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Source area definition for local climate zones studies. A systematic review

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ABSTRACT

The correct contextualisation of urban measurements is one of the challenges that urban climate researchers have been dealing with for decades. The Local Climate Zones scheme (LCZs) emerges as a system for characterising these measurements from the thermal perspective. The rapid embracing of the LCZs by researchers from many disciplines, altogether with its adoption for other purposes such as planning, has led to an inexistent or, at its best, flexible use of the source area definition. This practice might call into question the contextualisation of many measurements, highlighting the imperative need to shed light on the source area methods within the urban context. In this study, a systematic review is conducted to compile previous experiences in which the source area was applied in the built environment. Results obtained from the systematic search are summarized and presented according to three scales: the inertial sublayer, the roughness sublayer, and the urban canopy layer. These previous experiences are studied according to their methodological contribution to the source area definition, emphasizing those studies that have considered this concept altogether with the LCZ scheme. This review aims at promoting the knowledge about footprint methodologies and its correct application within the LCZs.

1 INTRODUCTION

Climate change and its related extreme events have led to an increasing interest for more precise and reliable temperature measurements. According to the IPCC [1], over the last few decades the number of climatic observations has increased by several orders of magnitude and has led to the reduction of short-term uncertainties. Hundreds of measuring stations have been deployed and provide continuous data on different atmospheric variables. FLUXNET [2], which collects several of those variables, is one of the most relevant networks and counts already with more than 800 in-situ measurement sites all around the world. Spatial agencies such as NASA and ESA have also developed strategies for increasing free public access to their remote-sensing products and findings [3,4]. Accessibility to climatic data has never been as wide and democratic as it is today.

The UN-dependent World Meteorological Organisation (WMO) periodically updates its guidelines regarding the contextualisation of measurements, the processing of metadata and its homogenisation [5,6]. The WMO has published a specific guideline for measuring in urban areas [7], where particular atmospheric characteristics might be found. The strong variability of the urban context, both horizontally and vertically, might generate strong variations among different measurements placed within few meters of each other. In that sense, the accuracy of many Urban Heat Island (UHI) studies were recently questioned due to the absence or incomplete definition of the measurement context, where the dual differentiation between urban-rural was traditionally accepted [8].

Understanding the city as a continuum from urban to rural and the standardisation of the process using specific metadata have been the keystones of many urban climatic classification systems [9–13]. All of them present an equivalent methodological approach, identifying and measuring similar parameters (*indicators*) on the horizontal scale and relating them with a set of uniform zones or *classes* (see **Table 1**).

The LCZ scheme [14] differentiates itself from the other systems in two ideas. In the first place, this scheme relies on two principles extracted from the classification theory: the *inductive*

generalisation and the *logic division*. These are important as they give the structure to the system and contribute to keep it simple: a set of quantitative indicators relate to a set of qualitative urban classes (*inductive generalisation*), which at the same time keep a subclass-superclass relationship (*logic division*). The second idea is that the classification includes both urban and rural areas, in what is called *the landscape*. In this scheme, the gradient from urban to rural can be easily characterised and, therefore, easily compared with other cities or contexts.

Table 1 Main schemes used as urban climate classification system

REF.	SCHEME	ACRONYM	AUTHORS	INDICATORS		CLASSIFICATION		CITATIONS ¹	STANDARD. LEVEL ²
				Type	Number of indicators	Type	Number of classes		
[9]	Urban Climatic Maps	UCMap	Knoch (1963)	Qualitative	12	Undefined	-	60 ^a (40)	●○○○
[10]	Urban Terrain Zones	UTZ	Ellefsen (1991)	Qualitative	7	Discrete	17	59 (7)	●●○○
[11]	Urban Climate Zones	UCZ	Oke (2004)	Qualitative	4 (10)	Discrete	7	- ^b (6)	●●○○
[12]	Thermal Climate Zones	TCZ	Stewart & Oke (2009)	Quantitative	6	Discrete	20	15 (6)	●●●○
[13]	Urban Zones for Energy partitioning	UZE	Loridan & Grimmond (2012)	Quantitative	2 (5)	Continuous	Not applicable	42 (7)	●●●●
[14]	Local Climate Zones	LCZ	Stewart & Oke (2012)	Quantitative	10	Discrete	17	359 (91)	●●●○

¹ The metrics have been extracted with the Scopus search engine, looking for the direct citations of each document. In parenthesis appears the number of publications that have cited in their title, abstract or keywords the complete name of each system. Acronyms were not considered.

² The standardisation level is associated with the following description: *Low* (qualitative indicators without a specific classification system); *Medium* (qualitative indicators associated to discrete a classification); *High* (quantitative indicators associated to a discrete classification); *Complete* (quantitative indicators associated to a continuous classification)

^a The UCMap classification was first suggested by Knoch [9], but the most cited document regarding this classification system is Ren et al. [15].

^b The UCZ classification appears in a WMO report with a whole set of recommendations for carrying out precise measurements in an urban context. As the UCZ classification system represents only a small fraction of this document, the author has decided not to include the number of direct citations.

Despite being a relative recent proposal, the LCZ has already gained a lot of recognition. **Figure 1** represents the citing evolution of the most relevant urban heat island studies between 2007 and 2017. It shows how the LCZ scheme has aroused an increasing interest since 2013, little after it was first published, becoming one of the most cited documents under the UHI topic of this decade. The explanation to such success might also be related to the wide range of applications that this classification system has. Urban climate researchers have used it not only for contextualising measurements, which was its original purpose, but as a classification of the urban fabric itself [16–18]. In that sense, the LCZ scheme has inspired many international initiatives, contributing to the expansion and awareness of the urban climate knowledge among researchers [16,19]. However, the adoption of the LCZs for a wide range of purposes has contributed to a flexible use of its original methodological approach. In that sense, and contrary to what can be done when

classifying the urban fabric, the delimitation of the context of a measurement should not be settled arbitrary, but considering very specific parameters, like the height of the measurement or the roughness of the landscape. This concept, which has aroused little interest regarding the LCZ scheme, is called the *thermal source area*.

Figure 1 Ten-years citing evolution of the 20 most cited documents under the "urban heat island" topic. Source: Scopus

1.1 The source area concept

The thermal source area could be defined as the total area that contributes to the thermal behaviour at a given point, hence outlining the limits of the context for any field observation. It should be noted that this term only refers to the temperature, while *source area*, or just *footprint*, refers to a more generic definition that would include any scalar measurement [39,40]. In fact, the first studies focused on the relationships between the surface properties inhomogeneities and the *flux-profiles* within the boundary layer, and regarding different parameters such as the energy flux, the water vapour, or diverse pollutants [41–43].

As it can be seen in **figure 2**, the extension of the source area usually spreads upwind, where its location and size depend on the sum of several factors. The source area increases its size and distance from the sensor while rising the height of the observation (z_m), the surface roughness, or

weather stability. The *footprint function* represents the contribution that each point of the source area has to the total measurement. Over homogeneous surfaces, it reaches its peak (f_{max}) at certain distance, and then decreases logarithmically to the infinite [39]. Uncertainties arise when addressing near-the-ground measurements within a heterogeneous context, where surface properties might vary within few hundred meters. This turns to be crucial in almost any urban context, where the source area might be very sensible to surface properties variations.

Figure 2 Illustration of the source area and the footprint function. Source: Schmid [39]

The source area definition is fundamental for the local climate zones application. According to the process established by Stewart & Oke [14], the thermal source area should be taken into account in phase two, right after the collection of metadata and before the local climate zone identification. The source area could be either computed with a footprint model or empirically approximated by field measurements [44]. Under stable atmospheric conditions, the thermal source area for a screen-height sensor might extend few hundred meters away, yet it needs to be further investigated within the urban context (see **figure 3**).

Figure 3 Illustration of the thermal source area regarding the LCZ scheme. Source: Stewart & Oke [14]

Regardless of that, many researchers have avoided to explore this concept within the LCZs, adopting the approximation given by Stewart & Oke [14] or just choosing a cell-size that would fit with their local climate analysis: the width of a block, the pixel size from a given remote sensor technique, or the emission inventories resolution [45–50]. In fact, there might be many advances in that field of knowledge that are not linked with the urban climate study, maybe due to the current use of scientific databases, where narrow searching might lead to strong barriers for interdisciplinarity and knowledge transfer. The present paper undertakes a *systematic review* of the current advances on the source area definition and its applications within urban areas.

1.3 Aims and objectives of the study

The aim of this work is to perform an organised search and synthesise all the available literature on the existing methodologies for estimating the source area of a sensor within an urban context, and to examine the uptake of these methodologies in the LCZ studies. For that purpose, three main objectives were settled:

- To identify the most appropriate approaches to estimate the source area within the urban context.
- To analyse the most relevant results, identifying the main methodologies, their strengths and weaknesses, and their applications and limitations.
- To determine the degree of embracement of these methods by the current LCZ studies.

2 MEANS AND METHODS

Systematic reviews are pointed out as the most efficient and less biased methodology for reviewing the existing scientific evidence [51–54]. Regarding urban climate studies, and despite traditional approaches such as narrative reviews [55–57] or critical reviews [58–60] are the most used ones, an increasing interest for systematic reviews is arising [8,61]. In that sense, this paper performs a qualitative systematic review on the source area concept regarding its degree of

development within the urban areas. For narrative purposes, though, this study will be referred to it as a systematic review.

Systematic reviews are usually conducted within a methodological framework [54,62,63], being available several guidelines from different renowned organisations [64–66]. In this paper we followed the PRISMA Statement from Moher et al. [63], which has been recently used in other urban studies [67–69]. Besides the well-known PRISMA flow diagram, the PRISMA Statement also provides a checklist with multiple items regarding the report of information across the whole review, which has also been used to validate the process. **Figure 4** shows an adapted PRISMA flow diagram, consisting of four phases: *Identification* (1), where a combination of keywords are used to explore scientific databases and find potential relevant results; *Screening* (2), in which non-related documents are discarded; *Eligibility* (3), consisted in ranking results and select the most relevant ones; and *Analysis* (4), in which relevant information is extracted, processed and synthesized.

Figure 4 Phases of the present review, based on the PRISMA flow methodology [63]

To provide a clear framework for future systematic reviews on this topic and to facilitate the identification phase within search engines, this paper reviews literature up to 2017, which is the last whole year available. Search results were saved in the open-source *LaTeX* format for its processing and were analysed with the help of a spreadsheet software.

