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Authors: Luke Leung, Associate Partner, Skidmore, Owings & Merrill
Peter Weismantle, Associate Partner, Skidmore, Owings & Merrill

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Sky-Sourced Sustainability - How Super Tall Buildings Can Benefit From Height

Luke Leung PE[1] and Peter Weismantle AIA, RIBA[2]

[1/2]Associate Partner, Skidmore, Owings & Merrill LLP, 224 S. Michigan Avenue, Chicago, IL 60604

Luke.Leung@som.com Peter.Weismantle@som.com

Luke Leung

As an Associate Partner in Building Services/Sustainable Engineering Department of Skidmore, Owings & Merrill LLP, Mr. Leung leads a MEP building service team from conception to construction for large and tall buildings. He works as a MEP team leader to incorporate the most sustainable, innovative and sensible solutions according to the needs of each project. Additionally, he is a member of ASHRAE Technical Committee 9.12 on "Tall Buildings", Chairman on ASHRAE seminars and forums in "High-rise Residential Design" and "Sky Sourced Sustainability" etc., a member of Chicago Council on High Rise Building (CCHRB), LEED accredited professional, California Association of Building Energy Consultants Certified Energy Plans Examiner, Chicago Energy Code Energy Consultant and has won multiple design awards. He is currently the MEP team leader on a confidential tower, the potentially tallest building in USA and also Burj Dubai, the tallest building in the world. Developed one of the first active stack effect management system in super tall buildings. Currently he is working with top professionals and fire department in Chicago in enhancing fire fighting strategies for tall buildings in the city. He has an MBA from The University of Chicago, a MS and BAE from The Pennsylvania State University.

His prior experience included: ZhengZhou Greenland Plaza , a new mixed-use development. The 280 meter tower, including a 5 stars Marriott hotel, class A office, retail and entertainment, will be the tallest building in Western China; renovation of 230 M Renaissance Center (General Motors Global HQ) in Detroit, the tallest building in Detroit and largest renovation in the country at the time; Jinta Tower in TianJin, 335 M tall tower, potentially the tallest in the city; Nanjing Greenland Tower, 380 M tall mixed use tower in Nanjing, etc.

Peter A. Weismantle

Peter A. Weismantle, is an Associate Partner in the Chicago office of Skidmore, Owings & Merrill LLP (SOM). As a Senior Technical Architect, he focuses on mixed-use and multi-phased projects, specializing in super-tall towers for projects in Europe, Asia, the Middle East and the United States.

Peter's career began at SOM in 1977. Upon completion of Chicago's 1.8 million sf McCormick Place Exposition Center Expansion in 1987, he relocated to assist in the establishment of the SOM London office. In the six years he worked in the UK, Peter participated in major projects in London including the Broadgate, Ludgate and Canary Wharf developments. Upon his return to Chicago in 1993, he assumed the primary architectural technical design role on the 421m tall, 3.0 million sf Jin Mao Tower in Shanghai. Following that, Peter also worked on the initial design of the 92 story, 2.6 million sf Trump International Hotel and Tower – Chicago. Beginning with SOM's successful competition entry in mid-2003, Peter has directed the architectural technical design of Burj Dubai. This 5.0 million sf, super-tall, mixed-use tower located in Dubai, UAE is comprised of residential, commercial, hotel and retail areas.

Currently, Peter is working on several major projects including 300 meter super-tall towers planned for Shanghai and Wenzhou, China, a 5.0 million sf mixed-use development in Dallas and a 575 meter super-tall hotel in Las Vegas.
Peter received a Bachelor of Arts from Lehigh University and a Master of Architecture from the University of Pennsylvania, Graduate School of Fine Arts.

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Luke Leung PE[1] and Peter Weismantle AIA, RIBA[2]

[1/2]Associate Partner, Skidmore, Owings & Merrill LLP, 224 S. Michigan Avenue, Chicago, IL 60604

Abstract

Utilizing the earth and near-grade environment as a source of energy has historically been a common practice. Beyond solar and wind, designers do not usually look towards the sky as the source of additional benefits. The objective of this paper is to make tall building designers more aware of the additional sources of sustainability "in the sky", how these sources change with altitude and how this knowledge can benefit the design, construction and operation of tall buildings.

