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Daylight Availability of Living Rooms in Dense Residential Areas under Current Planning Regulations: A Cross-Region Case Study in China

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Abstract: After the pandemic, as it becomes more feasible to study and work from home, the quality of residential daylighting has attracted increasing attention. With the rapid growth of high-density residential areas, China is confronted with the incoordination between site planning and interior daylight availability across a wide region. Therefore, this paper investigates the applicability of planning regulations for daylight availability in dense residential areas under different climates across China, with the aim of providing data to optimize design strategies. ClimateStudio and ALFA were used to calculate the daylight factor (DF), daylight illuminance, spatial daylight autonomy (sDA), useful daylight illuminance (UDI), and melanopic equivalent daylight illuminance (m-EDI) of living rooms in four practical mixed housing estates in different Chinese daylight climate zones. The results showed that most of the studied units failed to meet current standards of DF and $sDA_{300,50\%}$ for residence. However, more than half of these units still had high potential for UDI and met the recommendation of m-EDI by daylight only. The results verified the importance of integrative consideration of the local daylight climate and interior unit design for residential area layout planning. Finally, this paper suggests two topics for further exploration to bridge the gap between area planning and interior daylight availability in dense residential areas.

Keywords: daylight availability; dense residential areas; climate-based daylight modelling (CBDM); integrative lighting

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1. Introduction

Daylight, including sunlight and skylight, plays an essential role in energy efficiency, improving occupant performance, health, and wellbeing in buildings [1–3]. In the in- and post-pandemic era, as working from home has become more common [4–6], people might stay home longer, which attracts increasing attention to the quality of residential daylighting. The quality of interior daylighting depends on both the interior and external design, the latter of which plays a major role [7], especially in high-density urban residential areas with high obstructions [8–10]. Therefore, regulations of external environment planning should tie in with interior daylight design recommendations [11]. However, residential area planning is generally regulated in terms of multiple factors such as economic success, ventilation and so on, not only daylight availability [9,12]. Investigating how site planning affects residential daylighting in practice can help optimize planning methods and improve daylight availability in residential areas.

There are various daylight metrics used as benchmarks in the residences (Table 1). One of the most widely used metrics is the daylight factor (DF) [13], as well as some derived metrics such as average DF and minimum DF. Although the DF is recognized as a practical metric around the world, it still has some limitations. A consensus is that DF is calculated under an overcast sky, which can be insensitive to season, time of day, building orientation, and even site location [13]. Therefore, considering the variation in climates, different thresholds of DF requirements are set across regions [14–16]. However, the applicability of the different thresholds for DF remains in the dark. For example, even in the same residential spaces, European standards were found to be more difficult to comply with than local standards in Sweden [17].

Table 1. Standards of daylighting in residence.

Year	Standards	Region	Metric	Date	Time	Sky Model
2013	GB 50033-2013 Standard of daylighting design of buildings [14]	China	DF		10:00–14:00	Overcast sky
			Illuminance			
2016	CASBEE—New construction (2016 Edition) [18]	Japan	DF			Overcast sky
2019	GB/T 50378-2019 Assessment standard for green building [19]	China	DA_{300} for 60% of the occupied area, eight hours per day on average			TMY
2020	LEED v 4.1 RESIDENTIAL BD+C MULTIFAMILY HOMES [20]	U.S.	Illuminance	Equinox	9:00–15:00	Clear sky
2020	DGNB System—New buildings criteria set 2020 [21]	Germany	DF			Overcast sky
			Color rendering index R_a			
			Duration of exposure to daylight	17 January and equinox		
2021	BREEAM International New Construction Version 6.0 [15]	U.K.	DF			Overcast sky
			Uniformity			
2022	EN 17037:2018+A1:2021 Daylight in buildings [16]	Europe	Sunlight exposure	1 February–21 March		Sun-path diagram
			DF			Overcast sky
			Illuminance	Annual		TMY
2023	WELL v2 Q4 2023 [22]	U.S.	$sDA_{300,50\%}$	Annual	8:00–18:00	TMY

Considering the limitation of the static daylight metrics like DF, dynamic daylight metrics are raised to assess building daylighting based on the annual hourly illuminances under local typical meteorological year (TMY) data, which is also called climate-based daylight modelling (CBDM) [23]. Widely used dynamic metrics include daylight autonomy (DA) [24], useful daylight illuminance (UDI) [25], spatial daylight autonomy (sDA), annual sunlight exposure (ASE) [26], and others. Some of these metrics have been used to assess daylighting of residence in some standards (Table 1). According to the CBDM methods, a new analysis framework called the residential daylight score (RDS) was introduced to monitor both daylight sufficiency and sunlight access and took daily and seasonal analysis into consideration [27]. However, the dynamic daylight metrics for residences fail to reach a consensus. For example, the sDA requirement is stipulated under experiments for general working scenes [26,28], but directly used in some standards for residence as well (Tables 1 and 2). The high light requirement used in working spaces may not be suitable for residential spaces [29]. In addition, the correlation between seasonal variation in daylight availability and annual criteria requires further exploration [30].

Moreover, apart from these dynamic daylight metrics, circadian metrics such as circadian stimulus (CS), equivalent melanopic illuminance (EML), and melanopic equivalent daylight illuminance (m-EDI) are also defined to assess non-visual effects from light to maintain circadian rhythm and alertness of occupants [31–33]. Nevertheless, the circadian metrics are not yet required for residential daylighting [19,22]. A previous study tried to present a graphical method to assess the cumulative non-visual effects of daylight considering the eye orientations, special positions, and timing of exposure [34], and demonstrated the sensitivity of circadian daylighting to climate and building orientations in residential dwellings across Europe [35].

Table 2. Standards of daylighting in office.

Year	Standards	Region	Metric	Date	Time	Sky Model
2013	GB 50033-2013 Standard of daylighting design of buildings [14]	China	DF		10:00–14:00	Overcast sky
			Illuminance			
2016	CASBEE—New construction (2016 Edition) [18]	Japan	DF			Overcast sky
2019	GB/T 50378-2019 Assessment standard for green building [19]	China	DF			Overcast sky
			DA_{300} for 60% of the occupied area, four hours per day on average			TMY
2020	DGNB System—New buildings criteria set 2020 [21]	Germany	DF			Overcast sky
			Color rendering index R_a			
			Annual relative useful exposure	Annual	7:00–18:00	
2021	LEED v4.1 BUILDING DESIGN AND CONSTRUCTION [36]	U.S.	$sDA_{300,50\%}$	Annual	8:00–18:00	TMY
			$ASE_{1000,250}$	Annual	8:00–18:00	TMY
			Illuminance	Equinox	9:00–15:00	Clear sky
2021	BREEAM International New Construction Version 6.0 [15]	U.K.	DF			Overcast sky
			Uniformity			
2022	EN 17037:2018+A1:2021 Daylight in buildings [16]	Europe	DF			Overcast sky
			Illuminance	Annual		TMY
			Daylight Glare Probability	Annual		
2023	WELL v2 Q4 2023 [22]	U.S.	$sDA_{300,50\%}$	Annual	8:00–18:00	TMY

There are only a few daylight metrics directly related to residential area planning. Sunlight access duration of the residences is one of the widely used metrics seen in China, Germany, the UK, Japan, and so on [37], which is calculated by the geometrical sun-path method [16]. Given the variation in climates and development across regions, different sunlight duration requirements are defined for different locations (e.g., varied sunlight hours on different typical days or probable sunlight hours over the year) [11,38,39]. Based on the sunlight duration regulation, sunlight spacing–height equations (Figure 1), a similar form known as vertical obstruction angle, are set by some local governments to simplify the planning process [12]. At the same time, the shadowed area on a typical day is also used somewhere [40]. However, some regulations regulate the same sunlight duration for a wide range of areas with different daylight climates [38]. The rough ranked requirements and implementation of sunlight duration regulations may not be suitable for all types of residences or climates [11,41]. This is especially true for high-density residential areas. In cities located at high latitudes, such as the north of Europe, annual sunlight duration is appropriate [11]. In regions situated at the middle latitudes including central Europe and Harbin in China, the sunlight duration on a particular day in winter is more suitable than annual sunlight duration [11,42]. Meanwhile, in the cities of low latitudes like Hong Kong, sunlight access could be excessive in summer but sometimes insufficient in winter [43]. Hong Kong has struggled for years to gain daylight in high-density residential areas, with various explorations of planning regulations. Based on the vertical daylight factor (VDF) on the surface of the window, the unobstructed vision area (UVA) was developed to regulate open space out of the window that should not be overlaid on the site plan [12]. As an extension of UVA and another widely used metric vertical sky component (VSC), visible sky area (VSA) was set to calculate the contribution of sky patches to the center of the windowpane, to guarantee the VDF of high-rise residential buildings [44]. It can be seen that the current residential planning regulations do not tie in with the recent interior daylight requirements, not considering the dynamic or circadian daylight metrics.

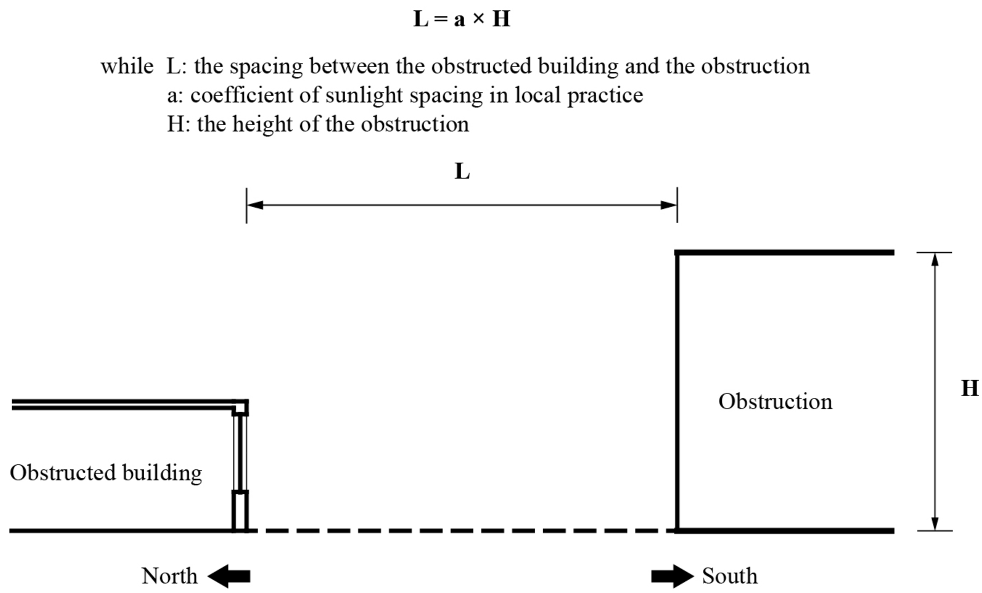

Figure 1. Sunlight spacing–height equation method for residential area planning.

Several researchers have attempted to explore the correlation between residential area planning and interior dynamic daylighting. In northeast China, urban layouts substantially influenced the daylighting potential across the south façade in buildings, but not significantly for other orientations [45]. Within one housing estate, planning factors such as the location of the building, orientation, and floor position, have an impact on the dynamic daylight in units [46]. Through wide surveys, the UDI criterion displayed the strongest association with urban density than DF and point-in-time illuminance metrics [17]. Residential daylight design metrics are needed to differentiate temporal and qualitative aspects of daylight in residential architecture to optimize high-density urban design proposals [47]. Since daylight affects the physical and mental health of occupants in residence [3,48], it is also necessary for multi-spectral evaluations of the indoor non-visual daylight environment [49]. However, there are still few studies on the relationship between circadian daylighting and site planning in residential areas.