2.1 Identification

Scopus, ScienceDirect and Web Of Science (WOS) were selected as main search engines due to their focus on peer-reviewed research literature and wide range of multidisciplinary topics. Thus, the identification of relevant studies was carried out only among peer-reviewed literature. Interviews, reports, and non-indexed books related to the LCZ scheme were ruled out, as neither their quality nor their representativeness could be assessed.

Regarding the keywords selection, two parts should be differentiated. In the first place, every single search includes the words “source area” or “footprint” (keywords “A”) as, despite the fact that they represent slightly different concepts [40,70,71], many researchers use both in the literature indistinctly (e.g. [72–74]). Secondly, with the purpose of keeping results within the urban and LCZs scope, the two previous items were combined through Booleans operators with other keywords (keywords “B”). Keywords “B” were defined in two steps: first, keywords related to the urban climate were used (such as “heat island” or “local climate”). Results were then filtered to identify the most relevant records of this first search and keywords contained within these results were added to the identification process. To keep a balance and avoid narrow searching, six categories were established and no more than five concepts were considered within each one of them. 30 keywords “B” were then finally used and might be found in **Table 2**.

This exploration was carried out over the title, abstract and keywords (“TAK” search), and only in the case of ScienceDirect was extended to the whole document (“ALL” search). When the number of results were under 10, the “ALL search” included the keywords “B”. By contrast, when the outcomes were too many (above 100 in both “source area” and “footprint” searches), another keyword “C” was included to refine the search.

Table 2 Summary of all the keywords used during the identification phase

KEYWORDS A		KEYWORDS B		KEYWORDS C
“source area” “footprint”	AND	CLIMATIC DEFINITION	“urban heat” OR “heat island” “local climate” OR “climate zone” “urban climate” “microclimate” “micrometeorology”	
		URBAN CONTEXT	“urban canyon” “heterogeneous” OR “heterogeneity” “spatial variability” “impervious surface” “urban landscape”	AND AND
		TYPE OF MODELS	“analytical model” “stochastic model” “lagrangian model” “large-eddy simulation” “computational fluid” OR “fluid dynamics”	AND
		FLUX CONCEPTS	“energy flux” “turbulent flux” “urban physics” “heat flux” “energy balance”	AND AND
		ATMOSPHERIC SCALES	“surface layer” “inertial sublayer” “roughness sublayer” “urban canopy” OR “canopy layer” “urban boundary” OR “boundary layer”	AND
		MEASURING CONCEPTS	“scintillometer” “eddy covariance” “temperature measurement” “air temperature” “flux measurement”	AND
				“urban”

2.2 Screening

All the records obtained with the different keywords and search engines were screened to exclude repeated and non-related documents. Non-related documents were identified when the terms *footprint* or *source area* (keywords “A”) do not refer to the meaning given in this review, like *sediment source area*, *carbon footprint* or *building footprint* (see **Table 3**). Since it is relatively common to find more than one meaning for the same word in a single record, these non-related terms were not used as an exclusion criterion during the identification process. Instead, a manual identification of those words was performed in the screening phase. While the WOS and Scopus records were screened looking at their title, abstract and keywords, the ScienceDirect results were full-text screened.

Table 3 Summary of non-related themes for the searched keywords identified during the screening phase.

KEYWORDS	NON-RELATED THEMES	EXAMPLES
“source area”	when referring to: <ul style="list-style-type: none"> - ecosystem sources - chemical processes - sediments motion 	“supply source area”, “potential source area”, “dust source area”, “source area soils”, “pollen source area”, “sediment source area”, “valley-head source area”
“footprint”	When referring to: <ul style="list-style-type: none"> - greenhouse effect - measurement or size - chemical processes - remote sensing 	“carbon footprint”, “environmental footprint”, “chemical footprint”, “building footprint”, “aerial footprint”

2.3 Eligibility

At this stage, each record was evaluated according to its relevance level. Unlike the two previous phases (identification and screening), all records were examined completely, including the main body of the publication and its references. To this effect, three levels of relevance were used to classify every record. **Table 4** recaps the classification criteria, which vary from *low* to *high* relevance. In case of doubt, records were placed in the highest considered level. This ensured that no record would be discarded accidentally when applying the eligible criteria. A level 2 *low relevance* was required to be eligible for the analysis phase.

Table 4 Relevance criteria for classifying the screened records

LEVEL	RELEVANCE	DESCRIPTION
1	High	Addresses the “source area”/ “footprint” concept within urban areas and the surface layer.
2	Medium	Mentions the “source area”/ “footprint” concept within urban areas and the surface layer.
3	Low	Mentions the “source area”/ “footprint” concept within homogeneous or rural areas, or above the surface layer.

2.4 Analysis

Results were analysed following a two-fold strategy. In the first place, highly relevant references were differentiated into *case studies*, *methodological approaches*, and *reviews*. Then, the most relevant findings were extracted following different approaches:

- *Case studies* were tabulated according to the measurement's location and atmospheric context, the size of the source area, and the application of the LCZ scheme (**Table A.1**).
- *Methodological approaches* were identified and related to case studies and were evaluated according to their use in the urban context (**Table 6**).
- *Reviews* were used to give complementary information regarding the *case studies* and the *methodological approaches* and reinforcing the structure of the analysis section. For that purpose, *reviews* were classified according to their main topic (**Table 7**).

Figure 5 Flowchart representing the identification, screening, eligibility and analysis phases of this systematic review

After all relevant results were explored, an analysis of the source area definition was carried out differentiating three scales: the *inertial sublayer* (ISL), the *roughness sublayer* (RSL), and the *urban canopy layer* (UCL). The source area definition and its use within LCZ studies was addressed in each one of these contexts, particularly regarding the most common practices, remaining uncertainties, and future trends. **Figure 5** presents a flowchart diagram covering all the stages within this systematic search.

3 RESULTS

3.1 Overview of the search results

This systematic review identified 3,244 potential documents, while only 135 results were classified as *highly relevant* within this review. Barely 1% of results were not accessed, mainly due to language barriers. **Table 5** shows the distribution of the literature results according to the search engine and the level of relevance.

Table 5 Relevance of the identified documents by search engine. The value in parenthesis gives the contribution of each search engine to the total amount of unique results (total results, excluding the repeated).

LEVEL	RELEVANCE	SCIENCEDIRECT	SCOPUS	WEB OF SCIENCE	UNIQUE RESULTS
1	High	51 (37.8%)	75 (55.6%)	65 (48.1%)	135
2	Medium	71 (74.7%)	18 (18.9%)	17 (17.9%)	95
3	Low	307 (61.4%)	177 (35.4%)	200 (40%)	500
-	Not relevant	1,399 (56.3%)	902 (36.3%)	689 (12.2%)	2487
-	No access/other	0 (0%)	27 (90%)	16 (53.3%)	30
TOTAL		1828 (56.4%)	1189 (36.7%)	987 (30.4%)	3244

All highly relevant results are next differentiated in three categories: *case studies*, where the authors present a field campaign in which measurements were contextualised using the source area concept; *methodological approaches*, in which a novel methodology for estimating the

footprint is described; and *reviews*, which synthesize information regarding a specific topic related with the source area.

A total of 90 *case studies* were classified with a 3 *high relevance* level. Their methodological approach, measurement characteristics, atmospheric context and, in case the research was published after 2012, the application of the LCZs, was summarized in **Table A.1 (Annex 1)**. These case studies constitute the core of this section, pointing towards differences in the methodological approach that were applied within the urban context.

Table 6 links most of the existing footprint models with all the urban case studies found within this systematic review. These models are summarized according to their methodological approach, which could be analytical dispersion solutions, lagrangian stochastic models, computational fluid dynamics such as Large-Eddy Simulations (LES) or Reynolds-Averaged Navier-Stokes equations (RANS), or an ensembled combination of different ones (LES-LS, RANS-LS). This table also includes the spatial dimensions each model might be able to reach, going from the most basic 1D analytical approaches to the most complex 3D LES-LS models. At this point it should be noted that, the simpler the methodology, the lesser resource intensive it normally is, and which certainly has an important weight when choosing for a method to estimate the source area.

Many reviews were also identified and used to articulate the results section. **Table 7** presents some of the most relevant reviews according to their focus, which might be the atmospheric physics over urban or heterogeneous contexts, the footprint estimation, or the measurement techniques. Keywords given by the authors are also included to facilitate the identification of the main theme by the reader.

Table 6 Overview of some of the most relevant footprint models, and its uptake by urban case studies. Adapted and updated from Foken[71], Leclerc [44], Vesala et al. [70] and Schmid [40].

