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Impact of urban wind environment on urban building energy: A review of mechanisms and modeling

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ABSTRACT

In the context of global warming, improving energy-use efficiency is an important research topic in the fields of green buildings and eco-cities. There is an indivisible coupling relationship between the urban climate and urban building energy (UBE). Urban wind environments (UWE), including urban thermal and humid environment, is widely believed to have a significant impact on building energy consumption as a key microclimate element. However, despite decades of development of the UWE calculation module in numerical simulation tools, there is still a lack of reviews on the UWE impact mechanism on UBE. In this paper, the mechanisms of UWE influence on building energy consumption, building-scale simulation tools, and city-scale simulation tools, as well as the coupling and validation methods of these tools in the past decades are reviewed. Therefore, this study can provide the necessary foundation and general workflow for building physicists and urban climatologists to simulate and analyze the impact of UWE on UBE. The problem with the current building energy model and urban building energy modelling is that the UWE is not considered comprehensively, and CFD and other methods are used to obtain accurate results. The future challenge is to improve the accuracy of the energy consumption calculation from the perspective of UWE impact, optimize the calculation module, obtain a balance between calculation speed and accuracy, and propose validation and calibration guidelines focused on UWE impact on UBE.

1. Introduction

1.1. Background

By 2040, the global primary energy consumption is expected to increase by 32 % compared with that in 2017 [1]. Buildings consume a large proportion of the total energy produced. Most people spend 90 % of their day indoors [2]. Combined with rapid economic and technological developments and to enhance their living conditions, individuals are increasingly focusing on improving heating, ventilation, and air conditioning (HVAC) systems, hot water production systems, lighting systems, and other exterior equipment. Buildings accounted for 32 % of the world's total energy use in 2010, with the building sector in certain developed countries consume up to 40 % of the total energy [3]. In addition to consuming large amounts of energy, the construction sector contributes to approximately one-third of global greenhouse gas emissions [4].

Numerous factors influence the urban building energy (UBE). An increasing number of studies have shown that urban wind environment (UWE), including urban heat and humidity, has a significant impact on building energy consumption as a key urban microclimate element [5]. UWE refers to the comprehensive phenomenon of wind distribution in time and space within a city and its interaction with the urban environment and is an integral part of the urban climate. The UWE differs significantly from the wind environment in urban suburbs, where the absence of buildings and other factors lead to higher wind speeds than in urban areas [6]. This review primarily investigates the impact of UWE on building usage. The change in airflow around the building and the

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convective heat transfer of the building envelope are the main processes involved in the UWE affecting the building energy loss [7–9].

The urban building energy model (UBEM) is a tool for assessing the energy consumption in urban buildings [10]. Most physics-based UBEMs have evolved from building energy models (BEMs). Given the significant influence of UWE on the building energy consumption, it is essential for UBEMs to incorporate models that describe their impact [11]. With the continuous development of BEMs, many considerations have been made regarding the impact of UWE. Currently, common UBEM tools (e.g., CityBES, UMI, and CItySIM) combine weather files and coupled climate models to consider UWE [12–16]. However, current methods for calculating and inputting UWE in UBEMs lack accurate UWE data and often require a combination of microclimate models to simulate UWE changes in real-time [17]. UBEM tools lack consideration of integrated microclimate (e.g., local wind speed and windward) effects and must couple Computational Fluid Dynamics (CFD) methods to perform dynamic simulations [18]. Therefore, it is necessary to summarize the modeling methods of UWE in numerical simulations to provide a basis for relevant researchers to study the impact of the UWE on building energy.

Based on the above discussion, three major objectives are presented in this review. First, we comprehensively summarize the mechanisms and theoretical models of the impact of the UWE on the energy use of urban buildings, separately addressing building and urban scales. Second, we review the existing methods and tools for calculating the energy consumption of urban buildings considering the UWE effects and summarize the developments and shortcomings in this field. Finally, we provide an overview and evaluation of the validation and calibration methods for assessing the impact of UWE on the use of urban buildings.

1.2. Previous reviews

Although few reviews have focused on the influence of UWE on UBE use, some reviews relevant to this topic can be found. Most of these studies focused on only one aspect, namely, indirect influences. Ferrando et al. [19,20] reviewed the UWE data input in a building energy model. Delzendeh et al. and Chen et al. [21,22] investigated the impact of occupant behavior, such as window opening and ventilation, on building energy consumption. Li et al. [23] explored the relationship between UWE and urban heat island (UHI) effect, emphasizing their influence on building energy consumption. Malys et al. [24] conducted a study investigating the substantial impact of microclimate, including UWE, on the building energy consumption. Although the impact of UWE on building energy consumption has been addressed in most studies, few studies have emphasized the mechanisms and modeling approaches of UWE. Hong et al. [25] reviewed and compared the coupling methods of the UBEM with other urban system models. Wong et al. [20] provided a summary review considering urban climate factors, such as UWE, in different building energy models. Lauzet et al. [26] illustrated how building energy models consider the local climate in an urban context, including computational models in some BEMs and coupling methods with microclimate models.

Despite these efforts, an in-depth and comprehensive review of the impact of the mechanisms and modeling of UWE on UBE is still lacking. Most existing studies input UWE data through building energy models or microclimate models coupled with building energy models to assess the impact of UWE. There is a lack of comprehensive reviews summarizing the characteristics of UWE on building energy consumption in terms of theoretical models and modeling methods.

This review examines the mechanisms and theoretical models that underline the impact of UWE on building energy consumption. It summarizes the current approaches and workflows adopted by various energy consumption models when considering UWE at both building and city scales. This study provides valuable guidance for energy-saving measures in urban areas affected by UWE and for the optimization of numerical models.

1.3. Objectives and structure of the review

The objectives of this review are as follows:

- To provide a comprehensive review of the mechanisms by which the UWE affects building energy consumption, including ventilation, infiltration, convective heat transfer, and indirect effects.
- To investigate the development of existing theoretical models, including calculation methods for UBE consumption models.
- Identifying methods and tools for practical applications of UWE in energy model workflows and investigating studies on other urban models.
- To determine validation methods and metrics, propose modeling tools, and apply methods for UWE input and calculation.

Considering the research background and gaps discussed above, this study conducts a systematic review of the mechanisms, theoretical models, simulation tools, and methods that influence the UBE consumption of UWE. The remainder of this paper is structured as follows: Section 2 introduces the impact mechanisms of UWE on UBE and theoretical models; Section 3 introduces the UWE data acquisition and general workflow in building-scale simulations; Section 4 summarizes the numerical tools and simulations related to the impact of UWE; and Section 5 presents two kinds of research for validating and calibrating the impact of UWE on energy consumption in urban buildings and reviews relevant studies. Fig. 1 illustrates the framework of this study.

2. Impact mechanisms of UWE on UBE and basic theoretical models

Various mechanisms describe the impact of the UWE on the UBE. UWE, as one of the microclimate elements, according to existing research, has fundamental impact mechanisms on UBE that mainly include: (1) influencing other microclimate elements; (2) affecting the heat transfer of building envelope and HVAC loads; (3) altering the energy exchange between buildings within the urban environment and related urban climatic effects (such as the UHI); (4) influencing the energy consumption behavior of other urban elements (such as vegetation, transportation, and human activities); and (5) other indirect mechanisms. These mechanisms manifest differently at both the building and urban scale. The physics behind these mechanisms and their theoretical models are discussed below.

The impact of the UWE on building energy consumption can be attributed to several key factors: (1) UWE influences building ventilation and infiltration, affecting the overall energy balance [9,27]; (2) UWE alters convective heat transfer on the building envelope, resulting in variations in energy exchange [28–30]; (3) UWE indirectly impacts building energy consumption by influencing other factors such as occupant behavior, wind-driven rain, pollutant dispersion, UHI, urban green infrastructure (UGI), and pedestrian wind comfort [23,31–34]. In this section, we provide an in-depth review of the underlying principles and methodological models associated with these mechanisms. Fig. 2 illustrates the mechanisms by which UWE influences building energy consumption.

2.1. Ventilation and infiltration effect of UWE

The air exchange inside and outside a building can categorized as: ventilation and infiltration. Ventilation refers to the deliberate introduction of outdoor air into a building and can be categorized into two types: natural and mechanical ventilation. Infiltration refers to the ingress of outdoor air into a building through unintended openings, such as cracks and gaps, and the regular use of exterior doors for entry and exit. This is commonly referred to as air leakage and highlights the unintentional nature of the airflow. Ventilation and infiltration are driven by the pressure differences in the building envelope caused by

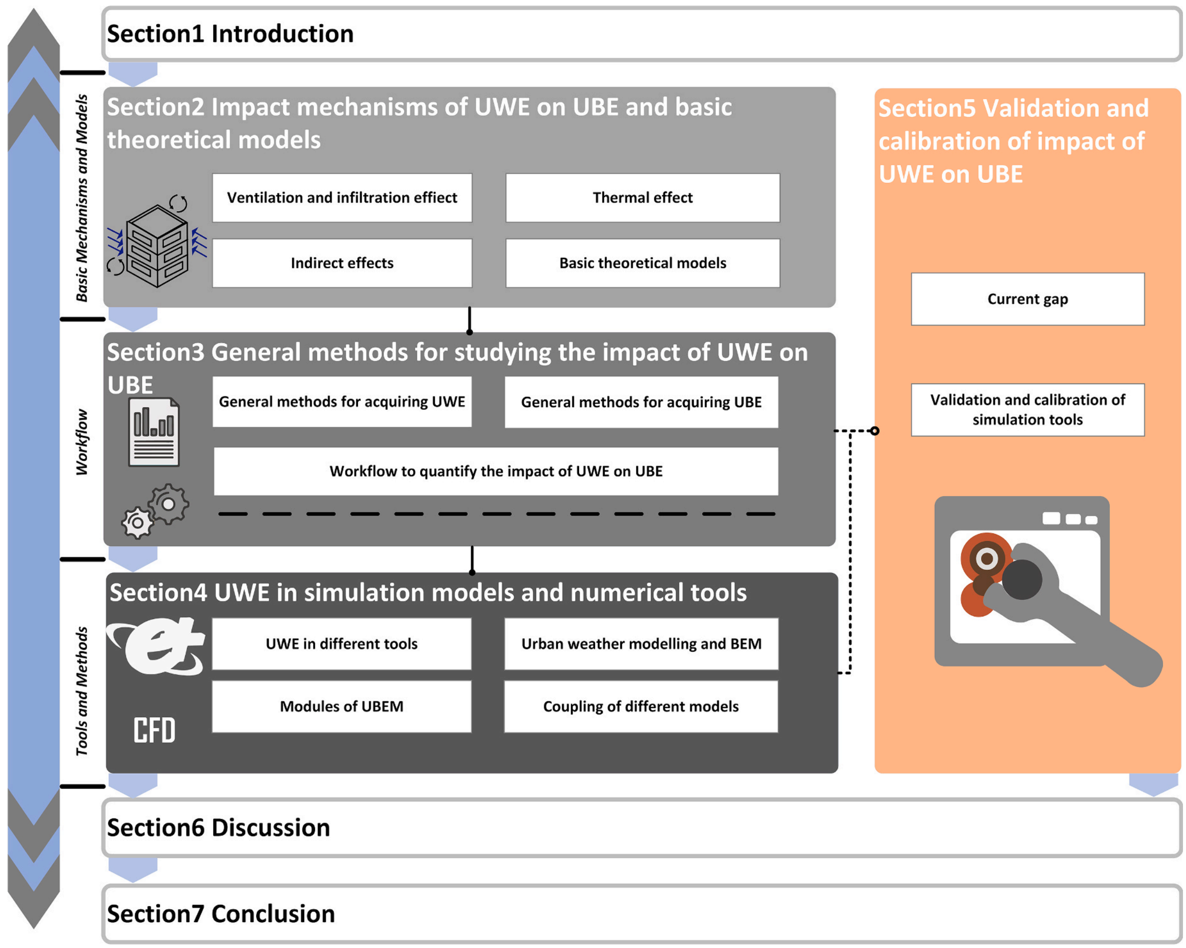

Fig. 1. Framework of study.

wind or buoyancy.

