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Review of urban surface parameterizations for numerical climate models

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ABSTRACT

Built environment changes the radiative, thermal and hydrological properties of the land surface creating higher temperature over urban regions known as the Urban Heat Island (UHI), enhancement of precipitation and warm season thunderstorms causing flash flooding, and intensification of pollutant concentrations in urban regions. Rapid urbanization and climate change are expected to exacerbate urban surface effects on health, economy and the environment. It is therefore necessary to study the impact of urban surfaces on local and large scale surface and atmospheric processes. High resolution climate models with heterogeneous but realistic land surface representations can reproduce the urban surface effects relatively accurately. In the last three decades, there have been interesting developments in urban surface parameterizations. Simultaneously, the growing computational power has created an opportunity to run climate models at high resolution. Therefore, this is probably the most favorable time to couple different scale urban surface parameterizations with climate models to better understand urban-rural weather or climate interactions and to generate information required for urban-related impact and adaptation studies. However, very few review studies have focused on the growing need for urban surface parameterizations processes relevant to improve urban weather and climate prediction systems at various scales. This paper therefore fills this gap by critically reviewing urban surface parameterization developments, evaluating the most important processes and identifying the data needed for linking urban surface models to climate models over the last three decades. Consequently, it proposes ways to improve the existing processes and/or incorporate the missing processes for better simulation of urban weather/climate. It also explores progress towards future applications of urban climate models and processes that these models need to represent in response to changes in human energy consumption behavior from fossilized fuel to renewable energy resources, climate change, population growth, land use/cover transition and pollution.

1. Introduction

More than half of the world's population live in urban regions. Projections indicate, this number will increase to over 60% by 2050 (UN, 2014). In response, more buildings and roads are under construction to fulfill the demand for housing, mobility and recreation. This, however, puts so much pressure on urban energy and water consumption. For example, urban regions are known to have higher temperature than the rural regions because of the built in urban structures which absorb most of the incident radiation, stores it and

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releases it in the form of thermal radiation during the night. This creates up to 2°C or more warmer region in the center of the cities than rural regions (e.g., Oke, 1997; Oleson et al., 2011). The mean annual land surface temperature difference between urban and rural areas reaches up to 12°C during the early night (e.g., Klysik and Fortuniak, 1999; Cai et al., 2017) but lower than this during the solar day. This phenomenon is called the Urban Heat Island (UHI). UHI creates urban discomfort and significantly decreases the outdoor air quality influencing people to consume more energy for air conditioning and ventilation systems than the rural population. Correlating UHI with energy consumption in US cities with large number of populations such as Los Angeles, Washington, Dallas, Tucson and Colorado springs, Akbari et al. (2009) reported 1.5 to 2% increase in peak electricity load for every 1°F increase in urban temperature. Salamanca et al. (2013) assessed the summer time air conditioning consumption and found out significant increase in urban energy consumption load than in rural regions. There are also reports of deaths from UHI related heat waves. So, adaptive policies are laid down in many municipalities to counter the energy and life losses from the heat waves: such as greening and lightening the color of urban surfaces that would lower urban temperatures and reduce cooling energy. In the US, these strategies are estimated to save up to 25% of the 200 billion kilowatt hours of energy spent for air conditioning (Waggoner et al., 1991). These strategies, however, depend on the availability of water for vegetation growth and irrigation and raise issues of water supply.

Urban regions are also affected by the intensification of pollutant concentration, enhancement of warm season thunderstorms and precipitation causing flash flooding over urban regions (Changnon et al., 1971; Dixon and Mote, 2003; Bornstein and LeRoy, 1990, June; Bornstein and Lin, 2000; Diem and Brown, 2003; Shepherd and Burian, 2003). Enhancement of precipitation happens because of the creation of convergence region due to increased surface roughness, thermal perturbation of the boundary layer that would create UHI circulation, enhanced urban aerosols and mechanical diversion of precipitation by urban canopy (Molders and Oleson, 2004; Shepherd, 2005). People living in urban areas are also experiencing climate related disasters such as tornadoes, tsunamis, typhoons, hurricanes and other water and wind storms. These urban effects on climate and the impact of climate change on urban regions under growing urban population necessitate the development of seamless urban weather and climate prediction systems that incorporate urban surfaces for impact, adaptation and mitigation studies. Urban planners therefore need to build climate resilient cities or reinforce ways to mitigate or adapt to the negative impacts of climate change on built environment (Emmanuel, 2005).

Climate models are therefore indispensable tools for the prediction of the impact of climate and the understanding of complex interactions among land, atmosphere and oceans. Since its early inception as General Circulation Model (GCM), there have been significant progresses in a predictive capacity of NWP models. Improved computational facility and the science underlying the physics and dynamics of climate models, significantly improved the resolution and hence the predictive capacity of current climate models. These have created an opportunity for the representation of more realistic land and atmospheric processes, which have further improved the predictability of weather from a few days to weeks in advance.

Better representations of heterogeneous land forms such as orography, surface roughness due to variable land cover such as urban regions, vegetation and crops, land-sea and other contrasts can be achieved by high resolution climate models. Consequently, the spatial resolution of GCMs have improved from hundreds of kilometers to around 100 km or less in the last couple of years. The regional climate models (RCMs), however, have much better resolution from 50 km to around 5 km and less (Rummukainen, 2016). High resolution regional climate models then have improved representations of finer spatial details and better simulated temporal variabilities.

Affordability of high resolution climate simulations, therefore, create an opportunity to account for urban surfaces in climate models because of the need for better prediction of climate and weather processes related to air quality, pollution, and impact of climate change. For example, air quality declines with an increase in population and industries in urban areas and megatowns. Representing real urban surface effects is useful for reliable prediction of the energy budget, water cycle, flows and dispersion in complex urbanized regions. To this endeavor, it is essential to develop techniques on how to treat surfaces where the roughness elements are taller than the lowest model level such as the roughness from urban building and vegetation. Considerations should also be made regarding anthropogenic heat and water emissions from large metropolitan areas (Oke, 1981).

Arnfield (2003) extensively explored the literature for the previous two decades prior to 2003 after reviews by Oke (1979), Changnon (1981), Landsberg (1981), Oke (1988), Taha (1997), Fernando et al. (2001), and Roth (2000). Most of the reviews mainly focused on the urban turbulence characteristics in the planetary boundary layer (PBL), urban-rural contrast in meteorological variables (e.g., UHI and rainfall), and/or techniques of observational studies. It is only in the late 2000s that reviews targeting urban parameterizations for numerical weather and climate prediction models appeared in literature (e.g., Masson, 2006; Grimmond, 2006; Kanda, 2006 and Kanda, 2007; Roth, 2007; Baklanov et al., 2009). Such literature reviews can be referred from Table 1 in chronological order following the developments of urban canopy models in the early 2000s(see Table 2).

However, identifying weaknesses, strengths and limitations of the state of the science of current urban climate models in representing relevant processes and recommendations to incorporate missing processes is not fully articulated by previous studies. From the output perspectives, interesting intercomparison studies were performed by Grimmond et al. (2010) and Grimmond et al. (2011) using many urban parameterizations schemes developed in different parts of the world. Results from the international project that documented all the models have wide variations of performance for individual energy fluxes and there is no model that performs well across all fluxes. Therefore, identifying weaknesses in representing urban surface properties, processes that need attention and data is critical at this point in time when urbanization and climate change impacts are looming.

This paper therefore explores literature on the urban modeling processes used in NWP models in the last three decades through follow-up of step-by-step historical developments (Section 2), identify the most important processes (Section 3), and evaluate these most important processes, strengths, weaknesses and limitations of the techniques used in current urban representations and data requirement for urban climate models (Section 4). It further proposes ways to incorporate or improve relevant processes for better simulation of urban weather and climate suitable for impact, adaptation, mitigation and process studies (Section 5). In Section 6,

Table 1
Literature reviews on urban meteorology in the last three decades.

Reference	Description of the review
Oke (1988)	The urban energy balance
Changnon (1992)	Weather modification in urban areas
Taha (1997)	Urban climate and heat islands
Roth (2000)	Review of atmospheric turbulence over cities
Fernando et al. (2001)	Air circulation and contaminant dispersion in cities
Arnfield (2003)	Two decades (1980-2003) comprehensive review of urban climate
Shepherd (2005)	Current investigations of urban-induced rainfall and recommendations for the future
Oke (2006)	Towards better scientific communication in urban climate
Grimmond (2006)	Progress in measuring and observing the urban atmosphere
Masson (2006)	Urban surface modeling and the meso-scale impact of cities
Kanda (2006) and Kanda (2007)	Scale modeling of urban climate and progress in urban meteorology
Roth (2007)	Review of urban climate research in (sub) tropical regions
Hidalgo et al. (2008)	Advances in urban climate modeling
Baklanov et al. (2009)	Reviews, perspectives and treatments of meteorological and air quality models for urban areas

potential applications of future urban climate models for climate mitigation, adaptation, resiliency and sustainability are explored. Finally, conclusions, recommendations and challenges are presented (Section 7). Fig. 1 gives summary of the review process followed in this paper. This review paper, however, is not an exhaustive review of the non-dynamic (not based on the concept of physics) empirical statistical modeling studies that followed on-site measurements only to analyze the impact of urban surfaces on climate.

2. The development of urban canopy models for mesoscale climate models

Historically, the study of the impact of urban surface properties dates back to around 200 years. Luke Howard(1772–1864) published the first edition of a book about the urban climate in 1818 (Landsberg, 1981). Later in 1918 and 1950 by Taylor in Paris, France and Shiotani and Yamamato in Tokyo, Japan, measurements were done in these respective cities and comparisons were made with rural sites (Roth, 2000). More studies followed (e.g. Landsberg, 1981; Oke, 1982; Shepherd et al., 2002; Oleson et al., 2010; Huang and Lu, 2015; Ren et al., 2015; Huszar et al., 2014) and they all demonstrated that there is higher temperature and associated foggy air (or “city fog”) over the cities than the rural sites.

Prior to the 1980s, statistical techniques were used on surface flux observations to extract the impact of urban surfaces on climate. These statistical methods (referred to as empirical statistical models) are based on the assumption that the physical behavior of urban surfaces is contained in the observed data. Comparison of weather and climate elements are made with observations of a site for a considerable period of time. According to Landsberg (1981), four various statistical techniques had been employed to identify the impact of urban surfaces from natural environments: 1) assuming urban influence is zero initially (urban influence comes later in the day than in the morning), 2) taking measurements at one or more sites in rural and urban environments and comparison of the mean values, 3) analysis of long time trends in sample measurements, 4) assuming that industrial workweek and traffic create difference between workdays and weekends in human influences on atmospheric parameters. In the first technique urban influence is assumed to be negligible at $t = 0$. Using samples at time $t = 0$, the urban influence can be determined at a later time t assuming the invariance of the climate of the region. This can only be done under the assumption of the absence of the climate variability of the region, thus it is not a good way of quantifying the impact of cities (Landsberg, 1981). The second approach is establishing urban influence from the difference of the measurements taken at the two specific sites designated as urban and rural. The most frequent and third method is the comparison of time trends from the observation information of the two environments. The fourth method usually consumes measurements and comparisons of Monday–Friday values with Saturday–Sunday values to reveal urban effects.The assumption in this category is that industrial workweek and traffic create difference between workdays and weekends in anthropogenic heat fluxes which affect the urban weather and climate.

According to Roth (Roth, 2000), the studies before 1980s had mainly focused on mean temperature in the urban boundary layer (UBL) using measurements from balloons, tall TV towers, or helicopters. Mostly, the focus was on the dispersion of air pollutants and hence large scale flow and mean values had been enough. There were other various intentions of these studies depending on most important issues in different locations. In Japan, for example, the knowledge was used for design of tall buildings that are resistant to occurrences such as hurricanes, tsunamis and other intense storms and therefore special consideration was given for peak wind velocities and the vertical stratification of wind guests (Roth, 2000).