REFERENCE		ACRON.	MODEL	APPLICAT.*	CASE STUDIES
[75]	Schuepp et al. (1990)	SP90	1D Analytical	Yes (3)	Dorsey et al. [76]; Jacobs et al. [77]; Stabler et al. [78]
[79]	Schmid and Oke (1990)	SO90	1D Analytical	Yes (7)	Grimmond et al. [80]; Grimmond [81]; Kaplan et al. [82]; Lemonsu et al. [83]; Rooney [84]; Rooney et al. [85]; Schmid et al. [86]
[87]	Leclerc and Thurtell (1990)	LT90	1D Lagrangian		
[88,89]	Horst and Weil (1992; 1994)	HW92/94	1D Analytical	Yes (3)	Jacobs et al. [77]; Järvi et al. [90]; Lee et al. [91]
[39,92]	Schmid (1994; 1997)	SD94/97	1D/2D Analytical	Yes (11)	Barlow et al. [93]; Contini et al. [94]; Häb et al. [95]; Kanda et al. [96]; Kordowski & Kuttler [48]; Liu & Sun [97]; Oke et al. [98]; Pawlak et al. [99]; Rooney et al. [85]; Weber & Kordowski [100]; Zielinski et al. [101]
[102]	Kaharabata et al. (1997)	KA97	2D Analytical		
[103]	Leclerc et al. (1997)	LC97	1D LES		
[104]	Baldocchi (1997)	BI97	1D Lagrangian		
[105,106]	Rannik et al. (2000; 2003)	RK00/03	2D Lagrangian		
[107]	Hsieh et al. (2000)	HH00	1D Analytical	Yes (11)	Contini et al. [94]; Gioli et al. [108]; Morin et al. [109]; Oliphant et al. [110]; Ramamurthy and Pardyjak (2011); Roth et al. [111]; Song & Wang [112]; Sparks and Toumi [113]; Velasco et al. [114–116]; Ward et al. [117]
[118]	Kormann and Meixner (2001)	KM01	1D Analytical	Yes (26)	Ando and Ueyama [119]; Auvinen et al. [120]; Björkegren and Grimmond [121]; Christen et al. [122]; Crawford et al. [123,124]; Feigenwinter et al. [125]; Helfter et al. [126]; Hellsten et al. [127]; Kent et al. [128]; Kota et al. [129]; Kotthaus and Grimmond [130,131]; Kurppa et al. [132]; Lee et al. [91]; Lietzke et al. [73]; Liu et al. [133]; Nordbo et al. [134]; Park et al. [135,136]; Rapsomanikis [137]; Salmond et al. [138]; Ueyama and Ando [139]; Valach et al. [140]; Wang et al. [141]; Zou et al. [142]
[143]	Kljun et al. (2002)	KN02	3D Lagrangian		
[144]	Kljun et al. (2004)	KN04	1D Analytical	Yes (8)	Bergeron and Strachan [145]; Guidolotti et al. [146]; Hiller et al. [147]; Langford et al. [148]; Mårtensson et al. [149]; Menzer and McFadden [150]; Park et al. [135,136]
[151]	Sogachev and Lloyd (2004)	SL04	2D/3D RANS (1.5-order)	Yes (2)	Järvi et al. [90]; Vesala et al. [152]
[153]	Cai and Leclerc (2007)	CL07	3D LES-LS		
[154]	Prabha et al. (2008)	PA08	3D LES		
[155]	Steinfeld et al. (2008)	ST08	3D LES-LS	Yes (2)	Auvinen et al. [120]; Hellsten et al. [127]
[156]	Hsieh and Katul (2009)	HK09	2D RANS-LS (2-order)		
[157]	Kljun et al. (2015)	KN15	2D Analytical	Yes (1)	Inagaki et al. [158]

* Application in an urban context.

Table 7 Overview of some of the most relevant reviews regarding urban atmospheric physics, footprint estimation or measuring techniques. Symbol (●) indicates the most relevant focus while (○) indicates a theme minorly addressed.

REFERENCE	Atmospheric physics	FOCUS Footprint estimation	Measurement techniques	KEYWORDS *
[159] Stull (1988)	●		○	boundary layer meteorology; turbulent flow; convective mixed layer; turbulent flux
[160] Flesch (1996)		●		atmosphere; stochastic methods; Lagrangian model; atmospheric trajectory; boundary layer flux
[161] Mahrt (1996)	●	○		bulk aerodynamic formulation; drag law; heat flux; surface fluxes
[162] Aubinet (1997)	○		●	eddy covariance; temperature fluctuation; aerodynamic method; flux measurement
[163] Roth (2000)	●		○	mixing-layer analogy; roughness sublayer; urban boundary layer; urban turbulence
[40] Schmid (2002)		●		footprint; micrometeorology; atmosphere exchange; modelling; flux measurements
[164] Arnfield (2003)	●			urban climate; energy budget; urban roughness; urban heat island; atmospheric turbulence
[22] Voogt & Oke (2003)	○		●	remote sensing; urban climates; rural
[165] Vesala et al. (2004)	○	●		boundary layer; footprint; heat flux
[166] Göckede et al. (2007)		●	○	flow field; Lagrangian analysis; stochasticity; surface layer; turbulent boundary layer
[167] Roth (2007)	●		○	tropical urban climatology; tropical urban heat island; tropical urban energy balance
[70] Vesala et al. (2008)	○	●		footprint; source area; turbulent flux; atmospheric turbulence; atmospheric pollutants
[168] Grimmond et al. (2010)	●		○	urban climate modelling; observations; adaptation; mitigation; built environment
[169] Mahrt (2010)	○	○	●	eddy correlation; fluxes; turbulent transport; mesoscale flux; aircraft flux
[170] Velasco & Roth (2010)		●		anthropogenic source; carbon flux; neighbourhood; eddy covariance; urban pollution
[171] Vesala et al. (2010)	○		●	-
[172] Feigenwinter et al. (2012)	○	●		urban heat island; street canyon; eddy covariance; urban ecosystem; urban surface
[173] Rannik et al. (2012)	●		○	-
[164] Barlow et al. (2014)	○		●	urban balance; boundary layer; roughness sublayer; surface heterogeneity; mesoscale circulations
[45] Christen (2014)	○	●	○	atmospheric measurement; urban atmosphere; carbon dioxide; eddy covariance; greenhouse gases
[44] Leclerc & Foken (2014)		●	○	-
[71] Foken (2008; 2017)		●		atmospheric process; environmental meteorology; experimental methods; heterogeneous surface; measurement techniques
[174] Toparlak et al. (2017)	●		○	Adaptation measures; building energy consumption; computational fluid dynamics; urban physics; sustainability

* Selection of the keywords given by the authors or proposed by the databases (five maximum)

The source area size might range from few tens to thousands of meters away depending on a combination of multiple factors. Among all of these, there are some aspects that scientist cannot control when carrying out measurements, such as the wind direction and speed, or the atmospheric stability. These parameters introduce variations in the size and shape of the source area, thus requiring a continuous update along with their measurements. Authors normally report the average source area differentiating among wind sectors [99,130,138,145] and including a description of the weather conditions during the measurement campaign. In some cases, data is filtered to exclude measurements under certain stability conditions [128,132,148,175]. A description of other variables that influence the size of the footprint, and which are set by the authors, is also commonly reported. These include the height of the measurement and its surroundings, the measuring technique, the methodology used for modelling the footprint, and the land cover properties of its surroundings. Overall, and altogether with the information already mentioned, scientist report the size of the source area graphically including different percentages of the flux, typically 60, 70, 80 and 90%.

Figure 6 summarises the maximum source area reported by all the case studies included in **Table A.1**, and according to some of the factors mentioned above. In most cases they are presented as a range of the maximum source areas for all wind sectors. There is a clear tendency for larger source areas when increasing the percentage of the considered flux or when increasing the relative height of the measurement. This tendency is faded out when looking at the season of the year, which correlates in many cases with atmospheric stability, and might be due to the filtering of measurements, the time of the day when measurements were carried out, or the latitude of the measurement site.

The absence of a common framework for the available results, as well as the high number of influencing variables, makes very difficult when not impossible to carry out a meta-analysis, which would be the ideal scenario for a systematic review. However, and despite these uncertainties, about 75% of these studies place the source area from 100 to 1200 meters away, which might be related with a common methodological framework for estimating the source area.

In that sense, a meta-synthesis is more suitable for summarising scientist's common trends and shared assumptions regarding the estimation of the source area and its use within the LCZ scheme.

Figure 6 Maximum source area distance for all case studies identified during the systematic review, and related with the considered atmospheric scale (top), the season of the year (middle), and the percentage of the flux contributing to the source area (bottom).

3.2 Detailed analysis of the results according to the three Surface Layer scales

As most of these authors agree, the concept of scale is fundamental for understanding the atmospheric processes that occur within the *surface layer* (SL) and, therefore, to determine the best methodological approach for estimating the source area. This section will be next presented

according to these urban atmospheric scales. According to **Figure 7**, three different contexts must be differentiated in the SL: the *inertial sublayer* (ISL), the *roughness sublayer* (RSL), and the *urban canopy layer* (UCL).

Figure 7 Climatic scales and vertical layers found in urban areas. PBL: Planetary Boundary Layer. UBL: Urban Boundary Layer. UCL: Urban Canopy Layer. Source: Oke [176]

3.2.1 The inertial sublayer (ISL)

The ISL develops in the upper part of the surface layer, from the upper limit of the RSL, the so-called *blending height*, to the top of the SL. This part of the atmosphere links both the regional and the local scale, therefore reflecting the effects that the surface introduces in the atmospheric boundary layer structure [164]. Within this layer, and under neutral conditions, turbulent fluxes are mostly constant with height, so it can be assumed as a constant-flux layer with a homogeneous flow where the logarithmic wind laws apply [177]. With non-neutral condition, Monin-Obukhov Similarity theory might be used to explain turbulent fluxes near the ground (M-O theory, [178]).

These two assumptions, which were ideally developed for flat and horizontally homogenous surfaces, were extensively accepted in rural areas [71]. These have been borrowed by urban

climate studies, extending the wind log-profiles and M-O theory assumptions to measurements within the urban inertial sublayer; the main consensus is that, well above the blending height, turbulent fluxes might be already well mixed [164,170,172]. Despite that this principle might not be true for urban context [163,173], this simplification has allowed urban climate researchers to use analytical footprint models that easily delimit the most likely source area of their measurements.

The ISL has therefore become the most common scale for carrying out urban flux measurements (see **figure 8**). Schmid et al. [86] is one of the first known references that reported heat flux measurements over a city altogether with the use of the source area concept to contextualise it. Grimmond et al. [80,81] kept using the footprint to study energy flux measurements at the same location in Vancouver, while other studies started arising in other places: Mexico City [179], Christchurch [180], Tokyo [96], Marseille [83,181], Essen [100], Houston (TX) [135], Basel [125,138], Helsinki [134], Swindon [117,182], Gongju [91], London [124], Black Rock City (NV) [110], Łódź [101], and Nanjin [142].

Figure 8 Maximum footprint distance related with the atmospheric context, for all highly relevant case studies. UCL: Urban Canopy Layer; RSL: Roughness Sublayer; ISL: Inertial Sublayer; z_m : measurement height; z_R : blending height.

Similar experiences can be found among gas measurements. Regarding the urban context, the most common ones are the CO₂ flux studies, which might be found in Mexico City [114,116], Helsinki [90,120,132,134,152], London [72,113,121,126,131,183], Vancouver [122,184], Montreal [145], Saint Lake City (UT) [185], Baltimore (MD) [123], Florence [108,186], Beijing [112,133], Basel [73], Minneapolis-Saint Paul (MN) [150], Singapore [187], Sakai [139], Black Rock City (NV) [110]. Other gas fluxes like CH₄ [99,108], VOCs [129,135,140,148], NO_x [188], water vapour [77] or aerosols [149] were also studied altogether with a previous footprint analysis.