Exterior environmental factors including temperature, pressure/air density, solar, wind, moisture and their relationships with altitude are discussed. Selected approaches are suggested on how to benefit from them. Since current energy Codes and "Green" building standards do not address the issue of environmental variations with altitude; the sky has potential to offer unique energy saving opportunities and possibly add to the quantified sustainability of a tall building.

Where possible, a 1 km (3,281 ft) tall tower in Dubai is used as an example for illustration.

Keywords: Tall Buildings, Altitude, Sources of Sustainability

Introduction

While ground source energy is commonly known, except for solar and wind power, sky sourced environmental benefits are not commonly discussed in the building design community. Harvesting selected forms of sky sourced energy, for example by taking advantage of the temperature lapse rate, may arguably have little or no material impact to the environment. To better understand what the sky can offer is important because the next generation of super tall buildings promise not only to be much taller but, due to the current concern with the environemnt, must be more sustainable than existing buildings. For example, Burj Dubai (Figure 1), currently under construction, will be significantly taller than the tallest building ever built (Figure 2) and has multiple considerations regarding sustainable design. Beyond Burj Dubai, plans have been announced in Dubai and other predominantly Middle-Eastern and Asian cities for even taller structures. Several proposals have already been announced for towers of 1,000 meters or more. It is therefore of timely interest that designers understand how the sky can benefit the next generation of tall buildings.

Figure 1: Burj Dubai Under Construction, July 2007

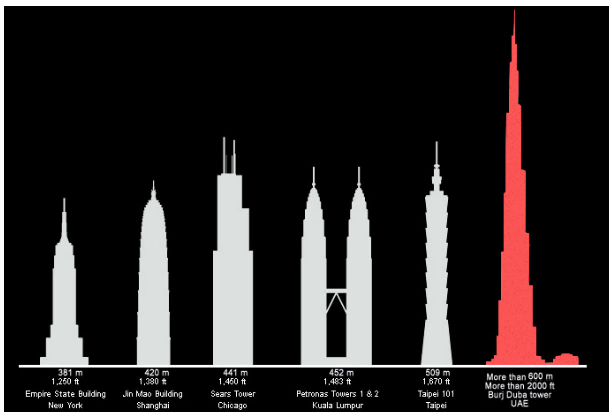


Figure 2: Comparative Heights of the Worlds' Tallest Buildings

Study on Environmental Effects of Height and Energy Usage

Little study has been done on the effect of height in the energy usage of tall buildings. During the design of the Freedom Tower, the National Renewable Energy Laboratory in the US was charged to model the energy consumption using a program called Energy Plus. The modeling included temperature and wind effect changes with altitude but did not include changes in air pressure, moisture or air density. The result of the simulations indicated that "…environmental factors that vary with altitude have a significant effect on the annual total building cooling and heating energy… reduction in total building annual cooling and heating energy of approximately 13% when no environmental factors are compared to all factors combined. Shading has the largest individual effect." Given the nature of the building and the environment, the percentage may be even higher if air pressure, moisture and density were included. It should be note that the study included the shading effect of the buildings around the tower, which accounts for about 9% of the energy savings (Peter G. Ellis and Paul A. Torcellini, 2005

Weighted Average - More Favorable Environment for Cooling Dominated Tall Buildings?

One observation from the Freedom Tower study is using the mid-level of a uniform tower and multiplie by the total number of floors is a good approximation of energy consumption for the entire tower (Peter G. Ellis and Paul A. Torcellini, 2005). This approximation needs to take into account the impact of stack effect. In general, no matter how tall a building is, the ground environment is "fixed". The taller the building in hot and humid climate, the greater the decrease in the "weighted average" of the temperature, air density and moisture, and higher the reduction in energy use. Using Dubai as an example, the temperature using Dry Adiabatic Lapse Rate (ADLR) with altitude at the mid-level of a 500 M tall building is 43.7 ºC (110.6 ºF), the lapse rate temperature for the mid-level of a 1000 M tall building is 41.2ºC (106.2 ºF), see Figure 3. The moisture amount and air density also exhibit similar pattern. Focusing on the environmental elements, it is