Research has shown that UWE can significantly affect the infiltration of buildings, thereby influencing heating and cooling loads [35]. Emmerich and Persily [36] revealed that 13 % of the heating load and 4 % of the cooling load in office buildings can be attributed to air infiltration. Ventilation is typically induced by three mechanisms: the stack effect, wind pressure, and mechanical ventilation. The UWE influences the variation in pressure gradients by changing the wind speed and direction [37]. Therefore, it is crucial to develop relevant models based on these mechanisms to calculate indicators such as air change rates, which are essential for describing changes in building energy consumption [38].

In previous studies, four primary categories of predictive models have been used to estimate infiltration in buildings: theoretical, empirical, single-component, and building characteristic models [39]. Empirical models are closely related to building energy usage and simulation tools and can be further divided into two types: single-zone infiltration models (e.g., Lawrence Berkley National Laboratory (LBL) model, Chartered Institution of Building Services Engineers (CIBSE) model, and air infiltration development algorithm (AIDA) model) and multi-zone infiltration models (e.g., Building Services Research and Information Association (BSRIA) model and National Research Council (NRC) model). Since the development of ventilation (airflow) models in the 1970s, more than sixty different models have been developed [40–43]. According to Choi et al. [44], these models can be classified in three stages: early stage (1970–1989), development and consolidation stage (1990–2015), and integration into building energy simulation programs (2016–present). This is due to the thermal effects resulting from ventilation and infiltration, which in turn impact building energy consumption. Researchers have recognized the interactions between building airflow dynamics and thermodynamics. In certain cases, this interaction extends to the dynamics of air pollutant dispersion. Consequently, an approach has been proposed to integrate multi-zone airflow analysis with building thermodynamics and pollutant dispersion analysis (e.g., discrete thermal-flow analysis method (DTFAM)) [45]. Table 1 lists the main ventilation and infiltration models, most of which are used in building energy simulation tools or as their predecessors.

The simplest model for predicting the ventilation performance is the semi-empirical model, which shows that the UWE affects the ventilation airflow rates by influencing the airflow around the building [46]. For building infiltration, LBL developed the first widely used infiltration model, the LBL model, the modern version of which is known as the ASHRAE basic model [47]. More advanced methods for predicting ventilation and infiltration include multi-zone airflow network modeling and CFD simulation models. An essential trend in enhancing the accuracy of multi-zone airflow network models is their integration with energy simulations and CFD. This integration provides the necessary boundary conditions for energy simulations and CFD models, resulting in improved accuracy and reliability [48–50]. The application of major infiltration and ventilation models in building energy simulation tools is discussed in detail in Section 4.

CFD was first introduced to the building industry in the 1970s [51]; CFD models allow fast and reliable calculation of detailed parameters of building ventilation performance and have been widely used in UWE and urban thermal environment simulations [52]. CFD models can predict ventilation and infiltration by the UWE more accurately than multi-zone airflow models. Four CFD turbulence models are commonly used to predict the ventilation and infiltration performance of the UWE,

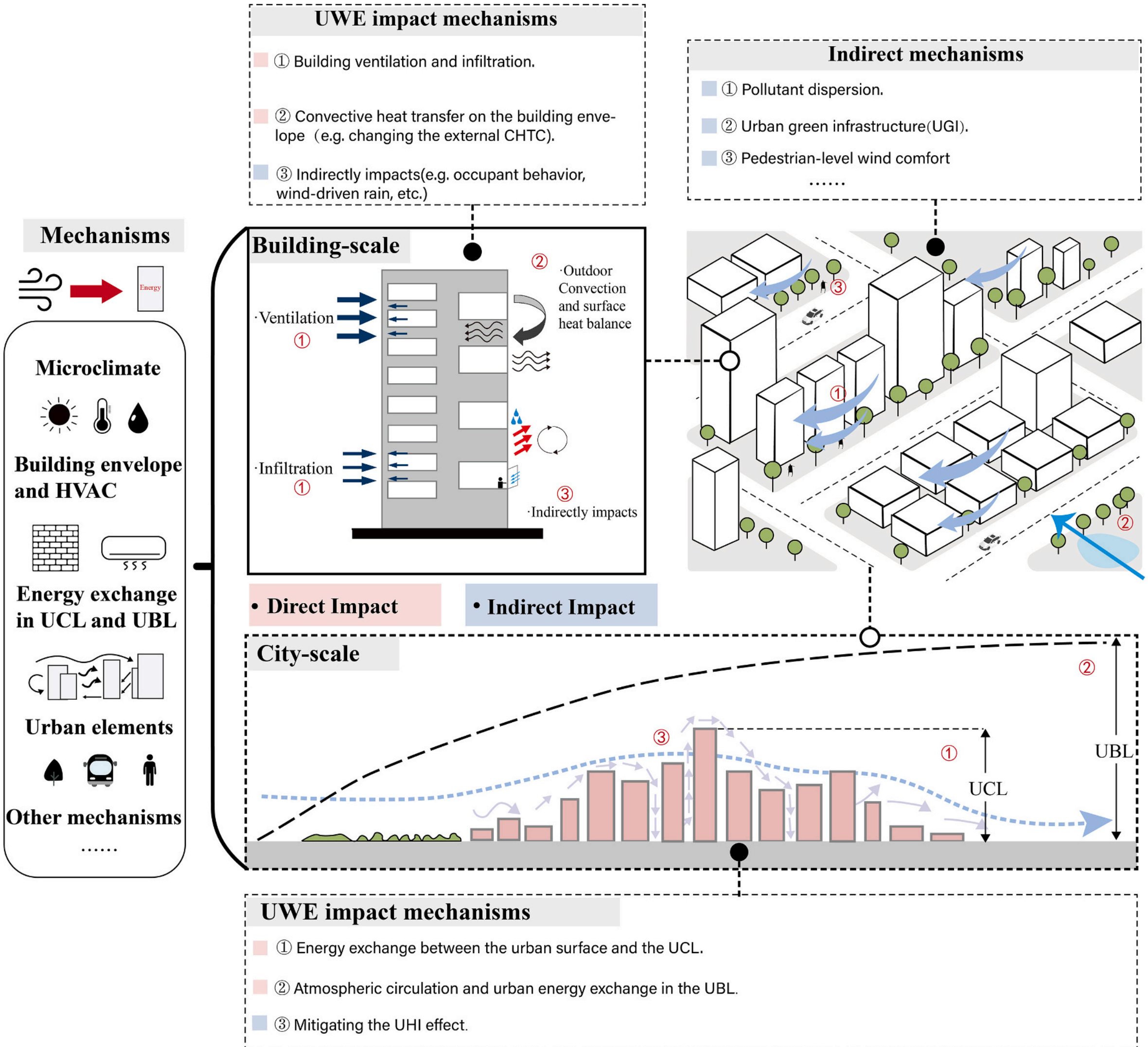

Fig. 2. Mechanisms underlying the impact of UWE on UBE.

namely, (1) direct numerical simulation (DNS); (2) large-eddy simulation (LES); (3) Reynolds averaged Navier–Stokes (RANS) equations with turbulence models; (4) detached eddy simulation (DES).

DNS provides highly reliable results by solving the Navier-Stokes equations without approximations or modeling. However, it requires an extremely fine grid resolution down to the fluid's Kolmogorov microscale, which demands substantial computational resources [53]. As a result, DNS is rarely used in practical studies of building ventilation and infiltration due to these computational limitations. Pope [54] illustrated that LES performance depends on factors like the SGS model, mesh, and numerical scheme. RANS models, including the standard k-ε model, Realizable k-ε model, RNG k-ε model, Low-Re k-ε model, SST k-ω model and so on, are widely used in indoor environmental simulations. Because the RANS model is significantly faster than the LES model, the RANS model is mostly used in building ventilation and infiltration simulations. Table 2 summarizes the CFD models and their characteristics.

2.2. Thermal effect of UWE

In urban settings, building heat transfer processes involve factors such as solar radiation, conduction through the building envelope, outdoor convection, and evaporative heat dissipation from external surfaces [58]. Studies indicate that the external convective heat transfer coefficient (CHTC) is a crucial physical factor affecting the UBE [65]. Calculating the CHTC requires consideration of the influence of the UWE on the building surroundings.

CHTC is an important parameter not only for building thermal loads but also for urban microclimate [66]. The CHTC is usually defined as:

$$h_c = \frac{q_{c,w}}{(T_w - T_{ref})}, \tag{1}$$

where $q_{c,w}$ is the convective heat flux perpendicular to the wall [W/m^2], T_w is the wall surface temperature [°C], and T_{ref} is the reference temperature [°C]. The convective heat transfer is expressed as follows:

$$Q_c = h_c A (T_{surf} - T_{wind}), \tag{2}$$

where h_c is the CHTC, A is the surface area of the wall [m^2], T_{surf} is the temperature at the surface [°C], and T_{wind} is the temperature of the surrounding wind [°C].

The most commonly observed form of CHTC correlation in the surveyed literature is the power-law function of u_{10} (linear expressions also exist for CHTC expressions that incorporate free-convection conditions) [67], which can be expressed as:

$$h = a u_{10}^m \tag{3}$$

where h is the surface-averaged external CHTC, u_{10} is the velocity at a

Table 1
Primary ventilation and infiltration models related to building energy consumption.

	Year	Model type	Model name	Supplemental
Infiltration models	1970	Multi-zone model	BSRIA model	
	1976	Multi-zone model	NRC model	
	1977	Multi-zone model	Electric-resistance model	
	1979	Multi-zone model	OFP model	
	1997	Multi-zone model	IAQ model	
	1977	Single-zone model	BRI model	
	1980	Single-zone model	LBL model	AIM-2 model predecessor
	1989	Single-zone model	AIDA model	
	1997	Single-zone model	CIBSE model	A module of the NiteCool model
Ventilation (airflow) models	1998	Empirical model	Semi-empirical model	
	2001	Empirical model	Semi-analytical model	Single-side ventilation
	1989	Network models	AIRNET model	
	1990	Network models	COMIS model	
	1993	Network models	CONTAM model	The first version appeared in 1993 and has been updated since then
	1989	Integrate models	DTFAM model	
	2002	Integrate models	Zonal model	

height of 10 m above the ground at the measurement station [m/s], and a and m are constants.

The accuracy of the CHTC directly affects building energy consumption. Recent studies have conducted actual and simulation-based investigations to assess the accuracy of CHTC and its relationship with the building envelope. They verified the correlation between UWE and CHTC, specifically for roof wind speed, near-surface wind speed, and building surface wind speed [68–70]. Understanding the relationship between UWE and CHTC helps clarify how UWE affects building energy consumption. Montazeri et al. [71] proposed a generalized expression for the average forced CHTC of building façades and roof surfaces considering parameters such as reference wind speed, windward building façade width, and height.

