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Review

Meteorological and Ancillary Data Resources for Climate Research in Urban Areas

Sorin Cheval [1,2,3,*], Dana Micu [4], Alexandru Dumitrescu [2,5], Anișoara Irimescu [2], Maria Frighenciu [6], Cristian Iojă [7], Nicu Constantin Tudose [3], Șerban Davidescu [3] and Bogdan Antonescu [8,9]

1 Department of Aviation, "Henri Coandă" Air Force Academy, 500187 Brașov, Romania
2 National Meteorological Administration, 013686 Bucharest, Romania; dumitrescu@meteoromania.ro (A.D.); anisoara.irimescu@meteoromania.ro (A.I.)
3 Torrential Watershed Management Unit, Brașov Station, National Research and Development Institute in Forestry "Marin Drăcea", 500040 Brașov, Romania; cntudose@yahoo.com (N.C.T.); s_davidescu@icas.ro (S.D.)
4 Department of Physical Geography, Institute of Geography, Romanian Academy, 023993 Bucharest, Romania; micudanamagdalena@gmail.com
5 Research Institute of the University of Bucharest, 030018 Bucharest, Romania
6 Doctoral School of Sciences, University of Craiova, 200585 Craiova, Romania; maria.frighenciu@gmail.com
7 Center for Environmental Research and Impact Studies, University of Bucharest, 1 Bd. Nicolae Balcescu, 010041 Bucharest, Romania; cristian.ioja@geo.unibuc.ro
8 Remote Sensing Department, National Institute of Research and Development for Optoelectronics INOE2000, 77125 Măgurele, Romania; bogdan.antonescu@inoe.ro
9 Faculty of Physics, University of Bucharest, 77125, Măgurele, Romania
* Correspondence: sorin.cheval@afahc.ro or sorin.cheval@meteoromania.ro

Received: 15 January 2020; Accepted: 20 February 2020; Published: 25 February 2020

Abstract: An increasing plethora of both meteorological and ancillary data are presently available for climate research and applications in urban areas. The data are often held by local or national institutions (i.e., meteorological services, universities or environmental agencies). This paper outlines a total number of 33 datasets, organized into three main categories of meteorological data resources (14 datasets) and four categories of ancillary data resources (19 datasets), selected for their potential to support urban climate studies, but also for their free accessibility. Such a collection cannot be exhaustive, but we aim to draw the attention of the scientific community to relevant datasets, freely available at temporal and spatial resolutions appropriate for urban climatology. Each dataset contains information about its availability, limitations, and examples of research in urban areas.

Keywords: urban climate; open data; data sources; urban climate monitoring

1. Introduction

Fast natural and anthropogenic variations have been observed at global, regional and local scale in the recent decades, triggering complex impacts on environment and society, such as biodiversity loss, land degradation, reduced water resources and migration. The world population has experienced continuous growth, and urbanization has brought the people living in cities to 55.2% of total world population [1]. At the same time, climate change is a high-priority topic for the public agenda, and huge efforts have been devoted to understanding the temporal and spatial variability of our atmosphere in order to enhance the accuracy of climate predictions. Numerous studies documented climate change hotspots from various perspectives, e.g., climate modelling [2], hydrology [3], or ecosystems [4]. As they are particularly vulnerable to both present and future climate impacts, with considerable risks for human security [5], cities are hotspots both for the present climate and climate change.

Cities are territorial structures with the highest heterogeneity among the spatial systems of the Earth. Cities are also a unique combination of more or less prevalent anthropogenic and natural patches, very diverse landscape fragmentation, land use and land cover, dynamic energy and material fluxes. The availability of consistent information represents a key condition for the daily functionality and long-term development of the urban areas. Climate services address data provisions, statistic indicators, overview or products useful for different applications. In situ observations and gridded data are extensively used for climate services, satellite and aerial remote sensing, crowdsourcing, big data and artificial intelligence have produced a true revolution in climate data assimilation, storage and modelling.

The need of meteorological input for the decision making in urban development has been acknowledged for a long time [6]. Meteorological data are primary resources supporting the climate services designed mainly for present necessities, and continuous information from many other fields, such as land cover, demography, economy, are needed for the efficient adaptation of urban communities to future climate. The combined use of meteorological and ancillary data requires comparable quality, continuity and fine temporal and spatial resolution for efficient applications in urban applications.

There is an extensive body of literature of urban climate studies, which employed a wide range of datasets derived through different algorithms or modelling assumptions from primary data resources (e.g., in situ measurements or satellite). However, these data products have never been overviewed to highlight their advantages and disadvantages and applicability for urban climatological studies. It is worth mentioning some examples of systematic reviews with topics related to urban climatology, which tackled the issue of urban climate/meteorological datasets indirectly, within assessments of methodologies for urban heat island (UHI) [7,8] or of development status of urban meteorological networks [9].

This paper aims at providing a review of the meteorological and ancillary data resources available for urban areas, with emphasis on the possible applications which facilitate the current use of climate resources and adaptation to climate change challenges in urban areas. The review presents relevant meteorological and ancillary data resources currently used in urban climatology, derived from ground-based measurements, gridded datasets, crowdsourcing, remote sensing and airborne sensors, and highlights the benefits and specific limitations of the datasets.

2. Methodology

This research relied on authors' experience in the field of climate research related to urban environment, but also on Internet search technique to find semantically important entities, by querying the Web of Science database of academic literature. The search targeted the English-written scientific articles disseminated within the scientific community as journal papers, conference proceedings papers or book chapters, published after 2000. Some examples of searching terms and syntaxes are: "urban climate", "urban climate reviews", "urban climate datasets", "meteorological and climate datasets", and "urban meteorological networks".

Acknowledging the high importance of other datasets and variables (i.e., anthropogenic heat flux or radiation fluxes), the review targeted three main categories of meteorological resources, namely (1) ground-based measurements, (2) gridded datasets, (3) remote sensing, and four categories of ancillary data. This review tackles four categories, namely (1) societal information, (2) land cover, (3) urban morphology and (4) climate change, adaptation and urban resilience. It has to be stressed that the approach is not aimed to be exhaustive and we consider it as a fundament for more comprehensive review reports.

3. Data Resources

3.1. Meteorological Data Resources

Based on the method of retrieval, the meteorological information can be classified in ground observations, model outputs, and remote sensing data, with different characteristics and utility. Ideally, the meteorological data should simultaneously address the following issues:

(a) Temporal and spatial stability and homogeneity. Ideally, the observations should be performed in constant locations, quasi-continuously over time, with limited and isolated gaps. The shortcomings related to missing data or changes in station locations can be successfully secured by homogenization procedures [10,11]. The period covered by satellite images can be too short and contain too many gaps for developing climatic studies, but the remote sensing products are valuable for meteorological applications as much as they are consistent temporally and spatially. While any meteorological data retrieved from urban sensors may bring valuable information, the data stability and homogeneity are sometimes difficult to address due to inherent spatial heterogeneity and to the intense changes of the urban morphology and land cover–land use categories.

(b) Reliability. The observations should comply with the WMO standards for the stations monitoring the regional climate or other known standards for monitoring the local climate [12,13]. Many synoptic stations worldwide are placed within the administrative limits of a city, but it is very likely that more sensors will capture more relevant information about of the multifaceted urban climate even if they are not placed in standard conditions [14–16].