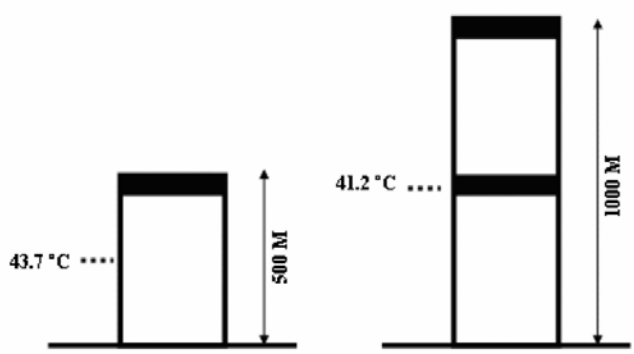


Figure 3: ADLR Lapse Rate Temperature at the Middle Floor of a 500 M (1640') Tall vs. 1000 M (3,280') Tall Building

possible that a cooling dominated tall building offers better "weighted averages" for energy savings. For a heating dominated building, the result may be opposite.

Investigations of Sky-Sourced Sustainability Using a Hypothetical 1 Km Tall Building

The authors assume that the next generation of super tall buildings will attain the "milestone" height of 1 kilometer (3,280 ft). Using a hypothetical residential building of that height, similar to Burj Dubai in mid-level floor plan and located in Dubai, the following is a "case study" covering elements available at height and suggestions on how to harvest and benefit from them. Summer design hour is used to quantify cooling loads reduction.

Temperature

Tall buildings in Dubai can benefit from dry bulb temperature drop as they rise in altitude. Taking advantage of lower temperatures above grade is not a new idea; it has been applied to the traditional wind towers design (See Figure 4). In standard atmosphere, dry bulb temperature decreases linearly with elevation in troposphere (lapse rate in lower atmosphere). There are 3 different ways to calculate lapse rate, ASHRAE (American Society of Heating, Refrigerating and Air Conditioning Engineers) method, Dry Adiabatic Lapse Rate (DALR) and Saturated Adiabatic Lapse Rate (SALR).

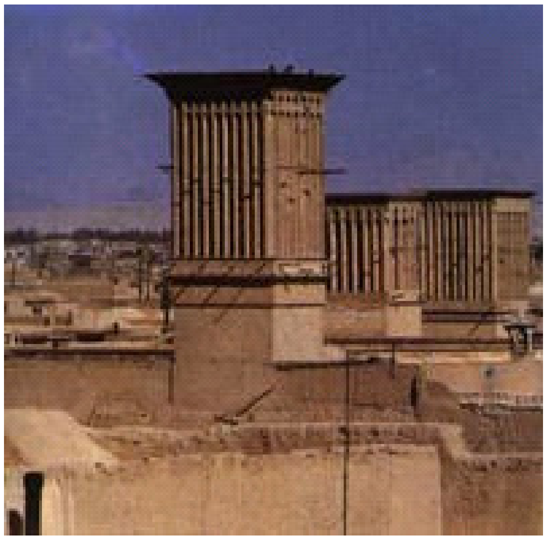


Figure 4: Picture of Wind Towers

ASHRAE method according to Chapter 6, Fundamentals Handbook (ASHRAE 2005) is applicable to an "average" atmosphere. Based on the summer design dry bulb is 46.1 ºC (115 ºF DB) at ground level, the temperature at the top of the tower is 39.6 ºC (103.3 ºF), see dotted line, Figure 5. In winter design condition, while the ground level temperature is 10 ºC (50 ºF), the top of the tower is 3.5 ºC (38.3 ºF). This formula is applicable to standard atmosphere, which likely will not happen in the summer design day in Dubai. See temperature drop gradients in summer using ASHRAE methods in Figure 5.