At the city scale, the CHTC plays a significant role in building energy consumption within diverse urban communities. The impact of the CHTC is determined using four key variables: wind direction, building shape, building height, and building spacing. At the neighborhood scale, the external windward side of a building has a direct impact on CHTC accuracy and thus on energy consumption results [7]. Shen et al. [72] developed a neighborhood-scale building energy simulation scheme combined with CFD simulations to improve the accuracy of the CHTC. The urban environment significantly influences the UWE around buildings and the CHTC of building surfaces. Therefore, incorporating the UWE and other urban environmental parameters into CHTC calculations is crucial for accurately assessing building energy consumption [73].

Table 2
CFD models and features for building ventilation and infiltration prediction.

Ref.	CFD model	Modified approach	Research subjects	UWE related variables ters st
[55]	LES	Wall-adapting local eddy viscosity	Building (room)	Relative humidity, ventilation rate, ventilation pattern
[56]	LES	Wall-adapting local eddy viscosity	Building (balcony)	Mean wind speed
[57]	LES	Self-adaptive subgrid-scale	Building(ducts)	Mean friction velocity, mean velocity
[58]	RANS	k-ε model, k-ω model	City, block	Infiltration rate, wind speed
[59]	RANS	Kato-Launder k-ω model	Building, Material	Velocity, temperature, turbulent kinetic energy
[60]	RANS	Standard k-ε model, RNG k-ε model, SST k-ω model	Building,	Wind speed, turbulent kinetic energy
[61]	LES	–	Building	Wind direction, wind speed
[62]	RANS	RNG k-ε model (low-rise buildings), SST k-ω model (high-rise buildings)	Building (Low-rise, High-rise)	Wind direction, wind speed
[63]	RANS	RNG k-ε model	Building (large-space)	Air infiltration rate, buoyancy forces, wind speed
[64]	DES	Delayed Detached-eddy Simulation	Building (interference between buildings)	Velocity, turbulence kinetic energy and dissipation

2.3. Indirect effects of UWE

In addition to directly affecting ventilation infiltration and convection and thus impacting building energy consumption, UWE can indirectly impact building energy consumption. These indirect effects include: (1) pollutant dispersion, (2) occupant behavior, (2) wind-driven rain (WDR), (4) UHI, (5) UGI, (6) and pedestrian-level wind comfort.

Air pollution can also lead to increased household energy consumption [74]. There is an interactive relationship between UWE, air pollution, and urban form from the macro-urban scale to the micro-neighborhood scale [75], suggesting that UWE can affect building energy consumption. For example, these factors accelerate pollutant diffusion. The most commonly used index is the volumetric flow rate (Q), which describes the relationship between wind speed and pollutant dispersion [76]. The equation used is as follows:

$$Q = \left(\int_A \vec{u} \cdot \vec{n} \, dA \right), \tag{4}$$

where $\vec{u}$ is the wind velocity vector; $\vec{n}$ is the direction normal to the opening domain surface; and A is the opening surface area.

Zhang et al. [77] found that the energy-saving potential of occupant behaviors, such as window opening, can range from approximately 5 %–30 %. Wind speed variation has a statistically significant effect on the window-opening behavior of occupants [78]. Air change rate (ACR) can be used to describe the interaction between occupant behavior and window opening [79]. WDR is an important factor that influences the hygrothermal performance of building envelopes, which in turn affects building energy consumption [80]. Recent studies using CFD simulations have shown that WDR loads are related to the UWE, with lower wind speeds resulting in lower WDR loads on building facades [81]. It is widely recognized that UHI has a significant impact on building energy use and can lead to an average 19 % increase in building cooling energy use [23]. By introducing wind speed ratio (WsR) and UHI intensity index, Liu et al. [82] showed that primary and secondary wind corridors are capable of accelerating wind speeds above 0.57 m/s and 0.75 m/s, respectively, exhibiting certain UHI mitigation benefits. Zhu et al. [83,84] proposed a grading system to demonstrate the energy-saving effect of UGI, wherein the UWE affects the aerodynamic effect of the UGI. The turbulent interaction between the airflow and plant canopy can be expressed as follows:

$$S_k = \rho LADC_d\left(\beta_p U^3 - \beta_d Uk\right), \tag{5}$$

$$S_\varepsilon = \rho LADC_d\left(C_{\varepsilon 4}\beta_p \frac{\varepsilon}{k}U^3 - C_{\varepsilon 5}\beta_d U\varepsilon\right), \tag{6}$$

where β_p is the fraction of the mean kinetic energy converted to k by drag [−], β_d is the dimensionless coefficient for the turbulence cascade short-circuit [−], $C_{\varepsilon 4}$ and $C_{\varepsilon 5}$ are model constants; ρ is the air density [kg/m^3], and C_d is the mechanical drag coefficient [−]; LAD [m^2/m^3] is the leaf area density.

Many studies have proven that wind speed significantly affects outdoor thermal comfort and wind is an important factor in heat and humidity exchange [85]. The wind environment directly affects pedestrian wind comfort, thus changing the energy consumption behavior of pedestrians, for example, by going indoors for cooling activities. However, current research on pedestrian wind environment focuses on the evaluation of indicators and the influence of building form [86]. No study has systematically examined this indirect effect.

Although numerous indirect effects of UWE have been demonstrated in related studies, a comprehensive summary of these indirect impacts on building energy consumption mechanisms is currently lacking. The existing research has predominantly focused on the direct effects of UWE. Future investigations should explore additional indirect mechanisms through which UWE affects building energy consumption, such as its influence on urban transportation. Furthermore, incorporating these indirect mechanisms into energy simulation processes should enhance the accuracy of the simulation results.

2.4. Basic theoretical models

2.4.1. Theoretical models of ventilation and infiltration

In BEMs, theoretical models for simulating ventilation and infiltration can be categorized as follows: (1) analytical models, (2) empirical models, (3) small-scale experimental models, (4) full-scale experimental models, (5) multi-zone models, (6) zonal models, (7) CFD models, and (8) hybrid models [87]. In practical applications, multi-zone models are commonly used to simulate the ventilation and infiltration processes. However, the boundary conditions for multi-zone models are often derived from empirical models to simplify calculations.

The infiltration caused by the UWE is related to the wind coefficient (fw), leakage area, and effective wind speed (v) as well as to the measurement of wind speed by meteorological stations. The basic formula for the total infiltration rate, considering the UWE and temperature, is as follows [88]:

$$Q_{\mathrm{int}} = \sqrt{Q_s^2 + Q_w^2} = A_0 \cdot \sqrt{\left(f_s^*\right)^2 \cdot \Delta T + \left(f_w^*\right)^2 \cdot v^2} = \frac{A_L}{1000}\sqrt{C_s \cdot \Delta T + C_w \cdot v^2}, \tag{7}$$

where C_s and C_w are the stack and wind coefficients derived from f_s* and f_w*, respectively, f_s* is the reduced stack, and f_w* is the wind factor.

In BEMs (e.g., EnergyPlus), the consideration of outdoor airflow relies on an empirical model defined as the function of temperature and wind speed with respect to the design values input by the user. Airflow network model (AFN) can dynamically simulate the airflow at each time step by calculating the total pressure difference between two air nodes. The wind pressure on the building envelope is usually expressed by the pressure coefficient (C_p), with the basic equation as follows [89]:

$$C_p = \frac{P_x - P_o}{P_d}, P_d = \frac{\rho \cdot U_h^2}{2}, \tag{8}$$

where P_x is the static pressure at a given point on the building façade [Pa], P_0 is the static reference pressure [Pa], P_d is the dynamic pressure [Pa], ρ is the air density [kg/m^3], and U_h is the wind speed, which is often considered at a building height h in the upstream undisturbed flow [m/s].

In terms of ventilation, models predicting the wind pressure coefficient and surface-averaged wind pressure coefficient are the most commonly used, and the two representative programs for airflow simulation are AIRNET and COMIS. In terms of infiltration, single- and multi-zone models have been developed, such as the LBL and AIM-2 models, on which the BEM continues to develop and apply ventilation infiltration modules. BEMs consider ventilation and infiltration effects from ventilation and infiltration constants, flow rate equations, and CFD modules, such as the TRNFLOW model used to calculate flow rate equations in TRNSYS and the direct setting of ventilation and infiltration rates for simulation in ESP-r [90]. DeST uses VentPlus to simulate natural building ventilation, combining ventilation and thermal simulation [91]. EnergyPlus has three infiltration models (design flow rate model, effective leakage area model, and flow coefficient model) and two ventilation models (design flow rate and wind and stack with open area model) [92,93]; TRNSYS has five infiltration models, which can be divided into two categories: regression and leakage area models. However, it does not have an airflow module and generally performs calculations using COMIS through the TRNBuild interface [94,95].

In summary, there are two main challenges in considering the impact of UWE on building energy consumption using simulation tools. Theoretical models that consider ventilation and infiltration are not available or are poorly developed in some tools. Further, some tools rely mainly on experience to set specific parameters in practical applications, and weather data inputs containing UWE do not accurately reflect the impact of UWE in the building neighborhood. Currently, there are no tools that can directly simulate the impact of UWE on building energy consumption. Therefore, the research trend in recent years has been to combine BEMs with microclimate modeling. Subsection 4.1 provides a detailed introduction to the BEMs tool, and Subsection 4.2 presents a review of the research on the coupling of BEMs with urban weather modeling.

2.4.2. Theoretical models of thermal effect

Several theoretical models have been developed for the BEMs of this module. Since the development of the classic model of external convection in the 1930s, models such as the McAdams, SimpleCombined, thermal analysis research program (TARP), MoWiTT, and DOE-2 have been developed [29,96–99]. Most of these models are used only in one type of BEM, such as IES and IDA, both of which contain only the McAdams model. Some BEMs also allow users to choose multiple models, such as EnergyPlus and ESP-r, but some do not consider CHTC models.

In addition, some models based on reduced-scale and on-site full-scale experiments have more comprehensive considerations for building and UWE elements, such as multi-surface modeling, turbulent natural and forced convection, and smooth vertical surface calculations. The TARP is an important predecessor of EnergyPlus, which is no longer used in subsequent versions, and is very similar to the building load analysis and system thermodynamics (BLAST) model [100]. The MoWiTT model was derived from experimental investigations conducted at the Mobile Window Thermal Test (MoWiTT) facility, as conducted by Yazdanian and Klems [101] for vertical surface calculations on the windward or leeward sides (e.g., glass). The DOE-2 model is a combination of the TARP and MoWiTT models [102] and considers not only the windward direction but also the surface tilt angle and texture. Table 3 summarizes the common CHTC theoretical models for most BEMs.

Major CHTC models are typically based on different scales of experiments and definitions of reference wind speeds. The difference in building energy consumption based on different CHTC models can reach

Table 3
Classical CHTC models in BEMs.

