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To cite this article: Nobuhiro Hirasuga and Luke Leung 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **294** 012038

Using computer climate generator versus conventional lapse rate to model skyscrapers

Nobuhiro Hirasuga[1] **and Luke Leung**[2]

1 MITSUBISHI JISHO SEKKEI INC., 2-5-1 Marunouchi, Chiyoda-ku,
Tokyo, 100-0005 Japan,
Nobuhiro.hirasuga@mj-sekkei.com
2 SKIDMORE, OWINGS & MERRILL LLP, 224 SOUTH MICHIGAN AVENUE
CHICAGO, IL 60604, USA,
Luke.leung@som.com

Abstract. The values of temperature and humidity at the top of skyscrapers are different from those near the ground. Thus, different mechanical systems, air flow rates, and other design parameters are required for such tall buildings. Conventional air temperature reduces linearly with increasing altitude, or lapse rate, of −6.5 °C/km. This study examines how the conventional lapse rate in a hot and humid region differs by using a computer-based climate generator in Dubai at an altitude of 600 m, we address three issues: whether the conventional lapse rate is always a good indicator of the climate profile, whether building design conditions change with altitude, and by how much the predicted energy consumption changes with altitude. Our first conclusion is that the conventional lapse rate may not always be a good indicator of the climate profile. The lapse rate is influenced by humidity. When humidity is low, the lapse rate tends to be higher and can reach up to −9.8 °C/km under adiabatic conditions. Conversely, when humidity is high, and as temperature drops with increasing elevation, condensation occurs and releases heat of vaporization, which warms the air and reduces the lapse rate. Under certain conditions, temperature inversion can occur, and the temperature above the ground may be higher than the temperature at 600 m altitude. Our second conclusion is that the linear lapse rate is not always a good predictor of design conditions. During the summer, there is a tendency to underestimate the lapse rate due to low relative humidity. In contrast, during winter, there is a tendency to overestimate the lapse rate due to low temperatures and high relative humidity. Last but not least, the linear lapse rate is not always a good indicator of energy consumption. Based on simulations, we found that differences in the lapse rate and the air density influenced the energy consumed by the air conditioning system in an office building. Specifically, between altitudes of 11 and 600 m, the energy consumption differed by approximately 5%.

1. Introduction

The temperature and humidity values at the top of skyscrapers are different from those near the ground. Thus, different mechanical systems, air flow rates, and other design parameters are required for such tall buildings. However, there are no design parameters to meet these requirements, even within the ANSI/ASHRAE Standard 169-2013 (Climatic Data for Building Design Standards) [1]. Therefore, we

IOP Conf. Series: Earth and Environmental Science **294** (2019) 012038 doi:10.1088/1755-1315/294/1/012038

must develop these design parameters because, globally, cities are becoming increasingly more centralized, taller, and more stratified.
In general, it is well known that temperature reduces linearly as altitude increases according to the conventional lapse rate of −6.5 °C/km. On the other hand, according to a previous study, it is also known that the lapse rate can vary depending on the weather and other surrounding conditions [2]. Phillips et al. examined these conditions through calculations by using a computer-based climate generator [3]. The data and results of these simulations, which can be obtained from RWDI (https://rwdi.com/en_ca/) in the EPW system file, would be useful for the design of high-rise buildings in the future.
Our study examines how the conventional lapse rate in a hot and humid region differs from the insights provided by the latest computer-based climate generator. Using Dubai and an altitude of 600 m as our case study, we focus on three issues: whether the conventional lapse rate is always a good indicator of the climate profile, whether design conditions change with altitude, and by how much the predicted energy consumption changes with altitude.

2. Lapse rate

As it is an important background concept for this paper, this section describes lapse rate. Equation (1) expresses the well-known relationship between altitude and air temperature, in which the value of Γ, also known as the conventional lapse rate, is −6.5 °C/km [4].

$$\Gamma = \frac{dT}{dz} \qquad (1)$$

where Γ is the lapse rate [°C /km], T is the temperature [°C], and z is the altitude [km]