Despite local climate zones were presented in the last decade [14], several studies have addressed them to describe the measurement context within the ISL. Its use has gone beyond the original *thermal* scope of the LCZ scheme, as it has been proven as a useful tool for many other parameters. Valach et al. [140] have recently used it when measuring the concentration of VOCs in London, while Pawlak et al. [99] have used it to compare methane fluxes in Łódź, and many other authors have also used it to contextualise CO₂ emissions [112,116,130–133,150,184,187,189]. In a recent review, GHG emissions were compared among different studies using the LCZ scheme [45,190]. As shown in **figure 9**, the LCZ seems to adapt in a good manner to other measurement parameters that also link with land cover properties.

Figure 9. (Left) Land cover percentages and LCZ classification for different GHG measurement sites. (Right) Correlation between CO₂ and the fraction of buildings, according to their LCZ class. Adapted from Grimmond and Christen [190].

Most of these studies used analytical footprint models, which might be differentiated between eulerian analytical models [39,75,79,88,89,92,118], and those that might be considered parameterisations of Lagrangian stochastic models [107,144,157]. According to results, Lagrangian stochastic approaches have not been applied within the urban context, probably due to the necessity of defining the wind field statistics. In few cases, the footprint has been directly derived from CFD techniques such as LES or RANS modelling, which require a 3D model and increase the resources needed for computing it.

The Kormann and Meixner [118,191] model is the most used one among analytical footprint models. Some of these methodologies might require different input parameters and assumptions, such as the Monin-Obukhov Similarity Theory (MOST) or logarithmic wind profiles already mentioned above (see Oke et al. [192] for a thoughtful explanation). Their performance mainly relies on the characterisation of the so-called *aerodynamic parameters*, which are the *zero-plane displacement* (z_d) and the *roughness length* (z_0). Kent et al. [128] have recently demonstrated their relevance among the footprint estimation, and which might in fact be higher than the footprint modelling itself (see **figure 10**). These values can be estimated using anemometer's observations, morphological information, or tabulated tables. One of the first and most used methodology is the height-based approach for urban areas proposed by Grimmond and Oke [193]:

$$z_d = f_d \bar{z}_H \quad (1)$$

$$z_0 = f_0 \bar{z}_H \quad (2)$$

where $\bar{z}_H$ is the mean height of the surrounding elements, and f_d and f_0 represent the empirical coefficients for each aerodynamic parameter, with a value of 0.7 and 0.1, respectively. Some examples found within this review are Velasco et al. [114,116], Roth et al. [187], Pawlak et al. [99], Crawford et al. [124], Zielinski et al. [101] and Ward et al. [117,182,194,195].

Among anemometric approaches in urban environments, the one derived from *Eddy Covariance* (EC) measurements [196] has been extensively used due to the prevalence of the EC technique for measuring energy fluxes [133,197]. Another interesting anemometric approach is the

scintillometer heat flux method proposed by Kanda et al. [96], and which also uses a measurement equipment very extended among urban environments.

Other estimations of these parameters might be done with morphometric approaches. These might include the ratio of urban plan occupied by roughness elements (McDonald et al. [198], found in [134,180]) or the standard deviation of the roughness-element heights, as proposed by Millward-Hopkins et al. [199] and Kanda et al. [200], and which might be found in recent studies [125,158].

While the latter ones seem to better agree with in-situ measurements, anemometric tend to give higher z_d and lower z_0 than morphometric, resulting in differences up to and above 100% [128]. Therefore, although the use of analytical footprint models might be allowed within the ISL, urban climate researchers should account for the correct estimation of the aerodynamic parameters and the uncertainties derived from them.

Figure 10 In the left and the centre, the zero-plane displacement (z_d) and the roughness length (z_0) are estimated according to different methodologies. In the right side of the figure, source areas for the same location and time period are estimated with Kormann and Meixner [118] and using the aerodynamic parameters derived from the Mho (a) and Mac (b) morphometric methods. After Kent et al. [128].

Scientists measuring within the ISL should also take horizontal heterogeneities into consideration. Even though Hellsten et al. [127] have demonstrated that over relative homogeneous urban arrangements a constant-flux layer above the blending height could be expected, this principle does not hold when it comes to urban structures with strong roughness variations. At this point it should be underlined that, depending on the measurement height and weather conditions, the footprint fetch of a measurement within the ISL might extend from hundred meters to several kilometres, covering different types of urban fabric. Strong variations within the urban context ‘seen’ by the sensor might introduce another degree of uncertainty among results from analytical footprint models.

In this direction, Vesala et al. [152] and Järvi et al. [90] have compared results within the ISL and over heterogeneous urban areas from an analytical and a more sophisticated model based in CFD (see section below for further information). They have corroborated that analytical models do not correctly reflect the contribution of each area to the overall flux. These models assume a horizontally homogeneous surface, and therefore produce a smooth footprint function where at certain distance the largest contribution is given, and from which it decays to the infinite. The CFD model identifies, on the contrary, different *high-contribution* distances, with a more reliable approach to the real urban structure (**figure 11**). The problem with CFD based models is that they are extremely resource demanding, and there is not yet an easy way to implement them.

Figure 11. Cross-wind integrated flux footprint as estimated for surface sources. Analytical model (Horst and Weil [88]; dashed line) and numerical model (Sogachev and Lloyd, [151]; solid line) are presented. After Järvi et al. [90].

Another problem with heterogeneous areas has to do with the local climate zone classification. This scheme was proposed for comparison purposes, but it is not prepared for heterogeneous-patchy areas. Heterogeneities should be kept within the described built and land cover types, or at least within a homogeneous mix of different ones. As stated by Stewart and Oke [14] (2012), transitional areas should be avoided when sitting the equipment. Otherwise, using the LCZ scheme might lead to similar problems as the ones identified by Stewart [8], who underlines the impossibility of comparing different measurements due to the poor definition of the context. In that sense, Alexander et al. [201] compared four measurement sites with its surroundings and decided to only consider the flux when the upwind LCZ was equivalent to the one at the measuring site (see **figure 12**).

Figure 12 LCZ description at the measurement site and its surroundings. After Alexander et al. [201]

For the sake of comparison, **figure 13** represents the urban context of four other studies that were found within this systematic review [116,131,132,201]. Red circumferences with a radius of 500 and 1000 meters are overlaid. In all cases, assuming a homogeneous urban context becomes more difficult as long the considered area increases. The Mexico City measurement site (upper-left image) contrasts with the one of London (lower-right one), where the Thames river covers almost half of the surface within the 500 m circumference. In the case of Dublin (top-right) and Helsinki (bottom-left), heterogeneities are more evident within the 1000 m circumference, where water bodies, parks or train stations might generate important heterogeneities under certain wind directions. Despite the degree of heterogeneity varies substantially among these studies, the four of them were classified by the authors as a *compact mid-rise* (LCZ 2), and all of them have used

an analytical footprint model to contextualise their measurements. This tendency has been a constant among all the reviewed studies within this research.

Urban climate researchers should bear in mind that measuring above the *blending height* is not a sufficient condition to guarantee the use of analytical footprint models. Special attention should be given to the degree of heterogeneity of the footprint, and for that purpose the LCZ scheme might be very useful. Classifying the context according to the LCZ after defining the footprint and corroborating that it is suitable for that purpose, which follows the LCZ guidelines proposed by Stewart and Oke [14], would be a good practice for measurements within the ISL.

Figure 13. Satellite image of the urban sites and location of the measurement equipment according to different studies. Top left: Mexico City, Mexico [116]. Top right: Dublin, Ireland [201]. Bottom left: Helsinki, Finland [132]. Bottom right: London, UK [131].

3.2.2 The Roughness Sublayer (RSL)

Uncertainties increase when approaching the theoretical limit of the blending height (z_R). Under it, the roughness sublayer (RSL) develops in two different scales: the bottom part, which in urban contexts is usually referred as the urban canopy layer (UCL), and the upper part, which is normally denoted as the RSL (see **figure 7**). The last one could be considered as a transition layer between the UCL, the microclimatic scale where most of the urban activities take place, and the ISL, where the effects of the land surface are already well mixed and representative of the local scale. In that sense, and contrary to the ISL, Monin-Obukhov Similarity theory does not apply at the RSL level. Within this layer, turbulence dominates the flow and depends on the spatial characteristics underneath, which introduces many doubts about the source of the energy flux [44]. The wind aerodynamics and the footprint modelling at this scale have been roughly investigated, mainly through scale models placed within wind tunnels and CFD computation [199,202–204], normally assuming homogeneous 3D layouts.

All these considerations bring the difficulties that urban climate researchers might have to deal with to the fore, in case their measurements are carried out within this layer. To avoid these uncertainties, urban climate researchers usually try to avoid this scale when placing their instruments, therefore situating them as high as possible and trying to reach the ISL. There are many different methods to establish the depth of the RSL, which determines the height of z_R or *blending height*. The general consensus among researchers is that it should be somewhere between 1.5 and 5 times the average height of the roughness elements (h_b), and closer to $2 \cdot h_b$ the most part of the time [193,205,206]. However, this limit is not static and might change its position within the day. In urban environments, where buildings easily rise tens of meters tall, reaching such heights might be a complicated task, particularly if there are legal constraints for erecting towers above the urban canopy [163]. These arguments are reflected in most of the RSL studies found in this review (see **figure 14**), which measurements are placed near the blending height limit $z_m/z_R = 1$ (where $z_R = 2 \cdot z_B$).

Figure 14 Relative height of the measurements classified as RSL case studies. Dotted line indicates the region where uncertainties might arise regarding the definition of the atmospheric context.

Despite these limitations, authors frequently implicitly *assume* to be within the ISL [48,83,94,121,145,146,183,207] or explicitly *state* that they are measuring within the ISL [100,109,112,133,137,140], even though some doubts might arise about it. Not many urban climate researchers recognise they struggle to justify the climatic context of some of their measurements [113,128,139] and, in a similar way, not many studies have focused in the RSL *on purpose* [84,96,98,138]. Previous studies have pointed out the uncertainties these RSL-ISL measurements might introduce in the source area estimation [70].