These earlier studies were based on point measurements restricted to particular field of urban surface turbulence. Surface observations of such kind, however, are not accurate representations of the urban influence on climate. It is because, observation information are rarely available as it is challenging to identify the height at which measurements should be done, and more importantly the approach is not based on the physics underlying the surface characteristics, such as solar radiation balance, energy fluxes and water balance (Roth, 2000). This has left clear scientific gap because of the poor representation of spatial stratification of the surface properties and its impact on urban atmosphere. The limitations are partially attributable to the experimental difficulties encountered in cities because of the complex heterogeneity of urban surfaces making difficult choices for measurements and hence continuous observations are performed from fixed towers, which are restricted in height and width. This may not provide sufficient

Table 2
Summary of historical development of urban surface parameterizations for climate models in the last three decades in chronological order.

Reference	Description of the urban model	Climate model
Carlson and Boland (1978)	Surface heat flux/temperature model for Urban-Rural canopy	-
Oke (1981)	Canyon geometry and the nocturnal urban heat island	-
Sievers and Zdunkowski (1986)	Microscale urban climate model (MUKLIMO)	-
Kimura (1989)	Heat fluxes over a complex land-use surface	-
Tso et al. (1991)	Urban climatological model with and without heat storage	-
Johnson et al. (1991)	Urban surface heat island model	-
Brown and Williams (1998, November)	An urban canopy parameterization for Mesoscale meteorological model	HOTMAC
Saitoh et al. (1996)	Urban heat island model	-
Mills (1997)	An urban canopy-layer climate model	-
Bruse and Fleer (1998)	Urban block parameterization	ENVI-met
Taha (1999), Taha and Bornstein (1999)	Modifying a mesoscale meteorological model to better incorporate urban heat storage: A bulk parameterization approach	CSUMM, MM5
Montávez et al. (2000)	A Monte Carlo model for urban canyon temperature	-
Arnfield (2000)	A simple modle of urban canyon energy budget	-
Masson (2000), Lemonsu and Masson (2002)	Town Energy Balance (TEB) models	French Meso-NH, GEM, COSMO
Thielen et al. (2000)	Influence of urban surfaces on rainfall development	meso-γ - scale 2D model
Kusaka et al. (2001)	A single layer urban canopy model	-
Grimmond and Oke (2002), Offerle et al. (2003)	Local-scale urban meteorological parameterisation (LUMPS)	-
Martilli et al. (2002)	Urban building effect parameterization (BEP) model for mesoscale models	-
Kikegawa et al. (2003)	coupled mesoscale model (MM) - one-dimensional urban canopy model(UCM) - building energy analysis model (BEM)	Japan-MM
Shashua-Bar and Hoffman (2002), Shashua-Bar and Hoffman (2004)	The Green Cluster Thermal Time Constant (GCTTC)	-
Dupont et al. (2004)	Detailed urban and rural canopy parameterisation - SM2_U	MM5
Otte et al. (2004)	Urban canopy parameterisation - UCP	MM5
Kusaka and Kimura (2004)	Coupled single layer urban canopy model with simple atmospheric model	LCM2d
Kusaka et al. (2001), Chen et al. (2004)	Single layer urban canopy models for RCMs	WRF model
Harman et al. (2004b)	Scalar Fluxes from urban stress canyon - model	-
Best (2005), Essery et al. (2003), Harman et al. (2004a)	Representing urban areas in NWPs	UK Met Office MM
Kondo et al. (2005)	Development of multi-layer urban canopy model	NIRE-MM
Kanda et al. (2005)	A simple urban energy balance model for mesoscale (SUMM) simulations	-
Fortuniak et al. (2005)	Slab surface energy balance model	-
Dandou et al. (2005)	An urban parameterization scheme for mesoscale model	MM5
Baklanov et al. (2005),Baklanov et al. (2008), Mahura et al. (2005), Zilitinkevich et al. (2005)	Urbanized High Resolution Local Area Model (HIRLAM-U)	DMI-HIRLAM
Bonacquisti et al. (2006)	An urban canopy layer model	-
Lee and Park (2008)	A vegetated urban canopy model	-
Dupont and Mestayer (2006); Dupont et al. (2006)	Parameterisation of the urban energy budget (SM2_U) and integrate with the sub-mesoscale soil model (ISBA)	-
Harman and Belcher (2006)	The surface energy balance and boundary layer over urban street canyons	-
Hamdi and Schayes (2007)	Validation of the Martilli's urban boundary layer scheme	-
Tian et al. (2007)	Building integrated photovoltaics on microclimate of urban canopy layer	-
Krayenhoff and Voogt (2007)	Temperatures of Urban Facets in 2-D (TUF-2D - urban energy balance model	-
Oleson et al. (2008)	Representation and implementation of urban canopy model	CESM CLM-U, NCAR global climate model, CLM2-U
Hamdi and Masson (2008)	Inclusion of a drag approach in TEB	-
Salamanca et al. (2010)	Building energy system model, BEM	WRF
Trusilova et al. (2013)	Implementation of urban canopy model	COSMO-CLM
Huszar et al. (2014)	Representing urban canopy model in RCMs	RegCM4
Li et al. (2016)	Implementing urban surfaces in Earth System Models	GFDL-ESM

information about the environment it represents. It is thus, in such dire situation that the conception of urban surface parameterization proved necessary to integrate with NWP models to better represent the spatial stratification to have better overview of the impact of urban surfaces on weather and climate.

The weaknesses in using statistical techniques can be alleviated by coupling urban canopy models to climate models or modifying the dynamical equations to incorporate the impact of urban surfaces. It is only in the late 1980s that close examination of the impact of urban surfaces and hence urban parameterization based on dynamical equations were started (e.g., Oke, 1987; Roth and Oke,

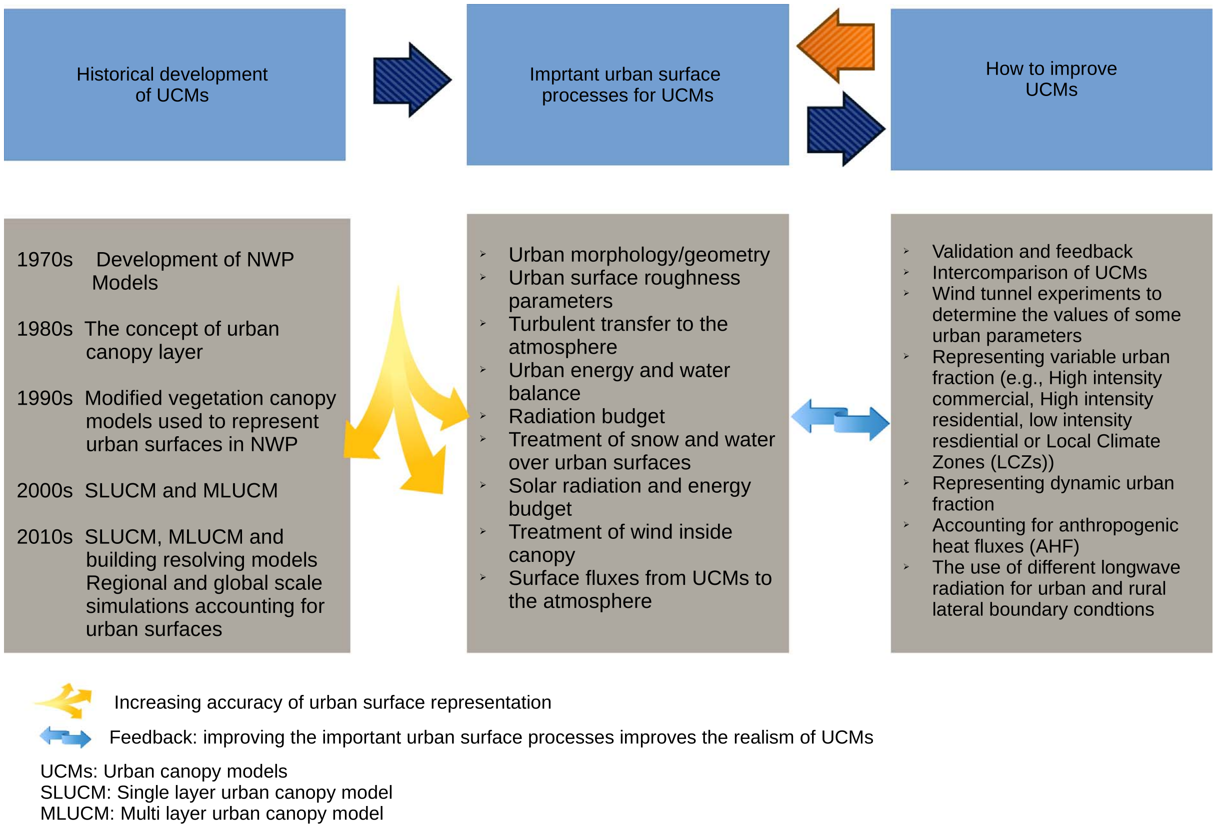

Fig. 1. This review process starts with historical development of urban canopy models, present important urban surface processes in urban canopy models and points out ways to improve these urban processes. The feedback arrows show the flow of knowledge and understanding between the respective categories.

1993) with an application for NWPs at the end of 1990s and beginning of 2000s (e.g., Masson, 2000; Martilli et al., 2002; Kusaka et al., 2001; Chen et al., 2004). Table 2 gives a summary of the development of urban surface parameterization studies conducted for NWP models in chronological order. The studies employed different techniques to represent urban surfaces into NWP models. The two common grand classifications are: (a) representing urban surfaces with bare soil (or adapting vegetation schemes) with modified heat capacities, thermal conductivities, surface albedo, roughness length, and moisture availability, and (b) by coupling an independent urban model with an atmospheric model. The latter is further divided into two categories: (i) simple building average urban canopy models and (ii) building resolving computational fluid dynamics (CFDs). The building average models can be: (ia) the single layer urban canopy models (SLUCMs) and (ib) the multilayer urban canopy models (MLUCMs). In the following sections, each of the four modeling approaches are discussed based on the level of detail and complexity of urban surface features they represent and their strengths and limitations. Furthermore, the application of these physical based urban climate models based on “fitness-for-purpose” guidelines and cross-scale modeling approaches are presented in detail.

2.1. Slab models (modified soil/vegetation schemes)

The traditional approach in urban parameterizations is using modified soil/vegetation schemes to represent the thermal effects of the city using elevated heat capacity and thermal conductivity than the values used for soil/vegetation. For example, the SM2-U model was developed on the physical bases to extend the land surface model, ISBA by including the urban surfaces such as roads and buildings in low, high and dense continuous urban canopies (Dupont et al., 2006). This is to reproduce the large urban heat storage that takes place in urban surfaces. To represent the momentum sink and the turbulence generated by roughness elements, large values of roughness parameters are used.

Representing urban surfaces with modified soil vegetation transfer scheme often called the slab model (see Fig. 2 (a)) treats urban geometry as a flat surface or similar to vegetation canopy with a large roughness length and/or small albedo (Brown, 2000). Hence, it assumes that buildings and roads have the same temperature, and treats the building height and coverage ratio implicitly in the surface layer.