Figure 1 depicts the various lapse rates that define the change of air temperature with altitude [2]. As shown, the lapse rate is not a constant value. Generally, the lapse rate varies with humidity. When the air is humid, the lapse rate reduces, and in contrast, the lapse rate increases in drier air.
When the relative humidity (RH) is high, as the air temperature drops with increasing elevation, dew condensation occurs. It is because of this phase change, latent heat energy is released into the atmosphere, and this heat raises the air temperature. Thus, when the RH is high, the lapse rate is small.
When the air contains a lot of moisture and no heat transfer into or out of the surrounding air occurs, this lapse rate is known as the wet adiabatic lapse rate; under these conditions, the rate of temperature decrease is −5.5 °C/km.
Conversely, if the amount of moisture in the air is small enough that condensation is minimal, the lapse rate will be higher than −6.5 °C/km. When the air contains so little moisture that condensation does not occur at all, this lapse rate is known as the dry adiabatic lapse rate; under these conditions, the rate of temperature decrease is −9.8 °C/km.
In addition, Figure 1 also illustrates a possible inverse situation (Line 1) in which the air temperature is higher in the sky than on the ground surface.

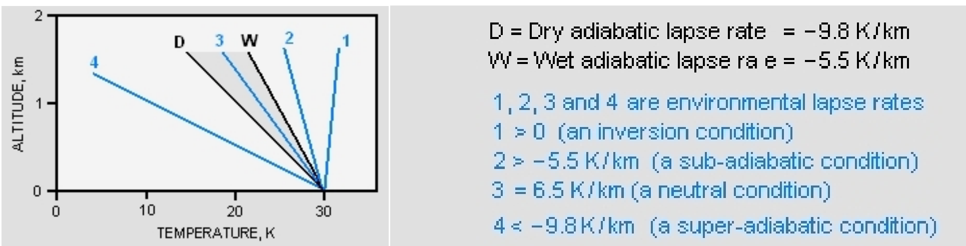

Figure 1. Diagram of the various lapse rates defining the change of atmospheric temperature with altitude [2].

3. Climate profile

This section explains the difference between the climate profile calculated using the conventional lapse rate (based on the ASHRAE ground-level weather file) and that calculated by the computer-based climate generator. Assuming a skyscraper in Dubai, we compared both calculations at an altitude of 600 m.

Figure 2 shows the dry-bulb temperature profile at ground level in Dubai according to ANSI/ASHRAE Standard 169-2013[5] WMO#412170 data. The dotted line in Figure 2 shows the temperature profile at 600 m using the constant conventional lapse rate of −6.5 °C/km. The shape of the corresponding ground-level temperature profile is identical to that of the ASHRAE data; however, the profile is shifted to the left.

In this study, we used the values calculated by RWDI as the simulation values from the computer-based climate generator [3]. Figure 3 shows the dry-bulb temperature at 600 m altitude, as simulated by RWDI. This graph also shows a dotted line representing the temperature profile using the constant conventional lapse rate. However, in this case, the ground-level temperature profiles are not identical in shape. An important observation is that the summer lapse rate is significantly higher than that of the winter.

Figure 4 compares the dry-bulb temperature and RH (ANSI/ASHRAE Standard 169-2013) for Dubai at ground level. Likewise, Figure 5 compares the dry-bulb temperature and RH (RWDI) at an altitude of 600 m. These charts plot the averages for each hour of each month. As shown, the dry-bulb temperature is almost the exact inverse of the RH.

At ground level in summer, the dry-bulb temperature exceeds 40 °C and the RH is only approximately 30%. During this season, there is some amount of moisture in the air, but because the temperature is very high, the RH stays low. When the temperature drops and as the altitude rises, the RH increases, but not as high as to cause dew condensation to occur. Therefore, the temperature lapse rate is high.

On the other hand, the winter temperatures are almost the same at both ground level and 600 m altitude because the design temperature in the winter is approximately 10 °C, and the RH is much higher than in the summer.

When the temperature drops, the moisture in the atmosphere condenses and heat is released. Therefore, the lapse rate decreases.

In addition, Figure 5 shows that, at an altitude of 600 m, the daytime and night-time outside temperatures are nearly equal throughout the year, and it is assumed that there is minimal influence from the rapid changes in the ground surface temperature. This suggests that using cold air at night (e.g., night purge ventilation) is not an effective strategy for saving energy on the upper floors of high-rise buildings.

Therefore, our first conclusion from this assessment of the weather data and simulations is that the conventional lapse rate may not always be a good indicator of the climate profile.