Ref.	Implementation in BEMs	Theoretical models	Equation	Variable description
[106]	EnergyPlus	SimpleCombined model	$h_{c,ext} = D + EVz + FVz^2$ (9)	D,E,F: material roughness coefficients; V_z: local wind speed calculated at the height above ground of the surface centroid.
[103]	ESP-r,IES,IDA	McAdams model	$h_{c,ext} = 5.678\left[m + n\left(\frac{V_f}{0.3048}\right)^p\right]$ (10)	m,n,p: roughness parameters for smooth and rough surfaces; V_f: free stream velocity.
[103]	ESP-r,TAS	CIBS model	$h_{c,ext} = 4.1V_{loc} + 5.8$ (11)	V_{loc} is 1 m/s for sheltered buildings; 3 m/s for normal buildings and 9 m/s for severe buildings.
[97]	EnergyPlus	BLAST model	$h_{c,ext} = h_{c,for} + h_{c,nat}$ $h_{c,for} = 2.537W_fR_f\left(\frac{PV_f}{A}\right)^{1/2}$ (12)	W_f: wind direction modifier; R_f: surface roughness multiplier; P: the perimeter of the surface; A: the area of the surface.
[107]	EnergyPlus,ESP-r	ASHRAE model	$h_{c,ext} = 18.6V_{loc}^{0.605}$ (13)	V_{loc} is 0.5 m/s for V_{10} and else is $0.25V_{10.}$
[97]	EnergyPlus (predecessor)	TARP model	$h_{c,ext} = h_f + h_n$ $h_f = 2.537W_fR_f\left(\frac{PV_z}{A}\right)^{1/2}$ (14)	W_f: 1.0 for windward surfaces; R_f: surface roughness
[101]	EnergyPlus,ESP-r	MoWiTT model	$h_{c,ext} = \sqrt{\left[C_t(\Delta T)^{\frac{1}{3}}\right]^2 + \left[aV_z^b\right]^2}$ (15)	Ct: turbulent natural convection constant; ΔT: temperature difference between the surface and air
[108]	EnergyPlus	DOE-2 model	$h_{c,ext(glass)} = \sqrt{h_n^2 + \left[aV_z^b\right]^2}$ $h_{c,ext(less\ smooth)} = h_n + R_f\left(h_{c,ext(glass)} - h_n\right.$ (16)	a: constant; h_n: natural convective heat transfer coefficient.

approximately 30 % [103]. In recent years, some studies have used CFD combined with BEMs for simulations, which can improve the accuracy of energy consumption and hc,ext calculations. Shan et al. [104] used cosimulations with EnergyPlus and Fluent to predict the thermal environment more accurately than independent CFD simulations, with an overall relative error of approximately 0.94 %. Miguel et al. [105] used OpenFOAM to calculate convective heat transfer from surrounding buildings in combination with EnergyPlus to consider the microscale outdoor conditions of interactions. As shown in Tables 3 and it is imprecise to calculate the effect of the UWE on building energy consumption using only the traditional CHTC model. Lauzet et al. [26] proposed the coupling of BEMs and urban weather models, which can better consider the local UWE and other climates, representing the future direction of development.

2.4.3. Theoretical models of indirect impacts

Subsection 2.3 summarizes the indirect impact of the UWE on building energy consumption. Herein, we discuss the relevant theoretical models for building simulation programs. Currently, occupant behavior is considered in most building energy simulation tools. Occupant behavior is represented using simplified static schedules and fixed settings (e.g., the deterministic schedule method in EnergyPlus and DesT), which overlook the stochastic and dynamic nature of occupant behavior. In 2005, Wang et al. [109] proposed a probabilistic model to predict occupant behavior in offices; however, it had limitations in describing different regions. Subsequently, another study introduced an agent-based model of occupancy dynamics, which has the advantage of being applicable to various regions and numbers of occupants [110]. In recent years, research in this field has focused on deterministic schedule models (e.g., Bayesian probability and support vector regression), stochastic schedule methods (e.g., hidden Markov model and dynamic Markov time-window inference), and more advanced machine-learning models (e.g., decision trees and genetic programming). Although many advanced models have been developed, obtaining occupancy schedules for building energy models using occupancy models remains the most commonly used method. The integration of behavioral models and numerical tools is still in its early stages [111]. However, there is still a gap in the integration of occupancy models with building energy tools.

In most BEMs, no dedicated module exists for considering other indirect influencing factors such as pollutant dispersion, which often requires CFD tools for calculation [75]. In the future, new theoretical models may need to be developed to account for these indirect factors and more accurately assess the impact of UWE on UBE.

3. General methods for studying the impact of UWE on UBE

3.1. General methods for acquiring UWE

3.1.1. UWE spatio-temporal heterogeneity

Recent studies have shown that the UWE varies with time and space [112,113]. For example, from a spatial perspective, urban center areas often have strong local circulation and turbulence owing to the blockage of high-rise buildings and UHI. Liu et al. [114] showed that UWE ventilation varies in different administrative zones in Shenzhen and that ventilation resistance can be improved by urban density and ventilation corridors. However, the characteristics of the UWE vary with time. For example, the UWE varies greatly between daytime and nighttime, with strong convection and turbulence usually present during the daytime which becomes smoother at night [115]. In addition, Pishgar-Komleh et al. [116] showed that the UWE differs significantly from season to season, with higher mean wind speeds in the cold season than in the warm season. The interaction between the urban built environment and

UWE can also significantly affect the aerodynamic parameters of the UWE (e.g., drag coefficient (Cd), displacement height (d), and aerodynamic roughness length (zo)) [117]. Some urban morphology parameters can affect turbulence characteristics (e.g., frontal area index (FAI), building height, roughness length, and building area density) and the spatial and temporal distribution of the UWE [118].

Currently, the description evaluation indices for UWE focus on human comfort, such as pedestrian wind comfort [119], pedestrian thermal comfort [120], pedestrian height wind environment [127], and pollutant evaluation [122]. Mathematical and statistical descriptions of UWE exist, such as the Weibull and Rayleigh distributions [123], wind power density (WPD) [124], and wind energy density (WED) [125]. However, there is no consensus regarding the evaluation of temporal and spatial differences. Table 4 summarizes the methods used to evaluate the spatio-temporal heterogeneity of UWE.

3.1.2. UWE data acquisition methods

Various weather data sources, including UWE, are available for UBE simulations. These sources can be acquired through dataset files, real weather data, climate models, and CFD simulations (Fig. 3).

The dataset files typically come in three formats, ddy, epw, and stat, obtained from the official EnergyPlus website. Another approach is to use typical meteorological year (TMY) data generated based on historical weather data and statistical analyses (typically 30 years). TMY data, including UWE parameters such as wind speed and wind direction, can be generated using the weather generator of TRNSYS [132]. Different regions have different types of TMY data such as TMY2 in Canada and WYEC2 in the United States, with varying quantities of data and precisions [133]. TMY files may yield exceptions for UWE data [134]; however, the results generated using Meteonorm tend to align better with the average measured values.

Many studies have utilized real UWE data obtained through observational methods and local weather stations or meteorological offices for UBE simulations. Chong et al. [135] showed that it is crucial to use real local weather data for energy model calibration, considering typical weather files only when local data are unavailable. Parameters, such as infiltration rates, often require data obtained from real measurements because of their significant impact on building energy use [136]. Commercial websites such as Weather Underground and applications such as Open Weather Map provide access to local weather station data, facilitating UWE data acquisition [137].

Future weather datasets generated by regional climate models offer greater availability and resolution [138]. These datasets include global climate models (GCMs), regional climate models (RCMs), urban weather generator (UWG), and weather research and forecasting (WRF) models.

Table 4
UWE spatio-temporal heterogeneity evaluation studies.

Ref.	Perspective	Indices	Evaluation method
[121]	Spatial distribution	Probabilistic, etc.	CFD
[126]	Spatial and temporal distribution	Prevailing wind direction, etc.	ENVI-met
[127]	Temporal distribution	Maximum, minimum and average values per unit of time	Actual measurement
[128]	Spatial distribution	Numerical simulation	Actual measurement and simulation validation
[129]	Spatial distribution	Average value per unit space, etc.	Development of prototype parametric models
[130]	Spatial distribution	Identify ventilation corridors	WRF + CFD
[131]	Spatial and temporal distribution	The central measurement data	Meteorological data analysis

These methods are applied to different scales of UWE data acquisition. For instance, Eichelberger et al. [139] used global climate models to predict wind speed changes under global warming conditions, whereas regional climate models are used to assess the impact of climate variables on regional energy demand. Kamal et al. [140,141] used the urban weather generator to consider urban geometry, land use, and other factors to estimate climate data.

CFD has also been developed for UWE applications [119], enabling an accurate assessment of impact of UWE on UBE. CFD can provide a field wind-speed environment to building energy simulations and integrate them over dynamic time steps [142]. In general, building energy simulations tend to ignore microclimates, such as field UWE. Yi et al. [143] combined natural grid models and CFD simulations to obtain field UWE conditions. However, CFD simulations still require high computational costs at the city scale, and balancing accuracy and computational speed is a challenge for such methods for obtaining accurate UWE data [144].

Overall, the consideration of UWE data, whether through empirical, observational, or simulation-based approaches, plays a crucial role in accurately assessing and modeling UBE.

3.2. General methods for acquiring UBE

The most direct methods for obtaining UBE data currently consist of two approaches: using the BEM and urban building energy modeling for simulation and calculation, which are discussed in detail in Section 4. Three methods are commonly used in this respect: (1) measured data, (2) energy reports, and (3) open data portals. According to previous research, these three data acquisition methods can be used to validate the results of energy consumption models [145].

Measured data are typically challenging for individuals to acquire and must be provided by energy companies or departments. Sokol et al. [146] used electricity and natural gas data provided by a utility company in Boston, USA to validate their Bayesian method. Trepci et al. [147] evaluated the impact of transit-oriented development planning principles on UBE performance using energy reports provided by the U. S. Energy Information Administration. Seyedzadeh et al. [148] used 4900 recorded data points from arbn consult platform (arbnco Ltd.) to propose a machine-learning-supported non-residential building energy performance prediction model. These methods are crucial for validating the energy consumption calculation results.

3.3. Workflow to quantify the impact of UWE on UBE

The impact of UWE on building energy consumption involves several aspects that need to be discussed in terms of different simulation processes. Fig. 4 illustrates the manner in which the UWE is considered in the building energy simulation process, which is divided into data acquisition, simulation calculation, and data validation.

At the building scale, energy simulations rely on transient heat transfer models to dynamically simulate the heat transfer process of a building and calculate its energy consumption and loads. The energy consumption of a single building is influenced by factors such as its geometric features, energy system, weather parameters, and occupant behavior [149]. Among these, the UWE plays a crucial role as a weather parameter in the simulation, affecting both the input conditions and microclimate around the building.

At the city scale, UBE modeling comprises three main components: (1) data input, (2) thermal simulation, and (3) model calibration and validation of the results. The UBEM is suitable for evaluating hundreds or more buildings and considering urban climate factors such as the UWE [25]. TMY data are commonly used to input UWE data but often ignore the impact of urban microclimates or other elements. Current research is focused on climate models such as the UWG to estimate climate data [150] and on multi-scale models coupled with real-time feedback (e.g., CityFFD-CityBEM) to dynamically consider UWE

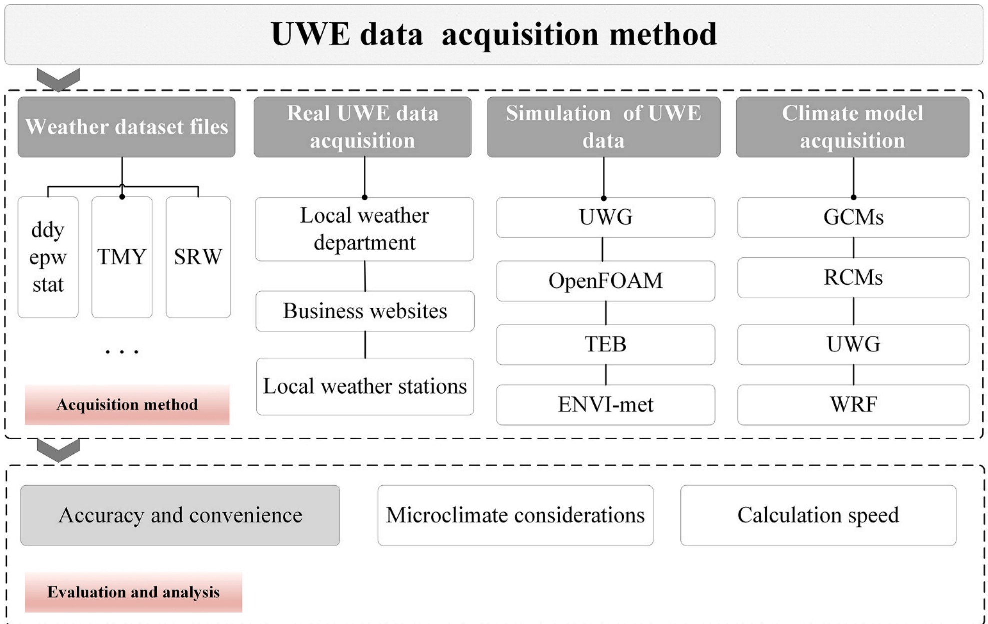

Fig. 3. Different UWE data acquisition methods.