The purpose of the slab model (see Fig. 2 (a)) is to calculate the effects of an urban canopy layer and provide energy and momentum fluxes to the atmosphere. In this type of models, the ground heat flux is similar to the surface temperature, i.e., $T_G = T_s$ (Fig. 2 (a)). The urban geometry such as surface roughness length, albedo, thermal inertia, and moisture availability are represented

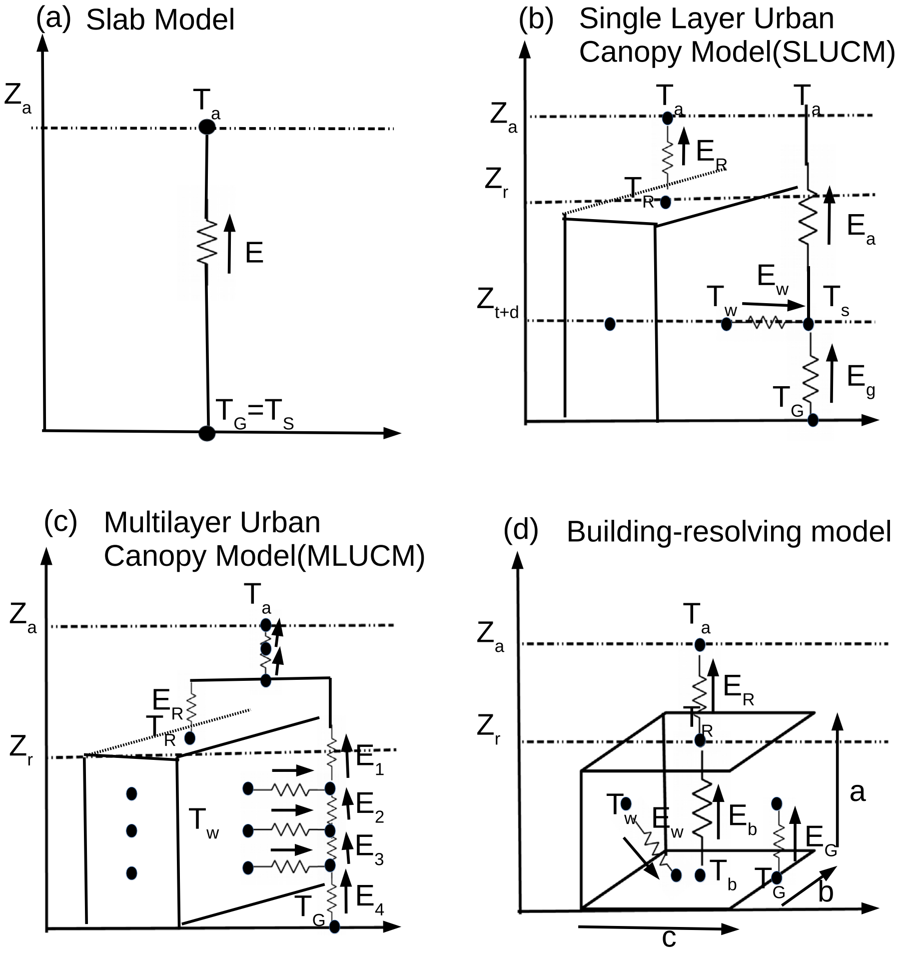

Fig. 2. Urban representation models: (a) The slab model where surface temperature (T_s) is equal to ground temperature (T_G):(b) the single layer urban canopy model (SLUCM), and (c) the multi-layer urban canopy model, and (d) building-resolving model, where T_a is the air temperature at reference height Z_a, T_R is the building roof temperature, T_W the building wall temperature, T_G the road temperature, and T_S the temperature defined at Z_{T+d}. E is the sensible heat flux, E_a is the sensible heat flux from the canyon space to the atmosphere; h_w from the wall to the canyon space, E_g that from road to the canyon space,E_R that from the roof to the atmosphere, $E_{1\ldots4}$ are sensible heat fluxes at multiple layers in the canopy, and E_b is indoor sensible heat flux from the building floor to the roof. The electrical circuit analogy is used to explain the transfer of heat from the wall, floor and roof to the urban canyon or the air above the buildings. The symbol —ʌʌʌ— is an electrical resistance analogy for thermal resistance, the analog of the heat transfer, E is current and the analogy of temperature difference (e.g., $T_R - T_a$), is voltage difference.

by tuning until the best simulation output is achieved (Kusaka et al., 2001).

This scheme is similar to the forest canopy schemes (Brown, 2000; Seaman et al., 1989; Menut et al., 1999) and divides the land surface into urban and non-urban fractions of which the former is treated as bare ground with modifications to surface characteristics. Such models were used during the early days when vegetation canopy models were incorporated into the regional climate models as part of the land system models. Heat storage was determined using a residual from the energy calculations (e.g., Oke and Cleugh, 1987). A semi-empirical formulation for the heat storage flux - the Objective Hysteresis Model (HM) (Taha and Bornstein, 1999; Arnfield and Grimmond, 1998) was later used to capture heat storage by urban surfaces.

This type of model is based on the surface layer scheme of the Monin-Obukhov (Monin and Obukhov, 1954) similarity theory for estimating bulk transfer coefficients, surface heat balance for estimating surface skin temperature, and a vertical diffusion equation for simulating urban temperature. In earlier climate models attempts have focused on improving the turbulent energy fluxes known as "thermal" part (e.g., sensible heat flux) or impact on the wind known as "dynamical" part and hence most approaches that use Monin-Obukhov similarity theory deal with the "dynamical" part. However, most of field observations (Rotach, 1993) indicate that such approach is unable to reproduce vertical turbulent fluxes in the urban roughness sublayer (RSL), i.e., from 50 to 100 m heights. It does not also take into consideration the surface energy balance from the shadowing and radiation trapping effects, and the only way of sink of momentum is near to the ground and is not distributed up to the building heights. Therefore, it lacks most of the urban surface effects to the air-flow such as (i) drag induced by buildings with consequent loss of momentum, (ii) enhancement of the transformation of mean kinetic energy into turbulent kinetic energy, and (iii) modification of the heat fluxes due to shadowing and radiation trapping effects (Martilli et al., 2002). Therefore, such representation of urban surfaces is not sufficient to reproduce the large heat storage that is characteristic of urban surfaces because the increased roughness length (for dynamical effects) favors the turbulent sensible heat flux than heat storage. The other problem is such soil/vegetation schemes cannot represent the heterogeneities present in the urban regions which is highly variable in space-time from neighborhood scale to local scale. It is therefore advisable to have detailed parameterization of urban surfaces and estimation of their surface and geometrical properties than simply adapting vegetation canopy models to represent urban surfaces. Explicit and independent (not as part of the vegetation or soil models) representation of urban surfaces proved important. This explicit representation of urban heterogeneities with different thermal properties and morphology can be achieved by independent and relatively complex urban canopy models. In such models, land surfaces are included through: (i) simple building-averaged models generally referred to as 'urban canyon' models (UCMs), or (ii) representation of individual buildings and shapes known as building resolving models.

2.2. Urban canyon models

The concept of urban canyon model (UCM) was developed by Oke and colleagues involving urban streets and a road bordered by two facing-walls (Oke, 1987). The space between the two facing walls above the road is called a canyon. The approach of the UCMs is simple averaging over urban geometries such as building height, width, impervious surfaces, and reducing input fields, to effectively represent urban surfaces with a minimum computational cost. Two different approaches are usually followed in UCMs. These are (1) the single layer urban canopy models (SLUCM) and (2) the multilayer urban canopy models (MLUCM).

2.2.1. Single layer urban canopy models

The Single Layer Urban Canopy Models, SLUCMs (Fig. 2 (b)) are based on simplified urban geometry but reasonably close to real urban surfaces. For example, buildings are considered to have 3D shape, and the schemes calculate separate energy budgets for roofs, walls, and roads and aggregated later at canopy level or diagnostic level. For example, the turbulent sensible heat flux from the roof to the air, E_R, from the building wall to the canopy, E_w and from the ground, E_G are calculated separately based on the temperature differences between the air and the roof, $T_R - T_a$, the canopy surface and the wall, $T_w - T_s$, and the canopy surface and the ground, $T_G - T_s$, respectively. Then E_G and E_w are aggregated to give the canopy energy flux, E_a. Finally, the two turbulent energy fluxes, E_R and E_a are transferred to the lowest level of the atmospheric models. Such urban representations give more refinement of the radiative budgets and turbulent heat and momentum fluxes than the slab model (Martilli et al., 2002), which assumes only one sensible energy flux, E from the urban surfaces, for example Fig. 2 (a).

Furthermore, unlike the slab model, the physics treated by the SLUCM scheme is relatively complete. It accounts for solar reflections and shadows and heat conduction method is often used to get storage energy for each of the different layers (thicknesses) of the roofs, walls, and roads. Snow and water are usually treated in separate energy budgets. The characteristics of air in the canyon follows specific parameterization. For example, the Town Energy Balance (TEB) (Masson, 2000) uses the logarithmic law for wind between the top of the canyon and the atmospheric level, and exponential wind profile below that level. Road orientations along different directions is considered. Simple averaging is usually used over 360° (for example by TEB). This type of model is known to have reduced computational cost because of the averaging over building heights, orientations over all directions in a grid cell and hence single-layer urban canopy models are the most widely used type of urban canopy models (e.g., Mills, 1997; Masson, 2000; Kusaka et al., 2001; Oleson et al., 2008, Huszar et al., 2014). However, it is not suitable if detailed vertical distributions of momentum, heat and moisture are required (e.g., for air quality studies) because the fluxes are calculated at few points in a canyon, e.g., at the ground level, center of the canopy and above the canopy (Fig. 2 (b)).

2.2.2. Multilayer urban canopy models

The other approach is called the multi-layer urban canopy model (MLUCM) (see Fig. 2 (c)). Unlike SLUCM, it divides the canopy into many sub-layers down to the road surface. For example, there are many layers of canopy turbulent sensible heat fluxes such as E_1, E_2, E_3, and E_4 (Fig. 2 (c)). Therefore, it is a better representation of the atmosphere in the urban canyon than both SLUCM and slab models. For example, the multilayer UCM developed by Martilli et al. (2002) called Building Effect Parameterization (BEP), allows direct interaction with the PBL, recognizes the three-dimensional nature of urban surfaces and captures the vertical distributions of heat, moisture, and momentum throughout the whole urban canopy layer. Such representation better simulates the mechanical and thermodynamic structure of the urban roughness sublayer and hence the urban boundary layer (Chen et al., 2010). It considers turbulent kinetic energy (TKE), potential temperature, and momentum both vertically (along the walls) and horizontally (on streets and roofs). Shadowing, reflections, and trapping of shortwave and longwave radiation in street canyons are taken into account by the radiation calculations on walls and roads. This approach is suitable for temperature and wind profiles within an urban canopy layer as it was able to simulate the most observed urban features such as UHI and enhanced inversion layer above urban surfaces (Chen et al., 2010). However, it is of higher resolution than SLUCM and requires more computational resource than even the current mesoscale climate models and hence this approach is appropriate for detailed urban studies when the computational resource is not a constraint.

2.3. Building resolving CFD models

Building resolving models (see Fig. 2 (d)) allow detailed examination of specific processes such as radiative effects and wind channeling. Most of the building resolving models consume Computational Fluid Dynamics (CFD) for the accurate simulation of thermal and airflow conditions inside and above the urban canopy (Fernando et al., 2001). For example, sensible heat fluxes inside the buildings such as from the wall to the floor, E_w and from the floor to the roof, E_b are calculated before outdoor fluxes (e.g., E_R) are computed (Fig. 2 (d)). Unlike the other UCMs, CFD's explicitly resolve turbulent flows at multiple scales from individual buildings to the boundary layer and hence represent more realistic effects of cities on the atmosphere. These microscale CFD models can be "scaled-up" (unlike "scale-down" in dynamic downscaling from GCMs to RCMs) to mesoscale models to provide detailed three-dimensional information of meteorological variables such as temperature, wind speed and precipitation. However, such models are at trial stage at this time and rarely used because they require high computational resources and huge initial and boundary conditions, making it difficult to use for regional or global scale climate model simulations. However, CFD models are useful during the testing and validation of the urban models because CFD models allow spatial averaging in contrast to point measurements, which are erroneous when spatially averaged (Martilli et al., 2002). The most commonly used CFDs are (a) the Reynolds Averaged Navier Stoke's (RANS) equations and (b) the Large Eddy Simulation (LES). RANS models parameterize all the turbulence, and resolve only the mean flow. However, LES models explicitly resolve the largest eddies, and parameterize the effects of the sub grid features. LES resolves time dependent and spatially averaged Navier-Stokes equations. CFD-RANS is found to lack the accuracy for complex configurations, i.e, they are less precise. On the other hand, CFD-LES is more accurate than RANS but much more expensive in CPU time (Baklanov et al., 2009), hence its use for climate models is limited.