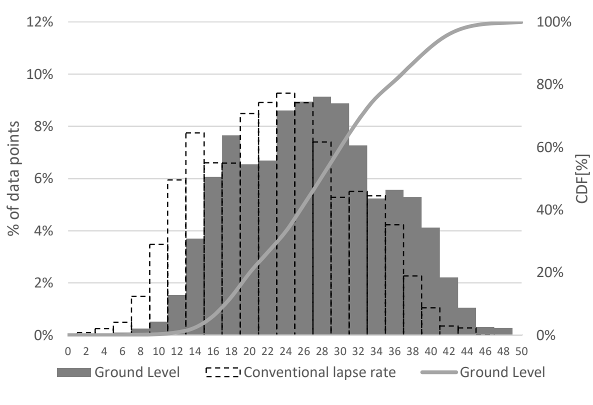

Figure 2. Dry-bulb temperature at ground level based on ASHRAE data.

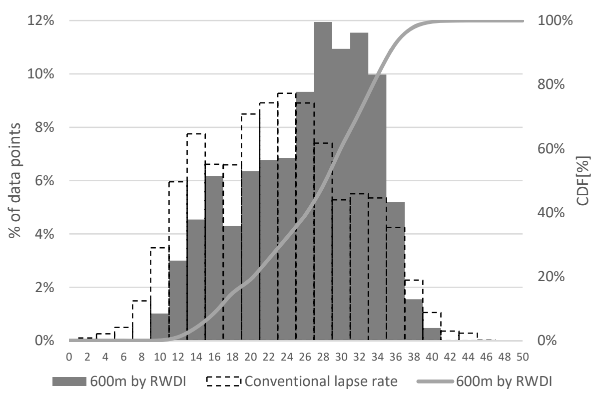

Figure 3. Dry-bulb temperature at 600 m altitude as simulated by RWDI.

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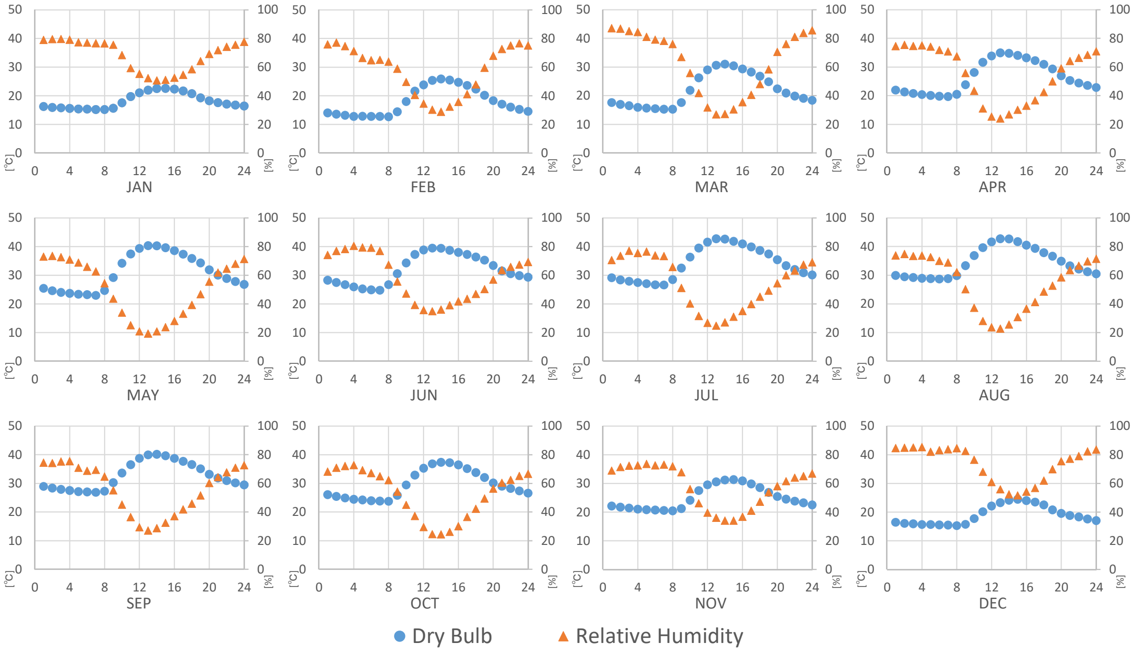

Figure 4. Dry-bulb temperature vs. RH （ASHRAE Standard 169-2013) for Dubai at ground level.