Authors normally discuss the convenience of using analytical footprint models within the RSL, which poses a question regarding how biased these estimations are. In that sense, Hellsten et al. [127] have used a LES-LS model to show how the footprint might look like at different heights over an urban canopy. They have demonstrated that at $1.8 \cdot h_B$ the source area of a measurement might resemble the shape of the footprint derived from an analytical model, while its extension might be overestimated (**figure 15**). This bias might be overcome if the input parameters for the analytical model are locally estimated [208,209], and particularly if some boundary conditions are fulfilled. For example, Zou et al. [142,210] have demonstrated that, closer to the top of the RSL, the classical relations that govern the ISL might be applicable. They also coincide with Yusup and Lim [211] and Yusup and Anis [212], when they say that under unstable (daytime) conditions local turbulent effects might be negligible. In those cases, filtering the measured data according to weather stability (u^* filtering), which is a common practice when carrying out EC

and scintillometer measurements [124,130,146,148], might reduce uncertainties regarding the source area definition within the RSL.

Figure 15. Comparison of flux footprints evaluated using the Kormann-Meixner (KM01) and the LES-LS model from Steinfeld et al. (ST08) for measurements at height $1.8 \cdot z_b$. After Hellsten et al. [127].

3.2.3 The Urban Canopy Layer (UCL)

All the uncertainties that arise within the RSL increase exponentially when reaching the UCL, but in contrast to what urban climate researchers try to do when approaching the RSL, the UCL is normally not avoided. There is a strong interest about this climatic context, as it has many implications for the urban life: buildings exchange energy mostly at this scale, people live in and breath the air contained within the urban canyon, and most of the anthropogenic emissions are generated and emitted to this atmosphere [213–216]. Furthermore, many of the strategies that urban planners might be able to adopt happen at this scale, such as increasing the greenery of streets and parks, smartly planning the traffic flow, or regulating the use of certain materials and equipment [35,217–220].

There are also no doubts that, within this scale, turbulence follows a different pattern than in the ISL and RSL [174,221–224], and therefore none of the classical assumptions might be adopted. Regarding the footprint modelling, very few authors have used analytical approaches for estimating the source area of their measurements. For instance, Häb et al. [95] developed a visualization framework for studying and contextualising measurements carried out using the transect methodology, using the model by Schmid [39,92] for estimating the source area. They underline the limitations of such modelling and point towards future improvement of the source area within their framework. Likewise, there are other authors who tend to use analytical models for comparison purposes, particularly when studying different scales simultaneously [138,207].

Figure 16 Comparison of dimensionless mean x-velocity obtained with LES, RANS, and wind tunnel measurements within a simplified building geometry. It can be observed that LES fits better than RANS with the experimental data. After Van Hoff et al. [225].

As mentioned above, the most accurate approach relies on Computer Fluid Dynamics. In last years it has been extensively used by urban climate researchers for modelling the microclimatic atmosphere [174,221,226]. Although most of these CFD models are based on RANS, it is commonly accepted that LES might be more reliable when simulating the UCL due to the higher resolution when modelling eddies [225,227,228] (see **figure 16**). In that sense, the model

presented by Steinfeld et al. [155] has been applied to demonstrate how different footprints might be obtained at different sites within the urban canyon [127]. According to **figure 17**, the footprint near the ground ($z_m = 0.25 \cdot h_B$) is significantly less predictable than the footprint right above the urban canyon ($z_m = 1.25 \cdot h_B$), particularly when it is situated perpendicularly to the wind direction (cases *b*, *c*, *d*). Under those circumstances a strong vortex conditions the source area estimation, where measurements taken near the vertical boundaries might be represented by a strong positive (source) or negative (sink) footprint. On the other hand, measurements carried out in the crossing of two urban canyons (case *h*) might be characterised by a more homogeneous footprint, similar in shape with those obtained at $1.25 \cdot h_B$ heights.

Figure 17 Footprint prediction by a LES-LS coupled model, for different positions within ($0.25h_B$, left) and just above ($1.25h_B$, right) the urban canyon. The situation of each position is described at the top. After Hellsten et al. [127].

Despite its high accuracy and the fact that LES-LS modelling significantly reduces CPU needs and expenses compared to other CFD approaches, it is still an unfordable solution for many research purposes. Due to these uncertainties and limitations, other authors have adopted different methods. One of the most common is to use correlations between surface cover and air temperatures to define the footprint that better *explains* the measured temperatures (see **figure 18**). Authors usually reference to the approximated source area for a screen-height sensor in urban contexts given by Oke [7] or Stewart and Oke [14] to test these correlations with radius of similar size, and which might range between 100 and 1000 meters. Examples for mobile [229–231] and fixed measurements [74,232,233] that have used correlations to estimate the source area were identified within this systematic review.

Figure 18 Correlation between urban heat island intensity (median and 95 percentile) and urban parameters, and which could be found among the LCZ indicators. After Van Hove et al. [74].

Similarly, Wang et al. [141] have used and compared the correlation approach with the analytical footprint model by Kormann and Meixner [118]. They have found that both methods behave likewise and produce similar results when normalising correlations. Some questions might arise regarding the precision of the correlation process, as it does not seem to provide more accurate information than analytical models (see **figure 19**).

Figure 19 Comparison of the normalised correlation between air temperature and land use, and the normalised footprint function with the K-M analytical model. (a) is for vegetation, and (b) for impervious surfaces. After Wang et al. [141].

A different approach was presented by Erell et al. [234], who embraced a simplification of the footprint function concept (see **section 1**). These authors divided the source area derived from an analytical model into different sectors and weighted them according to their proximity to the measurement site. The same procedure was used some years after by Kaplan et al. [82], who took up these data and classified the source area sectors into local climate zones, linking microclimatic temperatures with the LCZ scheme. In that sense, and despite there are still not many local climate zones studies in the UCL, the LCZ could have a twofold purpose in this scale. Further from contextualising measurements, they might also be useful to assure a certain degree of homogeneity in the surroundings of the measurement context, following a similar approach as the one developed by Alexander et al. [201] for the ISL (see **figure 12**). In other words, if the source area cannot be certainly defined, LCZ might be a good manner to guarantee that the upwind surroundings have similar characteristics to the sensor site.

4 DISCUSSION

The present study provides evidence that suggests that the thermal source area is not yet completely embraced by LCZ studies. The origin of such disassociation seems to be related with the wide use researchers make of the LCZ, particularly with those uses where the footprint definition might not be relevant or might be calculated differently, such as climatic urban planning with remote sensing techniques. Among in-situ turbulent measurements, the application of the LCZ scheme is not constraint to thermal studies, but also applied in many energy and CO₂ studies. However, while most turbulent flux studies embrace the source area estimation, thermal studies do not normally consider it. A possible reason for this might be found in the measurement capabilities of EC systems, which are the most common technique among turbulent flux studies and are normally provided together with a software package that includes the footprint estimation. Another possible cause leading to differences in the footprint adoption might be related with the atmospheric scale. While flux measurements concentrate in the ISL, where assumptions and simplifications regarding the atmospheric physics can be made, thermal studies are mostly carried out in the UCL, thus encountering more barriers when trying to find a suitable source area model.

Results also found that urban researchers seem to seek easy-to-use tools that might be able to give a reasonable guess of what the source area might look like, while using a little amount of easy-to-collect inputs. This might explain why, despite the great advances in CFD's precision and efficiency, there is still a clear preference for one-dimension analytical solutions in the ISL and for qualitative approaches in the UCL. For example the three-dimension lagrangian model by Kljun et al. [143], albeit it might be more accurate than any other analytical solution, it has never been applied by any urban case study, while its analytical parameterisations into one- [144] and two-dimensions [157] is extensively used in the urban environment. Their appearing robustness [165] as well as the extended thought that there is not yet a suitable footprint solution for urban environments push urban climate researchers to work with such models. Even though CFDs alternatives, particularly coupled LES-LS solutions, seem to be the near-future of footprint modelling, they seem to be yet underdeveloped and are still rarely used.

The findings of this study reveal there is a need for standardisation and systematisation. Regardless the footprint approach, there are strong differences in the estimation of the inputs and the reporting of the outputs. Aerodynamic parameters, for example, have a critical relevance within analytical solutions and can be estimated in many ways, therefore introducing strong uncertainties within the modelling process. In a similar way, source areas are reported using different flux percentages, varying from 50 to 99%, thus making the comparison of results from different studies more difficult. The high number of variables that are involved and affect the source area size and shape, as well as its high variability with time, makes urgent to establish a common framework for all turbulent flux studies. Similarly to what happened with the definition of the LCZ scheme, further discussion is needed to determine the most appropriate process for choosing the footprint model, estimating the input parameters, and reporting the source area size within the urban context.

In regard to the limitations of this systematic review, improving the application of the PRISMA methodology would be advisable. Particularly, the identification process through the combination of keywords should be improved to guarantee a higher degree of returned relevant results, which in this review was roughly a 25% (2,487 results out of 3,214 were classified as ‘not relevant’). In that sense there are already available methods and tools that could be implemented, such as contextual searching, and might therefore be taken into consideration in future reviews. The linearity of the screening and eligibility phases have also proven to be excessively resource and time consuming, although improving the identification phase would drastically reduce this issue.

5 CONCLUSIONS

This paper has systematically reviewed the knowledge on the source area definition within urban contexts and its application together with the Local Climate Zones scheme. It was found that, even though the estimation of the source area is rare among thermal studies, there is valuable knowledge regarding the footprint estimation within the measurement of other parameters, such

as the energy flux or CO₂ observations. Hundreds of studies were found to be related with the source area concept and were used to identify the most common trends and limitations among different methodologies and the atmospheric scales near the ground: the inertial sublayer (ISL), the roughness sublayer (RSL), and the urban canopy layer (UCL). The following conclusions can be drawn:

- The source area within the ISL is well documented and studied. Analytical solutions are the prevailing choice due to their simplicity and relatively high accuracy. The estimation of the aerodynamic parameters was found to be an important source of uncertainties and a limitation for comparing results. Defining the LCZ of a measurement at this scale could be also problematic when obtaining large footprints, as strong horizontal heterogeneities usually appear.
- The RSL is usually considered a transition layer that should be avoided when placing measuring instruments. Few experiences have intentionally studied the source area at this atmospheric level, and no specific footprint solution has been developed. Analytical models might be valid when using local estimations of the aerodynamic parameters, and when filtering is applied to only evaluate measurements under unstable atmospheric conditions. These simplifications, however, are based on few experiences and should be confirmed in the future by other studies.
- In the UCL, which is the preferred scale among thermal studies, analytical approaches should be disregarded. In this context the footprint has been treated very heterogeneously, from the most precise and resource-consuming methods (CFD-based models) to the most extended qualitative approaches based on temperature-land cover correlations. To tackle uncertainties regarding the size of the footprint, the LCZs can be used to classify the surroundings of the measurement site, so a certain degree of homogeneity could be guaranteed.