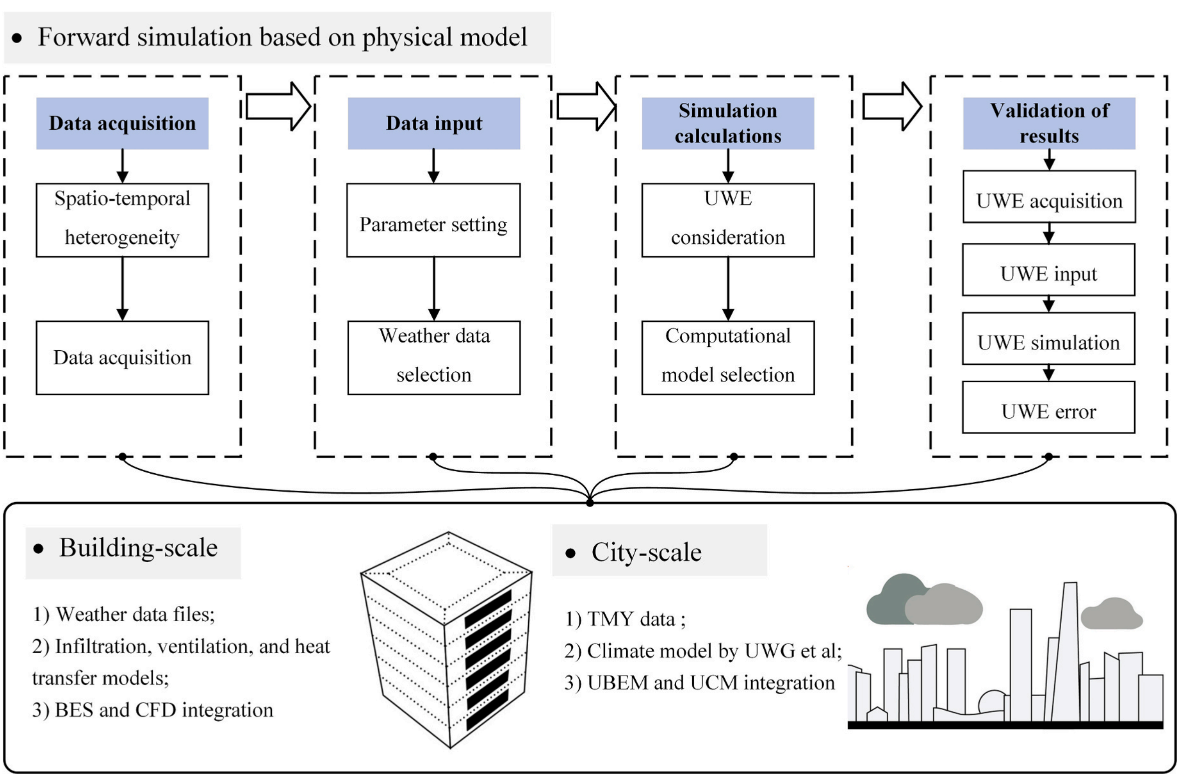

Fig. 4. Workflow of building energy simulation considering UWE.

impacts [151]. Section 4 reviews the UWE considerations for UBEM tools in detail.

4. UWE in simulation models and numerical tools

4.1. UWE in simulation methods and numerical simulation tools

4.1.1. BEM tools

Numerous techniques and tools are available for evaluating building energy consumption using BEM [152,153]. Widely utilized models include EnergyPlus, ESP-r, SOLENE, and TRNSYS. One of the key methods for simulating wall and roof heat fluxes in building energy simulations is the response factor method proposed by Nessi and Nisolle in the 1920s [154]. In the 1940s, Paschkis [155] at the University of Glumbia introduced the concept of the resistive capacitance (RC) network analysis for building simulation procedures. With the advancements in digital computer technology, analytical methods have been developed and widely adopted. The first building energy simulation programs such as DOE-2 and BLAST emerged in the 1960s in the USA. In the 1990s, EnergyPlus and other models were introduced and have since been extensively used and further developed [106]. Over the past decade, additional models such as BuildSysPro have been developed and studied [156,157].

Generally, in urban environments, building energy consumption is constantly influenced by the surrounding microclimate. The UWE is an important component of the microclimate and works in combination with geometry to influence the building energy exchange [158]. Lauzet et al. [26] states that it is meaningful to explore microclimate elements such as UWE with respect to building-scale energy use. This influence explains the differences between the simulation results and actual energy consumption.

4.1.2. UBEM tools

Since the 1970s, BEM has been widely used for building performance assessment, building stock analysis, and HVAC design [159]. In 2015, Reinhart and Davila [160] first defined UBEM as a type of building energy model covering spatial scales ranging from a single urban block to a district and even an entire city. The UBEM has been extensively applied in various domains, including building energy-efficient design, code compliance verification, building performance evaluation, retrofit assessment, and workflow optimization.

Currently, there are two main approaches for estimating building energy consumption at the urban scale: top-down and bottom-up [161]. The determination and input of the UWE are primarily performed using the bottom-up approach. The bottom-up approach involves subdividing buildings in a city into different types or individual units and considering their sum as the total energy consumption of the city buildings. Based on current research progress, bottom-up calculation models can be classified into:1) physics-based models, 2) data-driven models, 3) hybrid models, and 4) reduced-order models. Physics-based models consider detailed factors, such as the thermal properties of building envelopes, urban climatic conditions, inter-building interactions, heating and cooling systems, and occupant behavior, and can even simulate district energy systems. The calculation core of these models can be dynamic [162] or static [163]. They can also utilize calculation cores such as EnergyPlus, DOE-2, and eQUEST. Fig. 5 illustrates the different types of UBEM and the general workflow for simulating urban energy consumption while considering the UWE.

In the context of physics-based UBEM, the required data types can be categorized as: 1) geometric data (e.g., building footprints and building heights), 2) non-geometric data (e.g., HVAC systems, occupancy, and appliance patterns), and 3) meteorological data (e.g., solar radiation, temperature, relative humidity, wind speed, and wind direction). It has been acknowledged in Section 2.3 that urban climate significantly influences building energy consumption, and the choice of methods for obtaining weather data can lead to variations in simulation results [164]. Several existing tools are available for simulating weather data, such as BIM-based simulations (e.g., Revit), OpenFOAM, and UrbaWind. Mirza et al. [165] utilized OpenFOAM to analyze the mutual interaction between urban infrastructure and vegetation in a microclimate, where temperature and wind speed were found to experience maximum changes of 0.7 K and 0.4 m/s, respectively.

Data-driven UBEM approaches have also attracted considerable attention [166]. Many machine-learning algorithms such as linear regression, support vector machines, and neural networks have been employed to predict building energy consumption [167–169]. However, most of these data-driven models focus primarily on energy simulations of individual buildings, neglecting the interdependencies between buildings such as the interactions of UWE among different buildings [170]. The urban multi-scale environmental predictor is an open-source

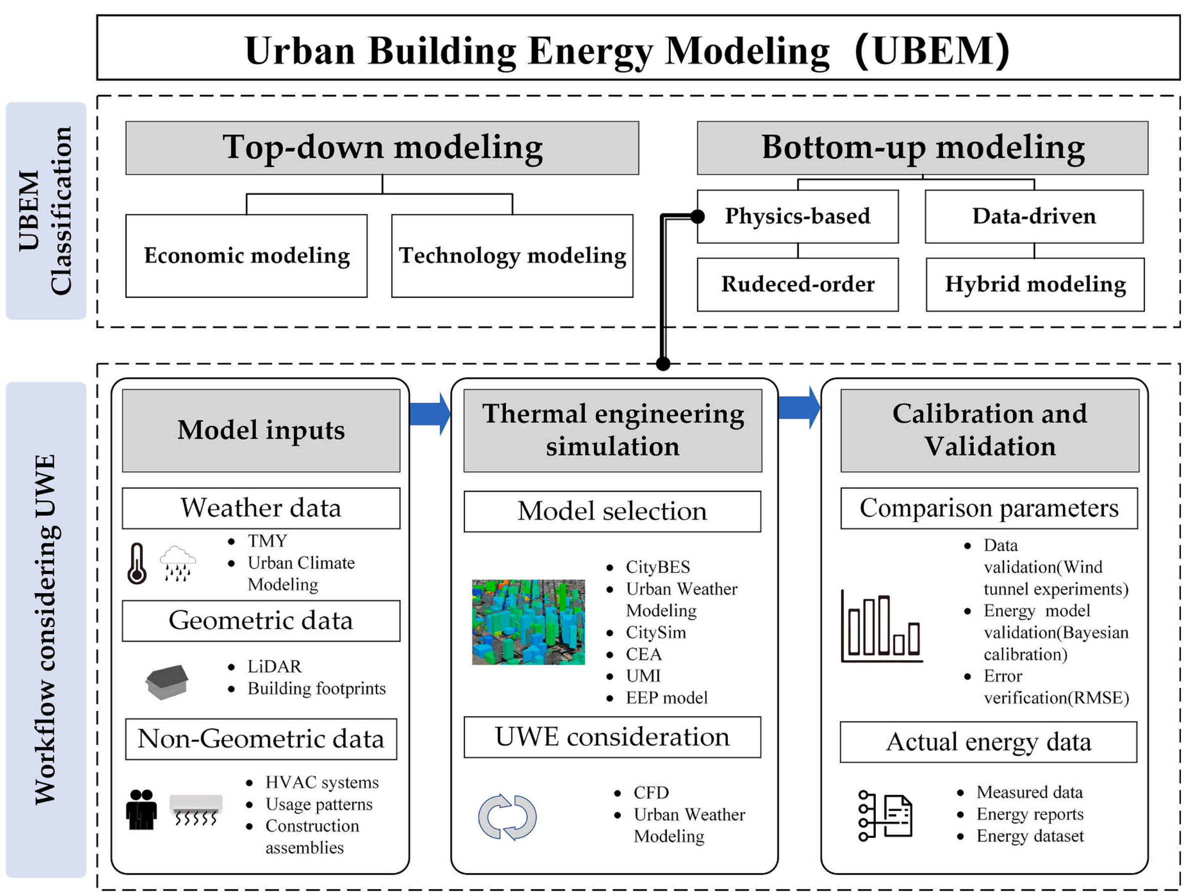

Fig. 5. The classification of UBEM and workflow for considering UWE.

tool that enables users to input atmospheric and surface data from various sources. It considers atmospheric turbulence effects to generate localized weather and UWE data [171].