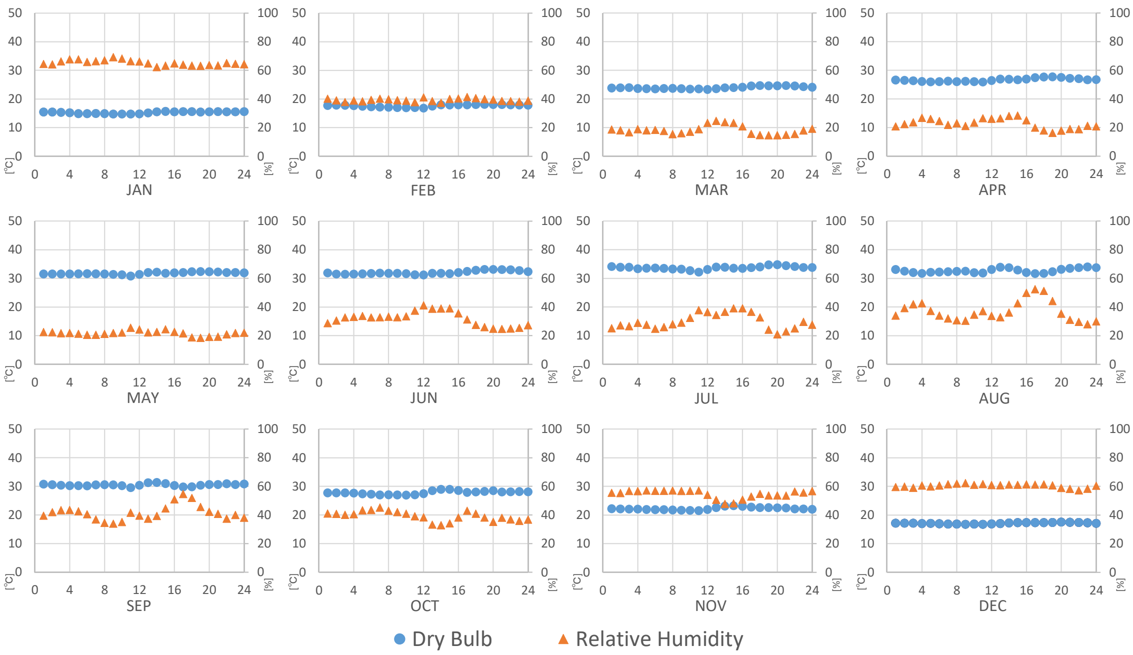

Figure 5. Dry-bulb temperature vs. RH (simulated by RWDI) at 600 m altitude

4. Design condition

In this section, we examine how the design conditions change at 600 m altitude. Figures 6 and 7 show temperature ranges based on the same sources as Figures 4 and 5, respectively. These graphs show the dry-bulb temperature ranges enclosed by the recorded high and low temperatures (round dots), the high and low temperatures calculated for the selected design condition (top and bottom of dot line bars), the average high and low temperatures (top and bottom of solid line bars), and the mean or average temperatures (centre bar). These values were calculated for each month over one full year. Table 1 shows our selected design condition (0.4%, 35 h), which denotes the 35 hottest or coldest hours (i.e., 0.4% of the year) in each weather file. First, we considered the summer season. The design temperature at ground level in summer was set at 45.9 °C. With this value, and using conventional lapse rate, the design temperature at 600 m altitude was calculated as 42.0 °C. However, this value differs from the summer design temperature condition according to the RWDI simulation. On the other hand, this temperature is very close to the value obtained according to the dry adiabatic lapse rate of −9.5 °C/km. We determined that this value is unusually high, despite the drop-in temperature due to increase in altitude and the fact that condensation did not occur. This finding suggests that, in high temperature climates, the design conditions for high altitude locations may be lower than those obtained according to the conventional lapse rate. Next, we considered the winter season. Because of the low temperatures, the RH in winter is relatively high. Thus, we compared our results according to the wet adiabatic lapse rate. Our results (Table 1) show that the design temperature obtained by simulation at 600 m altitude was higher than that obtained according to the wet adiabatic lapse rate. Moreover, this value was higher than the ground surface temperature. This observation can be attributed to the temperature inversion that occurs in Dubai for many hours during the coldest hours of the day. Under this condition, the ground cools much faster at night; thus, the air temperature near the ground also reduces faster than at higher altitudes. Therefore, our second conclusion is that the design conditions predicted according to the liner lapse will be incorrect.