(c) Metadata. Geographical coordinates, instrument specifications, information about the working procedures, spatial and temporal resolution and any changes which have eventually occurred along time must be associated to any meteorological observations and remote sensing products. Besides, information about the proximities are particularly important for sensors placed in an urban environment.

In the recent decades, urban areas have faced a rapid population increase and dynamic transformation of infrastructure and functions, generating a high demand for environmental data. The access to meteorological information has been significantly improved by higher instrumental accuracy, larger storage possibilities and faster transfer capabilities.

3.1.1. In Situ Meteorological Data

The in situ or ground-based observations represent the oldest method for monitoring the urban atmosphere. The Medici Network was the first meteorological network in the world, operated between 1654 and 1670, and included 11 stations, from which 9 were placed in European cities [17]. The longest-running meteorological records in Europe are registered in cities, such as Uppsala 1722, Padua 1725, Milan 1763, Stockholm 1754, Basel 1755, or Prague 1775 [18]. At present, the ground-based observations in urban areas are performed by (a) WMO stations, (b) Urban Meteorological Networks or, more recently, by (c) citizen observatories. While the data collected by WMO stations are available from national meteorological services, this paper focusses on data freely available, usually with a transnational coverage. The main benefits of using in situ meteorological data are the potential continuity of records, flexibility of locations and relatively good accessibility in term of cost and maintenance. The main shortcomings derive from the limited spatial coverage and relevance for urban conditions. The integrated use of in situ and remote sensing data results in more complex products for urban climate studies [19].

The **Integrated Surface Database (ISD)** consists of global hourly and synoptic observations compiled from more than 100 sources into a single common ASCII format and common data model. ISD has a global coverage and it contains a variety of hourly meteorological data from more than 20,000 stations worldwide [20], ranging from 1891 to present. Based on the ISD, the HadISD is a global sub-daily station dataset, homogenized and quality controlled, including extremes of temperature, pressure and humidity from about 7600 stations from 1931 to present [21].

The **Global Summary of the Day (GSOD**) dataset produced by the National Climatic Data Center (NCDC). These data are derived from the Integrated Surface Hourly (ISH) dataset, which includes global data obtained from the USAF Climatology Center (synoptic/hourly data). This dataset comprises daily averages computed from global hourly station data, providing access to daily weather elements including mean values of: temperature, dew point temperature, sea level pressure, station pressure, visibility, and wind speed plus maximum and minimum temperature, maximum sustained wind speed and maximum gust, precipitation amount, snow depth, and weather indicators (e.g., fog, rain, drizzle, snow, hail, thunder). GSOD data are updated on a real-time basis with a lag of 1–2 days relative to the date–time of the observations, based on Greenwich Mean Time, for about 9000 stations worldwide. Historical data are accessible from 1929 to the present, but the records since 1973 are more complete and consistent. This dataset was used to analyze the observed changes in climate extremes (temperature, precipitation and wind) in 217 urban areas and 142 paired non-urban and urban stations across the globe, over the 1972–2012 period [22].

The **European Climate Assessment and Dataset (ECA&D)** is a platform aggregating a daily series of observations provided by the climatological divisions of national meteorological and hydrological services of 63 participating European countries, as well as by station time series of the observatories and research centers throughout Europe and the Mediterranean [23]. The input data are provided by a total number of 69 participants, and they are tested for homogeneity and quality control by the ECA&D team. The platform provides access to a blended series, for which it has applied an automated updating procedure relying on the daily data extracted from SYNOP messages distributed in near real-time through the Global Telecommunication System (GTS) (including a procedure of gap filling based on a daily series of nearby observations located within a 12.5 km distance and at a height difference of less than 25 m), and a non-blended series, accessible for public use as provided by the participants. A predefined set of aggregated indices for climate extremes derived from the ECA&D is also available. Gridded daily temperature, precipitation and pressure fields constructed from the ECA&D create the E-OBS daily gridded database [24], available at 0.1° to 0.25° regular grids, covering the same geographic area from 1950 to present. E-OBS also allows grid box average comparisons with the results of Regional Climate Models for validation purposes [25–27]. These datasets were used in various urban climatology studies relying on observations addressing the challenges of climate change in European cities, e.g., assessment of the impact of climate change on thermal performance of residential buildings [28]; and change in extreme heat/cold stress [29–31].

Urban Meteorological Networks (UMNs) have been implemented in several cities around the world in order to supplement and detail the observations provided by standard WMO stations. It is extremely useful information for assessing the urban heat island (UHI), as it can capture the urban thermal behavior at better resolution than the WMO stations. [9] overview the scientific and logistical issues in a study of 24 UMNs from the USA, Europe and Asia. The urban climate of Bucharest (Romania) is currently monitored by 3 long-term WMO standard meteorological stations, and 6 sensors placed in urban conditions, fully operational since November 2014 [32]. The city of Ghent (Belgium) has implemented since July 2016 the MOCCA network (Monitoring the City's Climate and Atmosphere) to monitor the canopy layer UHI. [14] demonstrated the MOCCA network importance and its complementarity with two modelling approaches (i.e., the SURFEX land surface model and UrbClim boundary layer model). The Birmingham Urban Climate Laboratory (BUCL) is another high-density urban meteorological network (https://www.birmingham.ac.uk/schools/gees/centres/bucl/maps-data/index.aspx), comprising 25 weather stations and more than 100 air temperature low-cost wireless sensors, which provided hourly air temperature records in near real-time for the city of Birmingham (UK) between June 2012 and December 2014 [33,34]. The Berlin city (Germany) monitoring network of the Freie University, Institute for Meteorology (FUMINET) is measuring meteorological data every five minutes for microclimate and human thermal comfort investigations. Novi Sad (Serbia) has also implemented an automatic microclimatic urban monitoring network [35,36], comprising 25 urban stations and two stations located in non-urbanized environments, collecting air temperature and humidity data every 10 minute. In its turn, the climate of Szeged (Hungary) is monitored by 23 weather stations placed in urban conditions [37] and available at http://en.urban-path.hu/monitoring-system.html. UNM data can be accessed by contacting the corresponding authors/organizations.

Air temperature in the Barrow city (Alaska) and its surroundings has been monitored since 2001 through 70 temperature data loggers, for highlighting winter urban heat island [38] and urban-suburban soil temperature contrasts [39]. The winter heat urban effects were also investigated in the arctic city of Norilsk (Russia), using data provided by automatic weather stations, iButton sensors, combined with MODIS remote sensing data [40]. The lack of a dense network of air temperature measurement points across the Eurasian arctic region was the reason for the establishing in 2015 of the Urban Heat Island Arctic Research Campaigns (UHIARC) network, which provides access to accurate, spatially dense and interconnected climate information about temperature anomalies at city scale (http://urbanreanalysis.ru/uhiarc.html). This network was deployed in several mid-sized cities of the region and combines data provided by air temperature data loggers (iButton) and automatic weather stations located in each target city. Its importance and applicability were already proven in some studies focusing on the winter urban heat island in the cities of Apatity, Vorkuta, Salekhard, Nadym and NovyUrengoy of Russia [41,42]. In Asia, a Community Weather Information Network (CWIN) was established in Hong Kong in 2007 in order to improve the data coverage of the Hong Kong Observatory (HKO) by extending meteorological measurement in schools and at community levels. Using the data provided by CWIN, HKO provides improved impact-based forecasts at multi-time scales and warnings/advisories for several natural phenomena and processes (tropical cyclones, thunderstorms, heavy rains, landslides, flooding, cold/very hot weather episodes) [43].