4.1.3. Microclimate models and CFD tools

Micro-scale numerical models are important tools for engineers, architects, urban planners, and policymakers to analyze urban climates. It is more suitable for considering the integrated effects of urban form and building-scale UWE [172], which can generally be divided into physical and statistical models. Physical models include ANSYS FLUENT, ENVI-met, Townscope, OpenFOAM, and other CFD-based tools used for conducting simulations [173–175]. Statistical models are based on measured data and statistical methods to establish statistical relationships between meteorological parameters and various urban elements within cities, including the SOLUWEIG and RayMan models [176,177]. Generally, physical-based microclimate models consider ventilation calculations, surface convection with vegetation, urban morphology, and outdoor thermal comfort [178]. However, statistical models rely more on measured data inputs to calculate human thermal comfort (e.g., PET and PMV) and cannot be simulated for UWE.

Several studies have proposed novel simulation frameworks to improve the coupling between UWE and building energy simulations. For example, on the Grasshopper platform, ANSYS-FLUENT was integrated with EnergyPlus as a CFD output tool to enhance the coupling framework by incorporating the wind effects and airflow rates of the UWE into the outdoor thermal comfort [179]. Similarly, other studies have investigated the quantitative impact of local UWE on building energy by linking ENVI-met and EnergyPlus while considering outdoor surface convection due to UWE [180]. Furthermore, some studies have utilized OpenFOAM and WRF to acquire more accurate building-scale steady-state wind speeds and directions at a height of 10 m [181].

Although the use of microclimate models and CFD tools to simulate UWE is more flexible, it also faces the problem of high computational cost. In recent years, some fast and simplified numerical simulation methods such as the porous media model (PMM), fast fluid dynamics (FFD), and outdoor multi-zone model (MM) have emerged. Xu et al. [182] showed that porous media model and fast fluid dynamics were approximately 5 and 10 times faster than traditional CFD models, respectively, and the same study using the MM model was 5 and 20 times faster than ANSYS FLUENT and ENVI-met, respectively. Overall, this shows the direction of the future development and improvement of microclimate models.

4.2. Urban weather modelling and building energy simulation tools

4.2.1. UWE in urban canopy layer

The various boundary conditions affecting energy consumption at the building scale depend not only on the surrounding microclimate but are also influenced by large-scale urban climates [183]. According to Oke and Fernando et al. [184], the urban atmosphere can be divided into three scales: the) atmospheric boundary layer (ABL), urban boundary layer (UBL), and urban canopy layer (UCL).

The UWE in UCL refers to the integrated UWE effect in the space below the roof of a building, which has a direct impact on the energy consumption of a single building. Previous studies have summarized many metrics to quantify the UWE, such as exchange velocity, purging flow rate, mean age of air, amplification factor (AF), and wind velocity ratio (WVR) [121,185–187]. The urban canopy model (UCM), based on solving energy balance equations, is used to simulate the UWE and other climate elements by calculating the energy exchange between the urban surface and atmosphere. It includes key modules such as urban ground energy balance, building heat transfer, urban surface parameters, and wind speed correction. Mainstream UCM models include the building effect parameterization (BEP), TEB, TUF-3D, and WRF models, which consider the interaction between walls, roads, roofs, vegetation, and the UWE by incorporating the UWE into the energy balance model of the street canyon [188–190].

Masson et al. [191] classified the urban input data required for the most advanced mesoscale UCMs and microscale obstacle resolution models (ORMs) into five categories. UCMs can combine parameters such as roughness, albedo, building morphology, and materials to comprehensively assess urban atmospheric interactions ranging from a few hundred metres to several kilometers. They can be further classified into single-layer and multi-layer models depending on the degree of building simplification [192]. According to Pigliautile et al. [193], two models are commonly coupled to achieve highly accurate local climate assessments in complex and heterogeneous urban environments:1) meteorological mesoscale models such as the WRF and 2) microclimate models (MCM) to calculate heat, momentum, and mass exchange in urban environments. CFD models require considerable computational power; therefore, they are not easily integrated with long-term downscaling analyses. In contrast, UCMs are based on parametric subgrid scales of the urban environment; therefore, they can be used for long-term analyses with a relatively low computational effort [194].

4.2.2. Coupling of urban weather modelling and BEM

As mentioned in Section 3.1, the various types of meteorological dataset inputs to the BEM impose certain errors and have limitations in terms of the local climate. The more popular method of coupling CFD and BEM can compensate for this shortcoming but suffers from problems such as long computational time (applicable to a study period of a few hours to a day). In contrast, some studies have experimented with climate datasets using long-term observed weather data from multiple locations, which can predict and analyze the impact of urban microclimates on building energy consumption [195,196]. However, these models are often only applicable to specific locations. Some studies have

Table 5
Summary of coupled urban climate modeling and BEM studies.

Coupling approach	UWE parameters	Description	Ref.
TRNSYS + UWG	Wind speed and direction	Using UWG to generate urban air temperature, humidity, and building surface temperature; calculating urban canyon wind speed decay and inputting into TRNSYS	[200]
EnergyPlus + TEB	Infiltration/ ventilation air flow rate	Combining EnergyPlus and TEB models to calculate the energy performance of buildings and the urban climate around them. TEB calculates building surface temperatures more accurately	[201]
EnergyPlus + ENVI-met	Flow around and between buildings , turbulence	The building envelope is divided into connected units, which transmit information about the microclimate around the building to the EnergyPlus model	[180]
BuildSysPro + SOLENE-Microclimat	Wind speed and direction	Estimation of building microclimate based on SOLENE microclimate combined with BuildSysPro to study the thermal behavior of energy-efficient buildings in summer and winter	[202]
OpenFOAM + EnergyPlus	Street canyon airflows, indoor ventilation	Combining EnergyPlus and OpenFOAM to study ideal urban street canyon flow fields	[203]
WRF + EnergyPlus	Wind speed and direction , turbulence parameters	Coupling WRF, OpenFOAM, and EnergyPlus to study the urban thermal environment and UHI	[199]

introduced interfaces and methods into BEMs that allow these tools to take into account local climate parameters [197,198].

In the current study, the integration studies of urban weather modeling with EnergyPlus, TRNSYS, and SOLENE are more prominent. Table 5 summarizes the coupling studies of the two types of models and the considerations for the UWE. However, some studies have used a one-way output approach, lacking feedback from BEM to urban weather modeling [198]. Wong et al. [199] used the united climate model to link WRF with OpenFOAM to refine the horizontal resolution to meters. Finally, the model was combined with EnergyPlus and applied at the National University of Singapore campus to propose a multi-scale multi-physics field integration approach. Liu et al. [196] developed a multi-resolution multilayer urban climate model called MesoNH-TEB, considering near-surface climate variables (temperature, relative humidity, and wind) and BEM integration. Therefore, iterations and feedback between BEMs and urban weather modeling are the latest research directions. Providing new methods and frameworks to effectively integrate this feedback is a challenge and helps better consider the impact of UWE on building energy consumption.

4.3. Modules of UBEM for simulating UWE

Different UBEM models use different calculation methods. For instance, models based on dynamic heat transfer mechanisms, such as the CityBES, UMI, and MIT UBEM tools, often employ EnergyPlus as the calculation method. However, data-driven models rely on calculation methods such as ArcGIS. UBEM has evolved from BEM, and Subsection 2.4 describes the UWE calculation method used in BEM. From the perspective of UBEM calculation principles, physics-based models can be further categorized as: (1) detailed multi-zone dynamic thermal simulation models (EnergyPlus) and (2) reduced-order resistive capacitance models based on the simulation method [204].

The reduced-order resistive capacitance model is based on the standards established by the European Committee for Standardization (CEN) and the International Organization for Standardization (ISO) (e.g., International Standard ISO 13790 and German guideline VDI 6007) [205]. This modeling approach involves solving first-order linear non-homogeneous differential equations to calculate heat transfer and other related processes.

CitySim was developed in 2009 using Java and C++ with SUNtool as its predecessor. It is based on a reduced-order resistive capacitance model that allows for energy simulations ranging from a few to tens of thousands of buildings. CitySim considers the subspaces within buildings and connects them through circuit conduction via partition walls. The software incorporates a detailed solar radiation model [206]. The thermal model considers the influence of wind speed and wind direction. However, it does not consider the local urban microclimate (e.g., UWE) directly and relies on coupling with other models to incorporate the UWE effects [207]. Chen et al. [208] used CitySim to calculate the solar-induced wall temperatures of an idealized 5×5 building array and employed them as thermal boundary conditions in CFD simulations to investigate street canyon airflow patterns. The UMI, developed by the Massachusetts Institute of Technology (MIT) in 2013, is a model used to assess community- and urban-scale elements such as building energy usage, transportation, daylighting, and outdoor comfort. The UMI incorporates the UWG tool, enabling consideration of local urban microclimates. This accounts for the interactions between UWE and the urban environment [209]. CityBES, a representative physics-based model, is an open-data and computational platform designed to assess the energy performance of large-scale urban buildings. It can handle the CityGML and GeoJSON data formats simultaneously [25,210,211]. CityBES assigns the nearest weather file to each building based on its GIS location. However, for a city or region, the available TMY3 weather files may not be sufficient to capture local urban microclimate effects [212] such as local wind pressure. Researchers have developed an integrated platform that combines the city fast fluid dynamics (CityFFD) model, a city-scale fast-fluid dynamics model for microclimate modeling, with CityBES. This platform exchanges aerodynamic data between the two models at each time step, improving the accuracy of the boundary conditions, such as infiltration [213], by calculating the average wind speed on each building surface. The integrated platform achieves faster computation speeds than the traditional CFD models [151,214]. Table 6 summarizes the characteristics of the different UBEM tools and their consideration of UWE.

Recent research conducted in New York suggests that accurate consideration of the influence of UWE on building energy consumption can be achieved using high-resolution microclimate data, wherein the wind in Brooklyn can increase natural gas consumption in coastal area buildings by 10 % [215]. Overall, studying the relationship between the UWE and UBE presents two major challenges. On one hand, it involves coupling climate models with UBEMs that lack microclimate modules, and on the other hand, it requires striking a balance between the accuracy and computational speed of CFD simulations for UWE.

4.4. Coupling UBEM with other urban systems

Urban environmental boundary conditions, such as ambient air temperature, humidity, pressure, wind speed and direction, solar radiation, and specular and diffuse reflections, have a significant impact on the UBEM results. Hong et al. states that the development of new tools and methods to integrate UBEN with other urban systems is a very important research direction. Similarly, buildings influence the boundary conditions of urban microclimates. Section 2 and Subsection 4.2 discuss the principles and building-scale effects of UWE on the UBE, respectively. Many studies have proposed coupled research models for the UBE and urban weather modeling through urban boundary conditions. These models can be categorized as: 1) one-way coupling, such as WRF, and EnergyPlus and WRF-UCM-EnergyPlus coupling framework and 2) two-way coupling, such as CityBES and CityFFD and CitySim and canopy interface model (CIM) [199,213,224,225].