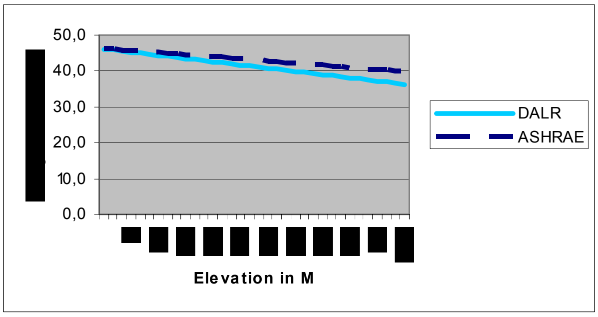


Figure 5: Exterior Temperature Gradient of a 1 kM (3,280 Ft) Tower in Dubai in Summer (SOM LLP)

The DALR method is more applicable to the summer design conditions in Dubai, when the outside condition behaves similar to an air parcel with less than 100% relative humidity (i.e. its temperature is above its dew point). The dry bulb summer design temperature is 46.1 ºC (115 ºF DB), which has capacity to carry a lot of moisture. Under this condition, heat gain or lost from outside the air parcel due to condensation is minimal. The DALR is approximately constant at 9.78 °C/km (5.37 °F/1000 ft, or about 3°C/1000 ft, See solid line Figure 5). The top of a 1 KM (3280') tower will be at 36.3 ºC (97.4 ºF).

The SALR method assumes the atmosphere is saturated with moisture. SALR is 4.9 °C/km (+ 2.7 °F/1000 ft or + 1.51°C/1000 ft). The temperature drop is less since condensation of moisture releases significant amount of latent heat to lessen the impact of temperature drop due to adiabatic expansion. This is only applicable in times when the atmosphere is saturated with moisture, which is unlikely at the summer design day in Dubai.

There are three major benefits for tall buildings that are dominated by cooling: lower cooling energy due to conduction heat gain, low sensible heat gain from unwanted infiltration and lower cooling energy from the wanted ventilation air. Based on an indoor condition of 23 ºC (73.4F), conduction heat gain can be reduced up to 46%. Similar percentage can be achieved for both infiltration and a sensible portion of ventilation air. Total energy savings using the mid-level of a 1 KM (3280') as an example, will result in a summer design hour load reduction of 9%.

While lapse rate is a normal phenomenon in lower atmosphere, it is by no means constant. Temperature inversions occur from time to time. Care must be taken in applying lapse rate for cooling equipment sizing. Energy consumption for the entire year for the 1 KM (3280') tower will benefit from the lapse rate.

Air Pressure

Air pressure decreases with elevation. Outdoor air pressure adjustment with altitude can be found in Chapter 6, ASHRAE Fundamentals 2005. It assumes dry air with the ASHRAE lapse rate indicated in Figure 5. Outdoor pressure drop for a 1 KM (3280') tower is indicated in Figure 6. The exterior pressure difference between the top and bottom of the tower is approximately 11.3% (see Figure 6).

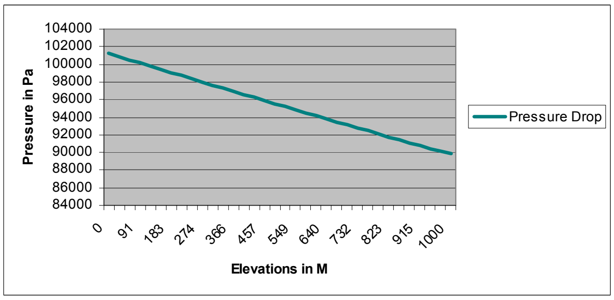


Figure 6: Air Pressure Change for a 1 kM (3,280 Ft) Tower in Dubai (SOM LLP)

Since air pressure decreases with altitude, this allows exterior air to expand and become less dense. Air density decreases with elevation. Assuming dry air with the pressures indicated in Figure 6, densities at different elevations are derived in Figure 7 using ideal gas law. For the outdoor conditions, the ASHRAE lapse rating according to Figure 5 is assumed. There is a difference of 10% in air density between the bottom and top of the building (See Figure 7).