There is still an inadequate number of networks providing data with an appropriate high spatial density for high resolution modelling of urban climate. This situation is mostly determined by security, associated high costs, and difficulty in finding appropriate measurements sites [9]. However, under the future changing climate projections with expected increases of weather extremes by the end of the 21st century in most regions of the globe [44], the need for denser measurement networks and high resolution meteorological data is likely to increase, especially in densely populated areas.

The potential of **crowdsourcing** to provide useful data for urban climatology has been carefully considered in the recent years, once the number of sensors held by citizen extensively increased [44–47]. Data collected either by volunteers running personal weather stations, such as Weather Underground or Netatmo networks [48], or by smartphones [49,50] are now publicly accessible and allow individuals to share real-time weather information. Such data are collected in non-standard conditions and quality control is mandatory, but they can be retained as a valuable data resource, with a continuous expansion, which could provide real-time and high temporal and spatial resolution meteorological information over areas with heterogeneous environments lacking in dense traditional meteorological networks such as cities.

Ref [47] provided a systematic review of crowdsourcing for climate and atmospheric research, identifying initiatives, projects and programs based on citizen science and amateur weather stations (e.g., UK Met Office Weather Observation Website in the UK; Meteoclimatic in the Iberian Peninsula; CoCoRaHS in the US; Birmingham snow depth; Air Quality Egg), mobile app (e.g., WeatherSignal; iCelsius), moving platforms (e.g., OpenSense), which have been implemented in many areas of regions around the world. The applicability of these data resources was demonstrated in several studies (e.g., [51–54]). A further example of applicability is offered by [55], who integrated air temperature measurements from the Weather Underground network of Atlanta and Chicago in the analysis of the performance of the National Weather Service Heat Warning System against ground observations and satellite imagery, by assigning them to the pixels of LST Aqua and Terra MODIS satellite retrievals. In this study, the crowdsource climate information was found to be reliable in the description of the general patterns described by the National Weather Service and weather station measurements. [56]

provide evidence of crowdsource meteorological data from citizen weather stations to improve weather forecasting with the Weather Research and Forecasting (WRF) model for two cities in Russia (Saint Petersburg and Moscow).

3.1.2. Gridded Datasets

Gridded climate datasets represent an alternative to instrumental measurements, especially for areas with spatially scarce distribution of WMO stations or poor quality measurements. While better spatial coverage provided at low cost is an important advantage, the gridded meteorological data are associated with a lower accuracy than the measurements, depending on the quality and density of input data.

The **E-OBS** dataset of the ECA&D provides free access to a long time gridded series of daily climate data for Europe, available at 0.1° spatial resolution, covering the period from 1950 to present [24]. E-OBS was also designed to allow grid box average comparisons with the results of Regional Climate Models for validation purposes [25–27]. Both ECA&D and E-OBS datasets were used in various urban climatology studies relying on observations addressing the challenges of climate change in the European urban areas, e.g., assessment of the impact of climate change on the thermal performance of residential buildings [29]; change in extreme heat/cold and heat/cold stress [29,30].

The **Climatologies at High Resolution for the Earth's Land Surface Areas (CHELSA)** dataset is hosted by the Swiss Federal Institute for Forest, Snow and Landscape Research WSL and is based on a statistical downscaling of the ERA interim global circulation model [57]. CHELSA has a global coverage, and it contains monthly mean temperature and precipitation for the time period 1979–2013 at a 30-arc sec–spatial resolution. Recently, [58] employed the CHELSA dataset, validated with independent station data provided by the Global Historical Climatology Network (https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/ global-historical-climatology-network-ghcn), to analyze the trend in urban heat island intensity from 1992 to 2012 for eight megacities in Asia. The study revealed the ability of the dataset to capture the characteristics of the urban heat island and a good match between the increase in air temperature and urban sprawl.

Berkeley Earth provides open access to historical temperature data products that allow statistical diagnostics of local urban climatologies and trend magnitudes based on the estimates of the monthly means of average, maximum and minimum surface air temperature anomaly over land areas [59]. The land temperature dataset has an extensive time coverage from 1753 (or 1833 for minimum and maximum temperatures) until present, relying on a large inventory of weather station observations (from over 30,000 weather stations). The dataset provides access to gridded temperatures, regional averages (available for the northern and southern hemisphere, country, state, city and individual station scale) and bias-corrected station data based on 'breakpoint' detection (using a similar method used in the Global Historical Climatology Network dataset—[60]) in station records, which resulted from changes in station location or measurement equipment. With regards to the water impact in metropolitan areas, the Service for Water Indicators in Climate Change Adaptation (SWICCA) offers open source climate impact information necessary for the sustainable management of watersheds, including urban areas, across Europe. The time-series of the future river flow and water-related indicators, bias-corrected data associated with three climate change projections (RCP 2.6; 4.5 and 8.5), socio-economic scenarios (0.1 deg. grid) and land use projections (10 km grid) are available through SWICCA, a service run by the Swedish Meteorological and Hydrological Institute (SMHI).

Other observational platforms may supplement the ground sensors with very useful information for urban climate research (i.e., airborne sensors or different vehicles). Here, we refer only to airborne sensors, which can be used for temperature profiling over the city and rural areas, infra-red imaging or the development of digital surface and elevation models. More than five decades ago, sensors placed in a helicopter were used to retrieve temperature and pressure information for studying the urban heat island effect in New York City [61]. Unmanned Aerial Vehicles (UAVs) or drones are conveying unprecedented advantages for urban climate monitoring, as they can retrieve the variability of temperatures across urban land surfaces, at high resolution and low cost [62,63]. The Natural Environment Research Council's Data Repository for Atmospheric Science and Earth Observation (**CEDA**) **data collection archive** provides access to several datasets of airborne observations by aircraft available from ongoing or ended collaborative projects, for assessing atmospheric composition and air quality in urban areas e.g., urban emissions (QUEFA), urban visibility (VISURB), biomonitoring of urban habitat (BIOHYPE), analysis of atmospheric chemical species and meteorological parameters (GASPOL) and airborne PM10 pollutants (PHYTOX), street-level air circulation and pollutants mix within the urban canopy (URBMET).

3.1.3. Remote Sensing Data

The need for reliable information with good spatial coverage in urban areas is also addressed by **remote sensing applications** aiming to retrieve data relevant for climate studies. Products delivered by satellite (Table 1), radar and airborne sensors represent a powerful tool set for urban climate studies, since the cost at user's desk and technical developments enhanced their availability for scientific research in the last two decades. [64] and [65] document the remote sensing of urban climates and differentiate the UHI, which refers to UHI effects in the canopy or boundary layer, by the surface urban heat island (SUHI), representing the radiative temperature difference between urban and non-urban areas at the level of the subjacent surface. The use of satellite imagery in urban climate studies may be impended by factors like cloudiness, technical limitation and various time constraints (i.e., short range or temporal discontinuities).

Table 1. Characteristics of satellite remote sensing products delivering Land Surface Temperature data.