With the rapid growth of high-density residential areas, China must confront the problem of incoordination between site planning and the interior daylight availability across a wide region. In terms of annual average total daylight illuminance (E_q, klx), there are five daylight climate zones (DCZ) in China [14]: DCZ I (E_q > 45 klx), DCZ II (40 klx ≤ E_q < 45 klx), DCZ III (35 klx ≤ E_q < 40 klx), DCZ IV (30 klx ≤ E_q < 35 klx), and DCZ V (E_q < 30 klx) (Figure 2a). Based on the DCZs, the national standard regulates average illuminance and different interior DFs in residences across China [14]. Nevertheless, residential site planning in China is regulated by sunlight hours in terms of another type of classification for climates, called building climate zones (seven different zones). The building climate zones are defined mainly based on the local monthly average temperature (Figure 2b) [38,50,51]. According to the national planning regulation [38], three types of thresholds for sunlight hours are regulated across China based on different building climate zones and urban populations: two or three hours on Dahan Day (20 January) or one hour on winter solstice day (22 December). Furthermore, to simplify the procedure of sunlight-based residential area planning, local governments always establish additional guidelines using the sunlight spacing–height equation (Figure 1) in practice to assist in fulfilling the sunlight duration requirement at various places across China [52–55], which makes the interior daylight quality in residences more indefinite. Under the circumstances, it will be questioned whether the daylight in the residence is sufficient for either daily life or working from home in Chinese dense residential areas.

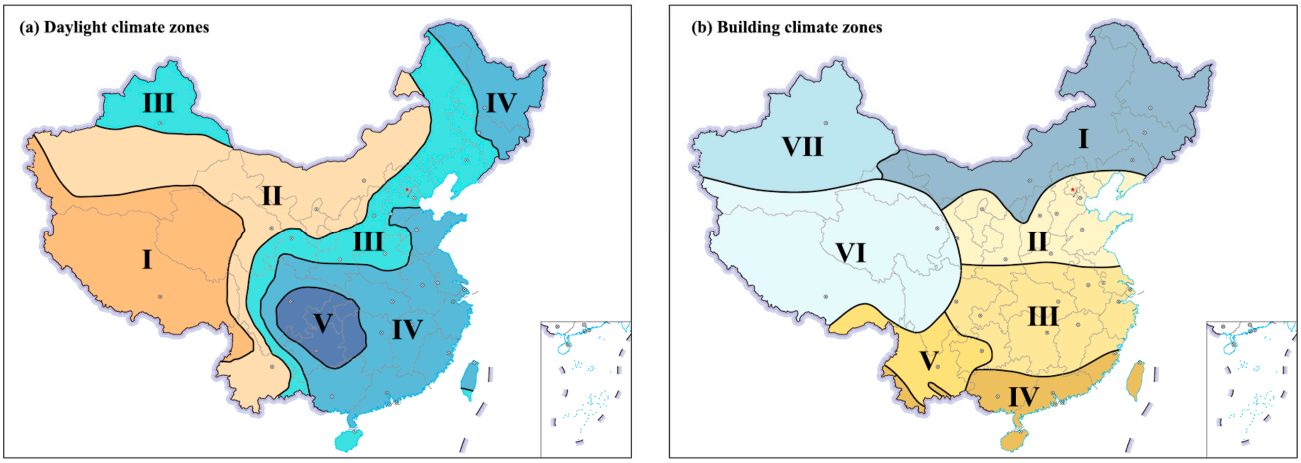

Figure 2. Comparison between daylight climate zones (**a**) [14,56] and building climate zones (**b**) in China [50,56]. There are five daylight climate zones in China in terms of annual average total daylight illuminance, and seven building climate zones mainly based on average temperatures in January and July, and average relative humidity in July.

This study, therefore, aims to examine the applicability of planning regulations for daylight availability in dense residential areas under different climates across China. Focused on the living room where the residents stayed the longest in the daytime based on a previous questionnaire survey by the authors, interior daylight availability in practical dense housing estates in different climate zones will be analyzed. The "integrative lighting", referred to both visual and non-visual effects of light on residents [57], was considered to assess the daylight availability in residences in this paper. There are two sub-questions to answer:

1. Under local daylight climates, does current local housing estate planning allow the living room to comply with the generic daylight requirements?
   a. What is the compliance with the current standards of DF and $sDA_{300,50\%}$?
   b. What is the potential of UDI?
   c. What is the difference in the variation pattern of daylight availability throughout months under different daylight climates?
2. Under local daylight climates, can current local housing estate planning help to satisfy the need for circadian lighting in the living room by daylight only?

In practice, real estate developers in China usually construct their systematic design procedures for housing estates. Each company pursues consistent profit expectations for their estate projects by the game between sunlight availability and land use efficiency, which is regulated by the other local planning requirements like plot ratio, building density, and so on [38]. In other words, the real housing estate projects of the same company can demonstrate the practical results of the local planning regulations to some extent. Furthermore, in high-density residential areas in China, mixed layout is one of the most widely used layouts, which mainly includes mid-rise (4–9 floors) and high-rise ($\geq$10 floors) multifamily buildings [38,51], for a better balance between sunlight availability and business benefit. Therefore, in order to answer the research questions, this paper selects mixed housing estates of the same real estate company. According to Figure 2a, daylight climate zone I covers areas with low population density, where the dense residential area may not be a significant concern and lack representative cases. Therefore, this paper only focused on four estates that are in four big Chinese cities in DCZ II–V, respectively. Based on computer simulations, DF, daylight illuminance, $sDA_{300,50\%}$, UDI, and m-EDI in the living room are used to assess the daylight availability of the residence. Investigating the daylight availability in these practical dense housing estates across China, this paper will examine the applicability of the current planning regulations under the local climate and attempt to explore improvements of residential area planning methods for better daylight availability in residence.

2. Materials and Methods

This section comprises three parts: characteristics of the four estates' bases, simulation models, and daylight simulation settings.

2.1. General Characteristics of Estates' Bases

Four Chinese cities were studied in this study: Kunming, Tianjin, Changsha, and Chongqing, all of which are municipalities or provincial capitals and serve as representatives of the surrounding areas. Given the national standard GB 50033-2013 [14], the four cities are in DCZ II to V, respectively (Table 3). Kunming, Changsha, and Tianjin have the same thresholds of plot ratio, while Tianjin has lower threshold (Table 4) [38]. All four cities use the spacing–height methods (Figure 1) in local guidelines for residential area planning. However, based on local situations, four cities define different series of spacing–height equations in terms of different factors in their planning guidelines, as seen in Table 4 [52–55]. Therefore, it is important to find out whether these guidelines are applicable in practice for daylight availability under local daylight climates.

Table 3. Locations and climate characteristics of the four studied cities [14,50,58].

City	Location	Daylight Climate Zone	Annual Total Solar Irradiation (kWh/m^2)	Building Climate Zone	Average Annual Temperature (°C)
Kunming	25.02° N, 102.68° E	II	1530	V	15
Tianjin	39.08° N, 117.07° E	III	1355	II	13
Changsha	28.22° N, 112.92° E	IV	1085	III	17
Chongqing	29.58° N, 106.47° E	V	848	III	18

Table 4. Thresholds of plot ratio set in the national standard [38] and factors defining the spacing–height equation used in local planning guidelines of the four cities [52–55].

City	Threshold of Plot Ratio [1]	Factors Defining the Spacing–Height Equations								
		Obstruction				Obstructed Building			Orientation	Angle between Buildings [4]
		Building Height	Building Type [2]	Façade		Building Height	Façade			
				Type [3]	Width		Type	Width		
Kunming	3.1	• [5]		•		•	•			
Tianjin	2.9	•	•	•			•		•	
Changsha	3.1	•		•	•		•		•	•
Chongqing	3.1	•			•	•		•		

[1] Threshold of plot ratio: maximum plot ratio threshold for high-rise buildings (10–26 floors) in each city; [2] Building type: the shape of the building (e.g., rectangular and square building); [3] Façade type: main daylit façade or side façade; [4] Angle between buildings: the angle between the main daylit façade of the obstructed building and the closest façade of the obstruction; [5] •: the factor is used in the local planning guidelines in this city.

Table 3 presents the locations and climate characteristics of the four cities. Between two cities in adjacent DCZs, the annual total solar irradiation increases by an average of 227 kWh/m^2. Figure 3 shows the monthly average unobstructed daylight illuminance (8:00–18:00) of the four cities, which were simulated using CBDM methods based on Chinese Standard Weather Data [58] (simulation method seen in Section 2.3). The four cities have different annual daylight characteristics. Kunming and Tianjin have the highest average unobstructed daylight illuminance in April, while Changsha and Chongqing have the highest in July. In July and August, the four cities have similar average daylight illuminances. Chongqing has the most variation in monthly average illuminance over the year, while Kunming has the least.

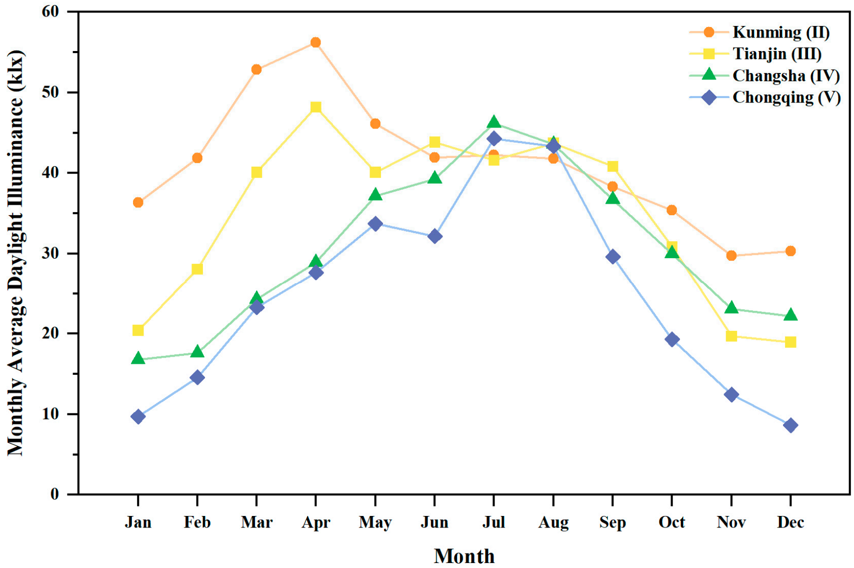

Figure 3. Monthly average unobstructed horizontal daylight illuminance (8:00–18:00) of the four cities (daylight climate zones, DCZ): Kunming (II), Tianjin (III), Changsha (IV) and Chongqing (V).

Referred to two additional Chinese national regulations [38,59], except for Kunming (one hour on winter solstice day), the other three cities use the same requirement of sunlight duration: two hours at the windowsill of the ground floor on Dahan Day (20 January) (Table 5), which means a similar planning logic for planners.

Table 5. National regulations of sunlight hours requirements in urban residential buildings in the four cities [38].

City	Kunming	Tianjin	Changsha	Chongqing
Building climate zone	V	II	III	III
Reference date	Winter solstice day (22 December)	Dahan day (20 January)		
Sunlight hours (h)	≥1	≥2		
Time period	9:00–15:00	8:00–16:00		
Position (for sunlight hours calculation)	Windowsill at the ground floor (or the external façade with a height of 0.9 m above the indoor floor)			

2.2. Simulation Models

Computer simulations are now available to conduct daylight research. Based on the Radiance simulation core, Daysim, DIVA, ClimateStudio, and other software are applicable to calculate annual daylight illuminances based on climate data [24,60,61]. Furthermore, through multiple color channels, several computer software can use spectra raytracing to predict the amount of light absorbed by an observer's non-visual photoreceptors, such as ALFA and Lark [62,63]. Therefore, this study applied computer simulations to calculate the daylight in residential areas across China.