2.4. Cross-scale modeling and 'fitness-for-purpose"

One of the most important but not well-understood concept in current urban climate modeling is which level of complexity and detail needs to be implemented into climate models. On the other hand, the availability or scarcity of morphological, initial and boundary data, and computational resources determines the details and complexity of the models for practical purposes. To this endeavor, Baklanov's "fitness-for-purpose" guideline (Baklanov et al., 2009) is an important first-step for practical model applications.

In the current state of modeling, there is no existing procedure or rule governing the appropriate level of detail and specificity that a model must have. As put by Baklanov et al. (2009), there is no "one-size-fits-all" modeling approach that addresses the wide range of modeling objectives.

Baklanov's "fitness-for-purpose" basically considered application areas such as, (a) mesoscale meteorological models, (b) urban air pollution and emergency response models, (c) chemistry/aerosols and climate integrated modeling, and (d) multiscale (cross-scale) modeling.

Based on developments of urban parameterizations and the increasing levels of sophistication introduced into today's mesoscale models, SLUCMs are relatively inexpensive and practical for NWPs and mesoscale meteorological models. That is why most of the current urban parameterizations used SLUCM for coupled simulations to high-resolution mesoscale climate models (Table 2, e.g., Masson, 2000; Kusaka et al., 2001; Kusaka and Kimura, 2004; Chen et al., 2004; Oleson et al., 2008; Huszar et al., 2014; Li et al., 2016). The community-based climate and weather models, for example, the Community Earth System Model, CESM (formerly Community Climate Model (CCM)) and the Weather Research and Forecasting (WRF) model employ the urban canopy models for the study and exploration of the impact of urbanization on climate and weather. In CESM, the atmospheric model is known as the Community Atmospheric Model (CAM), the land surface model, LSM, called the Community Land Model, CLM, and the CLM urban canopy model, CLM-U. The urbanization treatment in CLM-U is based on the "urban canyon" concept and it performs the simulation of how urban surfaces and climate change affect urban energy balance and climate. The model is useful to explore urban planning and heat island mitigation strategies and fit for the purpose of urban climate prediction (e.g., Oleson et al., 2008; Jackson et al., 2010 and Ching et al., 2014a). Concurrently, the community weather model, WRF consists of two dynamical cores, the Advanced Research WRF (WRF-ARW) and the Non-hydrostatic Mesoscale Model (WRF-NMM), the land system model, LSM known as Noah and the modified multi-parameterization version called Noah-MP. Other LSM options in WRF are the Sub-Mesoscale Soil Model-Urban, SM2-U and P-X model system. In the WRF model three treatments of urban surfaces exist. These are WRF-SLUCM (Kusaka et al., 2001), the Building Energy Parameterization, BEP (Chen et al., 2010) and its recent inclusion of the Building Energy Model, BEM (Salamanca et al., 2010). The diverse choices of model options for planetary boundary layer, PBL, LSMs and urbanized models in WRF results in different combination yielding different outcomes. This would bring about the challenge; that is identifying which combination of the parameterizations performs better for the intended application. Therefore, sensitivity tests are required and/or one has to rely on literature to identify the combination for the best output. However, this remains a challenge for the urban climate modeling communities because performing sensitivity experiments consumes lots of time and effort. It is also computationally expensive. On the other hand, searching for sensitivity studies in literature is equally challenging because only limited information is realizable from an ocean of previous studies and even it is impossible to find studies for some combinations of the parameterizations.

There are also other urban models fit-for meteorological applications, such as the Town Energy Balance (TEB) (Masson, 2000) model for meteo-France's, MeteoNH and Environment Canada's General Environmental Multiscale (GEM) model and the Met Office's Unified Model (Best, 2005).

For urban air pollution and emergency responses, urban meteorological models coupled to detailed dispersion and obstacle-resolving modeling approaches (e.g., CFDs) are appropriate. For example, the Community Multiscale Air Quality (CMAQ) model is used to simulate and understand the impacts of anthropogenic and biogenic pollutant emissions. Details of the CMAQ model for air quality and dispersion applications can be found from Ching (2013). Similarly, for the purposes of quantifying the impact of aerosols and other chemicals in the urban atmosphere on radiation (both longwave and shortwave), coupled chemistry/aerosol models with urban models could improve the performance of the mesoscale/synoptic-scale models. In this regard, the WRF chemistry model, WRF-Chem performs by coupling the meteorological model, WRF with the Chemistry model and allows for reasonable treatments of aerosol-radiation-cloud processes, cloud chemistry, and cloud-aerosol interactions that would improve the performance of the WRF model for meteorology and air-quality applications (Ching, 2013).

In recent years, cross-scale modeling approaches that integrate or use a combination of one or more of the modeling approaches are being implemented. For example, Chen et al. (2010) used the multilayer urban canopy model coupled to fine-scale Eulerian/semi-Lagrangian fluid solver (EULAG) and CFD-urban models in WRF to investigate the degree to which the forecasts can be improved from the feed-back from up-scaling of explicitly resolved turbulence and wind fields in complex urban environments by the fine scale urban models. For urban planning applications, the urban canopy models coupled to the finer-scale CFDs are important to clarify the interactive relationship between indoor and outdoor climate, considering heating and air conditioning systems of the buildings (e.g., (Ashie et al., 1999)).

The cross-scale modeling approaches (e.g., Kikegawa et al., 2003; Salamanca et al., 2010 and Chen et al., 2010; Salamanca et al., 2011) require both down-scaling of the initial and boundary conditions from the atmospheric models for the CFDs, and up-scaling the microscale flow features (such as channeling, enhanced vertical mixing, downwash, and street-level flow) resolved by CFDs back to the atmospheric model. This back and forth scale-adjusted feedback increases the accuracy of mesoscale weather forecasts and climate predictions for urban and neighboring regions. Such real time coupling mechanism is better than using the boundary and initial conditions traditionally used from observations data (e.g., atmospheric sounding data), which falls short of representing the spatial variability of weather elements within the urban regions (Chen et al., 2010). It has tremendous impact on air quality studies because it oftentimes results in inaccurate prediction of urban plumes. On the other hand, some of the current MLUCMs and SLUCMs have kept the internal building temperature constant and hence needs to be linked to other models dedicated entirely to the exchanges of energy and momentum between the interior of buildings and the outdoor air. For example, BEP is linked to the Building Energy Model (BEM) (Salamanca et al., 2010) to account for the diffusion of heat through the surface layers of floors, walls and roofs, the shortwave and longwave radiation exchange between the doors, windows and the indoor surfaces, the exchange of heat generated by the residents and equipment (refrigerators, heating, ventilation and air conditioning systems). Such independent building energy models allow exchange of heat and momentum between several floors which can provide a better estimation of the evolution of indoor and outdoor air temperature and humidity. It also helps to estimate the amount of energy consumption from heating and air-conditions systems to better predict their impact on weather and climate. According to Chen et al. (2010), the BEP + BEM had been implemented to WRF and it had significantly improved sensible heat flux calculations better than the MLUCM, BEP simulation alone. Similarly, the CFD coupled to the climate model had better produced the observed high-concentration tracers indicating the suitability of urban CFD coupled to the atmospheric model for air-quality purposes as outlined by Baklanov's (Baklanov et al., 2009) “fitness-for-purpose” approach. Therefore, cross-scale modeling approach can provide information encompassing wider scales and perspectives, and hence it is recommended specially for reasonable interaction and feedback from small scale turbulence to large scale climate phenomena.

3. Parameterizations of urban processes

3.1. Urban geometry and morphology

Building geometry plays an important role in modifying the urban climate. For example, thermal contrasts in calm and clear evenings are determined by building geometry and land cover (Stewart and Oke, 2012). Energy and water balance, and wind are affected by building geometry and surface albedo (Oke, 1987). Urban geometry is attributed to the shapes and orientations of buildings, roads and other human built surfaces that affect the mechanical, thermal and radiative properties of the atmospheric boundary layer.

Urban geophysical parameters such as building and road fraction, natural surface fraction, average height, building width, dynamic roughness lengths, surface albedo and emissivity, heat capacity, depth/thickness and thermal conductivity of the layers are used to refine specific urban surfaces in such canopy models. It also includes fraction of pervious (e.g., vegetated soil) and impervious (e.g., roads, sidewalks and roofs). The majority of impervious surfaces except roofs of buildings in urban areas are roadways and hence they are considered to be the road fraction. The pervious surfaces are vegetation and soil which are mostly treated as rural fractions.

The composition of the urban fraction (e.g., percent of wood, brick, stone in walls and percent of asphalt shingle, ceramic tile, and wood shingle in roofs) determines the thermal and radiative properties of the urban surfaces. Asphalt road composition may also vary depending upon the percent of materials used. In regional study, it is also important to classify regions with the same building and road construction materials. Building morphology is dependent on culture to some extent. For example, there are areas where the walls are built from mud and bricks. In other cultures, buildings are completely brick and cement. So, geographical knowledge of the region under study is also crucial in accurately representing urban regions in urban climate models.

Urban morphology and geometry are highly variable in space time. However, most of the current urban canopy models use static urban surfaces that do not reflect urban growth. Population growth in urban environment is evidence that urban land cover never stays the same. It is expected that urban land cover will increase horizontally and vertically. This modifies the urban thermal, radiative and hydrological properties and inaccurate representation of dynamic urban surfaces affects prediction of urban climate into the future under the looming urbanization and climate change. It is therefore recommended to connect current harmonized urban fraction with all its surface characteristics with future projections. For example, Hurtt et al. (2011) used a strategy to estimate the fractional land-use patterns and underlying land-use transitions annually for 1500–2100 at $0.5^\circ \times 0.5^\circ$ resolution. The same strategy can be consumed to dynamically predict future urban growth and hence urban geometry for use in urban canopy models.

During the energy calculations, sunlit and shadowed walls need to be treated separately. It is difficult to separate sunlit and shadowed wall and roads because of the complex road and wall orientations in urban regions. For sunlit fractions, surface albedo plays a significant role in the radiative balance estimations. Urban surface albedo decreases over urban regions because of the urban geometry (blocks separated by street canyons). It is because radiation is trapped inside the canyon and performs multiple reflection until absorbed fully by the wall and asphalt surfaces. According to Stewart and Oke (2012), these features of urban geometry decrease urban albedo to values around 0.15, which is much lower than rural landscapes except for forests and dark soils. The effect of snow is also different over urban and rural regions. The reason is that urban snow is affected by human intervention like snow ploughing and artificial snow melting (e.g., in Montreal salt is used mostly on sidewalks during snow season and snow is removed from the roads, in other places snow melting by heating may be used). UHI by itself has huge impact on snow melting and hence reducing the urban albedo, which further increases urban heat waves. In some urban regions, high reflectivity materials and paints are used to offset the heat absorption by urban surfaces. Greening urban surfaces also cools the urban environment through evapotranspiration.