Figure 7: Density Changes of Exterior Air for a 1 kM (3,280 Ft) Tower (SOM LLP)

Less energy is required to cool thinner outside air; both wanted through the ventilation system and unwanted through infiltration. This is especially true because the outside air is at a lower temperature (also likely less moisture, see "Moisture"). Intuitively, one will think an adjustment to outside air amount will be required to achieve the same *mass* flow rate, but ASHRAE Standard 62.1-2004 "Ventilation for Acceptable Indoor Air Quality" (ASHRAE, 2004) does not require altitude correction. In the footnote of the Table "Minimum Ventilation Rates for Breathing Zone":

"Volumetric airflow rates are based on an air density of 0.075 lb_{da}/ft^3 (1.2 kg_{da}/m^3), which corresponds to dry air at a barometric pressure of 1 atm (101.3 kPa) and an air temperature of 70°F (21°C). Rates *may* be adjusted for actual density but such adjustment is *not* required for compliance with this standard." This allows the same *volumetric* amount of outside air for ventilation at the bottom and the top of the building, though in reality the air at the top has lower air flow mass. Using the mid-level of a 1 KM (3280') tower, air density alone contributes to 10% of energy savings for ventilation and results in total summer design hour savings of 3%.

Wind

Wind speed increases with altitude. The magnitude depends on several factors including the coefficients related to terrain roughness and conditions at the meteorological station (ASHRAE 2005). See Figure 8 for a 1 kM (3,280 Ft) tower in Dubai average wind profile.

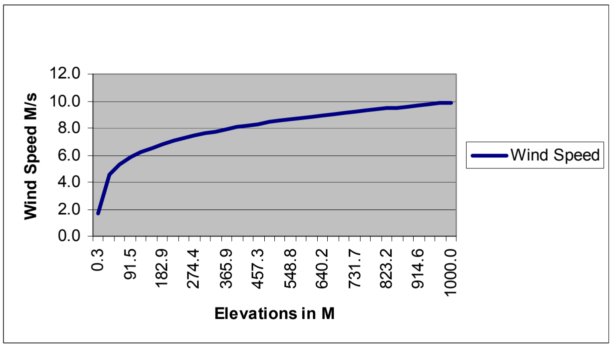


Figure 8: Wind Speed Changes of a 1 kM (3,280 Ft) Tower in Dubai (SOM LLP)

Higher wind speed increases the convection coefficient which, as a result, increases the heat transfer of a building to the outside. Also high wind speed increases the amount of infiltration. At the mid-level of the 1 KM tower, this will increase the heat transfer (U-value) by 8% and will increase heat gain at the summer design hour by 1%.

While in Dubai the higher wind speed will increase the amount of energy consumption, it is different for an office building located in more a temperate climate. The lapse rate of the environment can benefit a cooling dominated building if the outdoor environment is, for a substantial amount of time during the year, below the indoor design conditions. This was confirmed in the case of the Freedom Tower energy study.

By aligning the fan intake with the prevailing wind, ventilation system can benefit from the exponential increases of wind speed and form a wind-assisted ventilation system. At the mid-level floor of Burj Dubai, using an average wind speed of 6.5 m/s, wind can generate approximately 75 Pascal (.3" water gauge) of pressure at the intake. Taking advantage of this roughly translates to 6 to 15% savings in fan energy.

Taking account of the lowering of exterior temperature due to lapse rate as well as the exponential increase in wind speed, allows a tall building to benefit from passive ventilation. The alignment of the openings with prevailing wind has significant impact to the amount of outside air entering a building. This approach was recently applied in the design of a 260 M tall mixed use tower in China with a 90.5 M (296.8') tall sky atrium starting at 36th floor (164.8 M, or, 540.5' above grade). Using Computational Fluid Dynamics modeling, it was determined by allowing an opening of 10 SM facing prevailing wind rather than turning it 45 degree to the prevailing wind, 100,800 m3/h (59,294 CFM) of outside air can be introduced into the building rather than 20,736 m3/h (12,198 CFM, see Figure 9).