This study thus focused on the mid-rise and high-rise buildings within mixed housing estates. The four selected housing estates are property projects of the same company, with similar design procedure and logic. Each estate includes more than fifteen buildings in parallel. Given these features, the four estates could somehow present the local planning regulations on a single site. Based on the local government documents [64–67], the percentages of urban fabric covered by residential areas in the four cities are as follows: 30.49% for Kunming, 28.66% for Tianjin, 31.02% for Changsha, and 28.34% for Chongqing.

Figure 4 shows the layouts of the four estates, with plot ratios: Kunming (3.1), Tianjin (1.5), Changsha (2.9), and Chongqing (2.0). To analyze the general daylighting in the four estates, this paper focused on the average daylight condition at typical floors in each housing estate, rather than the highest or lowest daylight conditions in each estate. Of course, the extreme daylight conditions should be paid attention to, but it could be better analyzed in ideal layouts, rather than in a practical project with various influence factors. The two types of buildings (mid-rise and high-rise) were analyzed separately. Three floors were chosen for the mid-rise buildings: ground, middle, and top floors. Five floors were chosen for the high-rise buildings: ground floor, middle floor, top floor, and 25% and 75% of the building height. If the selected floor was calculated to be right between two physical floors, the lower floor was selected. Annual average vertical exterior daylight illuminances (8:00–18:00) at the geometric center of the south façade were simulated for all floors of all buildings in the four estates. For each selected floor of the same building type in each estate, one unit was selected as a representative whose illuminance was closest to the average illuminance of the same floor of the same building type in the estate. Finally, eight units in each estate (three for mid-rise and five for high-rise buildings) were selected to represent the average daylighting condition at quartiles of building height (Figure 4).

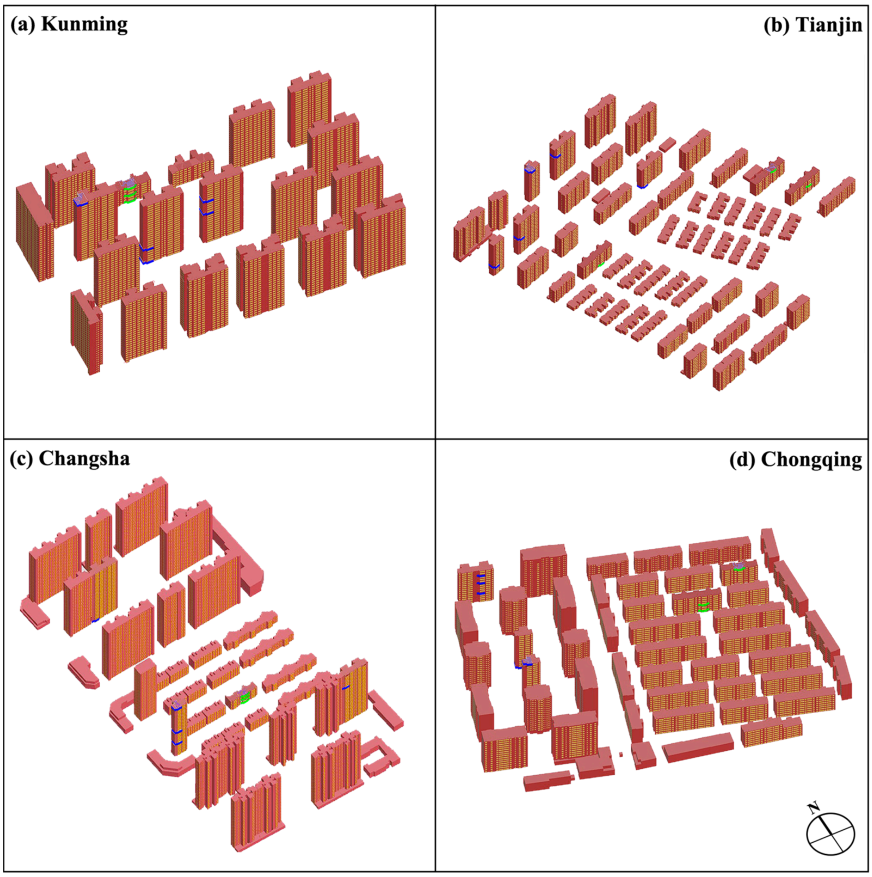

Figure 4. The simulation models of the four housing estates and eight selected units for each estate studied in this paper: (**a**) Kunming (daylight climate zone II, DCZ II); (**b**) Tianjin (DCZ III); (**c**) Changsha (DCZ IV); (**d**) Chongqing (DCZ V). Green units are in mid-rise buildings and blue units are in high-rise buildings.

In order to focus on the influence of the planning of residential areas, the same typical unit plans shown in Figure 5 were used for the four housing estates in this paper. The living room in each unit was chosen for detailed analysis. The orientations of the selected units in each city are as follows: 3.7° west of south in Kunming, 24.8° east of south in Tianjin, 3.6° east of south in Changsha, and 16.1° west of south in Chongqing.

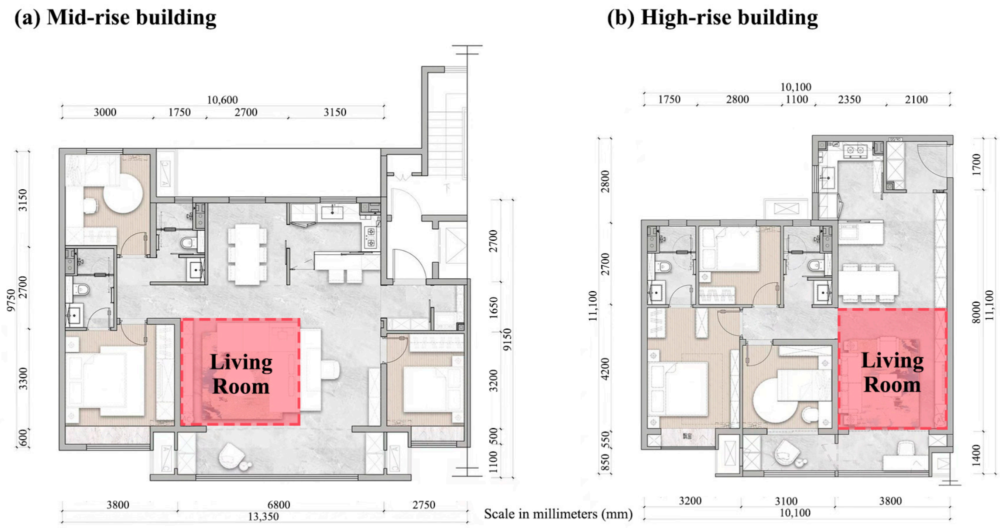

Figure 5. Plans of units of mid-rise (**a**) and high-rise (**b**) buildings.

2.3. Daylight Simulations

This study considered several daylight metrics. The general metrics such as DF, hourly daylight illuminances, and $sDA_{300,50\%}$ were simulated by ClimateStudio v1.8 [61]. A horizontal analysis grid with a spacing of 0.50 m was set for the sensor points at a height of 0.75 m [26]. DF was calculated under the CIE standard overcast sky at noon on 22 December. Average illuminance, $sDA_{300,50\%}$, and UDI were calculated based on TMY climate data of each city without blinds (8:00–18:00 for each day, and in total 3650 values of illuminances for a year) [58]. Average illuminance values were separated into monthly analyses. Referring to WELL v.2 [22], a sensor with a height of 55 inches (1.40 m) in the center of the living room, and the median EML value of the four orthogonal directions (face, back, and sides to the window) were calculated to be the measurement value for the center. EML was simulated by ALFA v0.5.7 [62] under both clear and overcast sky models on four typical days: 21 March (equinox), 22 June (summer solstice), 23 September (equinox), and 22 December (winter solstice), with a 60 min timestep from 8:30 to 17:30 (ten values per day) [68]. Given that EML refers to the equal energy spectrum, while the m-EDI corresponds more to the daylight spectrum of a sky with a CCT of 6500K (D65), after the simulation, the m-EDI of each unit was calculated based on the equation m-EDI = 0.9058 × EML [31,68,69]. Table 6 shows the simulation parameters used in this study. Suitable materials were selected in the material browsers of both ALFA and ClimateStudio that had the closest reflectance values, as follows: 0.80 for ceilings, 0.20 for floors, 0.50 for walls and furniture, 0.40 for façade, 0.20 for ground and transmittance, and 0.70 for glazing [22,26,36,45,70,71].

Table 6. Simulation parameters used in ClimateStudio (CSO) and ALFA [22,26,36,45,70,71].

Materials							
Position			**Material Name**	**Reflectivity**		**Transmittance**	
				P [1]	**M** [2]	**P**	**M**
Ground			Rock 7	0.20	0.15	-	-
Façade	Wall		Old White Street Paint	0.39	0.34	-	-
	Window		Dark Grey Painted Floor	0.13	0.14	-	-
Indoor	Wall		Dupont Off White 75	0.49	0.42	-	-
	Floor		Dark Grey Floor Tiles	0.20	0.19	-	-
	Ceiling		White Painted Room Ceiling	0.82	0.77	-	-
	Furniture		Dupont Desaturated White Blue 109	0.51	0.52	-	-
	Window	CSO	Clear-Solarban 60 (3)	0.12	-	0.70	-
		ALFA	Double IGU Clear Trivs 70%	0.11	0.11	0.70	0.70
Radiance parameters							
-ambient bounces			7	-ambient divisions			1500
-ambient super-samples			100	-ambient accuracy			0.1
-ambient resolution			300				

[1] P: photopic; [2] M: melanopic.

3. Results

This section includes three main parts: (1) the general distribution of daylight availability in the four housing estates; (2) the daylight compliance of selected units in the four housing estates; and (3) the circadian daylighting of selected units in the four housing estates.

3.1. General Distribution of Daylight Availability within Each Estate

From Figure 6, the four housing estates achieved significantly different distributions of vertical daylight under current planning regulations and local climates. The Kruskal–Wallis ANOVA test also confirmed, at the significance level of 0.05, the differences in the distribution of annual average vertical daylight illuminances at the center of the façade across cities. The estates in Kunming (13.3–33.5 klx) and Tianjin (16.6–38.3 klx) presented larger ranges of illuminances than Changsha (7.5–17.5 klx) and Chongqing (6.0–14.2 klx), for the higher possibility to receive more daylight. Within an estate, the daylight availability on the same floor varied more on lower floors than those on higher floors. Generally, mid-rise buildings achieved smaller variations than high-rise buildings for all four estates.

The eight selected units for each estate are highlighted in Figure 6. Although the eight units presented the average daylighting conditions of typical floors in each estate, they appeared at different percentile ranks of daylight availability in different estates, given the different planning layouts. It indicates the importance of integrated planning for balanced daylighting in residential areas.