Ground observations or remote sensing satellite informations may be employed to extract urban geometry and morphology parameters (Treitz et al., 1992). The values of these parameters depend on building shapes and construction materials, the sky viewing factor, thermal structure, the presence of snow or water on the roof and road, and source of heating inside the buildings which are different for different building shapes and sizes and hence accurate observation data can improve the outputs of urban climate models.

3.2. Determination of urban surface roughness and turbulent transfer to the atmosphere

Urban surface roughness determines turbulent heat and moisture exchanges between the urban surfaces and the atmosphere. The depth of urban boundary layer is different from the rural boundary layer because of the surface drag from the urban roughness length. Hence, the understanding of the depth of the urban boundary layer and pollutant dispersion above urban canopies are important for urban processes such as surface drag, shearing stress, wind profile forms and turbulence. In big cities, the urban roughness layer can go further above the first level of the atmospheric model and creates confusion about where to delineate the urban surfaces from the atmosphere (Oke, 1987).

Experimental techniques are used most of the time to determine values for urban surface roughness length. Such techniques oftentimes assume that roughness lengths are constants that are functions of the underlying surface types. For dense low buildings the experimental values of urban roughness lie between 0.4 and 0.7 m and for regularly built urban regions, the values lie between 0.7 to 1.5 m (Wieringa et al., 1993). The experiments indicate that the urban roughness is $\frac{1}{10}$ of the average building height. Therefore, most models adopt the $h/10$ analogy to represent urban roughness layer where h is the building height. For example, in the town energy balance (TEB) model Masson (2000) uses $z_{0,town} = h/10$ as a first approximation with an arbitrary limit of 5. However, due to the complexity of urban structures, experimental determination of the parameters is prone to errors and hence no conclusion can be drawn based on previous studies (Arnfield, 2003). Further developments in determining urban roughness lengths suggest that the roughness lengths are not only functions of the surface type but also dependent on meteorological variables such as temperature and moisture. These studies used the Monin-Obukhov similarity theory (MOST) which uses roughness lengths for momentum and heat and are based on the outdoor scale model experiments (Kanda et al., 2007) and tower measurements (Voogt and Grimmond, 2000) that would contribute to improve the physical based momentum and temperature roughness measurements of urban surfaces. Consequently, large eddy simulations (LES) also contribute to the understanding and parameterization of urban roughness for urban canopy models (e.g., Kanda et al., 2013). The MOST approach, however, requires an effective surface temperature that is an output from the urban canopy models and observation data whose availability is limited for most urban centers. Therefore, further studies and alternative ideas for various real urban sites are warranted (Kanda et al., 2007).

In an urban environment, the cause for turbulence is the higher surface roughness layer due to high buildings, trees and other large structures, and the urban heat island effect (e.g., Terjung and O'Rourke, 1980; Oke, 1997). Inhomogeneous surfaces modify mean kinetic energy of the flow into turbulent kinetic energy and produce high turbulent intensities, mixing due to wake diffusion and stratified pressure gradient in the leeward and downward part of the urban region (Roth, 2000). The aerodynamic characteristics of the urban surfaces are parameterized using either (a) the roughness approach, or (b) the drag-force approach. The roughness approach is the most widely used in mesoscale models in which a gridded roughness length and a displacement height are used to represent the impact of urban obstacles on the flow. This approach uses the Monin-Obukhov similarity theory to calculate the dynamic and thermodynamic surface exchange coefficients (Otte et al., 2004). However, urban regions are complex, which results in a generally reduced stability and it is not expected that general similarity schemes such as Monin-Obukhov similarity (MOST) framework are applicable (Martilli et al., 2002). Because the roughness approach cannot simulate the thermodynamic profiles below the displacement height and cannot reproduce the maximum observed turbulent kinetic energy (TKE). At fine scales (e.g., in the order of ~ 1 km), therefore, the roughness approach may not be sufficient for simulating urban microclimate.

Inside the urban roughness sublayer (URSL), the drag-force approach is used (Otte et al., 2004; Masson, 2000; Martilli et al., 2002). In this case, the lowest level of the computational domain is the real level of the ground without the displacement height. Some vertical heights may be added to allow for the detailed simulation of meteorological fields.

There were few studies regarding urban land surface turbulence fluxes. Roth and Oke (1993) and Roth and Oke (1993) compared measured data and came up with the conclusion that there is hardly a relationship between temperature and moisture characteristics due to the underlying spatial inhomogeneity (Masson, 2000).

Resolution of climate and urban models, and comparison with smaller-scale turbulence is an important indicator of the uncertainty in resolving turbulent fluxes. In mesoscale climate models (both GCMs and RCMs), with horizontal resolution greater than 20 km, subgrid scale atmospheric processes (e.g., moist convection, turbulence, and cloud microphysics) are unresolved. This creates uncertainty in feedback and interaction from smaller scales turbulence to large scale atmospheric processes. However, with the growing demand for high resolution mesoscale models with urban surface representations, the horizontal resolution gets close to ~ 1 km. In such situations, the ratio of turbulence integral scale to the sub-grid scale filter (SFS), $\frac{l}{\Delta} \sim 1$, the grid size lies within the terra incognita, TI (Wyngaard, 2004). Consequently, the PBL parameterizations produce ensemble mean fluxes by sub-grid scale motions which do not resolve turbulence accurately. The horizontal spatial homogeneity of smaller-scale turbulence can only be resolved by spatially averaged turbulence closure schemes outside of the TIs. The uncertainty in TI also affects the interaction between larger-than-grid-mesh size, convectively induced secondary circulations (CISCs) (e.g., cells and rolls), with smaller-scale turbulence (Ching et al., 2014b) and hence high resolution urban climate models falling under TI length scale remain a significant challenge for models applications as it affects feedback and interaction between larger scale atmospheric processes and smaller-scale turbulence, imposing uncertainty to the model outputs.

3.3. *Urban energy and water balance*

The total solar radiation is unequally distributed over urban surface area because of its three-dimensional geometry. In general, the net solar radiation and downward infrared radiation balance the sensible heat flux, latent heat flux, anthropogenic heat flux, and conduction heat flux between the surface layer and the underlying layer. A general energy balance equation (e.g., Oke, 2002) for an urban surface is, therefore,

$$R_\star + L_\star = E_\star + LE_\star + E_{\star s} + \Delta E_{\star A} + E_{\star c} + E_{\star A} \tag{1}$$

where R is the net solar radiation, L is net infrared radiation, E is sensible heat flux, LE latent heat flux, E_s is the energy stored in urban surfaces, ΔE_A is the advective term due to the net horizontal transfer of sensible and latent heat, E_c conduction heat flux between the surface layer and the underlying layer, and E_A is anthropogenic energy flux (e.g., combustion, heating and ventilation systems). The subscript $\star$ denotes roof, road or wall.

Urban surfaces have higher sensible heat flux than rural surfaces because of lower albedo and the surface absorptivity of buildings and roads. There is higher latent heat over rural regions where vegetation is the dominant land cover type than urban regions. So urban regions generally have higher sensible heat flux and lower latent heat flux than their rural counterparts.

The parameters in Eq. (1) are dependent on geographical location (e.g., latitude, longitude and altitude) and the city characteristics (e.g., high density commercial or low density residential). In equatorial climate, heat storage is a dominant factor but in mid-latitude high rise and dense cities where traffic is higher and industries are common, anthropogenic heat flux is the main parameter affecting urban energy balance.

From the energy balance equation, the prognostic temperature evolution equation for the urban surface layers roof, wall, and road for snow covered and snow free fractions can be calculated as (e.g., Masson (2000)).

$$C_{\star,*}\frac{\partial T_{\star,*}}{\partial t} = (1 - f_{snow\star})\frac{1}{d_{\star,*}}(R_\star + L_\star - E_\star - LE_\star - E_{\star s} - \Delta E_{\star A} - E_{\star c} - E_{\star A}) + f_{snow}\frac{1}{d_{\star,*}}(E_{\star snow,*c} - E_{\star,*}) \tag{2}$$

where the subscript $\star$ denotes either road, wall or roof, * denotes the temperature of the ith layer of the considered surface, C represents the heat capacity, d denotes the layer thickness and f_{snow} is the snow fraction on the surface (which is zero on the walls).

In most of the current models, more simplified versions of the above equations are used. There is a wide variation of energy flux calculations by the models. Some models (e.g., TEB, Masson, 2000) resolve domestic heating by supposing a constant internal temperature, whatever the external temperature is. The heat is then released towards the wall/roof surfaces and then towards the atmosphere through the conduction flux formulation. Others consider (e.g., Salamanca et al., 2010; Chen et al., 2010) sophisticated indoor to outdoor flux calculations.

Similarly, the water balance in urban regions (e.g., Oke (2002)) is

$$p + F + I = LE_\star/L_v + \Delta r + \Delta S + \Delta A \tag{3}$$

where p is precipitation, F is anthropogenic water release, I is urban water supply piped in from rivers or reservoirs, L_v is latent heat of vaporization, Δr is urban water release in the form of sewage or surface runoff, ΔS is water storage changes in the ground and ΔA is the net moisture advection to/from the city air volume.

The water evolution equation in urban surfaces is

$$\frac{\partial W_\star}{\partial t} = P + F + I + \Delta r + \Delta S + \Delta A - LE_\star/L_v,$$
$$\text{where} \quad W_\star < W_{\star,max} \tag{4}$$

When water is saturated, runoff occurs. The roof reservoir runoff goes directly into the road reservoir. Typical drainage or evacuation happens after few days.

Domestic and industrial water demand is higher during the day with peak use in the morning and evening (Oke, 2002). This water is lost from the system via evapotranspiration or runoff.

Anthropogenic water flux is usually ignored in current urban canopy models. Horizontal flux of evaporation from gardens or parks, irrigation water are seldom taken into account. Releases from factories and water vapor flux into the air are also other sinks that need attention but mostly ignored for simplicity.

One of the challenges to account for anthropogenic water and energy fluxes from the urban surfaces is the unavailability or scarcity of flux data from urban sewage disposal systems, irrigation and evaporation from urban surfaces. Nevertheless, there have been flux measurements from few urban towers for some cities in the world (e.g., FLUXNET, 2015; Baldocchi et al., 2001) for measuring surface-atmosphere exchanges of energy, water and greenhouse gases that can be used as model input and/or to evaluate or verify urban land surface models. Consequently, such urban flux measurement towers are useful to prepare an inventory of urban surface emissions such as greenhouse gases, pollutant concentrations and anthropogenic heat and moisture. However, such measurement sites are very limited in number and operate for few months or years limiting their availability to represent grid point sizes for the consumption of urban climate modelers. It is therefore recommended that more measuring towers need to be merged with other mobile and crowd-sourcing facilities (e.g., WUDAPT, Ching et al., 2014a) and available for urban climate researchers both for input to urban climate models and for validation purposes.

3.4. Urban radiation budget

The amount of solar irradiance received in urban canopy can be reduced by the shadowing effect of buildings, urban surface albedo and the boundary layer pollutants (e.g., aerosols and photochemical smog). The amount of attenuation depends on the city structure and the presence of particulate and gaseous pollutants. Urban radiation depletion of 3%, 9%, 33%, and 22% are reported for central St Louis (Peterson and Stoffel, 1980), Hangzhou (Chuanchen and Jisong, 1982), Hong Kong (Stanhill and Kalma, 1995), and Central Mexico City (Jáuregui and Luyando, 1999). From these studies, it is conclusive that the more attenuation occurs in cities with significant industrial aerosol or photochemical smog and high rise buildings, the less solar radiation reaches the urban surfaces. For example, seasonal air pollution with origins from neighboring areas of Mainland China, results in a high level of atmospheric particulates in Hong Kong (Ho et al., 2003). Solar irradiance in Hong Kong is also affected by the sky view factor because sky high buildings block part of the incoming solar radiation. Not only Hong Kong and cities in China but other regions have the same problems. Mexico city, for example, has air polluting smog (Williams et al., 1995) and hence reduced solar irradiance.

