | 9 | 3.2 | 20 | Cfb | 模型模拟 | 表1 ^[72] |
| 布鲁塞尔(比利时) | 2 | 9 | 3.1 | 15 | Cfb | 模型模拟 | 表1 ^[72] |
| 根特(比利时) | 2 | 9 | 2.0 | 16 | Cfb | 模型模拟 | 表1 ^[72] |
| 奥洛穆茨(捷克) | 2 | 9 | 2.4 | 1 | Cfb | 移动测量 | 图3 ^[73] |
| 柏林(德国) | 2 | D | 3.5 | - | Cfb | 站点观测 | 图7c ^[74] |
| 布拉干萨(葡萄牙) | 2 | RCD | 1.0 | 1460 | Csb | 站点观测 | 图4 ^[75] |
| 第戎(法国) | 2 | 5 | 1.8 | 1 | Cfb | 站点观测 | 图10 ^[76] |
| 南锡(法国) | 2 | D | 4.4 | 26 | Cfb | 移动测量 | 表1 ^[77] |
| 都柏林(爱尔兰) | 2 | D | 4.2 | 3 | Cfb | 移动测量 | 图5 ^[78] |
| 格拉斯哥(英国) | 3 | D | 2.7 | - | Cfb | 站点观测 | 图12 ^[79] |
| 米兰(意大利) | 2 | D | 1.5 | 1 | Cfa | 站点观测 | 表5 ^[80] |
| 诺维萨德(塞尔维亚) | 2 | A | 2.0 | 1095 | Cfb | 站点观测 | 图2 ^[45] |
| 塞格德(匈牙利) | 2 | D | 4.8 | 12 | Cfb | 站点观测 | 图7 ^[81] |
| 乌普萨拉(瑞典) | 2 | D | 4.2 | 9 | Dfb | 移动测量 | 图8 ^[82] |
| 成都(中国) | 1 | B _G | 2.4 | 3 | Cwa | 移动测量 | 表2 ^[83] |
| 重庆(中国) | H | 2 | 0.9 | 2 | Cfa | 移动测量 | 图8 ^[84] |
| 南京(中国) | 2 ₄ | D | 3.1 | 78 | Cfa | 站点观测 | 表3 ^[85] |
| 台北(中国) | 1 | A | 3.3 | 1 | Cfa | 移动测量 | 图5 ^[86] |
| 香港(中国) | 1 | 9 | 6.1 | 2 | Cwa | 移动测量 | 图7b ^[87] |
| 所有地区(新加坡) | 1 | 7 | 1.7 | 1 | Af | 模型模拟 | 表9 ^[88] |
| 部分地区(新加坡) | 4 | 9 | 2.0 | 5 | Af | 站点观测 | 表2 ^[89] |
| 长野(日本) | 2 ₄ | D | 3.7 | 9 | Cfa | 移动测量 | 图3 ^[82] |
| 科钦(印度) | 2 | 9 | 4.1 | - | Am | 站点观测 | 图3 ^[90] |
| 那格浦尔(印度) | 3 | 6 | 2.5 | 7 | Aw | 站点观测 | 表7 ^[91] |
| 奥本(美国) | 3 | A | 2.6 | 7 | Cfa | 站点观测 | 表3 ^[92] |
| 奥佩莱卡(美国) | 3 | A | 2.2 | 7 | Cfa | 站点观测 | 表2 ^[92] |
| 温哥华(加拿大) | 1 | D | 4.6 | 4 | Csb | 移动测量 | 图7 ^[82] |
| 克雷塔罗城(墨西哥) | 2 | B | 4.9 | - | Csa | 站点观测 | 图8 ^[93] |
| 圣保罗(巴西) | 3 | D | 3.8 | 5 | Cfb | 移动测量 | 表3 ^[94] |

注: H为作者定义的“河岸区域”类型;RCD为作者定义的“郊区”类型;2₄为LCZ 2内分布面积较小的LCZ 4;B_G为LCZ B内分布面积较小的LCZ G;-表示文献中未提供详细数据;*表示根据柯本气候分类法划分气候类型;对于同一城市的多次研究,选取较全面的研究数据。

中国香港地区, LCZ 6(开阔低层建筑)夏季白天类内气温差可达5.4 K^[117],但在匈牙利塞格德, LCZ 6在夏季白天类内气温差却小于1.0 K,而在夏季夜晚类内气温差增至约1.5 K^[81]。②冠层类内热岛强度通常小于地表类内热岛强度,这同样是因为与气温相比,地表温度受地表物理属性的影响较大,其时空异质性相对更高^[118]。