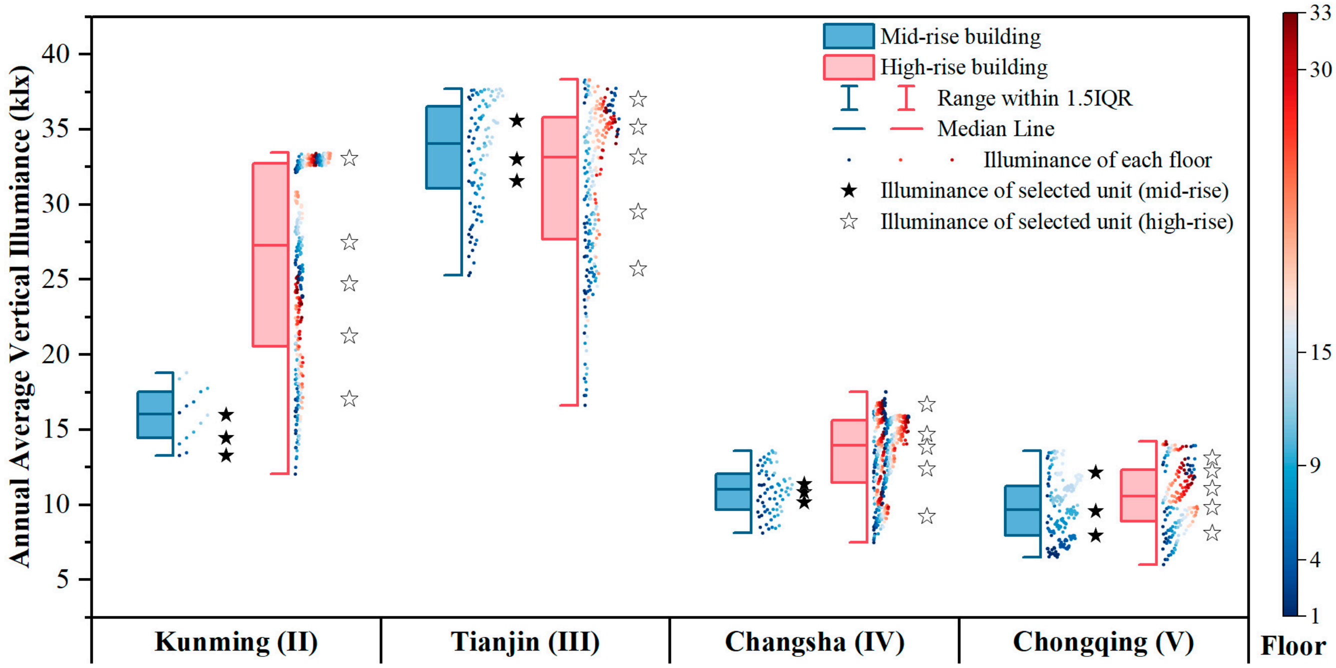

Figure 6. Distribution of annual average vertical daylight illuminances (8:00–18:00) at the center of the south façade in the four housing estates: each point presents the vertical illuminance at one floor façade of one building. Eight selected units of each estate are highlighted. For mid-rise buildings (black stars from the lowest to highest): ground, middle, and top floor. For high-rise buildings (hollow stars from the lowest to highest): ground floor, lower quartile of the floors (25%), middle floor, upper quartile of the floors (75%), and top floor.

3.2. Daylight Compliance

From this section on, the analysis focuses on the interior daylight availability of the eight selected units in each estate. Section 3.2 presents daylight compliance in terms of generic daylight metrics used in residences, considering the visual effects of daylight.

3.2.1. Daylight Compliance with Current Standards

Based on the Chinese national standard GB 50033-2013 [14] and WELL standard [22], daylight factor (DF) and $sDA_{300,50\%}$ of living rooms were chosen as the benchmarks for daylighting analysis in this subsection. The national standard regulates that DF of the living room should be 1.8% in Kunming, 2.0% in Tianjin, 2.2% in Changsha, and 2.4% in Chongqing, while the WELL standard recommends that $sDA_{300,50\%}$ is achieved for >55% (one point) or >75% (two points).

Figure 7 shows the daylight compliance of the selected units in the four housing estates. These selected units hardly met the national DF standards, especially for high-rise buildings. Regarding $sDA_{300,50\%}$, no high-rise unit achieved the $sDA_{300,50\%}$ recommendation. Three units of the mid-rise buildings in Tianjin and the top floor of mid-rise buildings in Chongqing achieved 55% for $sDA_{300,50\%}$. Only the middle and top floors of mid-rise buildings in Tianjin exceeded the DF standard and 75% for $sDA_{300,50\%}$. Current planning of the estate in Tianjin had a higher potential for daylight compliance of mid-rise buildings under the local daylight climate.

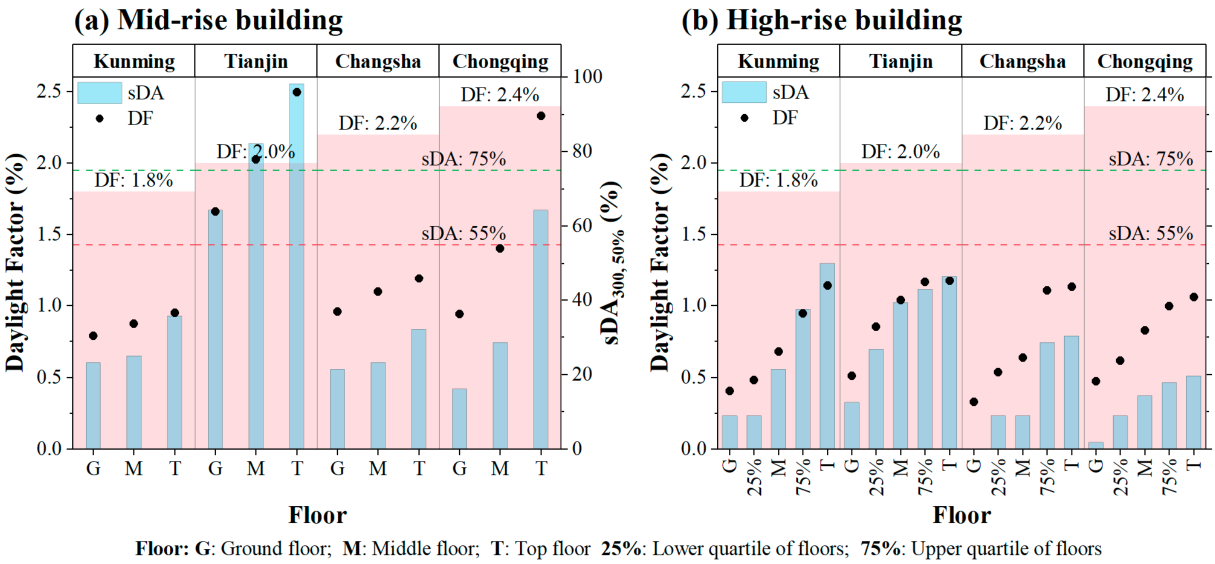

Figure 7. Average daylight factors (DF) and $sDA_{300,50\%}$ values (8:00–18:00) in the living room of the selected units in the four housing estates: (**a**) mid-rise building; (**b**) high-rise building. Red areas present that DF values are lower than the local standard. Red and green dashed lines present the 55% and 75% (recommended thresholds) for $sDA_{300,50\%}$, respectively.

Apart from daylight compliance, the variations in daylighting between units and estates can also be seen in Figure 7. In the four estates, mid-rise buildings had generally higher DF and $sDA_{300,50\%}$ values than high-rise buildings. On the one hand, it can be explained in part by the different dimensions of the window and living room for the two types of units (Figure 5). In mixed residential layouts, it might be an area balance to have a compact arrangement of unit plans for high-rise buildings but a capacious arrangement for mid-rise buildings. On the other hand, another possible explanation for this result was due to the low building height and low obstruction for mid-rise buildings in practical residential planning. For mid-rise buildings, both DF and $sDA_{300,50\%}$ varied a lot between estates: the estate in Chongqing achieved significantly larger variations between the ground and top floor (1.4% for DF, 48.2% for $sDA_{300,50\%}$), while the estates in Kunming and Changsha achieved similar and smaller floor variations. For high-rise buildings, the DF values of the four estates had similar ranges between 0.4% (±0.1%) to 1.1% (±0.1%); as for $sDA_{300,50\%}$, the estates in Changsha and Chongqing achieved lower values than the estates in Kunming and Tianjin. Furthermore, for high-rise buildings, there was no linear increase in the daylight values as the floor increases. When the floor exceeded the upper quartile (75%) for the estates in Kunming and Changsha, or the middle floor for Tianjin and Chongqing, the increments of daylight values of high-rise buildings decreased for each estate.

However, the daylight performance of each estate was different in terms of different daylight metrics. Although the units of mid-rise buildings in Changsha obtained higher DF values than the units in Kunming, they obtained lower $sDA_{300,50\%}$ values, implying that the DF may overestimate the daylight availability in Changsha. A similar trend was also demonstrated in high-rise buildings: there were similarities in ranges of DF of high-rise buildings across estates, but the $sDA_{300,50\%}$ values varied a lot. The distribution of DF values was closer to the distribution of $sDA_{300,50\%}$ values in the estate in Tianjin than in other estates.

3.2.2. Useful Daylight Illuminance Analysis

Referred to previous studies [45,72], daylight illuminances are divided into three ranges based on occupant preference: (a) UDI fell-short (UDI-f, <100 lx) means the high probability to switch on the artificial light; (b) UDI combined (UDI-c, 100–3000 lx) is perceived as useful and tolerable; (c) UDI exceeded (UDI-e, >3000 lx) suggests the high risk of overheating and visual discomfort. Therefore, it would be better to achieve more UDI-c and control the occurrence of UDI-f and UDI-e. This study also used the UDI to assess the daylight availability of the residences.

The UDIs of unobstructed south-oriented units (Figure 5) of mid-rise and high-rise buildings were simulated under the local climate of each city as benchmarks. The frequency of UDI-e in each unobstructed unit was no more than 1.95%, except for Tianjin: 9.07% for the unit of mid-rise building and 3.97% for the unit of high-rise building. Therefore, only UDI-c and UDI-f of the unobstructed units were set as benchmarks for each city (dashed lines in Figure 8). Without obstruction, the two types of units had different performances in different cities. In Kunming and Tianjin, the two unobstructed units had similar frequencies of UDI-c. However, unobstructed units in high-rise buildings had significantly lower frequencies of UDI-c than mid-rise buildings in Changsha and Chongqing.