However, the incoming long-wave radiation is enhanced by the increased urban heat island (UHI) or due to amplification by pollutants (Oke, 1982). There is, on average, a 10% increase with a maximum of 20% in Brandon, Manitoba (Suckling, 1980) compared with the corresponding rural surroundings. There were later studies on the enhancement of urban incoming long-wave radiation in relation to the higher urban surface temperature than rural regions (e.g., Estournel et al., 1983). Estournel et al. (1983) documented an increase of the downward longwave radiation flux at the urban Toulouse site by 15 W/m^2 during the day and 25 W/m^2 during the night.

Multiple reflections between the canopy walls and diffuse reflections from the roof wall and road are also important considerations in the urban radiation balance. Generally, in urban regions, albedo is lower than the rural regions because of the construction materials radiative and thermal properties. During winter season, in mid and high latitudes, snow also affects radiation budget (e.g., Lemonsu et al., 2010).

It is argumentative that whether urban energy is in balance between the lower albedo, high long-wave radiation and decreased solar irradiance. The lower albedo and high long-wave radiation tend to increase the urban energy while the decreased solar radiation due to air pollution and shadowing reduce the urban energy. Arnfield (1982) concluded that the energy balance difference between rural and urban regions tends to be small in the absence of a snow cover. It is because the heat island effect results in high incoming long-wave radiation and air pollution and shadowing tend to lower the incoming solar radiation. While most literature agree on such small difference in energy (e.g., Oke and McCaughey, 1983; Cleugh and Oke, 1986; Grimmond et al., 1996 obtained a 19% more net energy for Los Angeles urban region than the nearby rural region).

Net total radiation in the urban microclimate is affected by urban geometry, i.e., the position, orientation and shapes of buildings (Noilhan, 1981). The net total solar radiation received at the surface is

$$NS_{\star} = S_{\star} + L_{\star} \tag{5}$$

where $S_{\star}$ is the net incident solar radiation and $L_{\star}$ is the net long-wave radiation. Here $\star$ is the surface type, i.e., roof, wall, and road.

The net solar radiation is

$$S_{\star} = (1 - \overline{\alpha})(DS_{\star} + R_{\star} + D_{\star}) \tag{6}$$

where $\overline{\alpha}$ is the surface albedo, $DS_{\star}$ is the direct solar radiation received by the surface k, $R_{\star}$ is the solar radiation reflected by the surface j (e.g., left wall) and received by surface k (e.g., right wall) and $D_{\star}$ is the diffuse solar radiation received by the surface $\star$ (refer Fig. 3 for the simplified urban radiation balance model).

The direct solar radiation $DS_{\star}$ can be obtained from

$$DS_{\star} = \tau.\ I.\ [cosh.\ sin\beta_{\star}.\ cos(a - \gamma_{\star}) - sinh.\ cos\beta_{\star}] \tag{7}$$

where τ is the shading factor, I is the solar radiation received perpendicular to the solar radiation, h and I are the height and the azimuth of the sun, i.e.,

$$h = arcsin[sin\phi.\ sin\delta + cos\phi cos\delta cosH] a = arcsin\left(\frac{cos\delta.\ sinH}{cosh}\right)$$

where ϕ is the latitude, δ is the declination and H is the hour angle.

Similarly, $D_{\star}$ and $R_{\star}$ are determined with the assumption that sky diffuse radiation and reflected solar radiation are isotropic. It is to be pointed out that isotropic assumption underestimates the total solar radiation at the surface. The diffuse and reflected, i.e., $D_{\star}$

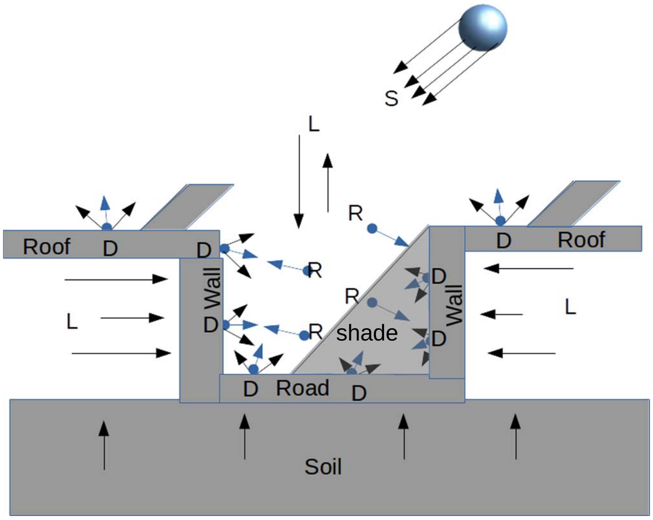

Fig. 3. Simplified radiation balance model in the urban environment. The roofs, walls and roads are partially lit and partially shadowed. *S* is the net incident solar radiation, *L* is the net long-wave radiation, *R* is the reflected radiation and *D* is the diffuse solar radiation received by the surface.

and $R_\star$ are functions of the sky view factor and the relative view of one surface type (e.g., wall) with respect to the other (e.g., road).

3.5. Treatments of snow, water and wind over urban surfaces

Urban surfaces intercept snow and water, and modify wind. Most urban canopy models use simple snow parameterization schemes to take into account snow density, albedo, temperature and thickness of water equivalent depth, radiation balance, sensible heat flux, sublimation, conduction and melting. Snow fraction is usually calculated based on the snow interception function. In TEB (Masson, 2000), for example, the snow interception reservoir fraction is $\delta_{snow\star} = W_{snow,\star}/(W_{snow,\star} + W_{snow,\star max})$, where the maximum snow reservoir $W_{snow,\star max}$ is set equal to 1 kg m^{-2}.

Rainfall is intercepted by roofs and roads and when saturation occurs, there is runoff from roofs and roads to the sewer system. In TEB, as an example, the snow-free fraction occupied by water is computed as $\delta_\star = (W_\star/W_{\star max})^{\frac{2}{3}}$ based on Noilhan and Planton (1989), where $W_{\star max}$ is the maximum. Snow removal is also taken into account in some models. But realistic representation of snow remains a challenge and most models do not have consistent snow parameterization schemes for urban surfaces and this also imposes significant uncertainty in the predictive efficiency of the models in cold regions.

4. Data for urban climate models

4.1. Urban geometry and morphology databases

For accurate representation of urban geometry and material composition, high resolution state-of-the-art urban databases are required. In this regard, the formation of National Urban Data with Access Portal Tools (NUDAPT) (Ching et al. (2009) and its follow-up World Urban Data Access Portal Tools (WUDAPT) (e.g., Ching, 2013; Ching et al., 2014a; Mills et al., 2015; See et al., 2015) are innovative, relevant and important. The databases are developed to produce and provide gridded high resolution data of buildings, vegetation, and land use for urban climate models. The datasets also include anthropogenic heating (AH) and population data. While NUDAPT is produced for US urban regions, its successor WUDAPT collects data from around the world ("crowd sourcing") with consistent methodology and stores it allowing access to anyone anywhere in the world. WUDAPT's framework: (a) uses the Local Climate Zones (LCZs) which can have 17 urban land (both built and natural) classification (Stewart and Oke, 2012), (b) uses structured crowd sourcing tools useful to sample land cover and land use types which help to get fractions of impervious surfaces (e.g., buildings, roads, pavements), pervious surfaces, grasslands, (c) develops online access to urban geophysical parameters such as building materials, building dimensions, canopy widths, and composition (e.g., bricks, muds), (d) provides tools to compare researchers around the world to compare the geometry and material morphology of one or more urban regions.

The relevance of accurate and more detailed urban information is critical for urban climate modeling at this time of rapid urbanization and climate change. It encourages and facilitates more researches which further improves urban simulations for decision and policy applications. Furthermore, data collection by means of "crowd sourcing" using internet technologies should be supported by other sources such as from ground and tower measurements (e.g., FLUXNET, 2015), and satellite remote sensing for extended information until the most accurate and refined level suitable for various scale simulations is achieved. Such refined and accurate urban databases are useful not only for urban climate modelers but also for urban planners and construction engineers and would enhance collaboration between experts from different organizations.

4.2. Long-wave radiation for natural and urban regions

In the current urban climate studies using urban canopy models, the same long-wave radiation forcing is mostly used for natural and urban regions. However, studies have shown asymmetrical distributions of long-wave radiation between urban and rural neighborhoods. It is because the urban canyon geometry and pollutant concentration have a significant impact in altering the emission/absorption of long-wave radiation to/from the atmosphere from within the canyons because of their reduced sky-view factors (Oke, 2002) and higher pollutants in the urban regions. Both factors tend to increase the downward long-wave radiation over urban regions by means of the overlying attenuation by pollution layers and the shadowing effect, which closes the atmosphere through which radiation escapes. Urban heat island is also found to enhance the incoming long-wave radiation due to amplification by pollutants. On average, an increase by 10% of the long-wave radiation was reported in Brandon, Manitoba (Suckling, 1980) as compared to rural regions. Urban Toulouse site was documented to have more long-wave radiation, an increase by 15 W/m^{-2} during the day and 25 W/m^{-2} during the night (Estournel et al., 1983). As discussed in Sections 3 and 4, lower urban albedo and higher long-wave radiation in urban regions tend to increase the urban energy while shadowing and attenuation by air pollutants decreases solar radiation and hence urban energy. The difference is mostly small unless in situations where snow cover and pollutant distribution affects the balance. Most of the previous studies (e.g., Oke and McCaughey, 1983; Cleugh and Oke, 1986) agree on such small asymmetries in energy balance between urban and rural regions. However, the difference is large sometimes depending upon the location of the city and proximity to industrial zones. For example, Grimmond et al. (1996) obtained a 19% more net energy for Los Angeles urban regions than the nearby rural regions. Therefore, it is better to have different long-wave radiation for urban and rural regions as input to improve the prediction of urban microclimate.

4.3. Dynamic urbanization

One of the most important yet understudied factors in urban climate parameterizations is consideration of how much of the land surface has been urbanized and projected to urbanize under population growth. There are few studies (e.g., Hurtt et al., 2011; Liu et al., 2014) that have tried to estimate the transition from rural to urban and in very rare cases (e.g., fire, sea-level rise) the transition from rural to urban. Due to the complexity of estimating such transitions, most of the recent urban canopy models assume that urban fraction is constant throughout the simulation period. But cities grow and the land cover change should be taken into account. It is necessary that the urban areas must be dynamic to incorporate the transition from rural land to urban land and vice versa to represent the realism of urban growth. The urban growth also helps to investigate the historical and future hydro-climatic impacts of urban expansions. Most of the current urban parameterizations such as TEB (Masson, 2000), the Community Land Model Urban (CLMU) (Oleson et al., 2008) and SLUCM-WRF (Kusaka et al., 2001) do not consider dynamic urban land use change as a modular entity in the models. But the models can be modified to consume dynamic urban transitions. There are few recent studies, however, which have incorporated urban growth (e.g., Li et al., 2016) based on land-use change harmonization study of Hurtt et al. (2011) for the smooth transitioning from the historical estimates of land use to future projections and urban expansion scenarios (low expansion, high expansion from the estimation of the Integrated Climate and Land Use Scenarios (ICLUS) project (e.g. Georgescu, 2015). The ICLUS project estimates urban expansion into the future based on domestic and international migrants for county-based housing unit allocation and has 1-ha resolution, at decadal frequency from 2000 to 2100. Hurtt's land-use change approach (Hurtt et al., 2011) and ICLUS's population based scenarios approach (Bierwagen et al., 2010) are important starting points for applications in urban climate models.