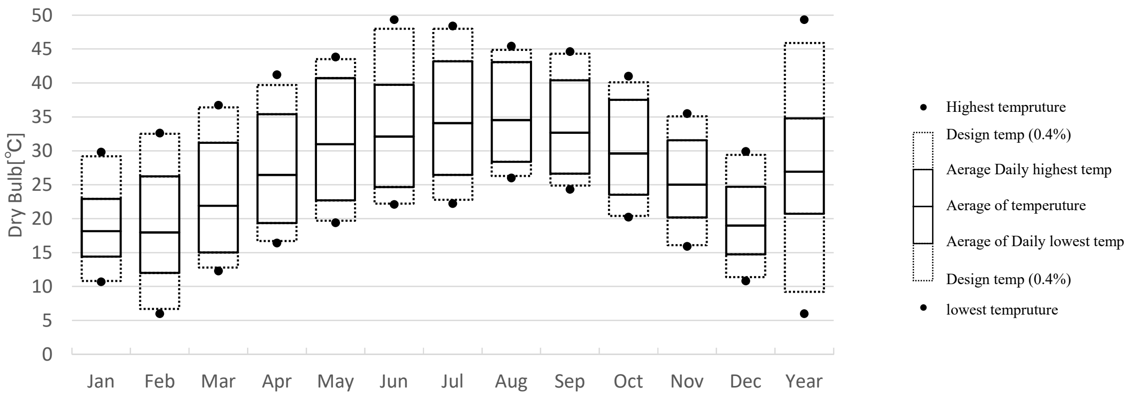

Figure 6. Temperature Range（ANSI/ASHRAE Standard 169-2013, Dubai, ground level）

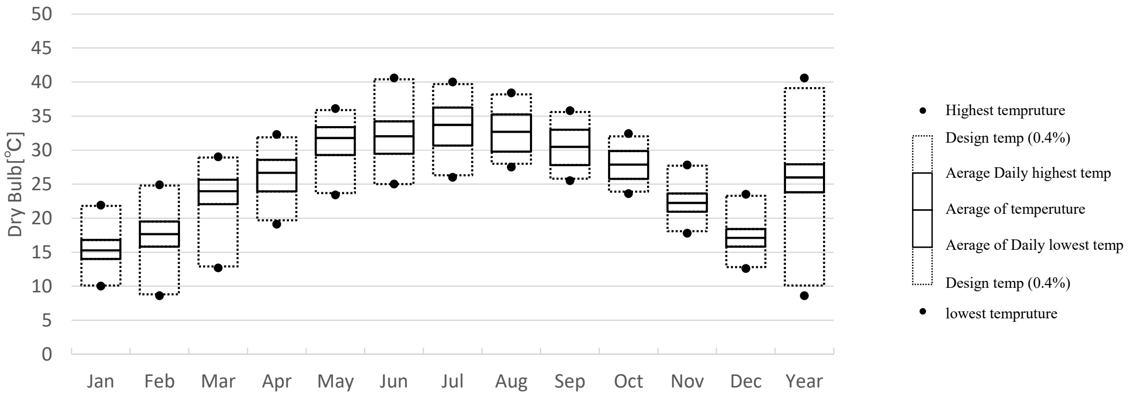

Figure 7. Temperature Range (Simulated by RWDI at 600m)

Table1. Design condition (0.4%, 35h)

	Weather file	Altitude	Lapse rate	Summer	Winter
		m	°C/km	°C	°C
Ground level	ASHRAE	11	-	45.9	9.1
Using conventional lapse rate	ASHRAE	600	−6.5	42.0	5.3
Using dry adiabatic lapse rate	ASHRAE	600	−9.8	40.0	-
Using wet adiabatic lapse rate	ASHRAE	600	−5.5	-	5.8
Simulated weather	RWDI	600	-	39.1	10.1

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5. Energy simulation

In this section, we examine how the energy use changes at 600 m altitude. We simulated energy usage by using data on outside air conditions as presented in the previous section.

5.1 Outline of the simulation

We built a model of a typical floor of an office building at an elevation of 600 m, and used this model to calculate the daytime energy consumption. We used the Energy Plus version 8.8.0 software for the energy simulation.