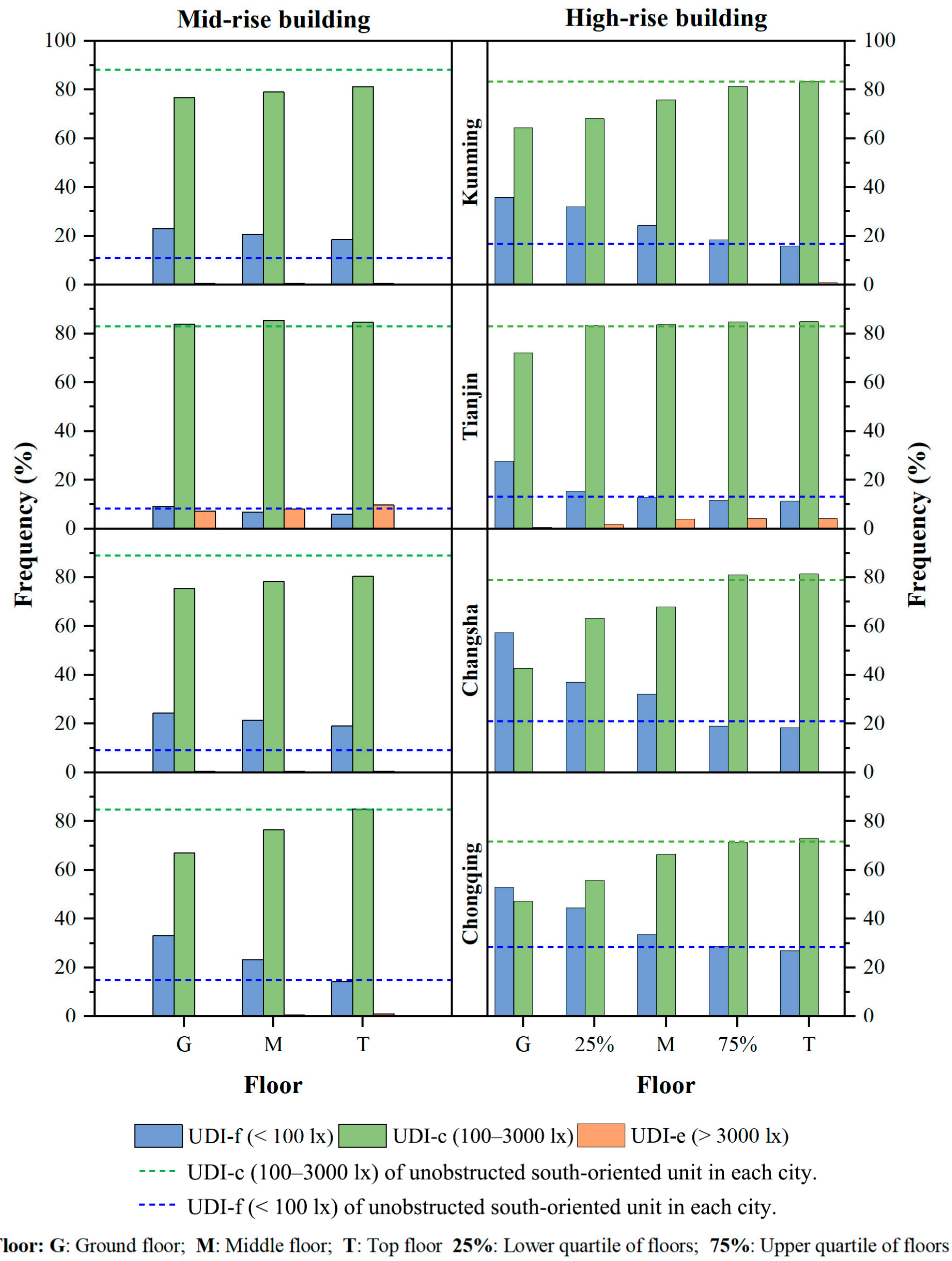

Figure 8. Frequencies of annual useful daylight illuminance (UDI, 8:00–18:00) in the living room of the selected units in the four housing estates. The reference dashed lines show the frequencies of UDI-c (100–3000 lx) and UDI-f (<100 lx) of the unobstructed south-oriented units in each city.

The annual frequencies of the three UDI ranges in the living rooms of the four estates are also shown in Figure 8 (columns). Higher floors had a higher potential to receive more UDI-c and less UDI-f. Most units in Tianjin received almost the same UDI-c as unobstructed conditions, and mid-rise buildings in Tianjin encountered a higher risk of excessive daylight with a higher level of UDI-e. However, most units in the other three cities achieved lower frequencies of UDI-c and higher frequencies of UDI-f than the unobstructed conditions. Especially the ground floors of high-rise buildings in Changsha and Chongqing received even higher frequencies of UDI-f than UDI-c.

3.2.3. Monthly Analysis

Relying on the CBDM [23], the daylight availability of different seasons can be analyzed in detail. Monthly average illuminances in the living room of selected units were calculated (Figures 9 and 10). Since the Chinese national standard [14] requires the interior daylight illuminance from 10:00 to 14:00, the monthly average illuminances were calculated in two time periods: 10:00–14:00 and 8:00–18:00. The average illuminances (10:00–14:00) had significantly higher values than illuminances (8:00–18:00) in winter in the estates in Tianjin and Changsha. For the estates in Kunming and Chongqing, however, the difference between the two time periods was not significant. The average illuminances during the two time periods had a similar trend of annual variation. In general, when compared to the monthly average unobstructed daylight illuminances of each city in Figure 3, the monthly daylight availability of these units presented varying trends, sometimes even opposite ones, due to the area planning.

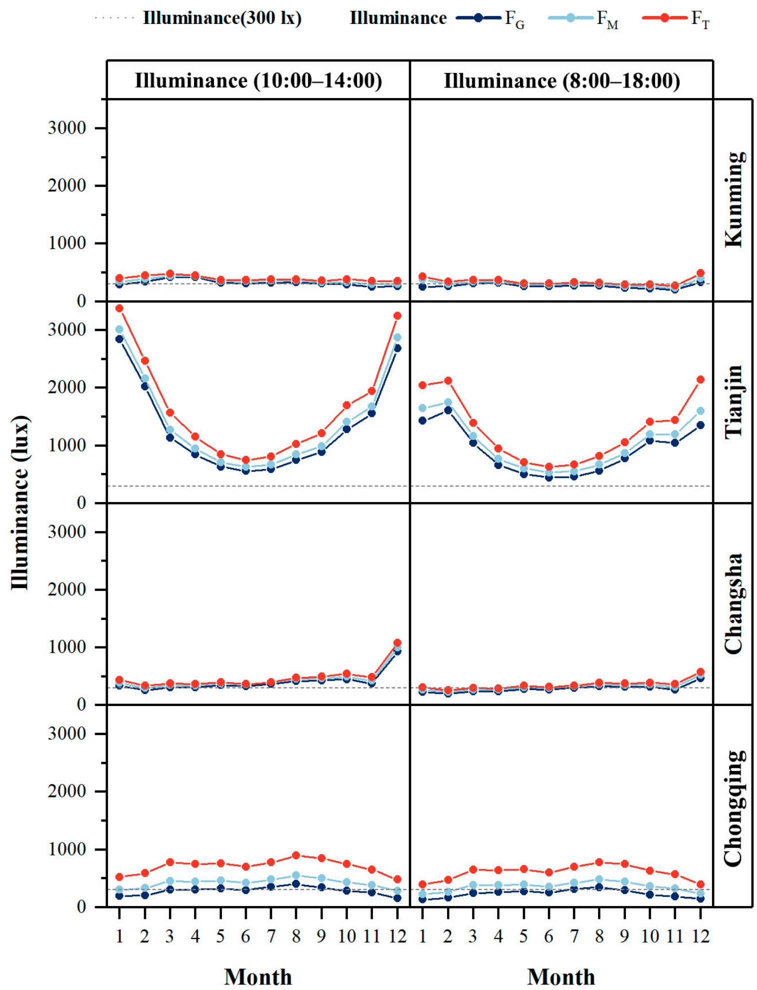

Figure 9. Monthly average daylight illuminances (10:00–14:00 and 8:00–18:00) in the living rooms of the selected units in the four housing estates (mid-rise buildings).

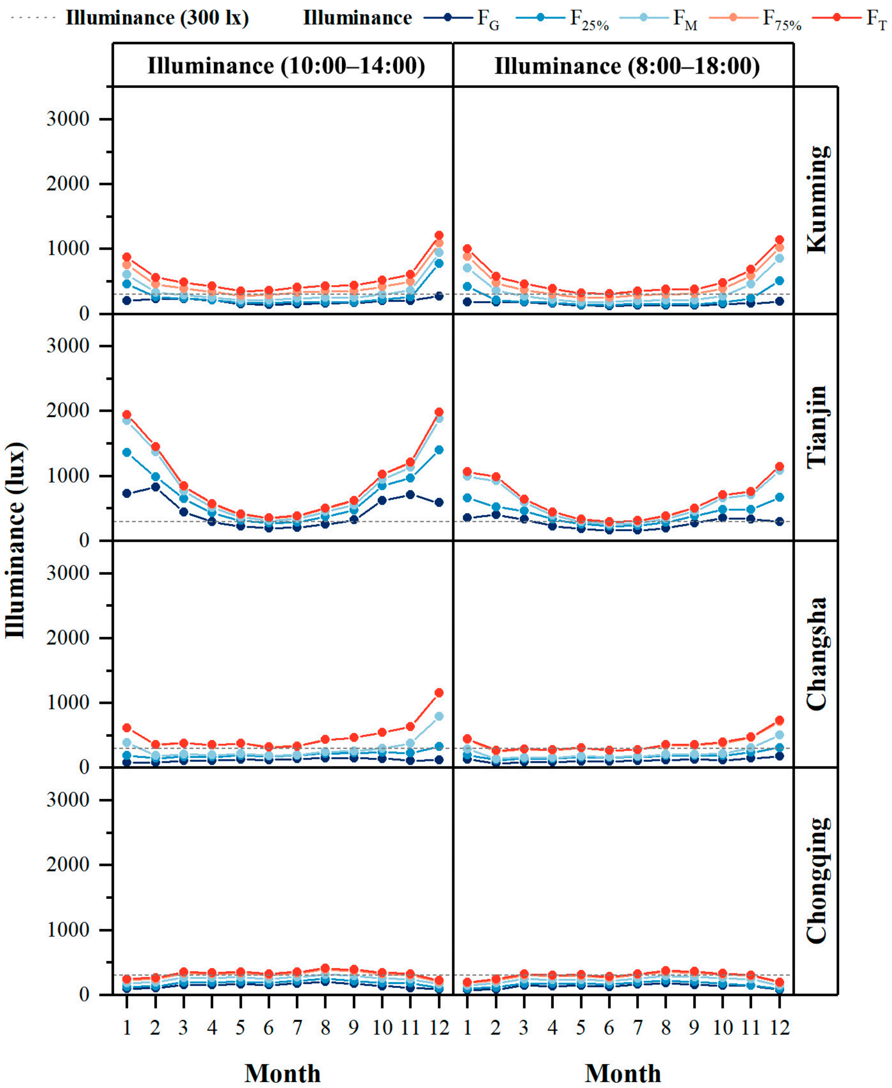

Figure 10. Monthly average daylight illuminances (10:00–14:00 and 8:00–18:00) in the living rooms of the selected units in the four housing estates (high-rise buildings).

Similar to the daylight conditions discussed in the previous subsections, mid-rise buildings achieved the highest values of daylight in the estate in Tianjin, while lower in Kunming and Changsha and midst in Chongqing (Figure 9). Additionally, mid-rise buildings in Tianjin presented the largest variation in illuminance levels throughout the months (1504 lx between December and June), with the peak value occurring during winter. In contrast, interior daylight illuminances in mid-rise buildings in Kunming and Changsha showed little sensitivity to the season. High-rise buildings experienced more complex daylight conditions (Figure 10). Except for the estate in Chongqing, the other three estates had lower values in summer than other seasons, which were opposite to the trends in Figure 3. Interestingly, sometimes different floors might present different annual variation trends, particularly for high-rise buildings. Taking Tianjin for example, illuminances on the ground floor of high-rise buildings peaked twice in February and October, while the other floors reach their peak in December.

Considering the Chinese national average daylight illuminance standard of 300 lx [14], mid-rise buildings generally had a high potential for compliance. Nevertheless, high-rise buildings still struggled with illuminance compliance: for Kunming and Tianjin, the ground floor met the challenge, as did other floors in summer; for Changsha and Chongqing, almost all units failed to comply with the illuminance requirement. Higher illuminances at upper floors (e.g., top floor) always suggested larger differences between floors for each city, on account of the low values and smaller annual variations at lower floors (e.g., ground floor). This can be seen in most mid-rise and high-rise buildings (Figures 9 and 10). For mid-rise buildings in Tianjin and Chongqing, sharp increments occurred between the middle and top floors. High-rise buildings had different floor variations between two time periods. For illuminances (10:00–14:00), sharp increments occurred between the ground floor and the lower quartile of floors (25%) for high-rise buildings in Kunming and Tianjin, while between the lower quartile of floors and middle floor in Changsha. For illuminances (8:00–18:00), sharp increments occurred between the lower quartile of floors (25%) and middle floor for high-rise buildings in Kunming and Tianjin.