To provide high-resolution results for the accurate assessment of the impact of the UWE and other urban environmental factors, some studies have integrated the UBEM with other urban models. However, a challenge in the current coupling approach is that the UBEM and other urban systems often operate at different spatial and temporal resolutions. UCMs operate at scales ranging from hundreds of kilometers to tens of meters, whereas UBEM considers various types of information for each individual building separately. In terms of time, CFD models such as OpenFOAM have time steps ranging from a few seconds to minutes [226], whereas UBEM typically operates at an hourly time step [227]. Therefore, a standardized data exchange framework is required to facilitate a more seamless collaborative simulation. One widely used approach is to employ collaborative simulation frameworks, such as the functional mock-up interface (FMI), for data exchange between models at runtime. This allows the exchange of simulation variables between each time step and EnergyPlus or other UBEM tools. However, these runtime data exchange frameworks rely mainly on data exchange mechanisms that are specific to certain tools or applications, making it difficult to generalize or use with other tools or applications.

Recent research has highlighted the applicability of coupled frameworks. Luo et al. developed a novel, flexible, and tool-independent semantic model (JSON) to facilitate data exchange between the UBEM and climate models. This architecture can be used across scales (urban blocks, districts, or entire cities/regions) and with various UBEM and climate modeling tools, demonstrating convergence within three iterations in a field study conducted in San Francisco [228]. Another study utilized a hybrid GIS-UBEM model combined with building integrated photovoltaic (BIPV) potential estimation methods to extend its applicability to different domains and spatial scales [229]. The stand-alone urban energy/climate model (SUECM) proposed by Afshari [230] dynamically interacts with the off-line atmospheric boundary conditions obtained from a historical mesoscale reanalysis dataset. It generates

Table 6
Characteristics of different UBEM tools and their consideration of UWE.

Type	UBEM Tool	Developer	Calculation method	UWE module	Description	Ref.
Physics-based method	SUNTool	EPFL (2003)	Reduced-order resistive capacitance model (SUNTool solver)	Empirical model	SUNtool uses Microsoft DirectX as the rendering engine for Java3D. However, the tool is unable to handle the computational aspects of urban microclimate.	[216]
	CitySim	EPFL (2009)	Reduced-order resistive capacitance model (CitySim solver)	Coupling climate models	Focuses on simulating building energy consumption with intergrated modules including thermal, radiation, and behavioral models that can be combined with other climate models.	[207]
	CityBES	LBNL (2015)	EnergyPlus	Assigning weather files (TMY)	Weather files cannot take into account local UWE and need to be combined with models such as CityFFD	[210]
	URBANopt	NREL (2016)	EnergyPlus(OpenStudio)	SDK modules	URBANopt is an open-source SDK. Combined with Ladybug tools, Dragonfly, OpenDSS and other plugins, it is possible to input to UWE	[217]
	MIT's UBEM	MIT (2016)	EnergyPlus	–	Using GIS data in combination with TMY files; unable to consider local UWE effects	[162]
	SEMANCO	FUNITEC (2012)	Custom simulation engine	–	SEMANCO integrates the various geographic scales at different demonstration scenarios, mainly considering CO_2 emissions; no UWE data input.	[218]
Data-driven method	EEP model	Cardiff University (2001)	ArcGIS/OS	–	A GIS and OS based planning tool to quantify urban energy use, including energy use and traffic flow; emission dispersal model and other sub-models; does not consider UWE.	[219]
	UrbanFootprint	Calthorpe Analytics	Self-developed models	–	UrbanFootprint tool uses its database of energy use to be able to plan energy efficient scenarios for buildings on urban plots	[220]
Reducded-order mothed	CEA	ETH Zurich (2016)	ArcGIS/Python	Meteonorm	Weather database stores time series of environmental temperature, relative humidity and solar transmittance data obtained using Meteonorm 7.0 software.	[18]
	OpenIDEAS	KU Leuven (2015)	Reduced-order resistive capacitance model	TMY	IDEAS.Climate contains the models needed to define all climate conditions in a simulation based on the *.tmy3 file format, IDEAS.Buildings includes external convection heat exchange related to UWE.	[221]
	TEASER	RWTH Aachen University (2018)	Reduced-order resistive capacitance model	TMY	The tool uses a data enrichment process to identify network models of various building prototypes without the input of climate data such as UWE	[222]
Hybrid method	Combining GIS and heat models	Nouvel et al. (2015)	ArcGIS/Reduced-order resistive capacitance model	OGC standard CityGML	The OGC standard CityGML is an open and versatile virtual city model that offers possibilities for UWE research.	[223]

hourly weather data using various observations from ground weather stations and remote sensing data. Owing to the widespread availability of urban LCZ maps, this approach is convenient and easily applicable to other cities.

All weather data used in the UBEM can be modified using information generated by climate models to better represent the surrounding climatic conditions of the study cases. Depending on the type of climate model used, local climate information or datasets specify the external air temperature, humidity, and wind speed without changing the climate file format. For instance, Mosteiro-Romero et al. [231] averaged the simulation results of air temperature, wind speed, and relative humidity for each façade using ENVI-met to obtain hourly values for each building in the area. The microclimate simulation results were then passed to City Energy Analyst (CEA) for energy demand modeling, revealing spatial cooling demand variations between −5% and +14 %. Another study demonstrated that when using measured or simulated microclimate data, the minimum average deviation error was 6 % compared with 12 % when using TMY data [232]. Overall, most researchers do not consider all local urban environments simultaneously and only partially correct thermal fluxes. For example, local calculations for the UWE and

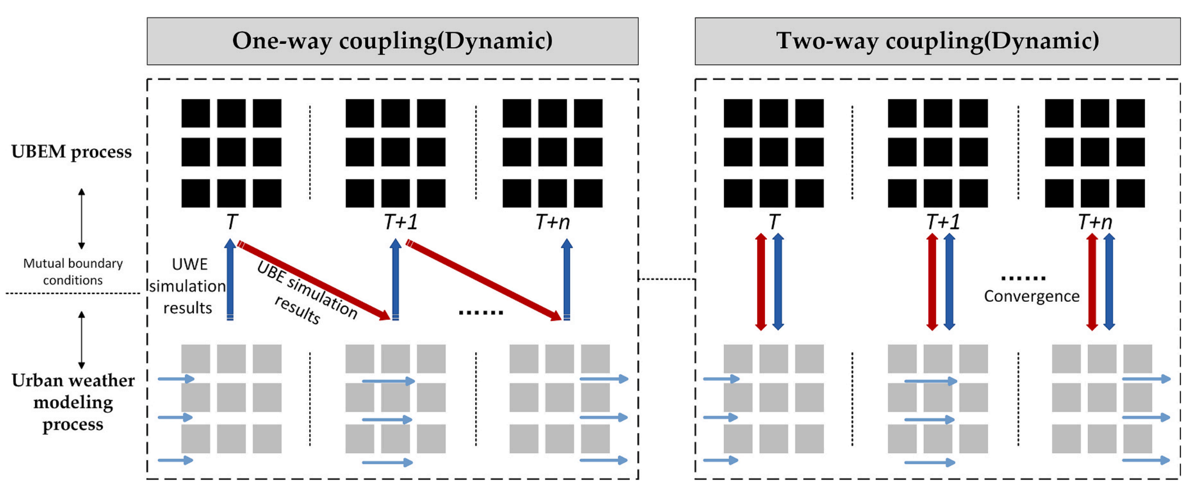

Fig. 6. Classification of coupling methods and transfer of boundary conditions.

the partial correction of convective heat flux are based on the local air temperature [233]. Fig. 6 illustrates the coupling methods of the two model types in terms of the time step and linking approach for urban microclimate factors, including the UWE, in the coupling process.

4.5. The quantitative impact of UWE on UBE simulations

As mentioned earlier, considering UWE in simulations can have a significant impact on UBE simulation results. Coupling BEM and UBEM with urban climate models, utilizing high-precision UWE data input, and employing other methods are all aimed at improving the accuracy of UBE simulations. Some current studies have quantitatively analyzed the improvements in UBE simulation accuracy due to microclimate factors like UWE. These improvements are assessed in terms of building energy consumption indicators such as heating and cooling loads, natural gas consumption, electricity consumption, cooling potential, and more. Additionally, employing multi-scale simulation methods in conjunction with CFD tools can significantly enhance wind speed accuracy compared to measured data. Table 7 summarizes the quantitative results from existing research on the accuracy of UWE and UBE.

5. Validation and calibration of impact of UWE on UBE

Based on previous content and literature studies, we review the validation of the impact of UWE on energy consumption in urban buildings; however, there is almost no literature directly related to it. The few studies that consider the validation of results only validate the accuracy of the simulation tool and the accuracy of the overall climate boundary conditions. Due to the vast scope of validation and calibration in CFD simulations, this section provides a concise review, specifically focusing on the validation and calibration of energy models. Additionally, we highlight the absence of research related to UWE in this Section. Therefore, in Subsection 6.5, we review studies for both types of relevance (CFD to obtain UWE data and simulation tools) and propose a possible future validation framework for the impact of UWE.

Studies have shown that the variance in physics-based models without model calibration is approximately 30 %, hindering their application in predicting absolute energy consumption [236].Validation of the UBEM tool results poses a challenging task owing to the limited availability of measurement data. In a review study by Dilsiz et al. [237], Bayesian calibration was performed using metered data with different spatial and temporal resolutions. The accuracy of the predictions based on annually aggregated data showed an error range between 10 % and 60 % depending on the subgroups within each aggregated dataset. The highest temporal resolution ranged from 50 % to 79 % on an hourly basis.

Although the research on UBEM calibration is limited, several validation methods have been proposed. From the perspective of the energy consumption simulation results, these methods can be categorized as follows: (1) validation using energy consumption datasets (annual or monthly), (2) validation using measured energy consumption data, and (3) validation using authoritative data such as government energy reports. From the perspective of the energy simulation process, the methods can be classified as follows: (1) validation of the accuracy of the physical models (e.g., Bayesian calibration and pattern-based methods) and (2) validation of the accuracy of data-driven models (internal validation methods) [25,145]. These validation approaches contribute to the assessment of the accuracy and reliability of UBEM tools and improve their performance in predicting the energy consumption in urban buildings. However, further research is required to develop standardized validation methods and enhance the availability of measurement data for the comprehensive validation of UBEM tools.

Most research lacks validation of weather data, and in cases where it is considered, the focus is often on temperature and humidity data rather than on the UWE. For instance, when using local weather files generated by an UWG, ae model requires 2650 iterations to converge [238]. Therefore, developing suitable methods to economically validate weather data, including UWE, remains a challenge. Therefore, it is essential to identify approaches that streamline the validation process to make it more computationally efficient.

6. Discussion

6.1. Current challenges

Current challenges lie in both the acquisition and processing of weather data (UWE) and the consideration of UWE in energy calculation processes. The UWE serves as an important weather parameter for inputting calculation conditions and continuously affects the microclimatic conditions surrounding buildings.

For computational convenience and ease of acquisition, meteorological data files such as TMY are commonly used. They are employed as boundary conditions for energy calculations and typically include UWE variables such as wind speed and direction. However, this approach does

Table 7
UWE and UBE accuracy improvement in selected studies.