Sensor	*Satellite*	*Spatial Resolution*	*Temporal Resolution*	*Time Span*
SEVIRI	MSG	3 to 5 km	15 min	2004 to date
AVHRR	NOAA	1.1 km	2 images/24 h	1981 to date
MODIS	Terra/Aqua	1 km	4 images/24 h	2000/2002 to date
SLSTR	Copernicus Sentinel-3	1 km	1 image/24 h	2017 to date
TM, ETM+, OLI, TIRS	Landsat 4, 5, 7, 8	60–120 m (30 m resampled)	1 image/8 or16 days	1982 to date

The World Meteorological Organization acknowledges 105 satellite instruments which have provided LST over time, categorized from primary to marginal relevance [66]. The first LST products were available at fair quality in the 1960s, but the first high-relevance products were delivered by the NASA satellite Nimbus-5 in 1973. However, the operation for urban climate research was prohibited by the 30 to 32 km spatial resolution.

The **Moderate-Resolution Imaging Spectro-Radiometer (MODIS)** instruments aboard NASA Terra/Aqua satellites have become a popular tool for urban climate studies due to a few major advantages: (1) spatial and temporal resolutions (1-km and 4 images daily) appropriate for urban climate applications; (2) significant time span, suitable for climatology, as the monitoring has been regularly performed since 2000 (Terra) and 2002 (Aqua). LST is a key parameter in the estimation of urban heat fluxes and highlighting the presence and magnitude of UHI (Figure 1) and heat health risk [67,68] and has been widely used in climatological studies at urban scale (e.g., [69–75]).

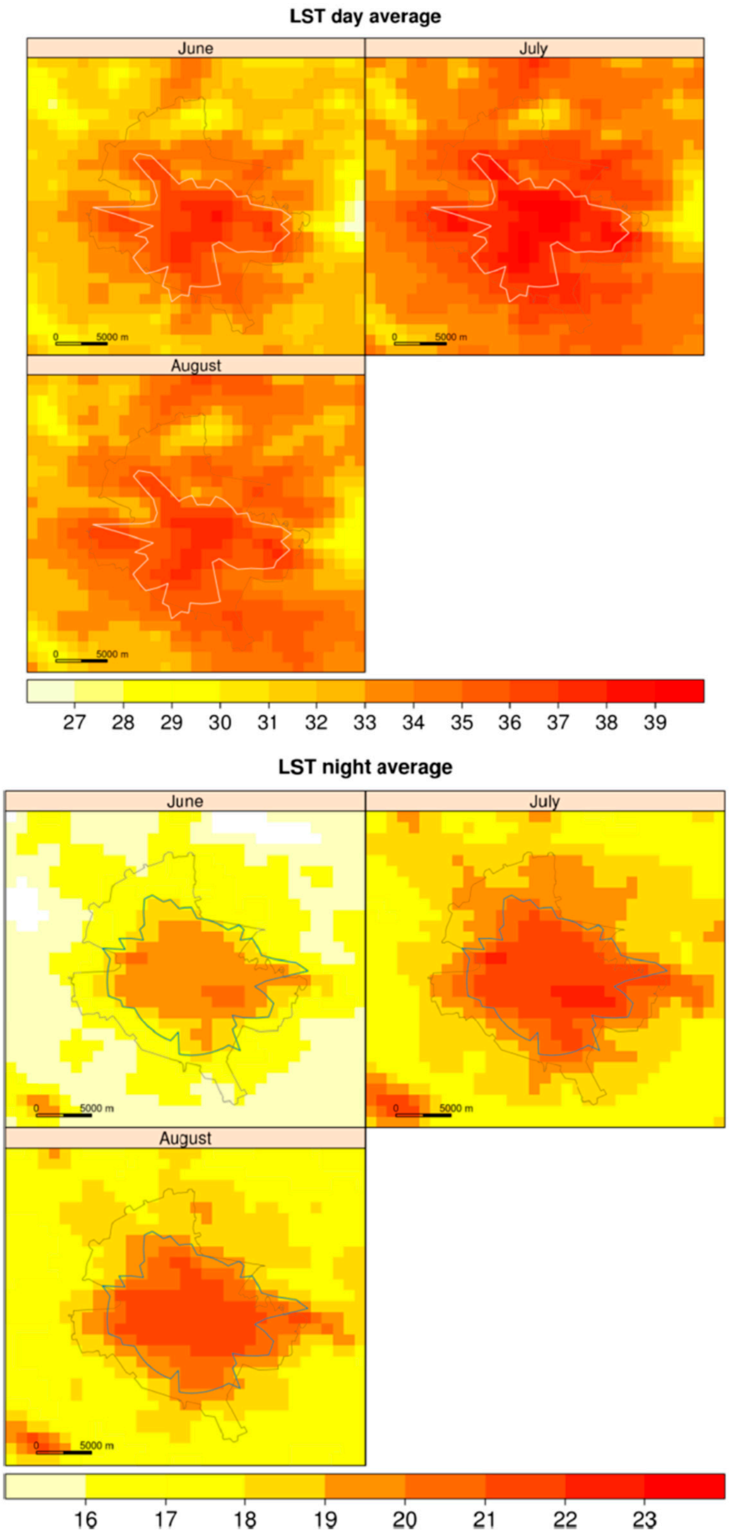

Figure 1. Average LST values and Bucharest's UHI limit (white contour line for daytime and blue contour line for nighttime), as retrieved from MODIS images (2000–2012). The administrative limit is marked with a light grey line [71] (Material from: 'Cheval, S.; Dumitrescu, A. The summer surface urban heat island of Bucharest (Romania) retrieved from MODIS images, Theor. Appl. Climatol., published [2015], [Springer]'.)

The **Spinning Enhanced Visible Infra-Red Imager (SEVIRI)** sensors placed on the Meteosat Second Generation (MSG) satellites operated by EUMETSAT provide LST information since 2004. The spatial resolution (3 to 5 km) is reasonable for investigating the urban environment, especially in cities with large extent covering dozen of kilometres, while the 15-min full disk coverage make SEVIRI a very robust tool for operational purposes, such as forecast and near-real-time meteorological evaluation.

NOAA's Advanced Very High-Resolution Radiometer (AVHRR) two and three instruments have retrieved LST at 1.1 km resolution since 1981. Early studies of the SUHI were based on AVHRR data [76–78], and the datasets are still used [79].

The Landsat missions jointly operated by NASA and the U.S. Geological Survey have provided a series of Earth Observation satellites since 1972. The spatial resolution of the **Landsat's Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS)** reached 30 m and contributed significantly to implementation of urban climate research [80–82]. Landsat is among the most widely used satellite resources in the detection and characterization of SUHI [83], due to its main advantages residing from the free availability (since 2008), long time series (more than 30 years), high spatial resolution (30 to 120 m) and the swath coverage of 185x185 km (Landsat 5, 7 and 8). However, the long revisiting cycle of 16 days, only daytime data availability, the strong dependence of weather conditions (e.g., cloud cover or cloud proximity which could result in missing data) and the lack of an operational Landsat LST product combining data from the Landsat sensors have to be noted as the main drawbacks impeding the detection and monitoring of inter-annual variability of SUHI [84,85]. In response to the need of an operational land surface temperature product for Landsat thermal data, [86] developed an operational algorithm for (emissivity correction and retrieval methodology) Landsat LST for all sensors, which have been successfully validated with in situ observations from four surface radiation budget network sites and two inland water bodies (Salton Sea and Lake Tahoe) in the US. The proposed algorithm will be implemented by the United States Geological Survey/The National Aeronautics and Space Administration and made available through the Land Processes Distributed Active Archive Center portal, which will provide access, for the first time, to consistent LST records dating back to Landsat 4 (1982 to present).