4.4. Anthropogenic heat and water fluxes

Anthropogenic heat fluxes have huge impact in urban energy flux modeling. It is not easy to get how much of the energy comes out of space heating, traffic, air conditioning and industrial wastes. It is highly seasonal and varies every hour in a day. Generally, energy consumption databases are used to get an estimate. For example, an estimated anthropogenic flux of 200 W/m^2 for central Tokyo (Ichinose et al., 1999) in summer and 400 W/m^2 in winter. Anthropogenic heat flux depends upon population density of a city. It also depends on the seasonal temperature variability in the urban regions. In some regions more energy is used for ventilation and others, especially in high altitudinal region where cold winter is strong more energy is used for heating. It is also dependent on economic activities of the city. Economically developed cities have higher traffic and hence higher anthropogenic emissions.

Anthropogenic energy source approaches or exceeds the net radiation, especially in the winter for cold climates and is higher during the day time with peak periods in the morning and evening. It also has the highest values in the city core (Oke, 2002).

Anthropogenic heat fluxes, E_A in Eq. (1) are mostly added as an extra turbulent heat flux at diagnostic model level (e.g., Masson, 2000; Salamanca et al., 2010) or as part of the main parameterization module.

It can be formulated as:

$$E_A = E_{FV} + E_{FH} + E_{FM} \tag{8}$$

where E_{FV}, E_{FH}, and E_{FM} are the heat released by vehicles and heating, ventilation and air conditioning (HVAC) sources, and metabolism, respectively.

Most urban models add an estimate of anthropogenic heat (AH) from vehicles directly to the sensible heat flux. For example, a diurnal profile of AH was added to the sensible heat flux with peak values of 90, 50, and 20 W m^{-}2 for the commercial or industrial (COI), high-intensity residential (HIR), and low-intensity residential (LIR) urban classes, respectively (Salamanca and Martilli, 2010).

The AH from HVAC systems is mostly difficult to estimate and hence models usually use a fixed building internal temperature. However, BEP + BEM model of Salamanca (Salamanca et al., 2010) used sophisticated HVAC estimation by means of an energy consumption (EC) model that computes the total heating/cooling loads for every floor of the buildings. Simultaneously, a comprehensive and independent estimation of anthropogenic heat flux based on population density for the estimation of metabolic heat flux,E_{FM}, number of cars, motorcycles, and freight vehicles with characteristic average vehicle speed and heat emissions assumptions for vehicle emissions, E_{FV}, and annual energy consumption databases and population density to estimate building anthropogenic heat flux, E_{FB} is used by the large scale ($2.5 \times 2.5^{\circ}$ resolution) urban consumption of energy (LUCY) model (e.g., Allen et al., 2011). Similarly, Dong et al. (2017) used a top-down methodology to estimate global anthropogenic heat emission with high spatial and temporal resolution (30 arc-seconds and 1 h) using information from human metabolic heating and primary energy consumption.

However, anthropogenic moisture and heat fluxes from sewerage and irrigation systems are not considered in most of the current urban models because of the challenge to get an estimate from waste and irrigation systems. In most models, anthropogenic water source/sink was not considered because of the obsolete computation of evaporation from gardens or parks. Irrigation water, if any, is not taken into account either. Irrigation water input is usually left for the land surface model dealing with the natural surfaces. Lighting and water heating systems are also not computed in most current urban models. These are important and exciting areas that need attention because these are where the effects are significant.

4.5. Variable urban geometry

In most of the urban canopy models, one urban class is representative of the entire urban region sufficient for few applications. It is done by averaging over heights and widths of buildings and roads in a grid cell. This is representative of average urban fraction or suburban regions instead of the whole urban and sub-urban areas, which is highly inhomogeneous over space and time. However, recently there are interesting developments to incorporate most of the diverse urban groups optimal for different applications (e.g., cross-scale modeling applications and fitness-for-purpose, Section 2.4). The versatile urban climate zones should be classified into sub-divisions to accurately predict the surface characteristics of urban regions. In this regard, the USGS national landuse dataset for urban areas are divided into four broad categories: open space, low intensity residential, medium intensity residential, and high intensity residential (Chen et al., 2004). The most recent urban classification implemented in WUDAPT data crwod-source facility (Section 4.1) uses urban classification based on the "local climate zones" (LCZ) (Stewart and Oke, 2012). Up to 10 built-in urban subdivisions are possible based on this LCZ classification such as compact high-rise, compact mid-rise, compact low-rise, open high-rise, open mid-rise, open low-rise, lightweight low-rise, large low-rise, sparsely built and heavy industry (Stewart and Oke, 2012). Similarly, about 7 classification for the natural (vegetation, bare soil/sand and water) such as dense trees, scattered trees, bush, scrub, low plants, bare rock or paved, bare soil/sand and water are used in LCZ. The land cover can also be bare trees, snow cover, dry or wet ground. They claim LCZ is better because it is local on the one hand and reflects the climatic nature of the area under study on the other hand. One of the advantages of LCZ classification is it helps to define UHI as the difference in temperature among the classes instead of the traditional urban-rural difference. It therefore simplifies the analyses of spatial radiative, thermal and hydrologic stratification based on heterogeneous intra-urban morphology on the formation of local climate.

It is conclusive that more detailed urban classification is very important for defining urban surface characteristics accurately in urban canopy models. However, the more classification is used the more computational intensive and complicated the model gets. In the mean time, averaging in a grid cell may prove sufficient considering the cost of time and computational resource. But, in the future, considering an improvement in computational platform, implementing more detailed urban classification in UCMs is important to accurately represent the urban surfaces to better predict the energy, radiative and hydrologic properties of urban regions.

5. Uncertainties and methods of improving urban climate models

As any climate model component, validation of an urban canopy model against observation is important. Unless validated, it is difficult to rely on the ability of the model to accurately reproduce and predict the physical properties of urban surfaces. In the validation process, both offline (uncoupled) and online (coupled) land surface model, consisting of urban canopy model, with the atmospheric model can be used. Both strategies have advantages and disadvantages. The uncoupled urban canopy model, without its own vegetation and soil parameterizations, lacks feedback from the atmosphere and the surrounding land surface types (e.g., vegetation and bare ground). However, it is free of the uncertainty induced from the atmospheric model. A coupled study of the urban canopy model with the atmospheric model, on the other hand, has the advantages of two way communication between the atmosphere and the urban surfaces. Sensitivity studies are performed targeting a chosen set of observations for parameter estimation. Such essential process is named tuning in the climate modeling community. Tuning consists of adjusting the values of uncertain parameters to produce outputs that fits well the aspects of the observed weather/climate. Even if tuning is an essential component of the climate modeling processes, there are issues whether such tuning a priori would constrain the model results in unintended ways and affect the reliability of climate projections. The challenge is that tuning by adjusting certain metrics may achieve improved performance at the expense of unphysical behavior in the metrics or processes, i.e., one can get "right for the wrong reasons" (e.g., Hourdin et al., 2017). This problem is known as over-fitting or over-tuning and it may affect our confidence on climate projections. The reader may find more information on tuning and its issues from Hourdin et al. (2017) and Baumberger et al. (2017).

Nevertheless, for validation purposes, continuous, accurate and reliable observation data is important. Obtaining point observations in such highly heterogeneous urban regions is challenging because the measurements require consistent data measuring methodology and representing horizontal and vertical model grids reasonably accurately. For example, data may be taken at the same height above ground, with the same electronic equipments and data storage devices (e.g., in some studies 32 bits and 64 bits data storage devices impose "round-off-error" uncertainty). Furthermore, identifying consistent location of the measuring towers/or sites (e.g., near buildings/roads or in the parks) is critical. Similarly, representing model grids by point measurements appropriate for validation purposes is an important factor. Here, model grid size should be at an appropriate resolution so that point observation and model grids can be compared with reasonable accuracy. However, if the grid resolution is large, mean values from many observation sites lying in the model grid are required. In general, the problems of model grid size representation and consistent data measuring methodology can be minimized by improving the density of meteorological observation stations and regular communication among field meteorologists.

Alternatively, approaches such as crowd-sourcing via the internet using the same data preparation techniques (e.g., WUDAPT) and from the network of large number of people or long path measurements using mobile equipments can be used for sampling and validation. However, consistency to the data measuring and preparation methodology is an issue and crowd sourced data should be taken cautiously.

Wind tunnel experiments may also provide approximate values of variables that may be difficult to obtain from field measurements (e.g., Lemonsu et al., 2004). Remote sensing or Geographical Information Systems (GIS) are also useful tools to get observation data that would be used for validation or to get estimates of urban geometry. Satellites data are useful to get urban surface parameters that would otherwise be difficult to obtain by other means (e.g., Jin and Shepherd, 2005).

There are lots of urban canopy models emerging and hence inter-comparison of the models and testing against the same observation data may improve the understanding of urban surface characteristics. International collaboration to compare the energy and water balance predictive ability of urban models is equally important. To this endeavor, the international urban water and energy balance inter-comparison project (Grimmond et al., 2010 and Grimmond et al., 2011) used about 32 urban parameterization schemes and documented all the models performed relatively well as far as energy balance is concerned with different skills. There is no best model for good performance across all the energy fluxes. However, the study found out that most of the models have strong bias in simulating latent heat fluxes. From the inter-comparison project, it was recommended that the urban canopy models, UCMs need to take into account vegetation to improve the predictability of latent heat fluxes. Integrating vegetation into the urban schemes also better represents the urban fluxes as compared to separate treatment of vegetation (e.g., Lemonsu et al., 2012).

As discussed in Section 4, processes such as different long-wave radiation in urban and rural simulations, dynamic urbanization for historical and future studies, anthropogenic heat and water fluxes, and variable urban geometry so far have not been considered in UCMs in combination. The downward long-wave radiation is higher over urban regions than rural due to amplification by UHI and attenuation by pollutants in the atmosphere. This needs to be taken into account and different driving data are needed for urban and rural regions as far as long-wave radiation is concerned. Consideration of anthropogenic heat and water fluxes could also improve the predictive capacity of urban canopy models. In some huge cities, the energy flux from anthropogenic sources exceeds the energy from solar radiation. So, such huge energy fluxes from cars, households and industries can not be ignored. Energy consumption databases, population demography, and the economic activity of the urban region are useful information to better estimate anthropogenic heat and water fluxes from cities. In this regard, Salamanca's (Salamanca et al., 2010) BEM model is exemplary and others should follow the same suit.

Implementing more detailed urban classification (e.g., open spaces, low intensity residential, medium density residential, and high intensity residential) could also improve the performance of UCMs. The "local climate zones" (LCZ) approach which has 10 divisions (compact high-rise, compact mid-rise, compact low-rise, open high-rise, open mid-rise, open low-rise, lightweight low-rise, large low-rise, sparsely built and heavy industry) (Stewart and Oke, 2012) may improve the performance of UCMs. Nevertheless, such too many classification needs high computational platform and bulky input field which consumes lots of time and effort. The complexity is lower, however, compared to building-resolving Computational Fluid Dynamics (CFD) models.

6. Future urban modeling applications

Recent developments in urban energy and water parameterization is promising, because the computational facilities are getting better. Future studies are likely to bring about new ideas into consideration. For example, there are emerging methods to mitigate urban heat island (UHI) by green and high albedo roofs, roads and walls. Further progress is happening on how to integrate solar panels with the urban surfaces in urban canopy models (e.g., Ortiz et al., 2016; Salamanca et al., 2016; Taha, 2013; Masson et al., 2014; Wang et al., 2006). The energy production from photovoltaic panels has proven benefits not only in terms of reducing dependence on fossil fuels but also reducing UHI in summer saving energy that would be needed for domestic heating, ventilation and air conditioning systems (HVACs). For example, it is found out that an energy saving of up to 11% for solar installations and 14% for cool roofs by Salamanca et al. (2016) are achieved in the study incorporating a photovoltaic panel parameterization with the WRF model in the investigation of the impacts of rooftop solar panels and cool roofs in Tucson, Phonix areas. Masson et al. (2014), on the other hand, found out that solar panels reduce the energy needed for air conditioning by 12% in summer and a slight increase in domestic heating by 3% in winter. This accounts for an energy saving of 9% from domestic consumption alone. Urban population is on the rise and the energy demand from renewable sources are expected to grow and hence future urban models should account for surfaces that would be covered by solar panels and wind turbines.