3.3. Circadian Daylighting

In this section, circadian metrics were analyzed to assess the daylight availability for working from home in the selected units, considering the non-visual effect of daylight. In a previous study [49], cloud cover ranging from 0–40% and 60–100% was classified as clear and overcast sky, respectively. The annual occurrences (8:00–18:00) of clear sky (C) and overcast sky (O) in the climate data of the four cities are as follows [58]: Kunming (C: 50%, O: 40%), Tianjin (C: 48%, O: 42%), Changsha (C: 48%, O: 41%) and Chongqing (C: 51%, O: 39%). Therefore, both clear and overcast skies were considered for the circadian daylighting analysis [73]. Hourly m-EDI from 8:30 to 17:30 at the center of the living room of each selected unit on four typical days are shown in Figure 11 (mid-rise buildings) and Figure 12 (high-rise buildings). Due to the significant variations in m-EDI values, a logarithmic scale was employed for the m-EDI axis in the figures.

In Figure 11, the daily variation trend for all mid-rise building units presented a smooth curve with a peak around noon under the overcast sky. The peaks of some estates occurred slightly earlier (e.g., Tianjin) or later (e.g., Chongqing) due to building orientations. Generally, living rooms of all mid-rise building units received the highest m-EDI values on 22 June (summer solstice) but lowest on 22 December (winter solstice) under the overcast sky, while midst on 21 March and 23 September (equinoxes). The mid-rise buildings in Kunming and Changsha achieved similar m-EDI values and small floor differences. The clear sky complicated the situation. On the other three days except for 22 December, the daily variation trends were more moderate under the clear sky compared to those under the overcast sky. On 22 December, under clear sky conditions, there were more abnormal m-EDI values that deviated from the smooth curves. Specifically, mid-rise buildings in Kunming achieved abnormally high m-EDI in the afternoon, while at noon in Changsha. Additionally, the ground and middle floor achieved abnormal lower values in the morning in Tianjin while higher values in the afternoon in Chongqing. The clear sky highlighted the effect of orientation on the daily m-EDI variations. Southeast-oriented units met the highest m-EDI values in the morning (e.g., Tianjin), while southwest-oriented units met in the afternoon (e.g., Chongqing).

Figure 12 presents similar daily variation trends for high-rise building units under the overcast sky as those for mid-rise building units in Figure 11, but with larger floor differences in Kunming and Changsha. Under the clear sky, 22 December also showed a different trend from other days, with larger floor variations observed across all high-rise building units in the four cities. The large floor variations occurred in the afternoon in Kunming and Chongqing, morning in Tianjin and till afternoon in Changsha.

Although there is no recognized non-visual daylight standard for residences, the WELL standard recommends that electric lighting is used to achieve at least 136 m-EDI (one point) or 250 m-EDI (three points) [22]. The WELL standard also regulates that the 136/250 m-EDI should be achieved for at least four hours (beginning by noon at the latest) for non-dwelling units, but no specification for residences. This paper, therefore, tried to explore whether the recommendations can be complied with in residences only by daylight. Table 7 shows the m-EDI compliance of each selected unit on four typical days under clear and overcast skies. Under the clear sky, 75% of the units met the 136 m-EDI recommendation in four days, and all units met it in at least two days. Noncompliance appeared at some units of high-rise buildings on the equinoxes. Under the overcast sky, 40.2% of the units still complied with the 136 m-EDI recommendation in four days, and all units in mid-rise buildings were still able to comply with the recommendation for at least three days. However, high-rise buildings had trouble on the ground floor and even higher floors on 22 December. Mid-rise buildings had a higher potential to comply with the 250 m-EDI recommendation than high-rise buildings. For high-rise buildings, the units in Tianjin showed a significant advantage over other cities for 250 m-EDI.

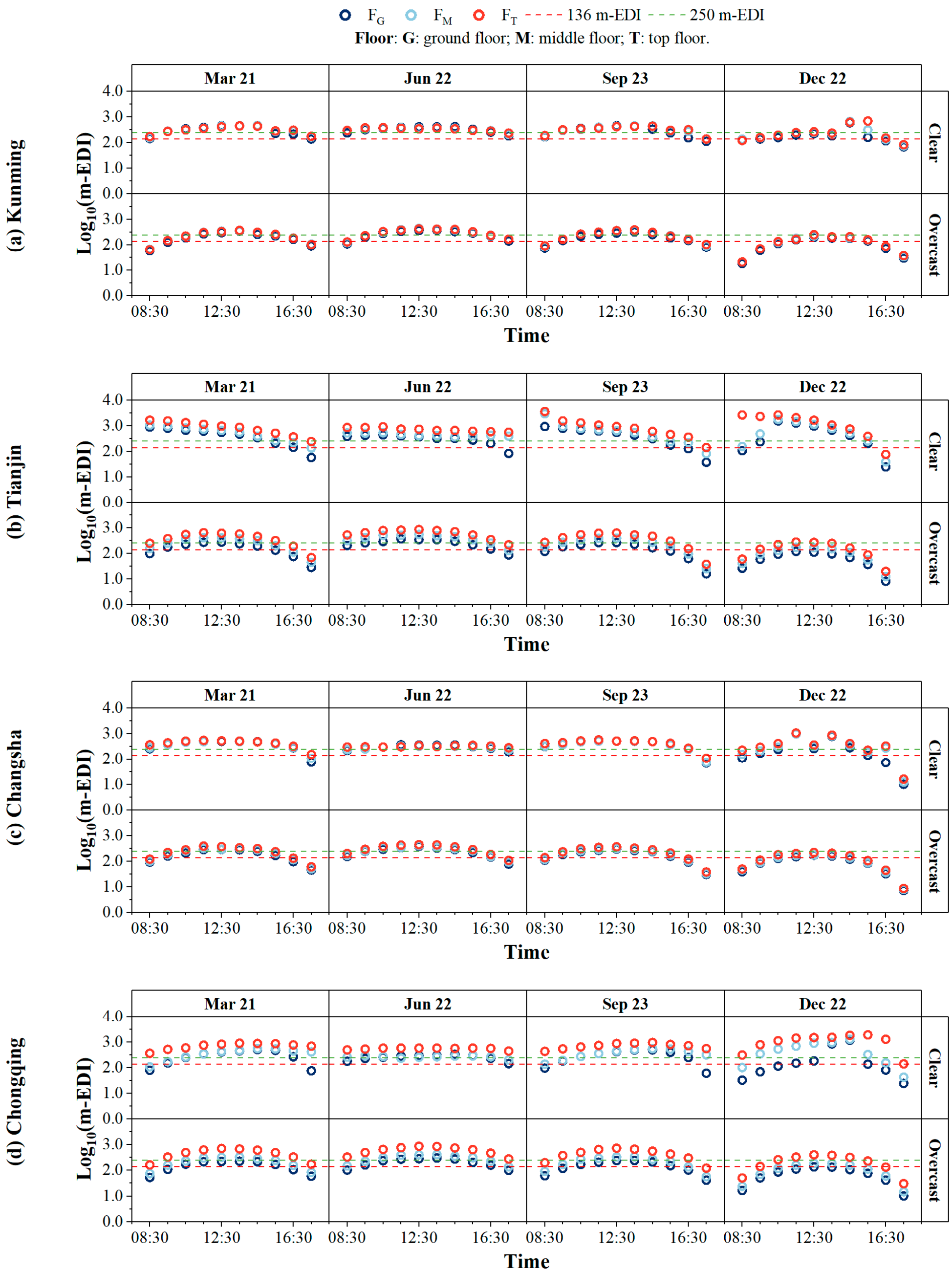

Figure 11. Hourly m-EDIs on four typical days at the center of the living room (8:30–17:30) of the selected units in the four housing estates (mid-rise buildings).

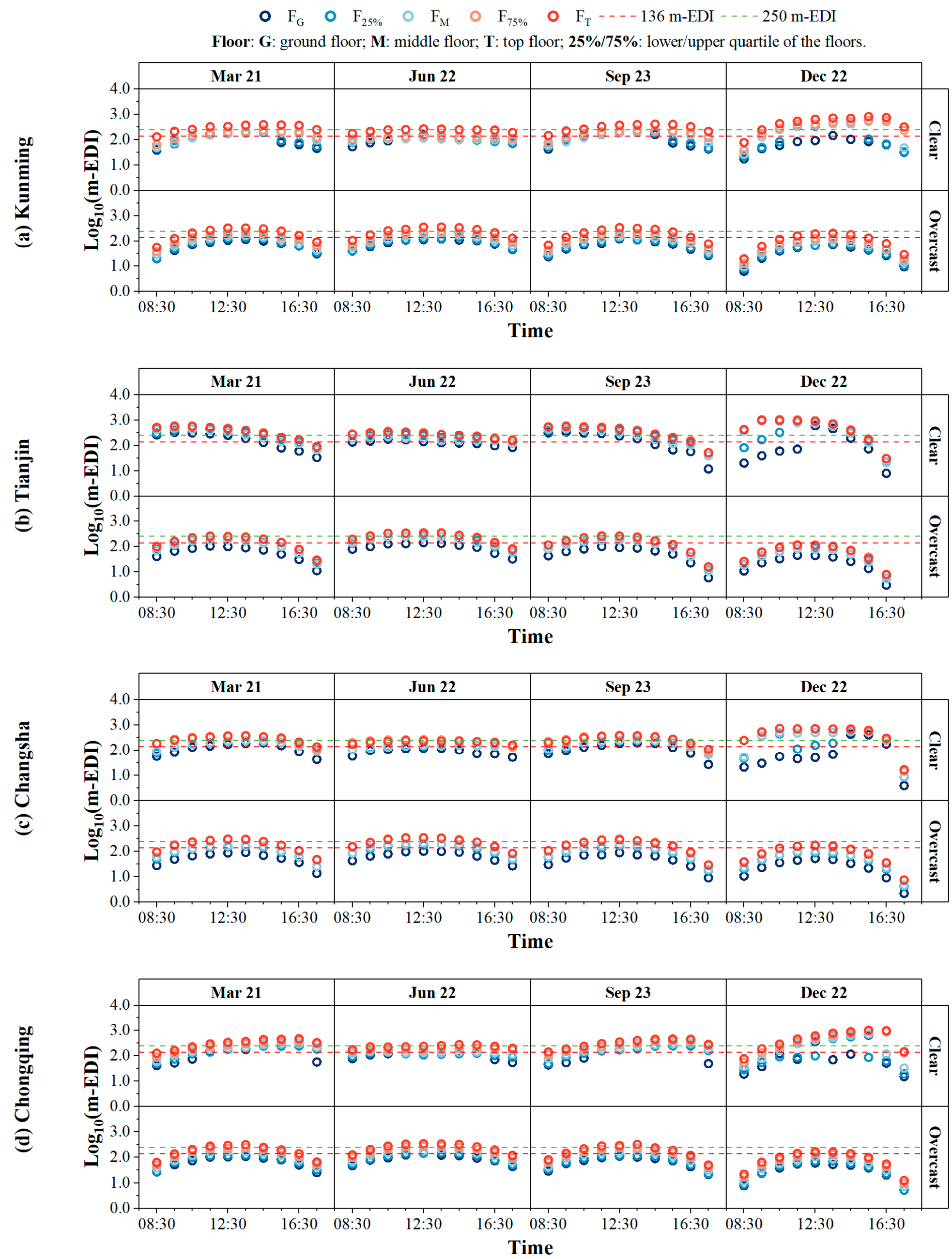

Figure 12. Hourly m-EDIs on four typical days at the center of the living room (8:30–17:30) of the selected units in the four housing estates (high-rise buildings).

Table 7. Non-visual daylight compliance of living room on four typical days for elected units in the four housing estates (based on WELL standard [22]).