The **Sea and Land Surface Temperature Radiometer (SLSTR)** sensor, on-board on Sentinel-3 satellite, have retrieved LST at 1 km spatial resolution and daily temporal resolution since 2016. UHI research is based on LST retrieved by SLSTR sensors [87].

The **Copernicus Atmosphere Monitoring Service (CAMS)** has been implemented by the European Centre for Medium-Range Weather Forecasts (ECMWF), and it offers reliable information for improving life quality and urban planning. CAMS combines satellite and non-satellite observations with computer-based forecast models to provide near-real-time analysis and forecast of air quality and atmospheric composition related to pollutants and greenhouse gases (e.g., particulate matter, pollen, nitrogen dioxide and sulphur dioxide). The CAMS service data portfolio comprises a broad range of CAMS products available for urban agglomerations, such as (1) solar radiation and UV, (2) air quality and atmospheric composition, (3) emissions and surface fluxes of pollutants and (4) greenhouse gases and radiative climate forcing.

The urban heat island (UHI) is a key challenge for climate change adaptation in urban environments worldwide. Exploiting the benefits of remote sensing resources, the Center for International Earth Science Information Network (CIESIN), University of Columbia released in 2013 the first version of the **Global Urban Heat Island Dataset**, providing access to global data of average summer daytime maximum (1:30 p.m. overpass) and nighttime minimum (1:30 a.m. overpass) land surface temperature (LST) for urban areas, as well as to data referring to LST difference between the urban extents and their rural surroundings within a 10 km buffer. This dataset relies on the urban extents resulting from the SEDAC's Global Rural-Urban Mapping Project, Version 1 (GRUMPv1) and land surface temperatures are from SEDAC's Global Summer Land Surface Temperature (LST) Grids (2013), which are derived from the Aqua Level-3 Moderate Resolution Imaging Spectroradiometer (MODIS) Version 5 global daytime and nighttime LST 8-day composite data (MYD11A2). LST grid data are available for a 40-day window from July to August (Julian dates 185 to 224) for the urban areas located in the northern hemisphere, and from January to February (Julian dates 001 to 040) for those in the southern hemisphere. This dataset allowed the analysis of surface temperature anomalies in more than 30,000 cities, which have been further used to model the links between population, background climate and UHI intensity [88].

Light detecting and ranging (LIDAR) is an active type of remote sensing technology that ensures collection of accurate elevation-based information about anthropogenic features of urban environments and land cover, with a great potential to assist smart cities and support climate change resilience at city scale [89]. This technology proved a good applicability in urban flood modelling related to storm water flow and accumulation [89,90], solar potential at building roof level and city parcels for identifying optimal solar panel parameters [89,91]; Figure 2 and emergency response planning using building footprints, building heights, travel and congestion times [89]. [92] reviewed the results of climatic and vegetation surveys in urban environments relying on static, mobile or aerial laser scanning. We identified few examples of microclimate urban studies employing the LIDAR technique for showing the vegetation effects on urban climate [93,94]. Such results highlighted the relevance of LIDAR acquired data in urban green space planning under an increasing need for urban climate change adaptation.

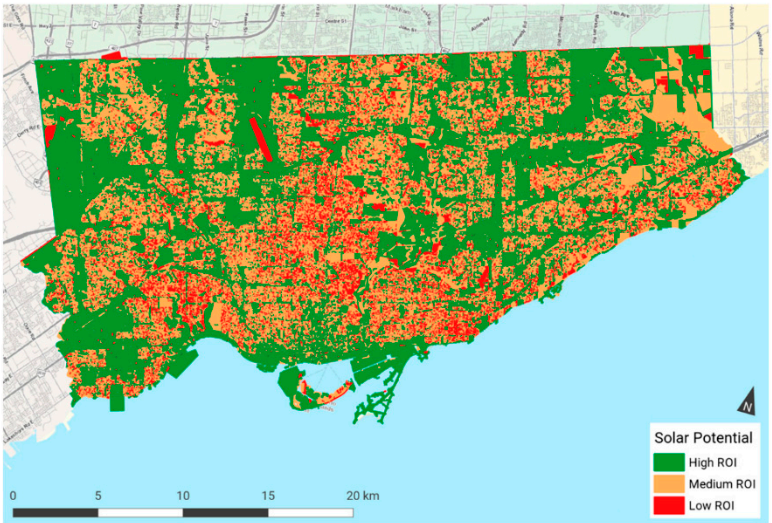

Figure 2. Estimation of solar potential in Toronto City using Lidar-derived DTM [89]

Table 2 summarizes the categories of meteorological data for urban climate studies and applications included in this review.

3.2. *Ancillary Data Resources*

Climate research always needs to be sustained by non-meteorological information, such as topography, roughness or anthropogenic influence, which can explain the formation and dynamics of certain atmospheric phenomena. Ancillary data are contextual information incorporated in urban climate studies together with meteorological input. [95] classify the input data for both mesoscale and microscale urban modelling in five categories, as follows: (1) land cover, (2) building morphology, (3) building design and architecture, (4) building use, anthropogenic heat and socio-economic data, and (5) urban vegetation data. This paper describes several data sources referring to air quality, land cover / land use, and urban morphology.

Table 2. Meteorological data sources for urban climate studies and applications.