5.1.1 Outline of the model building

Figure 8 shows the plan and elevation views of our model. Table 2 describes the outline of the model building. We created a one-floor model of the office building. The plan was a 45 m square shape with a 15 m square core at the center. The model height was 3000 mm. All the four exterior surfaces had the same elevation, and there was a 1200 mm high glass window (Z = 900–2100 mm). There was no exchange of heat with the upper and lower floors. The model was divided into an interior zone and a perimeter zone in each direction. The perimeter zone was set at 5 m from the outer wall. Thus, the model had nine zones, including the core. An interior wall separated the core from the office. We set different values of internal gain for the core and the office. These values were obtained from ASHRAE 90.1-2013.

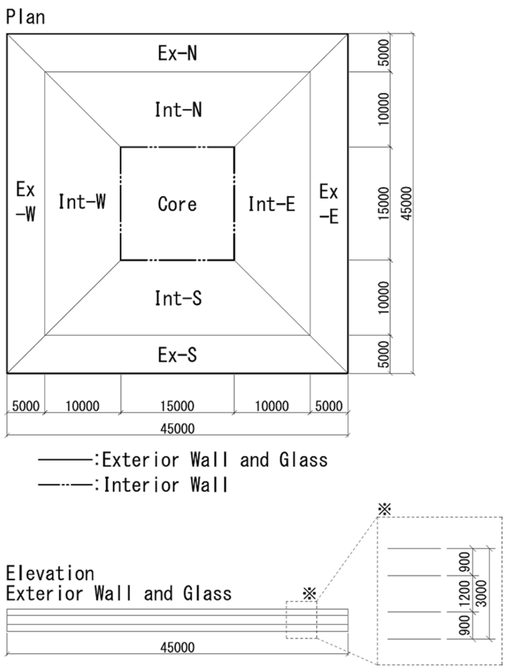

Figure 8. Plan and elevation

Table 2. Outline of the model building

Building use			Office	
Location			Dubai	
Model shape	Area		2025	m2
	Width		45	m
	Length		45	m
	Window	Height	1.2	m
		Width	45	m
		Direction	North, South, East and West	
Building envelope	Ext. wall	U factor	0.7	W/m2・K
	Int. wall	U factor	1.65	W/m2・K
	Window	U factor	2.84	W/m2・K
		SHGC	0.25	
Internal gains	People	Core	0.0108	person/m2
		Office	0.0565	person/m2
	Lights	Core	7.1	W/m2
		Office	10.5	W/m2
	Electric equipments	Core	5.38	W/m2
		Office	16.1	W/m2

5.1.2 Outline of HVAC and plant system

Figure 9 shows the diagram of the heating, ventilation, and air conditioning (HVAC) system and plant. Table 3 describes the outline of HVAC system and Table 4 describes the outline of the heating and cooling plant system. The HVAC system is a single-duct VAV system that can reheat each zone. The room is ventilated using a supply fan and a return fan, and the VAV distributes the air volume necessary for the load of each zone. Chilled water is produced by an electric HP chiller, and hot water is produced by a gas boiler and delivered to the heating coil and the VAV unit. The ventilation air flow

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rate was set according to the ASHRAE62.1-201 office rate. The air conditioning schedule was set from 6:00 AM to 10:00 PM on weekdays, but not set public holidays.