Building Type	Sky	Floor [1]	Kunming				Tianjin				Changsha				Chongqing			
			3/21	6/22	9/23	12/22	3/21	6/22	9/23	12/22	3/21	6/22	9/23	12/22	3/21	6/22	9/23	12/22
Mid-rise	Clear	G	3 [2]	3	3	1	3	3	3	3	3	3	3	3	3	3	3	1
		M	3	3	3	1	3	3	3	3	3	3	3	3	3	3	3	3
		T	3	3	3	1	3	3	3	3	3	3	3	3	3	3	3	3
	Overcast	G	3	3	3	1	1	3	1	0	3	3	1	0	1	3	1	0
		M	3	3	3	1	3	3	3	0	3	3	3	1	3	3	3	1
		T	3	3	3	1	3	3	3	1	3	3	3	1	3	3	3	3

Table 7. *Cont.*

Building Type	Sky	Floor [1]	Kunming				Tianjin				Changsha				Chongqing			
			3/21	6/22	9/23	12/22	3/21	6/22	9/23	12/22	3/21	6/22	9/23	12/22	3/21	6/22	9/23	12/22
High-rise	Clear	G	1	0	1	0	3	1	3	0	1	0	1	0	1	0	1	0
		25%	1	0	1	3	3	1	3	3	1	1	1	3	1	0	1	0
		M	1	0	1	3	3	1	3	3	1	1	1	3	1	1	1	3
		75%	1	0	1	3	3	3	3	3	3	3	3	3	1	1	1	3
		T	3	3	3	3	3	3	3	3	3	1	3	3	3	1	3	3
	Overcast	G	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		25%	0	0	0	0	1	1	1	0	1	1	1	0	0	1	0	0
		M	0	1	0	0	1	1	1	0	1	1	1	0	1	1	1	0
		75%	1	1	1	0	1	3	1	0	3	3	1	1	1	3	1	0
		T	3	3	3	3	1	3	1	1	1	3	1	1	3	3	1	1

[1] Floor: G: Ground floor; M: Middle floor; T: Top floor; 25%: lower quartile of the floors; 75%: upper quartile of the floors; [2] Compliance: 3: The unit achieves 250 m-EDI for at least four hours (beginning by noon at the latest) on this day, three points (green); 1: The unit achieves 136 m-EDI for at least four hours (beginning by noon at the latest) on this day, one point (orange); 0: The unit does not achieve 136 m-EDI for at least four hours (beginning by noon at the latest) on this day, no point (white or gray).

4. Discussion

After a series of analyses of these practical housing estates, it can be found that residences received different daylight availability under local daylight climates and current planning regulations.

Given the current daylight standards, most units of the four estates were not able to achieve both DF and $sDA_{300,50\%}$ requirements (Figure 7). Usually, daylight on the top floor is the closest to unobstructed conditions in the same city; in other words, it is probably in accordance with the local climate. However, in the estates in Kunming, Changsha, and Chongqing, some almost unobstructed units with a high level of daylight also struggled to meet the requirements (Figure 7), which means they were hard to comply with the standards by improving planning. Since the DF requirements were set under the overcast sky, and the $sDA_{300,50\%}$ requirement was stipulated under experiments for general working scenes [26,28], it is hard to state that the incompliance was due to unsuitable unit design or overhigh DF and $sDA_{300,50\%}$ requirements for residence [29]. We are eager to see further research on whether the above metrics are applicable and what requirements are suitable for residence.

As Figure 8 demonstrates, most units achieved UDI-c frequencies exceeding 60%, with some units even approaching 80%. Except for the estate in Tianjin, units in the other three cities showed more useful daylight on higher floors with less obstruction, which means the current residential area planning in the three cities hindered the units from achieving more useful daylight, especially for the lower floors of high-rise buildings. As for Tianjin, most floors received a high level of useful daylight, but also a high risk of excessive daylight. Therefore, the requirements for the spacing between buildings would be better to be larger in Kunming, Changsha, and Chongqing, while smaller in Tianjin. Compared to $sDA_{300,50\%}$, UDI is a more suitable metric for assessing the risk of excessive daylight at the same time [74], making it better for use in the planning procedure to ensure that spacing between buildings is neither excessively wide nor insufficient.

Monthly daylight values generally reached the peak in winter but bottom in summer except for Chongqing, as an opposite tendency to the annual variation in unobstructed daylight illuminance in Figure 3. In addition, higher daylight illuminance values at upper floors (e.g., top floor) always suggested larger differences between floors. This characteristic was always accompanied by low and little changed daylight values on the ground floor. Therefore, the variation between floors could be attributed to the obstruction of lower floors, which was caused by area planning. As a result, better site planning based on the local daylight climate could reduce the floor differences by guaranteeing daylight availability on the lower floors.

Furthermore, mid-rise building units in the four estates showed good performance in compliance with the m-EDI recommendation only by daylight even under the overcast sky. High-rise building units met some challenges, especially under the overcast sky. As this study only calculated circadian metrics on four typical days and under two types of sky models, the results provide limited demonstration of the circadian daylighting to some extent. For further research, local climate data will be considered for more detailed circadian daylighting analyses.

The combined impact of local climate, site planning, and unit design on daylighting in residences has been confirmed based on the results. Therefore, the three main impacts would better all be considered in sequence in planning phase for improved daylighting in residences. Local climate is the base. UDIs could be metrics to assess the integrated influence of site planning and unit design on interior daylight quality under local climate, for balancing the dimensions of unit (including the size of window and room) and the spacing between buildings. However, the iterative simulation may be complicated in practice for planners and designers. Therefore, for typical daylight climate, it is important to find the correlation between interior daylight values with both planning and unit design factors, which, if it exists, could be used in local planning guidelines for better daylight quality in residences.

Additionally, while this paper has primarily focused on the living room in residences, another study has emphasized the significance of daylight in the kitchen based on residents' satisfaction [29]. Future research can include more field investigations to further explore residents' preferences across China and suitable thresholds for daylight values.

5. Conclusions

In order to investigate the applicability of current planning regulations for daylight availability in dense residential areas under different climates across China, this paper used simulation methods to study daylight availability in four practical mixed housing estates in four different Chinese daylight climate zones.

This study has found that, based on the combined effects from the local climates and residential area planning, most of the studied units failed to meet the national DF standards or the WELL $sDA_{300,50\%}$ recommendations. However, more than half of these units could still reach a high level of UDI-c and comply with the m-EDI recommendation. The results raised two doubts: firstly, the applicability of these metrics and their thresholds to residences is uncertain; secondly, the current planning regulations may not be suitable for daylight availability under some daylight climates across China.

In conclusion, there is still a gap between area planning and interior daylight availability in dense residential areas in China. Further research is necessary to improve the planning regulations for higher daylight quality. The research should focus on two main topics: firstly, conducting field investigation to explore applicable daylight thresholds based on residents' wellbeing and satisfaction; secondly, conducting sensitivity testing of both planning and unit design factors for residential daylight availability, taking account of different daylight climates. Based on these, the gap between planning and interior daylight availability will be bridged, leading to improved residential daylighting design and quality of life.

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

Glossary

Group 1: Interior daylighting	
ASE	Annual sunlight exposure
CBDM	Climate-based daylight modelling
CS	Circadian stimulus
DCZ	Daylight climate zone
DF	Daylight factor
EML	Equivalent melanopic illuminance
m-EDI	Melanopic equivalent daylight illuminance
sDA	Spatial daylight autonomy
TMY	Typical meteorological year
UDI	Useful daylight illuminance
Group 2: Residential Area Planning	
$F_{G/M/T/25\%/75\%}$	Ground floor; middle floor; top floor; lower quartile and upper quartile of the floors of the building, respectively.
Sunlight Duration	The total number of hours on a typical day or during the year in which direct sunlight reaches the room or typical area (e.g., window or windowsill)
UVA	Unobstructed vision area
VDF	Vertical daylight factor
VSA	Visible sky area
VSC	Vertical sky component

References

1. Reinhart, C.F. *Daylighting Handbook I*; Building Technology Press: Cambridge, MA, USA, 2014.
2. Tregenza, P.; Mardaljevic, J. Daylighting buildings: Standards and the needs of the designer. *Light. Res. Technol.* **2018**, *50*, 63–79. [CrossRef]
3. Boyce, P.R. Light, lighting and human health. *Light. Res. Technol.* **2022**, *54*, 101–144. [CrossRef]
4. Dingel, J.I.; Neiman, B. How many jobs can be done at home? *J. Public Econ.* **2020**, *189*, 104235. [CrossRef] [PubMed]
5. Shimura, A.; Yokoi, K.; Ishibashi, Y.; Akatsuka, Y.; Inoue, T. Remote Work Decreases Psychological and Physical Stress Responses, but Full-Remote Work Increases Presenteeism. *Front. Psychol.* **2021**, *12*, 730969. [CrossRef] [PubMed]
6. Ng, P.M.L.; Lit, K.K.; Cheung, C.T.Y. Remote work as a new normal? The technology-organization-environment (TOE) context. *Technol. Soc.* **2022**, *70*, 102022. [CrossRef] [PubMed]
7. Littlefair, P. *Site Layout Planning for Daylight and Sunlight: A Guide to Good Practice (BR 209)*, 2nd ed.; IHS BRE Press: Berkshire, UK, 2011.
8. Littlefair, P. Passive solar urban design: Ensuring the penetration of solar energy into the city. *Renew. Sustain. Energy Rev.* **1998**, *2*, 303–326. [CrossRef]
9. Tregenza, P.; Wilson, M. *Daylighting: Architecture and Lighting Design*; Routledge: New York, NY, USA, 2011.
10. Mardaljevic, J. The implementation of natural lighting for human health from a planning perspective. *Light. Res. Technol.* **2021**, *53*, 489–513. [CrossRef]
11. Littlefair, P. Daylight, sunlight and solar gain in the urban environment. *Sol. Energy* **2001**, *70*, 177–185. [CrossRef]
12. Ng, E. Studies on daylight design and regulation of high-density residential housing in Hong Kong. *Light. Res. Technol.* **2003**, *35*, 178–179. [CrossRef]
13. Reinhart, C.F.; Mardaljevic, J.; Rogers, Z. Dynamic daylight performance metrics for sustainable building design. *Leukos* **2006**, *3*, 7–31. [CrossRef]
14. *GB 50033-2013*; Standard of Daylighting Design of Buildings. Ministry of Housing and Urban-Rural Development of the People's Republic of China (MOHURD): Beijing, China, 2013. (In Chinese)
15. Building Research Establishment. *BREEAM International New Construction, Version 6.0*; Building Research Establishment: Watford, UK, 2021.
16. *EN 17037:2018+A1:2021*; Daylight in Buildings. European Committee for Standardization (CEN): Brussels, Belgium, 2022.
17. Bournas, I. Daylight compliance of residential spaces: Comparison of different performance criteria and association with room geometry and urban density. *Build. Environ.* **2020**, *185*, 107276. [CrossRef]
18. Institute for Building Environment and Energy Conservation. Comprehensive Assessment System for Built Environment Efficiency—New Construction. 2016. Available online: https://www.jsbc.or.jp/research-study/casbee/tools/cas_nc.html (accessed on 30 November 2021). (In Japanese).
19. *GB/T 50378-2019*; Assessment Standard for Green Building. Ministry of Housing and Urban-Rural Development of the People's Republic of China (MOHURD): Beijing, China, 2019. (In Chinese)