3.3 影响因素综述

不同LCZ的划分依据是地表覆盖、地表结构、地表材质和人类活动的差异^[12],因此这4类因素通常是分析LCZ间温度差异的首要考虑对象,但在不同时间尺度下各因素的影响可能存在差异:

(1)地表覆盖。通常将其直接量化为植被覆盖率。无论在年、月和日尺度,LCZ均温与植被覆盖率普遍呈负相关关系^[119-120],且该关系在夏季或冬季更为显著^[96, 110]。如捷克布拉格的夏季,LCZ A(茂密树林)的地表温度可比LCZ 10(工业厂房)低约15.0 K^[17]。

表2 不同城市LCZ地表温度极值情况(按大洲排列)

Tab. 2 The extreme values of the land surface temperature among LCZ types over various cities (ranked by continent)

| 城市(国家) | 数据 | LCZ(T_{max}) | LCZ(T_{min}) | $T_{max}-T_{min}$ (K) | 计算天数(d) | 数据源 |
|-----------|--------|------------------|------------------|-----------------------|---------|-----------------------|
| 布拉格(捷克) | TIRS | 10 | A | 15.0* | 1 | 图 7f ^[17] |
| 布尔诺(捷克) | TIRS | 10 | G | 18.0* | 1 | 图 6e ^[17] |
| 第戎(法国) | TIRS | 8 | A | 11.0* | 1 | 图 11d ^[76] |
| 日内瓦(瑞士) | TIRS | 2 | G | 12.0* | 1 | 图 6 ^[95] |
| 塞格德(匈牙利) | TIRS | 2 | 9 | 5.3* | 1 | 表 3 ^[96] |
| 塞格德(匈牙利) | 热红外成像仪 | 2 | 9 | 6.0* | 1 | 图 5 ^[16] |
| 重庆(中国) | TIRS | 10 | 4 | 4.6* | 1 | 图 4a ^[97] |
| 福州(中国) | TIRS | 8 | A | 14.2 | 1 | 表 3 ^[98] |
| 杭州(中国) | ASTER | G | A | 6.4* | 2 | 图 4 ^[64] |
| 南京(中国) | TIRS | 3 | G | 11.1 | 3 | 图 4 ^[99] |
| 上海(中国) | ASTER | G | D | 6.5* | 1 | 图 4 ^[100] |
| 台北(中国) | TIRS | 7 | G | 8.0 | 1 | 图 7 ^[101] |
| 武汉(中国) | TIRS | 3 | G | 14.0* | 1 | 图 4 ^[102] |
| 珠江三角洲(中国) | MODIS | 2 | G | 6.5* | 4 | 图 5e ^[103] |
| 昌迪加尔(印度) | TIRS | 10 | G | 4.2* | 1 | 图 9 ^[104] |
| 迪拜(阿联酋) | MODIS | 2 | F | 4.6* | - | 图 14 ^[105] |
| 曼谷(泰国) | TIRS | 10 | G | 4.1 | 3 | 图 7 ^[106] |
| 日惹(印度尼西亚) | TIRS | E | B | 4.0 | 1 | 表 7 ^[107] |
| 万隆(印度尼西亚) | TIRS | 10 | A | 2.5* | 1 | 图 11 ^[108] |
| 菲尼克斯(美国) | ASTER | E | G | 25.6 | 1 | 表 6 ^[109] |
| 拉斯维加斯(美国) | ASTER | 7 | G | 16.8 | 1 | 表 6 ^[109] |
| 圣保罗(巴西) | MODIS | 3 | G | 9.5* | - | 图 6 ^[110] |
| 哈拉雷(津巴布韦) | TIRS | 2 | G | 19.4 | 3 | 图 4 ^[111] |
| 悉尼(澳大利亚) | 热红外成像仪 | 8 | A | 5.4 | 2 | 图 3 ^[112] |