- Finally, the degree of embracement of the source area by LCZ studies was proven to be low and very heterogeneous. The absence of a clear framework for estimating and reporting the source area, altogether with a lack of awareness among researchers on the relevance of the footprint, are found to be the main causes of this situation. Further research is needed to develop reliable and easy-to-use footprint tools for those scientists, particularly for measurements within the UCL.

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Appendix A.1 Case studies found within this systematic review

ID	Reference	Method. Reference ¹	City, Country	Measurement height [z_m] (m)	RSL height [z_R] (m)	z_m/z_R	Context ²	Max. footprint distance [X] (m)	Measuring Conditions ³	LCZ mentioned	LCZ applied
[201]	Alexander et al. (2016)	-	Dublin, IE Hamburg, DE Melbourne, AU Phoenix (AZ), US	$z_{m,DU} = 48.0$ $z_{m,HA} = 50.0$ $z_{m,ME} = 40.0$ $z_{m,PH} = 22.1$	$z_{R,DU} \approx 33^b$ $z_{R,HA} \approx 18^b$ $z_{R,ME} \approx 13^b$ $z_{R,PH} \approx 9^b$	1.1 2.8 3.1 2.5	ISL	$X_{XX} = 500$	- , - , -	Yes	LCZ 2 LCZ 8 LCZ 6 LCZ 6
[119]	Ando & Ueyama (2017)	KM01	Osaka, JP	$z_m = 111.0$	$z_R \approx 30^b$	3.7	ISL-ML	$X_{80} \approx 800-2400^d$ $X_{80} \approx 1000-4400^d$	DT,AV,AV NT,AV,AV	Yes	LCZ 3 ₄
[120]	Auvinen et al. (2017)	ST08 KM01	Helsinki, FI	$z_m = 60.0$	$z_R \approx 48^b$	1.3	ISL	$X_{90,ST08} \approx 1200^d$ $X_{90,KM01} \approx 2000^d$	AV,NE,SU	No	No
[93]	Barlow et al. (2008)	SD94/97	Salford, UK	$z_{m,1} = 50.0$ $z_{m,2} = 100.0$	$z_R \approx 16^b$	3.1 6.3	ISL-ML	$X_{90,1} \approx 2200^d$ $X_{90,2} \approx 5000^d$	DT,NE,SP	-	-
[145]	Bergeron & Strachan (2011)	KN04	Montreal, CA	$z_{m,1} = 25.0$ $z_{m,2} = 25.0$	$z_{R,1} \approx 21^b$ $z_{R,2} \approx 25^b$	1,2 1,0	RSL-ISL	$X_{80,1} \approx 500-1080^d$ $X_{80,1} \approx 640-1400^d$ $X_{80,1} \approx 580-1120^d$ $X_{80,1} \approx 520-1300^d$ $X_{80,2} \approx 420-800^d$ $X_{80,2} \approx 520-1320^d$ $X_{80,2} \approx 460-1920^d$ $X_{80,2} \approx 500-1120^d$	DT,UN,SU NT,UN,SU DT,UN,WI NT,UN,WI DT,UN,SU NT,UN,SU DT,UN,WI NT,UN,WI	-	
[72]	Björkegren & Grimmond (2016)	KM01	London, UK	$z_m = 46.4$	$z_R \approx 42^b$	1.1	ISL	$X_{50} \approx 250-1000^d$ $X_{80} \approx 700-1700^d$ $X_{95} \approx 1500-3000^d$	- , UN,AV	No	No
[122] [184]	Christen et al. (2011); Crawford & Christen (2015)	KM01	Vancouver, CA	$z_m = 28.8$	$z_R \approx 17^b$	1.7	ISL	$X_{50} \approx 100-260^d$ $X_{80} \approx 380-740^d$	AV,AV,AV	Yes	LCZ 9

ID	Reference	Method. Reference ¹	City, Country	Measurement height [z_m] (m)	RSL height [z_R] (m)	z_m/z_R	Context ²	Max. footprint distance [X] (m)	Measuring Conditions ³	LCZ mentioned	LCZ applied
[94]	Contini et al. (2012)	SD94/97 HH00	Lecce, IT	$z_m = 14.0$	$z_R \approx 15^b$	0.9	RSL	$X_{50} \approx 60-200^d$	AV,UN-NE,WI-SP	No	No
[123]	Crawford et al. (2011)	KM01	Baltimore (MD), US	$z_m = 41.2$	$z_R \approx 20^b$	2.1	ISL	$X_{50} \approx 1400-2100^d$ $X_{60} \approx 2000-3000^d$ $X_{70} \approx 3200-4800^d$	AV,AV,AV	-	-
[124]	Crawford et al. (2017)	KM01	London, UK	$z_{m,EC} = 49.9$ $z_{m,LAS} = 124.0^e$	$z_{R,EC} \approx 35^b$ $z_{R,LAS} \approx 29^b$	1.4 4.3	ISL	$X_{50,EC} \approx 350-650^d$ $X_{75,EC} \approx 800-1400^d$ $X_{50,LAS} \approx 2500^d$ $X_{75,LAS} \approx 5000^d$	AV,UN-NE,AV	No	No
[76]	Dorsey et al. (2002)	SP90	Edinburgh, UK	$z_m = 67.0$	-	-	ISL	$X_{XX} \approx 3000$ $X_{XX} \approx 5000$	- , UN, - - , ST, -	-	-
[234]	Erell et al. (2009)	CORREL.	Gothenburg, SE	-	-	-	UCL	$X_{XX} \approx 100-1000$	- , - , -	-	-
[125]	Feigenwinter et al. (2017)	KM01	Basel, CH	-	-	-	ISL	-	- , - , -	No	No
[108] [186]	Gioli et al. (2012; 2015)	HH00	Florence, IT	$z_m = 35.0$	$z_R \approx 28^b$	1.3	ISL	$X_{90} \approx 420-1700^d$	AV,UN,AV	No	No
[80]	Grimmond et al. (1991)	SO90	Vancouver, CA	$z_m = 29.0$	$z_R \approx 17^b$	1.7	ISL	-	- , - , -	-	-
[81]	Grimmond (1992)	SO90	Vancouver, CA	$z_m = 20.5$	-	-	ISL	-	- , - , -	-	-
[196]	Grimmond et al. (1998)	SD94/97	Chicago (IL), US Los Angeles (CA), US Miami (FL), US Vancouver, CA	$z_{m,CH} = 31.0$ $z_{m,LA} = 41.8$ $z_{m,MI} = 60.0$ $z_{m,VA} = 60.0$	-	5.9 3.0 5.9 3.8	ISL	-	- , - , -	-	-

ID	Reference	Method. Reference ¹	City, Country	Measurement height [z _m] (m)	RSL height [z _R] (m)	z _m /z _R	Context ²	Max. footprint distance [X] (m)	Measuring Conditions ³	LCZ mentioned	LCZ applied
[146]	Guidolotti et al. (2017)	KN04	Naples, IT	z _m = 26.0	z _R ≈ 44 ^b	0.6	RSL	X ₇₀ ≈ 80-540 ^d X ₉₀ ≈ 120-1780 ^d	AV, -, AV	No	No
[95]	Häb et al. (2015)	SD94/97	Gilbert (AZ), US	z _m = 1.0	-	-	UCL	-	-, -, -	No	No
[126] [72]	Helfter et al. (2011; 2016)	KM01	London, UK	z _m = 190.0	z _R ≈ 18 ^b	10.6	ISL - ML	X ₉₀ = 13900 X ₉₀ = 10000 X ₉₀ = 6900 X ₉₀ = 13900	DT, NE, WI DT, UN, SP DT, UN, SU DT, NE, AU	No	No
[127]	Hellsten et al. (2015)	ST08 KM01	idealised	z _{m,1} = 10.0 z _{m,2} = 50.0 z _{m,3} = 78.0 z _{m,4} = 100.0	z _R ≈ 80 ^b	0.1 0.6 0.9 1.3	UCL RSL RSL ISL	X _{75,2,ST08} ≈ 580 ^d X _{75,2,KM01} ≈ 500 ^d X _{90,2,ST08} ≈ 1200 ^d X _{90,2,KM01} ≈ 950 ^d X _{75,3,ST08} ≈ 1700 ^d X _{75,3,KM01} ≈ 900 ^d X _{90,3,ST08} ≈ 4000 ^d X _{90,3,KM01} ≈ 1400 ^d	-, NE, -	No	No
[147]	Hiller et al. (2011)	KN04	Minneapolis-Saint Paul (MN), US	z _m = 1.35	-	-	UCL	X ₈₀ ≈ 75 ^d X ₉₀ ≈ 105 ^d	-, -, AV	-	-
[77] [189]	Jacobs et al. (2015) Kleingeld et al. (2017)	SP90 HW92/94	Arnhem, NL Rotterdam, NL	z _{m,EC} = 41.0 z _{m,LAS} = 64.0 ^e	z _{R,EC} ≈ 36 ^b z _{R,LAS} ≈ 57 ^b	1.1	ISL	X _{80,EC} ≈ 1000 X _{80,LAS} ≈ 1750	-, -, -	Yes	LCZ 2
[90]	Järvi et al. (2009)	SL04 HW92/94	Helsinki, FI	z _m = 31.0	z _R ≈ 24 ^b	1.3	ISL	X _{64,SL04} = 500	-, NE, AV	-	-
[96]	Kanda et al. (2002)	SD94/97	Tokyo, JP	z _{m,EC} = 32.0 z _{m,LAS} = 24.0 ^e	z _R ≈ 17 ^b	1.9 1.4	ISL	X _{90,EC} = 1660 X _{90,LAS} = 1750 X _{90,EC} = 1240 X _{90,LAS} = 1250 X _{90,EC} = 304 X _{90,LAS} = 496	DT, ST, AU DT, ST, AU DT, NE, AU DT, NE, AU DT, UN, AU DT, UN, AU	-	-