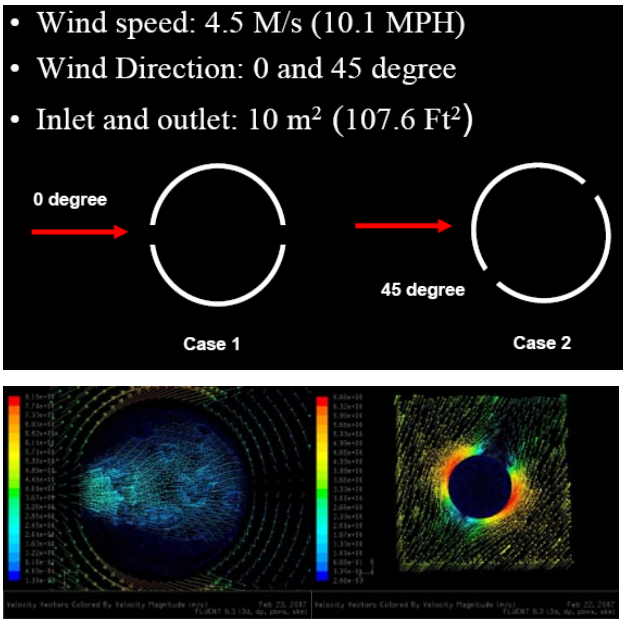


Figure 9: CFD Modeling of Wind Driven Ventilation; Left: Aligning a 10 M^2 (107.6 $Ft^{2)}$ Opening with Prevailing Wing; Right: Turning the Opening 45 Degree Away from Prevailing Wind (SOM LLP)

Wind speed increase with altitude is also beneficial to power generation using wind energy. Though one has to be careful about the economics of using wind driven micro turbines, manufacturers of wind micro turbines often use 4 M/s (8.9 MPH) as a guideline to determine "viability". In a tall building, wind speeds towards the upper portion will often times exceed that number.

Moisture

Moisture ratio can decrease with altitude depending on the dry bulb temperature, pressure and the lapse rate. Using data from MODIS orbiting satellite, vertical profile of moisture is developed using statistical regression. See Figure 10 (Seemann, 2006), for both the plot of temperature and moisture. It should be note that in the Figure, 1 hPa = 100 Pa (.4" H_2O), the chart approximate sea level at the origin of the Y axis. On the X axis, degree K minus 273.15 is degree Celsius. At sea level it is approximately 18.3 ºC (65.0 ºF). For the 1 kM (3,280 Ft) building, pressure at the top is approximately 900 h Pa (13.05 psi, refers to Figure 6), the dry bulb temperature lapse rate per satellite data is similar to Figure 5. Data available from different satellites appear to indicate that the moisture ratio decreases with increasing altitude. Depending on which equipment output one looks at (red dotted line vs. blue solid line in moisture mixing ratio), there is a 20-40% reduction of moisture in the air between the top and bottom of a 1 kM (3,280 Ft) tower. The pattern of moisture ratio decreases is similar to the ASHRAE dry bulb temperature drop profile.

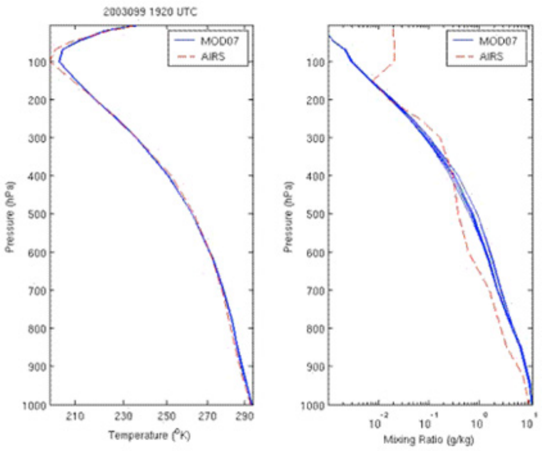


Figure 10: Temperature (left) and mixing ratio (right) profiles from orbiting satellite MODIS MOD07 retrievals (blue lines) and Aqua AIRS (red dashed), (Seemann, 2006)

Moisture reduction with altitudes is significant for tall buildings energy savings, especially in climates similar to Dubai with levels of high humidity in the outside air. The ASHRAE lapse rate formula at the mid-level of the 1kM tower will result in 4% cooling load reduction in summer.