20. U.S. Green Building Council. LEED v4.1 RESIDENTIAL BD+C: MULTIFAMILY HOMES. 2020. Available online: https://www.usgbc.org/leed/v41#residential (accessed on 12 November 2021).
21. German Sustainable Building Council. DGNB System—New Buildings Criteria Set 2020. 2020. Available online: https://www.dgnb-system.de/en/buildings/new-construction/criteria/ (accessed on 23 December 2021).
22. International WELL Building Institute. The WELL Building Standard™ Version 2. 2023. Available online: https://v2.wellcertified.com/en/wellv2-23q4/overview (accessed on 25 December 2023).
23. Mardaljevic, J. Examples of Climate-Based Daylight Modelling. In Proceedings of the CIBSE National Conference 2006: Engineering the Future, Oval Cricket Ground, London, UK, 21–22 March 2006.
24. Reinhart, C.F.; Walkenhorst, O. Validation of dynamic RADIANCE-based daylight simulations for a test office with external blinds. *Energy Build.* **2001**, *33*, 683–697. [CrossRef]
25. Nabil, A.; Mardaljevic, J. Useful daylight illuminances: A replacement for daylight factors. *Energy Build.* **2006**, *38*, 905–913. [CrossRef]
26. Illuminating Engineering Society of North America (IES). *Approved Method: IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE)*; IES LM-83-12; Illuminating Engineering Society of North America: New York, NY, USA, 2012.
27. Dogan, T.; Park, Y.C. A critical review of daylighting metrics for residential architecture and a new metric for cold and temperate climates. *Light. Res. Technol.* **2019**, *51*, 206–230. [CrossRef]
28. Reinhart, C.F.; Weissman, D.A. The daylit area—Correlating architectural student assessments with current and emerging daylight availability metrics. *Build. Environ.* **2012**, *50*, 155–164. [CrossRef]
29. Jakubiec, J.A.; Srisamranrungruang, T.; Kong, Z.; Quek, G.; Talami, R. Subjective and Measured Evidence for Residential Lighting Metrics in the Tropics. In Proceedings of the Building Simulation 2019: 16th Conference of IBPSA, Rome, Italy, 2–4 September 2019; pp. 1151–1159. [CrossRef]
30. Bauer, C.; Wittkopf, S. Annual daylight simulations with EvalDRC—Assessing the performance of daylight redirection components. *J. Facade Des. Eng.* **2015**, *3*, 253–272. [CrossRef]
31. Lucas, R.J.; Peirson, S.N.; Berson, D.M.; Brown, T.M.; Cooper, H.M.; Czeisler, C.A.; Figueiro, M.G.; Gamlin, P.D.; Lockley, S.W.; O'Hagan, J.B.; et al. Measuring and using light in the melanopsin age. *Trends Neurosci.* **2014**, *37*, 1–9. [CrossRef]
32. Rea, M.S.; Figueiro, M.G. Light as a circadian stimulus for architectural lighting. *Light. Res. Technol.* **2018**, *50*, 497–510. [CrossRef]
33. Al Enezi, J.; Revell, V.; Brown, T.; Wynne, J.; Schlangen, L.; Lucas, R. A "Melanopic" Spectral Efficiency Function Predicts the Sensitivity of Melanopsin Photoreceptors to Polychromatic Lights. *J. Biol. Rhythm.* **2011**, *26*, 314–323. [CrossRef]
34. Andersen, M.; Mardaljevic, J.; Lockley, S.W. A framework for predicting the non-visual effects of daylight—Part I: Photobiology-based model. *Light. Res. Technol.* **2012**, *44*, 37–53. [CrossRef]
35. Mardaljevic, J.; Andersen, M.; Roy, N.; Christoffersen, J. A framework for predicting the non-visual effects of daylight—Part II: The simulation model. *Light. Res. Technol.* **2014**, *46*, 388–406. [CrossRef]
36. U.S. Green Building Council. LEED v4.1 Building Design and Construction. 2021. Available online: https://build.usgbc.org/bd+c_guide (accessed on 12 November 2021).
37. Kanters, J.; Gentile, N.; Bernardo, R. Planning for solar access in Sweden: Routines, metrics, and tools. *Urban Plan. Transp. Res.* **2021**, *9*, 347–367. [CrossRef]
38. *GB 50180-2018*; Standard for Urban Residential Area Planning and Design. Ministry of Housing and Urban-Rural Development of the People's Republic of China (MOHURD): Beijing, China, 2018. (In Chinese)
39. Zhang, H.; Gao, T.; Liu, W.; Lu, Y. Domestic and Foreign Study Progress on Sunlight Control of Residential Plot. *Des. Community* **2019**, *1*, 97–102. (In Chinese)
40. Ministry of Land Infrastructure Transport and Tourism. Uniform Building Code. 2022. Available online: https://elaws.e-gov.go.jp/document?lawid=325AC0000000201 (accessed on 29 March 2023). (In Japanese)
41. Lau, K.L.; Ng, E.; He, J.Z. Preferred solar access in high-density, sub-tropical housing. *Light. Res. Technol.* **2013**, *45*, 317–330. [CrossRef]
42. Lu, M.; Du, J.T. Assessing the daylight and sunlight availability in high-density residential areas: A case in North-east China. *Archit. Sci. Rev.* **2013**, *56*, 168–182. [CrossRef]
43. Lau, K.L.; Ng, E.; He, Z.J. Residents' preference of solar access in high-density sub-tropical cities. *Sol. Energy* **2011**, *85*, 1878–1890. [CrossRef]
44. Hamzah, B.; Lau, S.S.Y. The development of visible sky area as an alternative daylight assessment method for high-rise buildings in high-density urban environments. *Archit. Sci. Rev.* **2016**, *59*, 178–189. [CrossRef]
45. Lu, M.; Du, J.T. Dynamic evaluation of daylight availability in a highly-dense Chinese residential area with a cold climate. *Energy Build.* **2019**, *193*, 139–159. [CrossRef]
46. Wang, J.; Wei, M.C.; Ruan, X.K. Characterization of the acceptable daylight quality in typical residential buildings in Hong Kong. *Build. Environ.* **2020**, *182*, 107094. [CrossRef]
47. Dogan, T.; Park, Y.C. Testing the residential daylight score: Comparing climate-based daylighting metrics for 2444 individual dwelling units in temperate climates. *Light. Res. Technol.* **2020**, *52*, 991–1008. [CrossRef]
48. Ticleanu, C. Impacts of home lighting on human health. *Light. Res. Technol.* **2021**, *53*, 453–475. [CrossRef]
49. Potocnik, J.; Kosir, M. The Necessity for Multi-Spectral Simulations of the Indoor Non-Visual Luminous Environment: A Simplified Annual Approach. *Buildings* **2023**, *13*, 1357. [CrossRef]

50. *GB 55016-2021*; General Code for Building Environment. Ministry of Housing and Urban-Rural Development of the People's Republic of China (MOHURD): Beijing, China, 2021. (In Chinese)
51. Architectural Design and Research Institute of Tsinghua University Co.; School of Architecture and Urban Planning of Chongqing University. *The Sourcebook of Architecture Design*, 3rd ed.; China Architecture & Building Press: Beijing, China, 2017; Volume 2. (In Chinese)
52. Bureau of Natural Resources and Planning of Kunming Municipality. Technical Regulations on Urban and Rural Planning Management in Kunming. 2022. Available online: https://www.km.gov.cn/c/2022-09-30/4566670.shtml?eqid=bef73d280002f9d70000000364892161 (accessed on 7 August 2023). (In Chinese)
53. *DB12/T 1040-2021*; Technical Specifications for Planning Management of Construction Projects. Tianjin Administration for Market Regulation: Tianjin, China, 2021. Available online: https://ghhzrzy.tj.gov.cn/zwgk_143/tzgg/202102/t20210222_5363547.html (accessed on 7 August 2023). (In Chinese)
54. The People's Government of Changsha Municipality. Technical Regulations on Urban Planning Management in Changsha (2018 Revision). 2018. Available online: http://www.changsha.gov.cn/szf/zfgb/2018nian_1202/201809251/201809/t20180918_6089749.html?eqid=ad55660d0232d0bc0000000264531886 (accessed on 7 August 2023). (In Chinese)
55. The People's Government of Chongqing Municipality. Technical Regulations on Urban Planning Management in Chongqing. 2018. Available online: https://www.gov.cn/zhengce/2018-01/23/content_5717667.htm (accessed on 7 August 2023). (In Chinese)
56. Ministry of Natural Resources of the People's Republic of China. Map of China GS(2019)1682. 2019. Available online: http://bzdt.ch.mnr.gov.cn/browse.html?picId=%224o28b0625501ad13015501ad2bfc0272%22 (accessed on 13 December 2023).
57. CIE. *CIE S 017:2020 ILV: International Lighting Vocabulary*, 2nd ed.; CIE Central Bureau: Vienna, Austria, 2020.
58. China Meteorological Bureau (CMB); Climate Information Centre, Climate Data Office; Department of Building Science and Technology, Tsinghua University. *China Standard Weather Data for Analyzing Building Thermal Conditions*; China Building Industry Publishing House: Beijing, China, 2005. (In Chinese)
59. *GB 50352-2019*; Uniform Standard for Design of Civil Buildings. Ministry of Housing and Urban-Rural Development of the People's Republic of China (MOHURD): Beijing, China, 2019. (In Chinese)
60. Ayoub, M. A review on light transport algorithms and simulation tools to model daylighting inside buildings. *Sol. Energy* **2020**, *198*, 623–642. [CrossRef]
61. Solemma LLC. ClimateStudio. Available online: https://www.solemma.com/climatestudio (accessed on 30 September 2022).
62. Solemma LLC. ALFA. Available online: https://www.solemma.com/alfa (accessed on 14 September 2021).
63. University of Washington; ZGF Architects LLP. Lark Spectral Lighting. Available online: http://faculty.washington.edu/inanici/Lark/Lark_home_page.html (accessed on 25 September 2023).
64. The People's Government of Kunming Municipality. Master Plan of Kunming (2011–2020, 2016 Edition). 2016. Available online: https://zrzygh.km.gov.cn/c/2020-05-21/3560340.shtml (accessed on 5 February 2024). (In Chinese)
65. Tianjin Municipal Bureau of Statistics; Survey Office of the National Bureau of Statistics in Tianjin. *Tianjin Statistical Yearbook 2023*; China Statistics Press: Beijing, China, 2023. Available online: https://stats.tj.gov.cn/nianjian/2023nj/zk/indexch.htm (accessed on 5 February 2024).
66. The People's Government of Changsha Municipality. Urban Master Plan of Changsha (2003–2020, 2014 Edition). 2014. Available online: http://zygh.changsha.gov.cn/zfxxgk/fdzdgknr/ghxx/zxgh/201902/t20190203_3214855.html (accessed on 5 February 2024). (In Chinese)
67. Chongqing Municipal Bureau of Statistics; NBS Survey Office in Chongqing. *Chongqing Statistical Yearbook 2023*; China Statistics Press: Beijing, China, 2023.
68. Lo Verso, V.R.M.; Giovannini, L.; Valetti, L.; Pellegrino, A. Integrative Lighting in Classrooms: Preliminary Results from Simulations and Field Measurements. *Buildings* **2023**, *13*, 2128. [CrossRef]
69. CIE. *CIE S 026/E:2018 CIE System for Metrology of Optical Radiation for ipRGC-Influenced Responses to Light*; CIE Central Bureau: Vienna, Austria, 2018.
70. *GB 50176-2016*; Code for Thermal Design of Civil Building. Ministry of Housing and Urban-Rural Development of the People's Republic of China (MOHURD): Beijing, China, 2016.
71. Reinhart, C.F. *Tutorial on the Use of Daysim Simulations for Sustainable Design*; Institute for Research in Construction, National Research Council Canada: Ottawa, ON, Canada, 2006.
72. Mardaljevic, J.; Andersen, M.; Roy, N.; Christoffersen, J. Daylighting, Artificial Lighting and Non-Visual Effects Study for a Residential Building. Available online: http://thedaylightsite.com/library-3/research-publications/papers/ (accessed on 1 March 2022).
73. CIE. *CIE S 011/E: 2003 Spatial Distribution of Daylight—CIE Standard General Sky*; CIE Central Bureau: Vienna, Austria, 2004.
74. Galatioto, A.; Beccali, M. Aspects and issues of daylighting assessment: A review study. *Renew. Sustain. Energy Rev.* **2016**, *66*, 852–860. [CrossRef]