Category	Dataset	Data Format	Spatial Resolution	Temporal Resolution	Temporal Coverage	Source
In situ	Integrated Surface Database (ISD)	ASCII	Data from 35,000 weather stations worldwide	Hourly, daily	1901 to present	https://www.ncdc.noaa.gov/isd
	Global Summary of the Day (GSOD)	ASCII	Data from over 9000 weather stations		1929 to present (since 1973 data are the most complete)	http://www.climate.gov/global-summary-day-gsod
	European Climate Assessment and Dataset (ECA&D)	ASCII	Data from 18,909 weather stations across Europe and the Mediterranean	Daily	1900 to present (blended series) and 1900 to a certain year (depending on the ECA&D participant)	https://www.ecad.eu/
	Urban Meteorological Networks (UMNs)	ASCII	Various	Hourly or sub-hourly	Various	http://en.urban-path.hu/monitoring-system.html https://www.birmingham.ac.uk/schools/gees/centres/bucl/maps-data/index.aspx Data could be accessed by contacting the owners
	Crowdsourcing	ASCII	Various	Sub-hourly	Various	https://dev.netatmo.com/ https://www.wunderground.com/pws/overview
Gridded Datasets	E-OBS	Grid (NetCDF- 4)	0.1 to 0.25° regular grids	Daily	1950-01-01 to 2019-07-31 (v20.0e the latest version —released on October 2019)	https://www.ecad.eu/download/ensembles/download.php
	Climatologies at High Resolution for the Earth's Land Surface Areas (CHELSA)	Grid (tif)	30 arcsec, ~1 km	Monthly	1979–2013	http://chelsa-climate.org/
	Berkeley Earth	ASCII, graphs	-	Monthly and annual summaries	1750-present (land only) 1850-present (land and ocean)	http://berkeleyearth.org/
	Service for Water Indicators in Climate Change Adaptation (SWICCA)					http://swicca.eu/
Remote Sensing Data	Moderate-resolution Imaging Spectro-radiometer (MODIS)	HDF4	1 km	Daily eight-day mean	2000-present	https://lpdaac.usgs.gov/tools/data-pool/ https://lpdaac.usgs.gov/tools/earthdata-search/
	Spinning Enhanced Visible Infra-Red Imager (SEVIRI)	HDF5	3 km	15 min Hourly Daily Weekly Monthly Seasonal Yearly	1991-present	https://landsaf.ipma.pt/ChangeSystemProdLong.do?system=LandSAF+MSG&algo=LST https://wui.cmsaf.eu/safira/action/viewProduktSearch?menuName=PRODUKT_SUCHE, https://land.copernicus.eu/global/products/lst
	NOAA's Advanced Very High Resolution Radiometer (AVHRR)	NetCDF	4 km	Daily	1978-present	https://www.bou.class.noaa.gov/saa/products/search?sub_id=0&datatype_family=AVHRR&submit.x=15&submit.y=6
	the Landsat's Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS)		30 m		1982-present	http://rslab.gr/downloads_LandsatLST.html
	Sea and Land Surface Temperature Radiometer (SLSTR)	NC	1 km	Daily	2016-present	https://scihub.copernicus.eu/dhus/#/home https://search.earthdata.nasa.gov/
	Copernicus Atmosphere Monitoring Service (CAMS)	Grid (NetCDF, Grib Edition2)	-	Daily and hourly	Near real-time data and hourly forecast	http://copernicus-atmosphere.eu

3.2.1. Societal Information

Urban Audit Data Collection of EUROSTAT is a valuable resource of indicators providing relevant information about the quality of life in individual European cities and their commuting zones (Functional Urban Areas). The key topics covered within the database include demography, housing, health, labor market, education, environment, transport and tourism. Data are collected by the National Statistical Institutes, the Directorate-General for Regional and Urban Policy and Eurostat. The statistics have been used in several climate change vulnerability assessments in European urban areas (e.g., [96–98]).

LandScan High Resolution global Population Dataset, created by the Oak Ridge National Laboratory, is a high-resolution population distribution dataset (30 arc seconds or 1km at Equator) available in a GIS raster (ESRI Grid) format. The dataset has a global coverage and comprises sub-national census records provided by the International Program Center Bureau of Census and is a valuable resource allowing assessments, estimations and visualizations of population at risk. This dataset was employed to identify major cities across the globe (administrative capitals or cities that account more than 1,000,000 inhabitants) to investigate the extent to which 520 iconic cities are likely to experience a shift in response to climate change by 2050 (future cities) relative to their current climate conditions (current cities), in relation to the changes in climate variability and seasonality [99].

3.2.2. Land Cover

Ref [100] published a comprehensive inventory of land cover (LC) products available at global and regional level, including high spatial resolution products useful for urban climate applications, used as a basis for this review.

The **Global Land Survey (GLS)** is a 30 m global land cover dataset, based on Landsat images. The U.S. Geological Survey (USGS) and the National Aeronautics and Space Administration (NASA) have collaborated to develop the Global Land Surveys (GLS) datasets. This collection contains images acquired from 1972 to 2012, centered on 1975 (based on images acquired from 1972 to 1983 and from 1982 to 1987), 1990 (based on images acquired from 1987 to 1997), 2000 (based on images acquired from 1999 to 2003), 2005 (based on images acquired from 2003 to 2008) and 2010 (based on images acquired from 2008 to 2012). The GLS datasets were used to estimate the intensity of urbanization [101].

The **Global High-Resolution Urban Data from Landsat** are produced by NASA Goddard Space Flight Center and the Department of Geographical Sciences at the University of Maryland from Landsat data and include:

(a) The **Global Man-Made Impervious Surface (GMIS)** is one of the first 30m global dataset estimates of fractional impervious cover derived from the Global Land Survey (GLS) for 2010. The GMIS dataset includes: the global percent of impervious cover and the uncertainty for the global impervious cover. The urban studies are related to urban extend [102];
(b) The **Global Human Built-Up and Settlement Extent (HBASE)** is one of the first 30 m global datasets and estimates the urban extend cover derived from the Global Land Survey (GLS) for 2010. The urban studies are related to urban extend [102].
(c) The **Urban Landsat: Cities from Space** (1999–2003) is one of the first 30m global datasets providing composite Landsat images and raw data for urban areas that can be used in interdisciplinary studies of remote sensing and the environment.

The GMIS and HBASE datasets are complementary. The built-up and settlement extend mask (in HBASE dataset) was created for the post-processing of the GMIS dataset.

All the datasets can be used for local modelling in order to study the urban impacts on the energy, water, and carbon cycles or to analyse at country level.

The **GlobeLand30 (GLOB)** is a high-resolution dataset (30 m) of global land use/cover, based on TM5 and ETM + of America Land Resources Satellite (Landsat) and the multispectral images of China Environmental Disaster Alleviation Satellite (HJ-1) from 2010) [103]. The LC product includes information on land cover data, and other information highly relevant for urban climate analysis, such as artificial surfaces (habitation, industrial and mining area, transportation facilities, and interior urban green zones and water bodies, etc.). GlobeLand30 was exploited by [104] for investigating the urban expansion impact on a global scale.

At European level most of the LC products at local level are produced under **ESA CCI LC** and **Copernicus Land Monitoring Service (CLMS)** initiatives. The **ESA CCI LC** products have global coverage at 300 m spatial resolution. The datasets were derived based on a multi-year and multi-sensor strategy of MERIS and SPOT-Vegetation time series, continued under the Copernicus Climate Change Service (C3S), implemented by the European Centre for Medium-Range Weather Forecasts (ECMWF) on behalf of the European Commission, in order to assure continuity. At C3S Climate Data Store (CDS), 27 land cover datasets (from 1992 to 2018) are available for download, used for climate modelling, urban expansion [105,106] or UHI [73]. Figure 3 illustrates the relationship between LST and land cover based on the CCI-LC dataset.

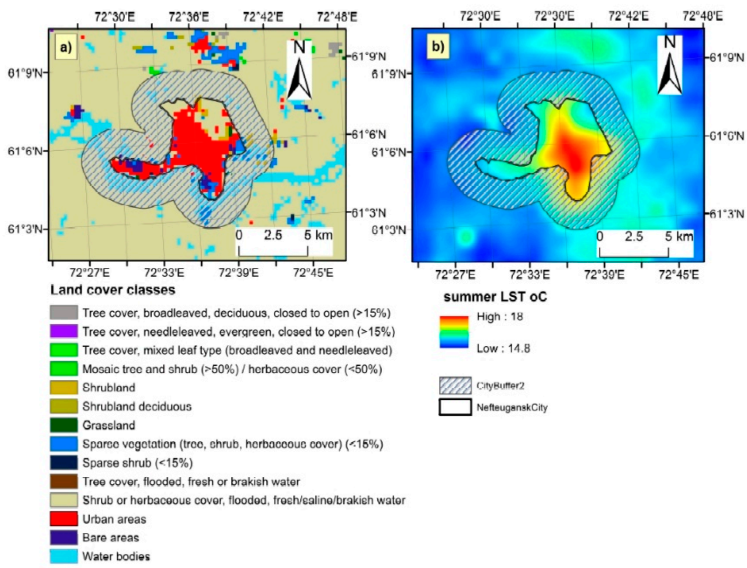

Figure 3. Example of CCI-LC and LST use in the urban study by [73].