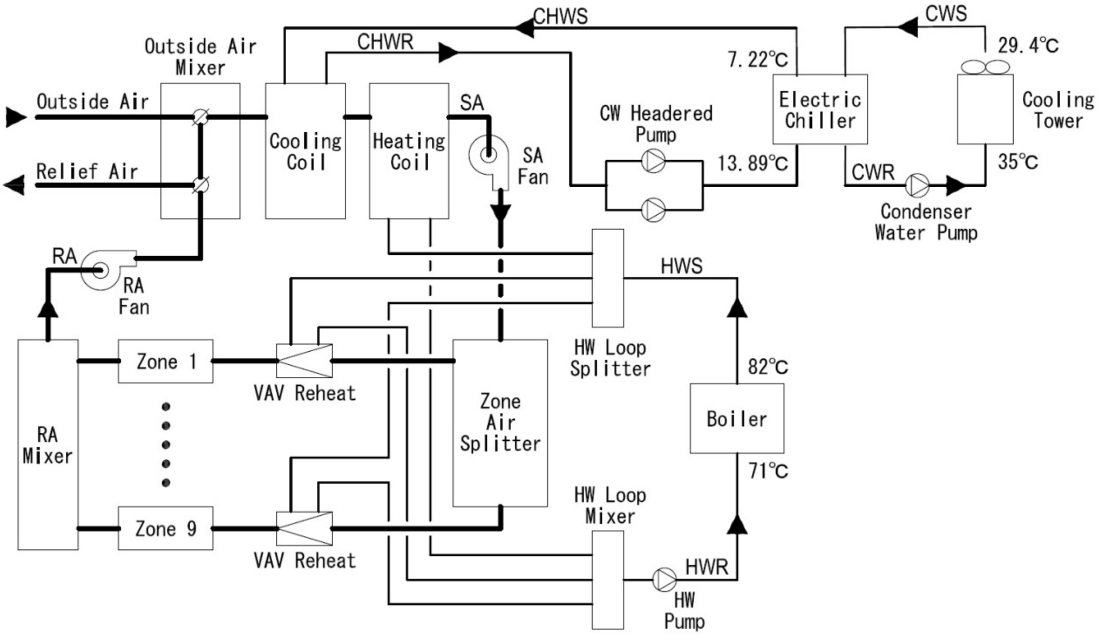

Figure 9. HVAC and Plant diagram

Table 3. Outline of HVAC system

HVAC system			Single duct VAV Reheat system	
OA Flow	Core	People	0	l/s・person
		Area	0.3	l/s・m2
	Office	People	2.36	l/s・person
		Area	0.3	l/s・m2
Cooling	Temperature		14	°C
	deltaT		11.11	°C
	SA Humidity ratio		0.0085	kg/kg(DA)
Heating	SA temperature		40	°C
	deltaT		11.11	°C
	SA Humidity ratio		0.008	kg/kg(DA)
SA FAN	Fan Total Efficiency		0.7	
	Pressure rise		1000	Pa
	Motor Efficiency		0.9	
RA Fan	Fan Total Efficiency		0.7	
	Pressure rise		500	Pa
	Motor Efficiency		0.9	
Airconditioning schedule		Day	Monday-Friday	
		Time	06:00-22:00	
Setpoint temperature		Summer	24	°C
		Winter	21	°C

Table 4. Outline of plant of heating and cooling

Chilled water	Chiller	Chiller type	Electric
		Condenser	water cooled
		Design loop exit temp	7.22 °C
		Delta T	6.67 °C
	Pump	Head	240 kPa
		Motor efficiency	0.9
Condenser water	Cooling tower	Type	Two speed
		Design inlet air temp	25.6 °C
		Design loop exit temp	29.4 °C
		Delta T	5.6 °C
	Pump	Head	210 kPa
		Motor efficiency	0.9
Hot water	Boiller	Fuel Type	NaturalGas
		Thermal efficiency	0.8
		Design loop exit temp	82 °C
		Delta T	11 °C
	Pump	Head	210 kPa
		Motor efficiency	0.9

5.1.3 Climate profile for simulation conditions

We ran the energy simulation using four different weather cases.

Case 1 is the standard reference condition, which was used according to the ANSI/ASHRAE Standard 169-2013 for Dubai at ground level.

In Case 2, we changed only the pressure in the Case 1 weather file to assume conditions at 600 m altitude. Equation (2) shows the relationship between height and pressure for the international standard atmosphere [6]. We used this approximate formula to calculate the pressure at 600 m altitude, and we changed all the values of the field atmospheric station pressure in the weather file to 94,400 Pa. We derived this value by substituting 0.589 km (the difference in altitude between 0.6 km and the Dubai ground level 0.011 m, according to ASHRAE169-2013) into Equation (2). It should be noted that this approximate formula includes the influence of the temperature lapse rate on the constant value.

$$p(z) = \left(\frac{44.331514 - z}{11.880516}\right)^{5.255877} \tag{2}$$

p(z) : Pressure [hpa]

z : Height [km]

Case 3 was the simulated weather file at Dubai at 600 m altitude using the computer-based climate generator by RWDI.

In Case 4, we changed the pressure and temperature from the Case 1 weather file. The pressure was changed to 94400 Pa, which was the same as Case 2. The temperature was varied according to the conventional lapse rate of −6.5 °C/km and uniformly decreased by 3.9 °C from the dry-bulb temperature. The absolute humidity was kept constant, and when the dry-bulb temperature exceeded the dew point temperature, the dew point temperature was reduced to match the dry-bulb temperature. Table 5 shows the weather files used for the simulations.