Solar

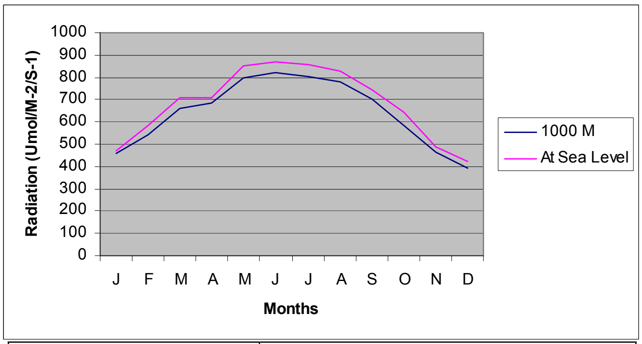
The effect of increased height is mixed when considering solar radiation. Under direct-beam clear-sky situations, the amount of solar radiation in general increases with altitude. This is especially true for UV radiation above the friction zone. For each 305 m (1000 foot) increase in altitude, there is roughly a 4 to 5% increase in incident UV radiation.

However, for the entire year, assuming normal periods of cloudy sky, at altitudes below 1 kM (3,280 Ft), the situation is less certain. The amount of solar radiation depends heavily on the local atmospheric conditions especially the quantity of aerosols present in the air. Regression analysis is often used to calculate solar radiation based on measured data, however, measured data for different altitudes in Dubai is not available.

In other parts of the world, solar radiation on horizontal surfaces actually decreases for cities at higher altitudes. Simple multiple linear regression analysis using US National Solar Radiation Data Base by Complex Systems Research Center (University of New Hampshire) indicated that altitude has a negative coefficient in the Eastern US cities (John D. Aber, May 2000). Using this equation, increases in altitude for different east coast cities actually leads to lower solar radiation. See Figure 8 using a 1 kM (3,280') altitude difference for two elevations in Richmond, Virginia (USA) as an example. This is likely because of orographic lifting of air masses which result in condensation and cloud formation. A similar relationship between solar radiation and cities at different altitudes is also supported by others (Chandel 2005).

Regarding the radiation unit:

$$\frac{\text{mol}}{\text{m}^2\,\text{s}} = \frac{\text{Wh}}{\text{m}^2\,\text{d}} \cdot \frac{3.6\,\text{kJ}}{\text{Wh}} \cdot \frac{2.05\,\text{mol}}{10^3\,\text{kJ}} \cdot \frac{\text{h}}{3600\,\text{s}} \cdot \frac{\text{d}}{\text{daylength (h)}} \cdot \frac{10^6\ \text{mol}}{\text{mol}}$$



Months	Differences (Sea level vs. 1000 M)
J	3.0%
F	8.0%
M	6.2%
A	3.6%
M	6.1%
J	5.3%
J	6.4%
A	5.5%
S	5.9%
O	9.5%
N	5.6%
D	7.4%

Figure 11: Solar Radiation Differences between Sea Level and 1 kM (3,280 Ft) using Regression Analysis on Measured Data (SOM LLP)

Vertical surface solar radiation has added complications because it is composed of three elements: 1. direct normal irradiance; 2. diffuse radiation from the sky and 3. diffuse radiation from the ground (ASHRAE Fundamentals 2005). Direct normal irradiance is a function of apparent solar irradiation, solar altitude, and the aerosol/water vapor in the air. For diffused radiation from the sky, additional angle of incidence of the sun and the ratio between diffuse radiation falling on a horizontal surface under a cloudless sky over direct normal irradiation on the earth's surface on a clear day will impact the quantity. Diffuse radiation from the ground is impacted by all the above factors plus ground reflectivity and the tilt angle of the surface of interest. For a tall building, while the direct normal irradiance and diffuse radiation from the sky is likely increasing (lesser atmosphere), the diffuse radiation from the ground is likely decreasing since there is a thicker air mass to travel through. The final radiation on the window depends on the local conditions of the three elements mentioned.