The CLMS offers LC products at global, regional (Pan-European) and local level, as follows:

(a) The **global LC product** is available only for 2015 based on Proba-V at 100 m spatial resolution. It uses the FAO Land Cover Classification System (LCCS), totaling 23 classes [107].

(b) The Pan-European LC products include:

i. **Corine Land Cover (CLC)** is a land cover inventory (in 44 classes) project initiated in 1980s and updated in 1990, 2000, 2006, 2012 and 2018 with 100 m spatial resolution.;

ii. **Pan-European High-Resolution Layers (HRL)** provide information on specific land cover characteristics (imperviousness density, forest, grassland, wetland and water bodies and the new small woody features [108], and are complementary to the CLC dataset. The imperviousness data have a spatial resolution of 20 m and 100 m for 2006, 2009, 2012 and 2015.

iii. The **European Settlement Map (EMS)** is a very high-resolution dataset with spatial resolutions of 2.5 m, 10 m and 100 m. The first dataset, released in 2014, mapped the settlements in Europe based on 2010–2013 images. During the last year, different improvements have been developed: benchmarking process with population data; increases the number of classes to 13 (buildings, green, streets, water, railways, airports, open space inside the built-up area and same categories outside the built-up area) [109].

(c) The **Local LC Products** include the **Urban Atlas (UA)** which provide reliable, inter-comparable, high-resolution land use maps with 17 classes for large urban zones and their surroundings (more than 100,000 inhabitants), at 10 m spatial resolution for 2006 and 2012. The UA is also including the Building Height at 10 m spatial resolution for 2012.

The **MODIS Land Cover product** is a 500 m global land cover dataset based on MODIS Terra and Aqua data from 2001 to 2018, extensively used in urban climate research [110].

The **GlobCover Portal** provides access to the results of the GlobCover project, an ESA initiative started in 2005 in partnership with JRC, EEA, FAO, UNEP, GOFC-GOLD and IGBP. The aim of the project was to develop a service capable of delivering global composites and land cover maps (with 22 land cover classes) using as input observations from the 300m MERIS sensor on board the ENVISAT satellite mission. ESA makes the land cover maps available, which cover two periods: December 2004–June 2006 and January–December 2009.

The **Open-ECOCLIMAP** dataset has been available since 30 June 2014 at The ECOCLIMAP program, and is a dual database at 1 km resolution, that includes an ecosystem classification and a coherent set of land surface parameters, that are primarily mandatory in meteorological modelling (notably leaf area index and albedo). Hence, the aim of this innovative physiography is to enhance the quality of initialization and impose some surface attributes within the scope of weather forecasting and climate related studies.

3.2.3. Urban Morphology

The World Urban Database and Access Portal Tool (WUDAPT) project is a community-based initiative of the International Association of Urban Climate (IAUC) which supports urban climate research and various forecasting applications on surface energy budget, meso- to urban-scale weather and atmospheric chemical composition and air quality. The tool adopted a common framework for acquisition, storage and dissemination of relevant data about urban form (e.g., surface cover, properties of construction materials, surface geometry) and function (e.g., transportation, energy use), which are relevant for a coherent description of heterogeneous urban landscapes, as a prerequisite for understanding the urban climate characteristics.

WUDAPT rely on the local climate zone (LCZ) typology scheme proposed by [111], which categorizes 17 distinct landscapes (out of which 10 are urban), in relation to a number of surface parameters related to the main built and land cover types. The procedure employs geospatial data (multi-year series of multispectral and SAR satellite observations) as input in the random forest classifier to detect specific features for both urban and natural LCZ types [112].

The WUDAPT portal provides free access to maps (in GeoTIFF and KML format) and metadata of classified local climate zones for more than 150 cities worldwide. Data are structured in a hierarchical format, with increasing details from level zero (local climate zones along with parameter ranges) to level one (more precise parameter values for each LCZs) and level two (detailed description of urban landscape parameters at refined scales suited for boundary-layer modelling).

Alternatively, urban morphology can be obtained from OpenStreetMap [113] or from the building-resolving data provided by the local authorities.

3.2.4. Climate Change, Adaptation and Urban Resilience

Urban Audit dataset through the Geographic Information System of the Commission (GISCO) supplies the users with geographical information concerning the boundaries of cities and the functional urban areas, defined according to the EC-OECD city internationally harmonized definition [114]. The coverage is the EU-28 plus Iceland, Norway and Switzerland, and the dataset is available in ESRI format (shapefile and geostatistical database) at scales ranging from 1:100,000 (2011-2014, 2018) to 1:3,000,000 (2001, 2004). [29] employed the Urban Audit GISCO dataset and the urban morphological zones from the European Environment Agency to analyze future change in heatwaves, droughts and floods in all 571 European cities targeted by Urban Audit, and to elaborate low, medium and high hazard impact scenarios in relation to climate projections of all ensemble members of CMIP5 for the RCP8.5 emission scenario. The study provides evidence of an increasing exposure to heatwave days in all cities, an intensification of drought in the southern European cities and increasing frequency of river floods in the northern European cities.

Urban Adaptation Map Viewer (UAMV) is a web platform available at <https://climate-adapt.eea.europa.eu/knowledge/tools/urban-adaptation/Urban-Adaptation-datasets>, aggregating information from various sources (e.g., Met Office, EURO-CORDEX, E-OBS dataset, C3S, JRC, Urban Audit) and providing free access to five types of datasets and metadata from European cities, as follows: (1) climate and climate related hazards (e.g., hot summer days, cooling degree days, extreme heat waves, winter heavy precipitation, meteorological drought, forest fire danger, sea level rise); (2) exposure of cities to climate-related hazards (e.g., areas and population affected by wildfires, river flooding, coastal flooding); (3) physical characteristics of urban areas (urban morphological zone—UMZ, share of green and impervious areas in city core and UMZs); (4) socio-economic characteristics of cities (e.g., population, share of elderly and children, share of lone-pensioner households, unemployed people); and (5) adaptation activities.

Lobellia Earth is a newly resealed (2018) web platform for visualizing and exploring the annual and monthly climatologies in user specific locations for the period 1981–2010. The visualization tool (as maps and graphs) of the past climate uses ERA5 data from ECMWF that allow the analysis of spatial distribution of air temperature (average, maximum and minimum air temperature), precipitation, average wind speed, wind gust and cloud cover and several climate extreme indices (e.g., frost days, warm nights, heavy and very heavy precipitation days). In this platform, the user could only visualize the climatological information (maps and graphs) about different target urban areas. The platform supports the UN Habitat's City Resilience Profiling Programme (CRPT) using downscaling and bias correction techniques for providing high-resolution climate projection data of EUROCORDEX project and tailored climate information about future climate change threats and vulnerabilities for five pilots of cities sensitive to climate change (i.e., Asuncion, Yakutsk, Maputo, Dakar and Port Vila). Climate projection data for the target urban areas are available only by request from the Lobelia Earth developers. Exploring the benefits of Earth observation, Lobelia Earth, with the contribution of Royal Netherlands Meteorological Institute, supplies air quality information for three European pilot cities (i.e., NO_2 and PM10 concentrations in Barcelona, Madrid and Amsterdam). Table 3 summarizes the categories of ancillary data for urban climate studies and applications described in this review.