注：-表示文献中未提供详细数据；*表示从文献图表中读取的估算值；对于同一城市的多次研究，选取最新或最全面的研究数据。

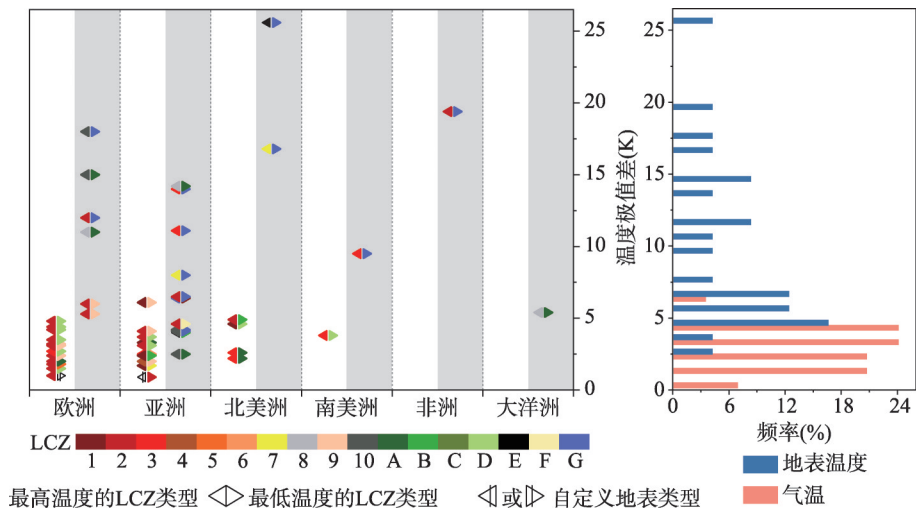


图6 不同城市LCZ类间气温极值(白色区域内)和地表温度极值(灰色区域内)情况

Fig. 6 The extreme values (maximum minus minimum) of the surface air temperature (white background) and land surface temperature (gray background) among LCZ types over various cities

(2) 地表结构。通常将其量化为天空可视因子 (Sky View Factor), 在日尺度对LCZ温度的影响较大。在晴朗白天, 不同高度和密度的建筑群区域的天空可视因子不同, 造成建筑遮蔽效应, 而建筑遮蔽与阴影能够产生显著的降温效应。研究普遍发现高层的LCZ 1 (密集高层建筑) 和LCZ 4 (开阔高层建筑) 气温低于中低层的LCZ 2 (密集中层建筑) 和LCZ 3 (密集低层建筑), 且温差可达1.5 K以上^[87, 101, 112]。在夜晚, 天空可视因子越大, 降温速率越大, 相应的LCZ温度则相对越低^[78, 121]。

(3) 地表材质。通常将其量化为地表反照率, 但由于城市地表材质极为复杂, 难以准确量化, 因此相关的定量研究较少^[122]。对于大面积较为均质的自然类型LCZ, 如LCZ A (茂密树林)、LCZ F (裸土或沙地) 和LCZ G (水体), 这三类LCZ地表反照率与其他类LCZ差异较大, LCZ温度特征明显; 而对于异质性相对较高的建筑类型LCZ, LCZ间平均地表反照率的差异并不大, 多数研究发现LCZ 2 (密集中层建筑) 和LCZ 3 (密集低层建筑) 的地表温度差异小于1.0 K^[16, 96, 101]。

(4) 人类活动。可将其量化为人为热排放^[123], 但由于人为热排放同样难以准确估算, 故大多数研究采用人口密度数据^[124]或夜间灯光数据^[125]等间接表征人类活动的差异。该因素在日内尺度对LCZ温度有显著影响。在白天, 人工热源相对集中的LCZ 8 (大型低层建筑) 和LCZ 10 (工业厂房) 的地表温度普遍较高, 在部分城市甚至比LCZ 1~3 (均属于密集型建筑) 更高^[17, 76, 98]。在夜晚, 与以办公楼为主的LCZ相比, 以居民楼为主的LCZ内人类活动更加频繁, 两类LCZ的气温亦因此差异显著^[126]。

大部分研究主要关注上述因素, 但事实上还存在其他潜在因素发挥重要影响, 这可能也是“类内热岛”现象产生的主要原因。这些因素包括:

(1) 建筑布局。尤其体现在建筑密集的LCZ 1~3。“封闭庭院”或“开敞联排”可能会使得风速、风向等气象要素产生显著区别, 形成不同的微气候, 进而影响空气温度^[114, 127]。“街道朝向”对地表接收的太阳短波辐射有所关联, 也能够造成不同区域地表温度的差异^[128]。

(2) 建筑材料。即使在同类LCZ (按标准定义同类LCZ可看作地表材质近似), 其内部建筑物既存在砂石、砖块、玻璃等不同建筑材料, 亦存在深色和浅色房顶等不同的材料颜色。不同建筑材料的热属性 (如反照率与热传导率) 差异较大, 由此造成地表温度的空间异质性相对较高^[104]。