ID	Reference	Method. Reference ¹	City, Country	Measurement height [z_m] (m)	RSL height [z_R] (m)	z_m/z_R	Context ²	Max. footprint distance [X] (m)	Measuring Conditions ³	LCZ mentioned	LCZ applied
[82]	Kaplan et al. (2016)	SO90	Bat-Yam, IL	-	-	-	UCL	$X_{xx} = 1000^d$	- , - , -	Yes	Mix
[128]	Kent et al. (2017)	KM01	London, UK	$z_{m,1} = 50.3$ $z_{m,2} = 48.9$ $z_{m,3} = 38.8$	$z_{R,1} \approx 43^b$ $z_{R,2} \approx 47^b$ $z_{R,3} \approx 47^b$	1.2 1.0 0.8	ISL RSL-ISL RSL	$X_{80,1,Mho} \approx 350-600^d$ $X_{80,1,Mac} \approx 950-1950^d$ $X_{80,2,Mho} \approx 250-450^d$ $X_{80,3,Mho} \approx 100-200^d$	DT,NE,AV	Yes	LCZ 2
[48]	Kordowski & Kuttler (2010)	SD94/97	Essen, DE	$z_m = 26.0$	$z_R \approx 24-32^b$	0,9	RSL	$X_{80} \approx 1000^d$	- ,NE,AV	-	-
[129]	Kota et al. (2014)	KM01	Houston (TX), US	$z_m = 60.0$	$z_R \approx 16-40^b$	2.2	ISL	$X_{80} \approx 1500^d$	DT, - ,SP-SU	No	No
[130]	Kotthaus & Grimmond (2012)	KM01	London, UK	$z_m = 48.9$	$z_R \approx 47^b$	1.0	RSL-ISL	$X_{50} \approx 100-220^d$ $X_{50} \approx 200-480^d$ $X_{70} \approx 320-800^d$ $X_{70} \approx 360-800^d$ $X_{80} \approx 480-1200^d$ $X_{80} \approx 500-1120^d$	- , - ,SU - , - ,WI - , - ,SU - , - ,WI - , - ,SU - , - ,WI	Yes	LCZ 2
[131]	Kotthaus & Grimmond (2014)	KM01	London, UK	$z_m = 48.9$	$z_R \approx 47^b$	1.0	RSL-ISL	$X_{50} \approx 140-280^d$ $X_{50} \approx 160-480^d$ $X_{70} \approx 260-480^d$ $X_{70} \approx 360-860^d$ $X_{80} \approx 360-720^d$ $X_{80} \approx 580-1300^d$	- ,UN,AV - ,NE,AV - ,UN,AV - ,NE,AV - ,UN,AV - ,NE,AV	Yes	LCZ 2
[132]	Kurppa et al. (2015)	KM01	Helsinki, FI	$z_m = 60.9$	$z_R \approx 48^b$	1.3	ISL	$X_{80} = 650-1150^d$ $X_{80} = 650-1000^d$	- ,UN-NE,SU - ,UN-NE,WI	Yes	LCZ 2
[148]	Langford et al. (2009)	KN04	Manchester, UK	$z_m = 95.0$	$z_R \approx 30^b$	3.2	ISL	$X_{80} = 1623$	- ,AV,SP	-	-

ID	Reference	Method. Reference ¹	City, Country	Measurement height [z _m] (m)	RSL height [z _R] (m)	z _m /z _R	Context ²	Max. footprint distance [X] (m)	Measuring Conditions ³	LCZ mentioned	LCZ applied
[188]	JD Lee et al. (2015)	KM01	London, UK	z _m = 190.0	z _R ≈ 18 ^b	10.6	ISL-ML	X ₉₀ = 4695	AV,AV,SP-SU	No	No
[91]	SH Lee et al. (2015)	HW92/94	Gongju, KR	z _m = 48.5 ^e	z _R ≈ 6 ^b	8	ISL	X _{60,LAS} ≈ 350 ^d X _{80,LAS} ≈ 600 ^d X _{90,LAS} ≈ 900 ^d	- , UN-NE,WI	No	No
[73]	Lietzke et al. (2015)	KM01	Basel, CH	z _m = 41.0	z _R ≈ 32 ^b	1.3	ISL	X ₅₀ ≈ 80-240 ^d X ₇₀ ≈ 140-420 ^d X ₈₀ ≈ 200-560 ^d X ₉₀ ≈ 300-880 ^d	- , - ,AV	Yes	No
[235] [97]	Liu et al. (2009); Liu & Sun (2010)	SD94/97	Nanjing, CN	z _m = 24.2	z _R ≈ 39 ^b	0.6	RSL	X _{xx} = 500	- , - ,AV	-	-
[133]	Liu et al. (2012)	KM01	Beijing, CN	z _m = 47.0	z _R ≈ 47 ^b	1.0	RSL-ISL	X ₅₀ ≈ 250-450 ^d X ₇₀ ≈ 450-800 ^d X ₈₀ ≈ 600-1200 ^d X ₉₀ ≈ 1000-2100 ^d	- , UN-NE,AV	Yes	Mix
[83] [181]	Lemonsu et al. (2004); Henon et al. (2011)	SO90	Marseille, FR	z _m = 43.9	z _R ≈ 40 ^b	1.1	RSL-ISL	X ₉₀ ≈ 500-1000 ^d	- , - ,SU	-	-
[232] [233]	Lindén (2011); Holmer et al. (2013)	CORREL.	Ouagadougou, BF	z _m = 1.7	-	-	UCL	X _{xx} = 400	AV,AV,AU	Yes	Mix
[149]	Mårtensson (2006)	KN04	Stockholm, SE	z _m = 118.0	z _R ≈ 30 ^b	3,9	ISL-ML	X ₇₅ = 1700-2400	AV,AV,SP	-	-
[150]	Menzer & McFadden (2015)	KN04	Minneapolis-Saint Paul (MN), US	z _m = 40.0	z _R ≈ 24 ^b	1,7	ISL	X ₉₀ = 800	AV,UN-NE,AV	Yes	LCZ 6
[49]	Middel et al. (2014)	-	Phoenix (AZ), US	z _m = 2.0	z _R ≈ 10 ^z	-	UCL	X _{xx} = 200	- , - , -	Yes	Mix

ID	Reference	Method. Reference ¹	City, Country	Measurement height [z _m] (m)	RSL height [z _R] (m)	z _m /z _R	Context ²	Max. footprint distance [X] (m)	Measuring Conditions ³	LCZ mentioned	LCZ applied
[109]	Morin et al. (2014)	HH00	Columbus (OH), US	z _{m,1} = 9.6 z _{m,2} = 15.0	z _R ≈ 16 ^b	0.6 0.9	RSL	X _{90,1} ≈ 15-25 ^d X _{90,1} ≈ 20-40 ^d X _{90,1} ≈ 200-225 ^d X _{90,1} ≈ 90-125 ^d X _{90,2} ≈ 200-375 ^d X _{90,2} ≈ 225-425 ^d X _{90,2} ≈ 225-500 ^d X _{90,2} ≈ 250-550 ^d	DT, -,SU NT, -,SU DT, -,WI NT, -,WI DT, -,SU NT, -,SU DT, -,WI NT, -,WI	No	No
[50]	Nichol & Hang (2012)	-	Hong Kong, CN	z _m = 1.0	-	-	UCL	X _{xx} = 10-100	AV, -,SU	No	No
[134]	Nordbo et al. (2013)	KM01	Helsinki, FI	z _{m,1} = 31.0 z _{m,2} = 41.8 z _{m,3} = 60.0	z _{R,1} ≈ 40 ^b z _{R,2} ≈ 42 ^b z _{R,3} ≈ 48 ^b	0.8 1.0 1.3	RSL RSL ISL	X _{50,1} ≈ 100-450 ^d X _{50,2} ≈ 300-450 ^d X _{50,3} ≈ 500-750 ^d X _{75,1} ≈ 300-950 ^d X _{75,2} ≈ 600-950 ^d X _{75,3} ≈ 1000-1750 ^d	-,NE,AV	No	No
[179]	Oke et al. (1992)	SO90	Mexico city, MX	z _m = 28.0	z _R = 15-23	1.6	ISL	X ₉₀ = 900 X ₉₀ = 1800	DT, -,WI NT, -,WI	-	-
[98]	Oke et al. (1999)	SD94/97	Mexico city, MX	z _m = 28.0	z _R = 36.8	0,8	RSL	X ₉₀ ≈ 200-400 ^d X ₉₀ ≈ 400-700 ^d	DT, -,AU NT, -,AU	-	-
[110]	Oliphant et al. (2017)	HH00	Black Rock (NV), US	z _m = 11.6	z _R ≈ 10 ^b	1,2	ISL	-	-, -, -	No	No
[135]	Park et al. (2011)	KN04 KM01	Houston (TX), US	z _m = 60.0	z _R ≈ 24 ^b	2,5	ISL	X _{90,KN04} = 900-1200 X _{50,KM01} ≈ 900 ^d X _{90,KM01} ≈ 2300 ^d	DT,NE, - DT, -,SU DT,-,SU	-	-