Table 3. Ancillary data sources for urban climate studies and applications.

	Dataset	Details (e.g., Data Format, Resolution, Year of Compliance)	Source
Societal information	Urban Audit data collection of EUROSTAT	Data format: ASCII Temporal coverage: 2010–2019 (depending on the indicator)	https://ec.europa.eu/eurostat/web/cities/data/database
	LandScan High Resolution global Population Dataset	Data format: ESRI Grid Spatial resolution: 30 arc seconds or ~1km at equator	https://www.eastview.com/resources/e-collections/landscan/
	Global Land Survey (GLS)	Data format: GeoTIFF Spatial resolution: 30 m Temporal coverage: 2010	http://earthexplorer.usgs.gov/
	The Global Man-made Impervious Surface (GMIS)		https://sedac.ciesin.columbia.edu/data/set/ulandsat-gmis-v1/data-download
	Global Human Built-up And Settlement Extent (HBASE)		https://sedac.ciesin.columbia.edu/data/set/ulandsat-hbase-v1/data-download
	Urban Landsat: Cities from Space		https://sedac.ciesin.columbia.edu/data/set/ulandsat-cities-from-space/data-download
Land cover	GlobeLand30 (GLOB)	Data format: GeoTIFF Spatial resolution: 30 m Temporal coverage: 2010 (2009–2011)	http://www.globallandcover.com/GLC30Download/index.aspx
	Copernicus Land Monitoring Service (CLMS)	Data format: GeoTIFF Spatial resolution: 100 m Temporal coverage: 2015	https://lcviewer.vito.be/download
	Corine Land Cover (CLC)	Data format: GeoTIFF, ESRI Geodatabase, SQLite Database Spatial resolution: 100 m Temporal coverage: 1990 (1986–1998), 2000 (+/- 1 year), 2006 (+/- 1 year), 2012 (2011–2012), 2018 (2017–2018)	https://land.copernicus.eu/pan-european/corine-land-cover/clc2018?tab=download
	Pan-European High-Resolution Layers (HRL)	Data format: GeoTIFF Spatial resolution: 20 m and 100 m Temporal coverage: 2006 (2005–2007), 2009 (2008–2010), 2012 (2011–2013), 2015 (2014–2016)	https://land.copernicus.eu/pan-european/high-resolution-layers/imperviousness/status-maps/2015?tab=download
	European Settlement Map (EMS)	Data format: GeoTIFF Spatial resolution: 2.5 m, 10 m and 100 m Temporal coverage: 2012 (2010–2013) Release: 2014, 2016, 2017	https://land.copernicus.eu/pan-european/GHSL/european-settlement-map/esm-2012-release-2017-urban-green?tab=download
	Urban Atlas (UA)	Data format: vector file ESRI format Spatial resolution: 10 m Temporal coverage: 2006 (2005–2007), 2012 (2011–2013)	https://land.copernicus.eu/local/urban-atlas/urban-atlas-2012?tab=download
	Building Height	Data format: GeoTIFF Spatial resolution: 10 m Temporal coverage: 2012 (2011–2014)	https://land.copernicus.eu/local/urban-atlas/building-height-2012?tab=download
	MODIS Land Cover	Data format: HDF4 Spatial resolution: 500 m Temporal coverage: 2001-2018	https://lpdaac.usgs.gov/tools/earthdata-search/, https://lpdaac.usgs.gov/tools/usgs-earthexplorer/, https://lpdaac.usgs.gov/tools/data-pool/
	GlobCover Portal	Data format: GeoTIFF Spatial resolution: 300 m Temporal coverage: 2005, 2009	http://due.esrin.esa.int/page_globcover.php
	Open-ECOCLIMAP	Data format: ASCII Spatial resolution: 1 km Temporal coverage: 2005, 2009	https://opensource.umr-cnrm.fr/projects/ecoclimap/files

Table 3. *Cont.*

	Dataset	Details (e.g., Data Format, Resolution, Year of Compliance)	Source
Urban morphology	World Urban Database and Access Portal Tool (WUDAPT)		http://www.wudapt.org/
Climate change, adaptation and urban resilience	Urban Audit dataset	Data format: ESRI shapefile and geodatabase Scale 1:100000 (UA2018, 2011–2014), scale 1:3 Million (UA2004, 2001) Temporal availability: 2015–2018 (UA2018), 2011–2014 (UA2011–2014), 2004 (UA2004), 2001 (UA2001)	https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/administrative-units-statistical-units/urban-audit
	Urban Adaptation Map Viewer (UAMV)	Available only for visualization (e.g., in ArcGIS JavaScript, ArcGIS Online Map Viewer, ArcGis Earth) Dataset comprises 15 indicators of climate and climate-related hazards (e.g., heat waves, heavy precipitation, meteorological drought, fire danger); 7 exposure indicators of cities to climate-related hazards (e.g., wildfires, river flooding, sea level rise); 4 indicators of physical characteristics of urban areas (e.g., urban morphological zone; percentage of impervious area in core city); 10 socio-economic indicators for cities (e.g., population, total use of water); adaptation activities of cities.	https://climate-adapt.eea.europa.eu/knowledge/tools/urban-adaptation/Urban-Adaptation-datasets
	LOBELIA EARTH	Available only for visualization as distribution maps and graphs using Climate Explorer (past climate)	https://www.lobelia.earth/

4. Conclusions

The rapid development of urban areas has derived complex challenges for environmental sciences, demanding better data, in terms of accuracy, resolution and easy accessibility. At present, there are several data sources providing valuable meteorological and ancillary information for urban climate research, and this paper presents an outline based on criteria like data availability, geographical coverage and, above all, the demonstrated utility for urban climate. We are confident that, far from being comprehensive, such an outline is a starting point and a useful tool for urban climate researchers and practitioners.

Five categories of meteorological data are identified and presented in this review paper, i.e., ground-based data and remote sensing, while the ancillary data can be classified in air quality, land cover/land use, and urban topography. One can remark the following conclusions: 1) the information sources providing meteorological and ancillary data for urban climate research are numerous; 2) spatial and temporal resolutions support a variety of applications, from weather forecast to climate modelling. It has to be mentioned that the combined use of data from various sources have a significant potential to support the improvement of data and products, as the shortcomings may be addressed with keeping the advantages associated to each dataset.

Author Contributions: Conceptualization, S.C., D.M., A.D., A.I.; methodology, S.C., D.M., A.D., A.I.; software, S.C., D.M., A.I.; validation, M.F., C.I., N.C.T., Ș.D. and B.A.; formal analysis, S.C., D.M., A.I. All authors have read and agreed to the published version of the manuscript.

Funding: This research was partially funded by Ministry of Research and Innovation, Romania, grant number PN-III-P1-1.1-PD-2016-1579.

Acknowledgments: This work was partially conducted in the framework of the research theme "Climate hazards in the Romanian Plain" of the Institute of Geography, Romanian Academy.

Conflicts of Interest: The authors declare no conflict of interest.

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