(3) 邻近效应。由于局部大气环流的影响, 在边缘效应的作用下, LCZ气温易受到邻近LCZ气温的影响。一般地, 城市中心气温较高, 而城市外围气温较低。因此, 就同类LCZ而言, 其处于城市中心区域气温较高, 而处于城市外围或边缘区域气温较低。例如, LCZ 6 (开阔低层建筑) 和LCZ 9 (零散建筑)^[46, 90]通常从城市中心到外围广泛分布, 受邻近效应影响较大。

除以上3类潜在因素外, 风速风向、云覆盖量、降雨、湿度等气象条件对温度影响同样较大^[129-132]。特别地, 对于遥感地表温度, 不同地表温度反演算法^[17]以及热辐射方向性效应^[128]等亦能够对热岛强度时空分异特征产生一定影响。

4 讨论与展望

在学界的共同努力下, 基于LCZ框架的城市热岛研究已取得了显著进展, 但仍存在以下不足: ① 温度数据获取手段不够丰富; ② 时空格局的探讨不够全面; ③ 影响因素缺乏定量分析。下文将针对这些问题分别进行讨论, 尝试提出针对性的建议, 并对未来的研究方向做出展望。

4.1 温度数据获取方面 获得在时间与空间维度足量的气温或地表温度数据是进行LCZ城市热岛研究的前提。就当前LCZ研究而言,气温主要基于城市内已有的为数不多的气象站点观测,但大区域内详细数据的可获得性不高;地表温度主要通过卫星热红外遥感获得,但受限于其时空分辨率难以兼顾和云遮挡效应,目前仅能分析少数时空位点的情况。以上两个方面严重阻碍了LCZ城市热岛时空格局研究进一步走向深入。

在气温数据获取方面,可考虑以下方法:①采用众包(Crowdsourcing)方法。例如,可以与环卫工作者合作,使其工作时随身携带测温仪,记录城市内不同街区的温度。相比于实地调查,利用众包方法有望获得更为丰富的数据。②充分利用公开数据网站和手机应用APP。部分气象网站和APP提供全球温度数据(例如网站<https://www.wunderground.com/>)和城市内不同区域的详细温度数据(例如彩云天气APP),可考虑合法采用网络爬虫的方法获取这些源数据。相比于实地调查,该方法更加高效。③气温时空区域重建。获得部分站点观测的气温数据以及遥感地表温度后,可基于统计模型,反演出空间连续的区域气温^[133]。但该方法往往基于全局统计关系,其能否适用于LCZ的局地尺度,尚需进一步探索。

在地表温度数据获取方面,可以考虑以下方法:①利用无人机搭载红外热像仪。随着无人机产业的快速发展,通过航空遥感获得地表温度数据的成本将大大降低。搭载红外热像仪的小型无人机可方便地进行多次重复观测,获得更加丰富的数据。②充分利用各类卫星遥感数据。例如目前除了利用Landsat上午时刻的数据,还可尝试结合Landsat夜间观测数据^[134],获得LCZ城市地表热岛的日、夜特征。又如,葵花八号(Himawari-8)气象卫星数据拥有时间分辨率高(10 min)的优势,尽管其空间分辨率较低(2 km),但对于异质性较低的区域值得尝试^[135]。未来,随着搭载热红外传感器小卫星的发射,有望获得具有更高时空分辨率的地表温度数据,用于辅助LCZ城市热岛研究。③借助模型或算法获得时间连续的高空间分辨率地表温度数据。例如,可采用遥感地表温度年内变化(Annual Temperature Circle, ATC)或者日内变化(Diurnal Temperature Circle, DTC)模型,重建LCZ年内或日内连续的地表温度数据集^[20, 136-137]。又如,可考虑耦合地表温度时空降尺度模型与多源卫星遥感地表温度产品,获得高时空分辨率的地表温度数据^[138-139]。此外,已有极少量研究利用城市气候模型模拟地表温度^[54, 140],但其适用性仍需更多探讨。部分小尺度气候模型(例如ENVI-met与UrbClim等)在今后研究中亦有一定潜力。