ID	Reference	Method. Reference ¹	City, Country	Measurement height [z _m] (m)	RSL height [z _R] (m)	z _m /z _R	Context ²	Max. footprint distance [X] (m)	Measuring Conditions ³	LCZ mentioned	LCZ applied
[136]	Park et al. (2016)	KM01	Houston (TX), US	z _m = 60.0	z _R ≈ 24 ^b	2,5	ISL	X ₆₀ ≈ 400-1050 ^d X ₉₀ ≈ 750-1700 ^d X ₆₀ ≈ 450-1000 ^d X ₉₀ ≈ 800-1650 ^d X ₆₀ ≈ 450-900 ^d X ₉₀ ≈ 800-1550 ^d X ₆₀ ≈ 450-1200 ^d X ₉₀ ≈ 800-1800 ^d	AV,AV,SP AV,AV,SP AV,AV,SU AV,AV,SU AV,AV,AU AV,AV,AU AV,AV,WI AV,AV,WI	Yes	LCZ 6b LCZ 5
[99]	Pawlak et al. (2016)	SD94/97	Łódź, PL	z _m = 37.0	z _R ≈ 22 ^b	1.7	ISL	X ₅₀ ≈ 125-200 ^d X ₇₅ ≈ 175-400 ^d X ₉₀ ≈ 300-750 ^d	DT,UN,AV	Yes	LCZ 3
[46]	Perera & Emmanuel (2016)	-	Colombo, LK	-	-	-	-	size of urban blocks	- , - , -	Yes	Mix
[185]	Ramamurthy & Pardyjak (2011)	HH00	Saint Lake (UT), US	z _m = 36.0	z _R ≈ 13 ^b	2,8	ISL	X ₉₀ ≈ 600-850 ^d X ₉₀ ≈ 4800-8800 ^d	- , UN,SU - , ST,SU	-	-
[137] [236]	Rapsomanikis (2015); Loupa et al. (2016)	KM01	Athens, GR	z _m = 30,0	z _R ≈ 34 ^b	0.9	RSL	X _{xx} ≈ 560-1545 ^d	- , - , -	No	No
[183]	Rigby et al. (2008)	-	London, UK	z _m = 87.0	z _R ≈ 22 ^b	4.0	ISL	X _{xx} = 1000	- , - , AV	-	-
[84] [85]	Rooney (2001; 2005)	SO90 SD94/97	Birmingham, UK Salford, UK	z _{m,1} = 45.0 z _{m,2} = 30.0 z _{m,3} = 20.0	-	-	RSL-ISL	-	- , - , -	-	-
[187]	Roth et al. (2016)	HH00	Singapore, SG	z _{m,1} = 20.7	z _R ≈ 17 ^b	1.2	ISL	X ₈₀ ≈ 400 ^d X ₈₀ ≈ 1000 ^d X ₈₀ ≈ 800 ^d	DT,AV,AV NT,AV,AV AV,AV,AV	Yes	LCZ 3

ID	Reference	Method. Reference ¹	City, Country	Measurement height [z_m] (m)	RSL height [z_R] (m)	z_m/z_R	Context ²	Max. footprint distance [X] (m)	Measuring Conditions ³	LCZ mentioned	LCZ applied
[138]	Salmond et al. (2012)	KM01	Basel, CH	$z_m = 31.7$	$z_R \approx 29^b$	1.1	ISL	$X_{50} \approx 70-200^d$ $X_{60} \approx 110-240^d$ $X_{70} \approx 140-320^d$ $X_{80} \approx 190-460^d$ $X_{50} \approx 140-300^d$ $X_{60} \approx 200-390^d$ $X_{70} \approx 260-540^d$ $X_{80} \approx 400-800^d$	DT,AV,SU DT,AV,SU DT,AV,SU DT,AV,SU NT,AV,SU NT,AV,SU NT,AV,SU NT,AV,SU	No	No
[86]	Schmid et al. (1991)	SO90	Vancouver, CA	$z_m = 28.0$	$z_R \approx 10^b$	2.8	ISL	$X_{50} \approx 325-850^d$	DT,AV,SU	-	-
[207]	Soegaard & Møller-Jensen (2003)	SD94/97	Copenhagen, DK	$z_{m,1} = 40.0$ $z_{m,2} = 10.0$	$z_R \approx 40-50^b$	0.9 0.2	RSL UCL	$X_{90,1} \approx 500$ $X_{90,2} \approx 100$	AV,NE,AV DT,NE,WI	-	-
[112]	Song & Wang (2012)	HH00	Beijing, CN	$z_m = 47.0$	$z_R \approx 50^b$	1.0	RSL-ISL	$X_{90} \approx 220-450^d$ $X_{90} \approx 200-750^d$	AV,UN,AV AV,ST,AV	Yes	Mix
[113]	Sparks & Toumi (2010)	HH00	London, UK	$z_m = 50.0$	$z_R \approx 50^b$	1.0	RSL-ISL	$X_{90} \approx 1600$	AV,AV,AV	-	-
[180]	Spronken-Smith (2002)	SD94/97	Christchurch, NZ	$z_m = 20.0$	$z_R \approx 12^b$	1.7	ISL	$X_{50} \approx 90-100^d$ $X_{50} \approx 250-800^d$	DT, -,SU DT, -,WI	-	-
[78]	Stabler et al. (2005)	SP90	Phoenix (AZ), US	$z_m = 1.0$	-	-	UCL	$X_{xx} = 20-450$	-, -, -	-	-
[237]	Szymanowski & Kryza (2011)	CORREL.	Wroclaw, PL	$z_m = 2.0$	-	-	UCL	$X_{xx} = 550-600$	DT,ST, -	-	-
[139]	Ueyama & Ando (2016)	KM01	Sakai, JP	$z_{m,1} = 111.0$ $z_{m,2} = 30.0$ $z_{m,3} = 16.2$	$z_{R,1} \approx 22-72^b$ $z_{R,2} \approx 25-42^b$ $z_{R,3} \approx 22-34^b$	3.0 1.0 0.6	ISL RSL-ISL RSL	$X_{80,1} \approx 1300-3000^d$ $X_{80,2} \approx 550-1000^d$ $X_{80,3} \approx 80-200^d$	DT,AV,DT	No	No

ID	Reference	Method. Reference ¹	City, Country	Measurement height [z _m] (m)	RSL height [z _R] (m)	z _m /z _R	Context ²	Max. footprint distance [X] (m)	Measuring Conditions ³	LCZ mentioned	LCZ applied
[230]	Unger et al. (2010)	CORREL.	Szeged, HU	z _m = 1.5	-	-	UCL	X _{xx} = 500	NT,ST,SU	-	-
[140]	Valach et al. (2015)	KM01	London, UK	z _m = 50.3	z _R ≈ 53 ^b	0.9	RSL-ISL	X ₇₅ = 750 X ₉₀ = 1000 X ₉₉ = 2000	- ,NE,AV	Yes	LCZ 2
[74]	van Hove et al. (2015)	CORREL.	Rotterdam, NL	z _{m,1} = 20.0 z _{m,2} = 18.0	-	-	UCL RSL	X _{xx,1} = 500 X _{xx,2} = 750	AV,AV,SU	Yes	LCZ 2
[114]	Velasco et al. (2005)	HH00	Mexico city, MX	z _m = 37.0	z _R ≈ 24 ^b	1.5	ISL	X ₈₀ ≈ 200-2100 ^d X ₈₀ ≈ 1300-4000 ^d X ₈₀ ≈ 500-2500 ^d	DT, - ,SP NT, - ,SP AV, - ,SP	-	-
[116]	Velasco et al. (2014)	HH00	Mexico city, MX	z _m = 37.0	z _R ≈ 19 ^b	1.9	ISL	X ₆₀ ≈ 100-1000 ^d X ₈₀ ≈ 200-2100 ^d X ₆₀ ≈ 500-1900 ^d X ₈₀ ≈ 1300-4000 ^d	DT, - ,SP DT, - ,SP NT, - ,SP NT, - ,SP	Yes	LCZ 2
[152]	Vesala et al. (2008)	SL04	Helsinki, FI	z _m = 31.0	z _{R,1} ≈ 39 ^b z _{R,2} ≈ 24 ^b z _{R,3} ≈ 18 ^b	0.8 1.3 1.7	RSL ISL ISL	-	- , - , -	-	-
[141]	Wang et al. (2016)	CORREL.	Phoenix (AZ), US	z _m = 2.0	-	< 0.5	UCL	X _{xx} = 300	DT,AV,SP	No	No
[182] [117] [195]	Ward et al. (2013; 2014; 2015)	HH00	Swindon, UK	z _{m,EC} = 12.5 z _{m,LAS} = 32.4 ^e z _{m,BLS} = 44.3 ^e	z _{R,EC} ≈ 10 ^b z _{R,LAS} ≈ 12 ^b z _{R,BLS} ≈ 14 ^b	1.3 2.7 3.2	ISL	X _{80,EC} ≈ 400 ^d X _{95,EC} ≈ 1300 ^d X _{80,LAS} ≈ 700 ^d X _{95,LAS} ≈ 2300 ^d X _{80,BLS} ≈ 1000 ^d X _{95,BLS} ≈ 2600 ^d	- ,UN,AV	No	No
[100]	Weber & Kordowski (2010)	SD94/97	Essen, DE	z _m = 35.0	z _R ≈ 34 ^b	1.0	RSL-ISL	X ₇₀ = 1000	- ,NE,AV	-	

ID	Reference	Method. Reference ¹	City, Country	Measurement height [z_m] (m)	RSL height [z_R] (m)	z_m/z_R	Context ²	Max. footprint distance [X] (m)	Measuring Conditions ³	LCZ mentioned	LCZ applied
[121]	Yusup & Anis (2016)	-	Pulau Pinang, MY	$z_m = 18.0$	$z_R \approx 30\text{-}32^b$	0.6	RSL	$X_{XX} = 450$	NT, -, AV	Yes	LCZ 5b
[101]	Zielinski et al. (2017)	SD94/97	Łódź, PL	$z_{m,LAS} = 35.1^e$	$z_R \approx 22\text{-}31^b$	2.7	ISL	$X_{60,LAS} = 250\text{-}450^d$ $X_{80,LAS} = 300\text{-}550^d$ $X_{95,LAS} = 850\text{-}1250^d$	DT, UN, AV	No	No
[142]	Zou et al. (2017)	KM01	Nanjing, CN	$z_{m,1} = 33.5$ $z_{m,2} = 48.5$	$z_{R,SUP} \approx 39^b$ $z_{R,URB} \approx 43^b$	0.9 1.1	RSL ISL (RSL)	$X_{75,1} = 500$ $X_{75,2} = 800$	-, -, AV	No	No

¹ Methodological reference abbreviations are described in Figure 6.

² Context abbreviations: *ISL* is the Inertial Sublayer. *RSL* is Roughness Sublayer. *UCL* is the Urban Canopy Layer. X_{XX} is the distance from the receptor including a $XX\%$ of the area that influences the measurement.

³ Measuring conditions abbreviations reference, in this order, to the time of the day (DT: Daytime, NT: Nighttime, AV: Average), the atmospheric stability (UN: Unstable, NE: Neutral, ST: Stable, AV: Average), and the season (WI: Winter, SP: Spring, SU: Summer, AU: Autumn, AV: Average).

^a According to the description given by the authors.

^b Approximated by $z_R = 2z_h$, where z_h is the average height of the surrounding buildings, which is given by the authors.

^c z_h is derived from the LCZ class, which is defined by the authors.

^d Graphically approximated from the representation that appears in the paper.

^e Average of measurement heights for scintillometers.