Approaches	Strengths	Limitations	UWE resolution	UWE accuracy	UBE accuracy
EnergyPlus + UrbaWind + Urban Weather Generator [150]	Highly efficient, no specialized knowledge required	No significant effect on indoor temperature prediction	Single building	Real-time calculation of district-scale wind pressure coefficients	Overestimation of cooling potential by 1 °C without the new tool chain
EnergyPlus + ENVI-met [180]	Consider complete microclimate elements	Slow computation and physical modeling differences	150 m*150 m	The wind speed around the building calculated by ENVI-met	Heating load decreased by 1.4 % considering air infiltration effects
WRF-UCM + OpenFOAM [181]	Accurate capture of wind direction and low normalized mean bias	Not considering the interaction between UWE and the ground and vegetation	Below 10 m	Increase the wind speed by an order of 1–2 m/s.	–
High frequency satellite data with climate reanalysis [215]	Rapidly capturing historical microclimate data.	Nonlinear relationships between variables might be overlooked.	2.5 km per cell	High spatial resolution climate dataset.	A 10 % increase in building natural gas consumption.
OpenFOAM + VirtualPULSE [234]	Uses the wind multiplier results to modify the weather data.	Building infiltration without considering neighborhood effects.	20 m*20 m	Optimizing the surrounding wind speeds around buildings using wind multipliers in eight directions.	1.Total building energy consumption: Decreased by 5 % 2.Sensible cooling and heating of infiltration component: 31 %, 29 %
Grasshopper + Regional Climate Model [235]	Accounting for both climate change and microclimate	The accuracy issue of past climate data and future climate data.	EPW file (Below 30 km) and measured data	Microclimate weather datasets	The daily peak cooling load may increase by 25 %, and so on.

not consider on-site UWE conditions. Although some studies have utilized CFD techniques and various UWMs to obtain more accurate UWE data, the widespread adoption of such coupling techniques remains challenging because of the trade-off between computational speed and accuracy in practical energy simulations. To meet this challenge, scientists from different fields must work together to find a balance between computational speed and accuracy to facilitate the application of coupling techniques.

In the context of considering weather data in building energy simulation processes, there has been significant development in the integration of various ventilation and heat transfer modules within commonly used BEM tools such as EnergyPlus, ESP-r, and TRNSYS [152]. Similarly, UBEM tools such as CityBES, UMI, and CitySIM have progressed in their computational cores and integration with mature modules [207,210,211]. However, as mentioned in Sections 2, 3, and 4, there is still a lack of consideration of microclimatic factors such as UWE. Consequently, researchers are continuously optimizing computational modules and exploring the coupling of different models to address these challenges. Based on the review conducted in this study, the current challenges faced include but are not limited to:

- Developing a workflow for obtaining weather data (UWE) applicable to energy consumption calculations at different scales to address the challenges of accuracy and computational speed in UBE simulations.
- Using CFD techniques to predict the UWE to match the energy model in terms of the calculation steps and quantify the impact of the UWE around the building.
- In addition to the currently studied pedestrian height UWE, the indirect impact of the UWE on other urban elements needs to be considered and comprehensively evaluated in terms of energy consumption impact mechanisms.
- Further development and improvement of the UWE calculation module in the energy consumption model are required to improve simulation accuracy.
- Considering the influence relationship between UWE, UBE, and urban form from the perspective of urban performance optimization.

6.2. Combining simulation tools at different scales

As mentioned in Subsection 4.4, achieving compatibility between UWM and UBEM is crucial at both temporal and spatial scales. However, the main challenge when integrating UBEM with other urban modeling systems lies in the suitability of the coupling framework, considering issues such as low spatial resolution and mismatched time steps. The focus should be on developing a framework that spans different scales, such as linking multiple-scale UCMs to refine microclimatic conditions at the meter scale (e.g., coupling WRF with OpenFOAM) [199,239]. This can provide accurate boundary conditions for EnergyPlus. Another aspect to consider is the applicability of the UBEM, which requires a standardized exchange mode to facilitate a collaborative simulation framework (e.g., SUECM and FMI) [230].

6.3. Suitable methods for acquiring UWE to simulate UBE

Currently, there is a lack of detailed research on the spatio-temporal heterogeneity evaluation criteria for UWE and its impact mechanism on the energy consumption of individual and urban buildings. There is also a lack of standardized processes and methods for obtaining and processing wind environment data, particularly for building energy calculations. The UWE is influenced by both regional atmospheric motion and irregular mechanical turbulence. Considering the main sources of UWE data acquisition currently available (i.e., dataset files, real weather data, climate model-based UWE, and CFD simulation-based UWE data), it is necessary to integrate and optimize a workflow to obtain UWE data suitable for both single-building and UBE calculations. Further innovations are required in this regard.

6.4. Modules in BEM and UBEM

From the perspective of urban energy savings, the impact mechanism of the UWE on building energy consumption is primarily applied to urban energy consumption calculation models. Although there have been studies on the joint simulation of microclimate and energy consumption models, they have mainly focused on different levels of simplification and assumptions in the parameterization and geometric models. Striking a balance between model complexity and computational speed remains a challenge. However, the consideration of the UWE in current urban energy consumption calculation tools is relatively lacking, and there is a lack of in-depth consideration of the computational core. The integration of UWE and energy consumption models has not yet been achieved (e.g., the approach of allocating weather files in the CityBES is still inaccurate) [212]. Therefore, addressing these issues from the perspective of computational core algorithm optimization or developing integrated platforms (e.g., CityBES and CityFFD)is crucial for current research [213].

6.5. Key barriers in validation and calibration

Verification and calibration remain challenging tasks. Clear guidance and practice regarding the input and output of simulation tools, validation methods, calibration performance evaluation, and simulation reproducibility are lacking. Consequently, the calibration of UWE data and simulation tools remains highly subjective, elusive, and almost impossible to reproduce. Pfenninger et al. [240] observed that with the increasing complexity of technical methods, verification studies should include open-source codes and methods to reduce redundant efforts and enhance research applicability.

However, most of the reviewed studies on the impact of wind environments on building energy consumption lack verification and calibration. Chong [135] proposed that in most automatic calibration frameworks, the material thermophysical properties, permeability, and internal load density are often selected for calibration, which have been shown to introduce uncertainties and may not be applicable to all studies.

Therefore, this study proposes a framework suitable for verifying and calibrating the impact of UWE on UBE by reviewing simulation tools, UWE characteristics, and the current state of research. This framework should contribute toward supplementing the existing knowledge in this field (Fig. 7). Based on this review, a possible validation and calibration framework is proposed. However, further studies are required to address this issue.

7. Conclusion

The effect of UWE on UBE is multifaceted. UWE affects building energy consumption by influencing energy exchanges with the surrounding urban elements and other factors. However, the UWE directly affects the accuracy of energy consumption calculations as a boundary condition in building energy models. This review provided an overview and summary of UWE data sources, mechanisms of UWE influence on building energy consumption, and considerations for UWE in simulation models and numerical tools. Based on the progress in existing research and the characteristics of the impact of UWE on building energy consumption at different scales, the challenges faced by the field were discussed. Furthermore, this review elucidated the coupling relationships between different urban weather models and BEMs/UBEMs, providing a comprehensive understanding of the different tools and computational models and methods for UWE. The main findings of this review are as follows:

1) This review supported research on the mechanisms of the impact of UWE on building energy consumption by summarizing theoretical models and technological developments in three major aspects:

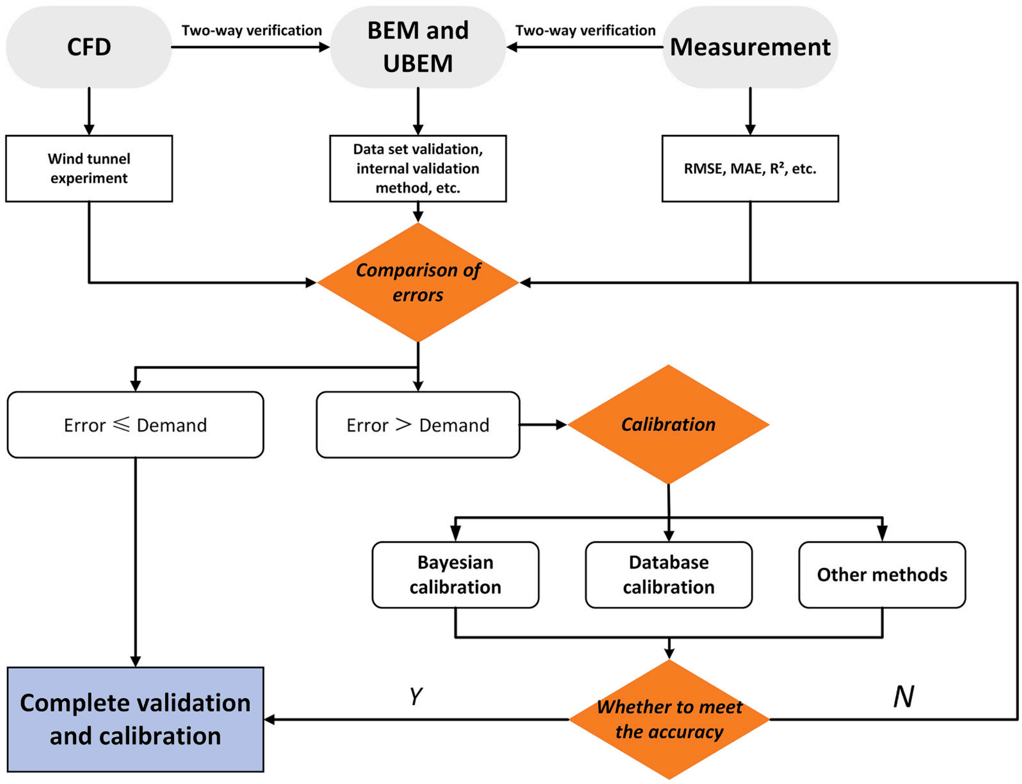

Fig. 7. Validation and calibration framework for the impact of UWE on UBE.

ventilation infiltration, convective heat transfer, and indirect influencing factors. It highlighted the significant role of CFD technology in UWE research, provided a summary and evaluation of existing data acquisition methods for UWE, and described the descriptive indicators of the spatio-temporal heterogeneity of UWE.

2) At the building scale, starting from existing BEM tools, the review focused on six energy exchange modes based on mainstream BEM heat transfer models. It summarized the theoretical models related to UWE and presents the considerations and limitations of different BEMs regarding UWE from a developmental perspective. The UWM serves as a supportive tool for accurate BEM calculations but still has certain limitations, necessitating the ongoing development of internal interfaces and coupling methods.
3) UBEM, the latest method for city-scale building energy assessment, often relies on weather files, such as TMY, to input UWE data in its forward simulation type. However, this approach often neglects the comprehensive impact of the urban environment and UWE, resulting in errors in building energy calculations. One-way and two-way coupling of the UBEM with the UCM can provide a more accurate consideration of the climate boundary conditions. However, challenges still exist, such as resolving the mismatch between temporal and spatial resolutions, and the need for a more widely applicable framework.
4) Studies have shown that the variance in physics-based models is approximately 30 % without calibration and validation. Although there have been attempts to validate these models, most of the focus has been on geometric and nongeometric data inputs. Studies that directly examined the impact of UWE on energy consumption in urban buildings are almost non-existent and lack a theoretical framework for validation and calibration. Developing suitable methods to validate weather data, such as the UWE, can minimize the number of calibration iterations, which remains a challenge for future research.

CRediT authorship contribution statement

Pengyu Jie: Writing – review & editing, Writing – original draft, Visualization, Methodology, Conceptualization. **Meifang Su:** Writing – review & editing. **Naiping Gao:** Writing – review & editing, Supervision. **Yu Ye:** Writing – review & editing, Supervision. **Xiaoming Kuang:** Writing – review & editing, Supervision. **Jun Chen:** Writing – review & editing. **Peixian Li:** Writing – review & editing. **John Grunewald:** Writing – review & editing. **Xiaoping Xie:** Writing – review & editing. **Xing Shi:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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