In some urban surfaces, parts of the roofs and ground are already covered by solar panels changing the radiative and thermal properties of the urban surfaces. This trend is expected to increase in the future as the shift of energy consumption from fossil fuels to renewable energy sources is expected. The emerging studies (e.g., Wang et al., 2006; Masson et al., 2014) are proofs that future urban canopy models will incorporate the radiative and hydrological properties of solar panels and wind turbines.

There is a growing demand for the output from the urban canopy models by urban planers to improve the current and future urban climate for human comfort. Selection of construction materials for housing and recreation may be made based on the information obtained from urban climate models (e.g., lightening and greening roofs). This reduces energy loss from heating and ventilation systems. Urban canopy models also give useful information about the impact of climate change under continuous emission of greenhouse gases and hence the information will be useful for adaptation and mitigation policies. Furthermore, urban models give an opportunity to explore options for better urban functioning, sustainability and air quality monitoring, under urban population growth.

From the modeling perspectives, the computational capacity will improve which would prove optimum to shift the modeling style from single layer urban canopy models (SLUCMs) to multilayer urban canopy models (MLUCM) and even to building resolving and hydrodynamic models. In effect, the resolution of urban canopy models will increase from mesoscale to microscale or integrating/coupling the two. The accuracy and prediction efficiency will improve by integrating urban characteristics that would come out from new understanding, from high resolution studies.

7. Conclusions and recommendations

In this review, the development of urban surface parameterizations from the past to present was discussed. The review has attempted to critically investigate the most important parameters/processes in urban models and ways to improve them. Furthermore, attempt was made to predict processes that will be implemented under an emerging understanding of the urban climate, improvement in observational input fields (from ground and satellite measurements) and computational facilities. This will have profound impact on future urban climate modeling applications such as understanding urban functioning, climate mitigation, resiliency, adaptation and sustainability studies under pressures of population growth, land use transition, climate change and air pollution.

The most important findings and recommendations are summarized as:

1. There is significant progress in urban surface parameterizations from measurement based empirical statistical studies to the current mostly used single layer urban canopy models (SLUCMs). SLUCMs are based on simplified urban geometry but reasonably close to real urban surfaces. They give more refinement of the radiative budgets and turbulent sensible and latent heat fluxes than simple consideration of urban surfaces as bare ground with modified surface characteristics and non-physical statistical models. Some studies have used the multilayer urban canopy model (MLUCM), which parameterizes urban heat and energy fluxes from many sub-layers. MLUCM represents the urban surface heterogeneity better than SLUCM and slab models, but it consumes higher computational resource and needs more input field than SLUCM and slab models. That is why the intermediate complexity SLUCM models are the most widely used urban canopy models. However, given the development of better computational resources, high resolution and relatively complex MLUCMs are realizable. Furthermore, progress is also made towards implementing building-resolving models that would take into account every and each building characteristics into computational fluid dynamics (CFD) models. Other few studies also attempted to couple the urban canopy models with intensive building resolving CFD models to clarify the interactive relationship between indoor and outdoor climate, considering heating, ventilation and air conditioning (HVAC) systems of buildings. While it is generally recommended that the cross-scale modeling approaches, i.e., integration of mesoscale climate models with intermediate level urban climate models and further coupling to microscale CFD models, are important to obtain more refinement and accurate results, the necessary level of complexity and detail is dependent on the application areas.
2. Which level of complexity and detail are required to represent urban surfaces in mesoscale climate models to improve urban weather/climate prediction systems? There is no one-way guideline that would address the wide range of modeling objectives and the choice of appropriate level of detail and complexity is based on the purpose and application area the model is to be used for. In this regard, Baklanov's (Baklanov et al., 2009) fitness-for-purpose guideline is an important consideration for the wide applications of urban climate models. Accordingly, for mesoscale meteorological purposes, intermediate complexity SLUCMs are relatively inexpensive and sufficient to reasonably simulate the urban surface effects. However, for detailed urban air pollution and emergency responses, microscale CFD models may provide appropriate channeling and dispersion information. Furthermore, cross-scale modeling approaches using nesting strategies from coarse resolution urban canopy models to high resolution microscale CFD models targeting specific area of practicality is important.
3. Simulation experiments benefit from databases of the fundamental physical parameters and urban geometry, which determine distinct urban climates. Better estimation of urban thermal and radiative properties such as building materials, geometry and reflective properties is useful in numerical modeling and interpretation of urban climate systems. However, there are few of such databases from which modelers obtain accurate urban parameters for effective simulation of urban weather and climate. It is generally recommended to establish more urban databases containing suitable urban parameters (e.g. building fraction, road fraction, surface albedo) and urban land cover change. In this regard, the formation of NUDAPT for US cities and its follow-up WUDAPT for the whole world for online data sharing based on consistent methodologies for the preparation and storage are reasonable and important. Such open to the world online databases with various scales will attract the attention of more climate modeling communities and would help improve urban weather/climate prediction systems.
4. Urban surface roughness determines the turbulent characteristics of the urban environment and it is therefore the cause for turbulence. The correlation between temperature and moisture depends on the underlying turbulence characteristics. In the past, experimental techniques were used to determine urban surface roughness values. However, because of the complexity of urban

structures, the determination based on experiments alone is not sufficient. Other attempts to improve urban roughness lengths based on the outdoor scale model experiments, tower measurements and large eddy simulations (LES) use the Monin Obukhov similarity theory and because of the complexity of urban surfaces, the stability is generally reduced and the simplified Monon-Obukhov similarity scheme may not be applicable. In TEB, for example, different heat fluxes are used for roof, wall and road (Masson, 2000). It is therefore conclusive that more experiments and studies on urban turbulence characteristics are essential to obtain values that accurately represent urban surface roughness and the relationship between urban surface fluxes such as heat and moisture.

5. The current urban models use incomplete energy and water budgets. For example, to account for heating, ventilation and air conditioning (HVAC) systems, most models (e.g., TEB, Masson, 2000) use fixed internal building temperature which then diffuses through layers of walls and roofs to the outdoor atmosphere. Salamanca et al. (2010) used a sophisticated yet independent building energy model (BEM) to calculate HVAC and its interaction with the outdoor air. Similar but with extended estimation of anthropogenic heat based on population density for the estimation of metabolic heat flux and building anthropogenic heat flux, number of traffic, their speed and heat emission assumption to determine vehicle emission by the urban consumption of energy model (LUCY, Allen et al., 2011) and the top-down methodology developed by Dong et al. (2017) are remarkable. However, still other anthropogenic heat (AH) and water fluxes are mostly neglected, for example, the heat from lighting, industrial waste and traffic. Furthermore, irrigation water and evapotranspiration from gardens and parks are mostly ignored but these are important for understanding the urban boundary layer, surface water availability and microscale advection of anthropogenic heat and water. Estimation for anthropogenic heat and water fluxes can be made directly from traffic counts, population data, homeowner questionnaires, utility records or indirectly from measurements. For example, traffic heat flux estimation can be obtained by subtracting week-days (Saturday–Sunday) from work-days (Monday–Friday) or the difference between high traffic time (e.g., 6 h–18 h) and low traffic time. The demand for domestic and industrial water is higher during the day with peak use in the morning and evening (e.g., Oke, 2002). The difference in domestic water consumption during the day and night gives an estimation of anthropogenic water flux. It may also provide an estimation of the amount of water used for irrigation and urban vegetation, which are lost from the system via runoff or evapotranspiration.
6. In the current urban models, the same downward long-wave radiation is used at the lateral boundary for urban and rural simulations. However, the downward long-wave radiation is higher over urban regions because of attenuation by pollutants and shadowing effect, which restricts an atmospheric window through which radiation escapes. The same long-wave radiation forcing has substantial impact on future projections because of the different responses from urban and rural surfaces under climate change transient simulations. It is therefore recommended that separate and independent long-wave radiation is used at the boundary of urban and non-urban simulations.
7. Numerical urban parameterization remains to be suitable to deal with the complexities and non-linearities of urban climate system. However, there is difficulty in obtaining observation data for validation of the models. It is difficult to rely on the outputs of the models without validation. Wider observational schemes from persistent ground measurements to continuous mobile sources are useful to provide boundary and initial conditions for urban climate models. Analogously, accurate and representative urban morphology and micro-meteorological data are useful for validation of the model outputs. It is therefore advisable to have more observation sites to get accurate measurements and strengthen collaboration between modelers and field climatologists to establish local, regional and global urban databases for ease of access and availability.
8. Availability and representativeness of observation information at model grid points for validation and improvement are important but challenging. The urban modeling communities rely on one or few and sometimes several points for model validation purposes whereas model grid sizes may not fit well to point observations both horizontally and vertically. The availability issue can be minimized by establishing more observation sites, crowd-sourcing facilities and field-campaigns. Simultaneously, with an ever increasing computer power, higher resolution urban climate models are realizable which with appropriate grid-sizes comparable with spatial observation. However, with an increased resolution, resolving turbulence is a problem and hence puts the model in the terra incognita “gray-zone” regime which remains to perplex the urban climate modeling communities.
9. Most of the studies using the current urban climate models do not account for urban expansions, i.e., urban fraction in a grid cell is static. However, the dynamic transition to/from urban to natural vegetation/soil is important to accurately predict future urban climate. Therefore, it is recommended to have guidelines or methodologies for predictions of urban and rural land use/cover changes and transitions from the past to the future (e.g., Hurtt et al., 2011).
10. Classification of urban areas into sub-classes (e.g., USGS classification of urban regions into open spaces, low intensity residential, medium intensity residential and high intensity residential (Chen et al., 2004), and 17 sub-divisions in LCZ (Stewart and Oke, 2012)) gives more detailed urban surface features than averaging over the whole urban domain to have one urban class representative of the whole urban regions in a grid cell. However, such detailed classifications require more input fields representative of each class and more CPU power. An intermediate classification may be sufficient to capture the thermal and radiative properties of urban surfaces accurately and would be sufficient for certain applications, for example urban meteorology. However, high resolution and detailed classification is required for urban water and air quality assessments and hence more urban classifications are necessary.
11. The growing urban population and climate change mitigation and adaptation policies would bring about changes to the urban cover. For example, the energy consumption changes from fossilized energy resources to renewable energy resources such as wind energy, solar energy, and thermal energy will cover part of the future urban roofs and bare land surfaces with solar panels, wind turbines and biogas wells. The thermal and radiative properties of these surfaces are different from the old style roofs and walls. Therefore, urban climate models should accommodate the changes to urban land surface fractions for reasonable and

accurate modeling of urban weather and/or climate. In this endeavor, there are emerging studies that have included solar panels into the fraction of urban surfaces and concluded that the panels indeed reduce urban temperature by absorbing most of the solar radiation (converting to electricity) and reflecting most back to the atmosphere (e.g., Masson et al., 2014; Wang et al., 2006; Salamanca et al., 2016). It is therefore advisable to be vigilant of the social, political, economic and environmental changes that would bring about changes in energy and water consumption, urban land use and cover (e.g., cool or vegetated roofs), and represent the changes into urban climate models accordingly. Furthermore, urban climate sensitivity studies for adaptation, mitigation, resiliency and sustainable development under pressures of global warming, population growth, urbanization and resource depletion are warranted.

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