Table 5. Weather files for simulation

	case1	case2	case3	case4
Base Weather File	ASHRAE169-2013 Dubai Ground Level	ASHRAE169-2013 Dubai Ground Level	600m Simulated by RWDI	ASHRAE169-2013 Dubai Ground Level
Changes	-	600 M Elev Pressure	-	600 M Elev Pressure Temperature using Conventional Lapse Rate
Pressure (Pa)	Weather file	94400 constant	Weather file	94400 constant
Lapse Rate (°C/km)	-	-	-	−6.5

5.2 Result of the energy simulation

Table 6 shows the results of the energy simulation under the categories heating, cooling, lighting, equipment, fan, pump, heat rejection for each weather condition separately. In addition, we calculated the total energy consumption and energy consumption per area. Then we compared the normalized result obtained for Cases 2–4 relative to that of Case 1.

The energy consumption of cooling and heating in Case 2 was less than that of Case 1 because the air density in Case 2 was lower than that of Case 1. As the air density decreased, the mass of the air also decreased, which meant there was less air mass to heat and cool. The regulation of ventilation volume in ASHRAE 62.1-2013[7] is set by volume at 1.2 kg (DA)/m^3 at 1 atm and 21 °C in General notes for table 6.2.2.1 Air density. However, it was not necessary to change the amount of ventilation due to the decrease in air density. Because the ventilation volume was not changed in the simulation, we determined that the use of cooling and heating energy had decreased mainly due to the difference in energy for treating the outside air. We attributed this finding to the fact that the HVAC system was a VAV system. The air density reduced at 600 m altitude, such that the amount of heat that the air could hold in the same volume become smaller, and thus the cooling capacity reduced. As a result, the total energy usage increased slightly mainly due to the increase in the power of the fan.

In Case 3, the energy used for both heating and cooling reduced because the outside air conditioning load was lower in both the summer and winter periods. However, for the same reason as in Case 2, the energy consumed by the fans in the VAV system increased. This occurred because of the low air density. Overall, the energy consumed was reduced by 3.8%.

In Case 4, the cooling energy consumption decreased, but the heating energy consumption increased. This observation can be attributed to the underestimation of the temperature at 600 m altitude according to the conventional lapse rate. In addition, the energy consumption by the fans was influenced by the reduction in pressure, but this influence was slightly decreasing because the influence from the reduction in the cooling load was stronger. Thus, the reduction in total energy consumption of 4.6% was the largest reduction among all the cases we simulated.

Therefore, our conclusion is that there is a difference of approximately 5% in the simulation result due to the difference in the method of predicting the outdoor air temperature at high altitude. Specifically, the conventional lapse rate is not always a good indicator of energy consumption.

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Table 6. Result of the energy simulation

		case1	case2	case3	case4
Base Weather File		ASHRAE Ground Level	ASHRAE Ground Level	600m Simulated	ASHRAE Ground Level
Pressure	Pa	Weather file	94400 constant	Weather file	94400 constant
Lapse Rate	°C/km	-	-	-	−6.5
Heating	MJ/year	1,490	1,300	1,320	2,749
	%	-	-13%	-11%	85%
Cooling	MJ/year	356,219	354,750	297,870	289,319
	%	-	0%	-16%	-19%
Lighting	MJ/year	317,630	317,630	317,630	317,630
	%	-	0%	0%	0%
Equipment	MJ/year	535,770	535,770	535,770	535,770
	%	-	0%	0%	0%
Fan	MJ/year	103,430	110,730	106,790	102,960
	%	-	7%	3%	0%
Pump	MJ/year	98,220	101,620	97,290	96,980
	%	-	3%	-1%	-1%
Heat Rejection	MJ/year	66,659	66,770	66,670	65,700
	%	-	0%	0%	-1%
Total	MJ/year	1,479,419	1,488,570	1,423,339	1,411,108
Normalized	MJ/m2year	731	735	703	697
Difference	MJ/m2year	-	5	-28	-34
	%	-	0.6%	-3.8%	-4.6%

6. Conclusion

In designing skyscrapers, the conventional lapse rate should be used with caution for predicting the climate profile, design conditions, and energy consumption. Owing to the increasing rate of construction of high-rise buildings, there is an urgent need to identify and use appropriate climate data of high altitudes.

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Acknowledgments

We would like to express our greatest appreciation to Mr. Ali Irani of Skidmore, Owings & Merrill, LLP. Without his assistance with the energy simulation, this paper would not have been possible.