4.2 时空格局分析方面

对城市热岛时空格局的全面认知是LCZ城市热岛研究中的重要课题。目前,就冠层热岛而言,空间分异特征仍不够明晰。在城市尺度下,部分特定LCZ(如LCZ E)的气温分布规律仍不够清楚。这主要是由于气温数据大多来源于少数离散的气象观测站点,而观测站点往往并未均匀分布于所有LCZ。在今后研究中可适当应用其他获取气温数据的方法。相对地,就地表热岛而言,其时间演变特征不够明晰,尤其体现于日尺度。这主要是因为目前仅能获取少量卫星过境时刻地表的瞬时温度产品。可尝试利用DTC模型(详见4.1节)模拟得到日内时间连续的地表温度数据^[141]。

此外,无论对于LCZ冠层还是地表热岛,都尚未在统一条件下,开展大范围城市间的区域乃至全球对比探索。尽管已有少数研究尝试比较了多座城市的LCZ城市冠层或地表热岛^[20, 81, 85],然而其研究条件尚未完全统一。一方面,作为进行LCZ全球城市热岛研究的重要基础,LCZ全球制图仍未完全实现,各城市LCZ制图结果主要来自于不同学者在不同时期的研究,这将难以保证制图结果统一性与时效性。另一方面,获取LCZ温度数

据时间未统一。各研究对城市冠层热岛研究的时间尺度不同, LCZ空气温度数据的时间可比性较差。考虑到LCZ体系普适性高且适宜推广至全球, 因此应当逐步开展长时间序列全球范围的LCZ热岛比较研究: 首先, 需得到大范围的LCZ制图结果。目前已有最新研究利用机器学习方法, 将LCZ制图范围扩展到大洲尺度^[142]。在相关研究项目支持下(例如WUDAPT项目^[143]等), 进一步深度应用各类高等机器学习算法, 有望实现LCZ全球制图。其次, 需获取详细的LCZ温度数据。拓展温度数据的获取手段在一定程度上将有助于丰富气温与地表温度数据源。最后, 在区域乃至全球对比分析时需特别关注以下问题: ① LCZ类型本身的变化。年内尺度下植被的物候效应、年际尺度下城市的扩张等因素可能会造成LCZ类型的改变^[144-146]。② LCZ均温的计算方法。由于类内热岛现象的存在, 同类LCZ温差可能过大, 因而将城市内所有同类LCZ的温度进行简单平均, 可能难以全面反映该城市各LCZ的温度特征。为了克服部分同类LCZ温差过大的不足, 在LCZ均温可考虑引入其距离市中心距离等因素^[46]。

4.3 影响因素研究方面

从形成机理层面深入分析LCZ城市热岛的影响因素, 将对城市热岛缓解措施或政策制定具有直接指导意义。但目前研究仍主要聚焦于在理想气象条件(晴朗无风)下, 定性分析地表覆盖、地表结构、地表材质和人类活动等因素的影响。因此仍需注意如下问题: ① 对其他潜在影响因素缺乏探索。例如, 在类内热岛方面, 当类内热岛强度过大时, 说明LCZ制图依据(即地表覆盖、地表结构、地表材质和人类活动)或许已不是类内热岛的主导影响因素, 这也意味着其他影响因素(如LCZ空间尺度、邻近LCZ的温度)未得到充分考虑^[113, 147-148]。又如, 在传统二分法框架下已发现背景气候对热岛强度有较大影响^[3]。类似地, 背景气候亦可能对LCZ城市热岛强度计算造成的一定影响。② 对多数影响因素缺乏定量分析。各因素对LCZ城市热岛强度的影响程度仍不够明晰。例如, 与LCZ冠层城市热岛相比, 非理想气象条件下各气象要素对LCZ地表城市热岛有一定的影响, 但各气象因子的影响程度还不清楚。

针对上述问题, 可考虑以下方法: ① 增加潜在影响因素的信息。例如, 在探究LCZ空间尺度的影响时, 可考虑增加单个LCZ面积与形状等信息。又或在探究LCZ邻近效应时, 可以附加相邻LCZ类型、与LCZ G(水体)的距离等^[90, 149-150]。② 对各影响因素与LCZ热岛强度进行归因分析。在城郊二分法的分类框架下, 现有研究已经总结出控制热岛强度时空格局的各类因子, 并利用相关分析^[10]、统计回归^[151]、模型模拟^[3]等方法对不同因子的作用进行定量化研究。近年来, 已有少量研究初步探索了各因子与LCZ热岛强度的相关关系^[152-154], 未来可考虑将归因分析方法应用到LCZ尺度上。