Sustainability and Energy Useage

Environmental factors can contribute significantly to the sustainability of a tall building. Using the mid-level floor of Burj Dubai as an example, the total amount of cooling load reduction at the summer peak design hour can be as much as 11% (assuming ADLR lapse rate, only include temperature and air density adjustments). This does not include moisture reduction because dry air is assumed and does not include other environmental elements. Calculating annual energy savings is more challenging since available energy programs are not sophisticated enough to model all these elements without additional enhancements.

Attempting to take advantage of a buildings' height has several implications for the architecture of that building:

1. Architectural expression can be influenced or modified based on the micro environment. Assuming that the architecture wants to reflect the nature of the environment, there may be a different expression between the top and bottom of the tower and on elements with different environmental exposures.

2. Current energy and green building standards seldom, if at all, address environment variations with altitude. It may be possible that designers can take benefit of the environment variations to capture energy savings.

3. Variation of the envelope: The U-value and shading coefficient design criteria can be different between top and bottom of the building envelope in order to optimize the curtain wall to the local conditions. Energy codes often mandate the maximum amount and type of glass permitted. Taking into account the local environmental conditions may confirm that different amounts of, or types of, glass can be used in a tall building. Care also should be taken when specifying the curtain wall to include more extreme temperature due to temperature lapse rate.

4. Similar to how wind is formed in nature, the differences in environmental conditions between interior and exterior can create air movement. This air movement can be captured for passive cooling and ventilation. In the Chinese mixed-use project mentioned earlier, 205,300 M^3 /hr of air is designed to move through the atrium during transitional seasons for cooling and ventilating the sky atrium.

5. Harvesting solar is likely more effective at the top of a tall building, especially if it is above the frictional zone where the significant amounts of aerosols are present. This is especially true in a city with a large amount of hours with clear-sky direct-beam radiation, such as Las Vegas. Inside the frictional zone, because of airbourne aerosols, local conditions need to be studied.

6. Although unlikely at height, there is a recent interest in greening buildings with vegetation at the exterior of a building. Care should be taken to review the type of vegetation based on the micro climate, especially in locations where winter design can be close to but above freezing. In those cases the temperature lapse rate may put the upper portion of the tower below freezing.

7. In cases where solar gain does not increase significantly with altitude due to local conditions, cooling dominated spaces prefer to be on the upper part of the building to benefit from lower temperature and heating dominated spaces prefer to be at the lower portion of the building.

8. For a cooling load dominated building, having high occupancy spaces at the top of the building (e.g. restaurants or clubs) though creating egress issues, can actually save a significant amount of ventilation energy because of the locally lower air density, temperature and moisture content of the outside air. These spaces will also use less fan energy because they are moving less dense air.

9. Also, for a cooling load dominated building, locating the primary outside air intake at the top of each zone will take advantage of lower air temperature, moisture and density (Figure 12). Furthermore, aligning the outside air intakes with the prevailing wind will reap the benefit of free wind energy. Lastly, locating the points of exhaust to take advantage of the inducing effect of wind flow downstream of the direction of the prevailing wind will assist in the removal of unwanted air.

10. Wind turbines prefer to be at the upper part of the building to take advantage of higher wind speed.

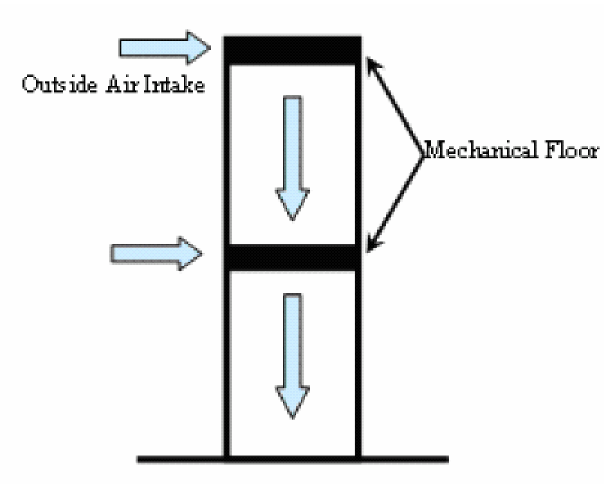


Figure 12

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