5 结论

本文采用统计和“荟萃分析”方法, 梳理并总结了LCZ冠层和地表热岛在温度数据获取手段、时空格局普遍规律以及主要影响因素等方面的进展, 并展望了未来的研究重点。结果表明, 迄今为止全球范围内已在超过130座城市开展了LCZ城市热岛研究, 这些城市主要集中于中纬度(35°N~55°N)的亚洲和欧洲地区, 且主要聚焦于冠层热岛和地表热岛。主要结论如下:

(1) 在温度数据获取方面: LCZ冠层和地表热岛的数据获取手段存在显著差别。就冠层热岛研究而言, 虽然站点观测和移动测量仍较为常用, 但模型模拟方法(文献数量占比38.3%)近年来逐渐受到重视。其他新方法值得进一步探索, 如众包方法、共享网

站数据利用、空气温度时空重建等。就地表热岛研究而言,目前以航天遥感为主(文献数量占比86.5%),但局限于TIRS、ASTER和MODIS的等热红外传感器地表温度数据产品。后续研究可考虑利用无人机热红外遥感或高空间分辨率静止卫星热红外遥感数据,以及借助模型或算法获得高时空分辨率遥感地表温度等。

(2)在时空格局方面:“LCZ类间热岛”现象普遍存在,而且“LCZ类内热岛”现象亦较为常见。就“类间热岛”而言,建筑类型(LCZ 1~10)的气温和地表温度普遍高于自然类型(LCZ A~G),LCZ类间气温极值差(均值为3.1 K)显著低于地表温度极值差(均值为9.8 K),该极值差在大部分城市往往在夏季或冬季达到最大。关于“类内热岛”的研究较少,亦没有鉴别出冠层和地表热岛强度显著较高的LCZ类型。今后研究可考虑:①继续深入研究类内热岛的时空特征;②发展更好的LCZ均温的计算方法;③逐步开展长时间序列全球范围LCZ热岛比较,但尤其要注意LCZ类型本身可能随时间变化。

(3)在影响因素方面:目前多数研究局限于定性分析热岛强度与地表结构、覆盖、材质和人类活动等因素的影响。今后应注重对各影响因素进行定量分析(如归因分析)。建筑布局、邻近效应、建筑材质、与LCZ G(水体)距离与背景气候等对LCZ热岛也有一定影响,尤其对类内热岛影响显著,故今后研究可考虑此类潜在的影响因素。

本文将有利于今后更好地从整体上把握LCZ城市热岛的研究现状和发展趋势,亦有望为缓解城市热岛效应做出贡献。

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Urban heat island studies based on local climate zones: A systematic overview

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Abstract: Since 2012, urban heat islands (UHIs) over various cities have been re-investigated under the local climate zones (LCZ) concept. However, a systematic overview of the recent progress in terms of the LCZ-based UHI studies remains lacking. This status quo has considerably restrained the UHI studies across global cities in a more standard manner. Here we comprehensively reviewed the preceding LCZ-based UHI studies with statistical- and meta-analysis. The literature review indicates that LCZ-based UHIs have been conducted over more than 130 cities globally, mostly located in the middle latitudes (35°N-55°N) within Asia and Europe. These investigations focus either on the canopy layer UHI (represented by surface air temperature, SAT) or on the surface layer UHI (denoted by land surface temperature, LST) or both. The overview was conducted mainly from three aspects including the "data acquisition", "spatiotemporal pattern", and "associated control". Our further findings show that: (1) On "data acquisition", satellite thermal remote sensing is the most important technique for retrieving LST, with the percentage of studies that employ this technique accounting for 86.5%. But for SAT, the main approaches include measurements by fixed stations (42.5%) and mobile vehicles (19.2%) as well as simulations by models (38.3%), among which the approach by model simulation has received more attention; (2) On "spatiotemporal pattern", the mean difference between the maximum and minimum temperatures among various LCZs for SAT (3.1 K) is significantly lower than that for LST (9.8 K), with relatively high magnitudes in summer and winter compared with the other seasons for these two types of temperatures. Prominent "intra-LCZ heat islands" were observed for both the canopy and surface UHIs; (3) On "associated controls", most studies are still qualitative on the analysis of the relationships between LCZ-based UHIs and their controls (e.g., surface structure and fabric, land cover type, and human activity). Other potential controls such as building typology and adjacency among LCZ types remain less considered. We finally provided several prospects for the LCZ-based UHI studies. We hope this overview would be helpful for improving the understanding of the current progress and upcoming prospects for the LCZ-based UHI studies.

Keywords: local climate zones; urban heat island; surface air temperature; land surface temperature; spatiotemporal pattern