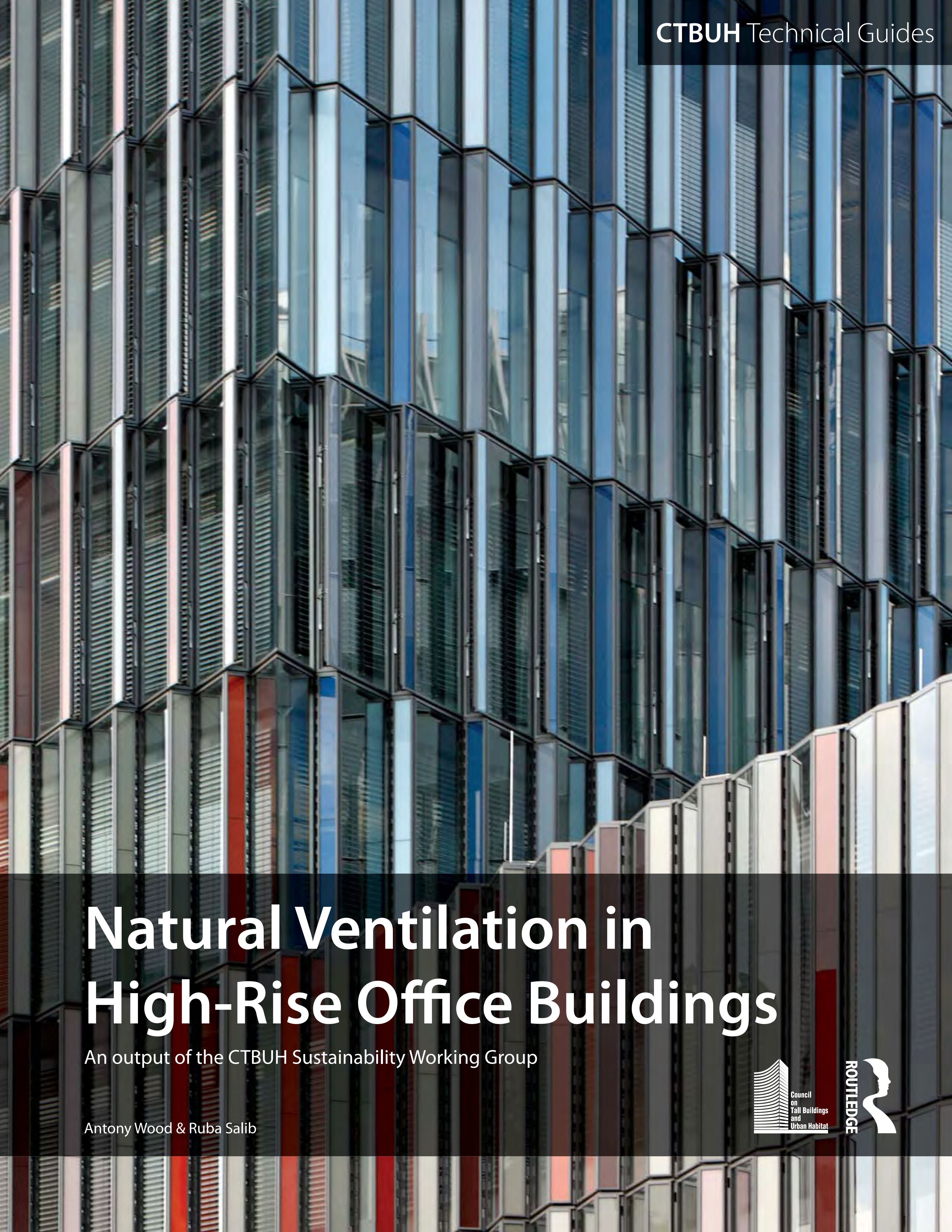

CTBUH Technical Guides

Natural Ventilation in High-Rise Office Buildings

An output of the CTBUH Sustainability Working Group

Antony Wood & Ruba Salib

Council on Tall Buildings and Urban Habitat

ROUTLEDGE

Contents

Preface

Increasing density in cities is now widely accepted as necessary for achieving more sustainable patterns of life to reduce energy consumption and thus combat climate change. The concentration of people in denser cities – sharing space, infrastructure, and facilities – offers much greater energy efficiency than the expanded horizontal city, which requires more land usage as well as higher energy expenditure in infrastructure and mobility. This is especially true in the face of the two major population shifts the human race is currently experiencing – rapid population growth and massive urbanization.

The United Nations forecasts 70 percent of the world's projected nine billion population will be urbanized by the year 2050, up from 51 percent of seven billion urbanized as of 2010.[1] The impact of this total figure of 2.8 billion people moving into cities over the next 40 years is perhaps better understood at the annual rate of 70 million people per year, or the daily rate of nearly 200,000 people. As a global species it means we need to build a new or expanded city of more than one million people every week for the next 40 years to cope with this urban growth. In the context of these numbers, it is clear that a continued horizontal spread of cities is unsustainable. Our urban agglomerations need to become much denser.

Tall buildings are not the only solution for achieving density in cities but, given the scale of these major population shifts, the vertical city is increasingly being seen as the most viable solution for many urban centers – especially those in developing countries such as China or India where population growth and urbanization is at its most pronounced. However, the full implications of concentrating more people on smaller plots of land by building vertically, whether for work, residential or leisure functions, needs to be better researched and understood.

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[1] Source: Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, World Population Prospects: The 2006 Revision and World Urbanization Prospects: The 2007 Revision, http://esa.un.org/unup

On the one hand there are many energy benefits from building tall. In addition to the larger-scale benefits of density versus horizontal spread, tall buildings offer advantages such as less materials (and thus reduced carbon) needed for enclosure per square foot of usable floor space created, a smaller surface area of envelope per floor area for heat loss/gain, a natural energy share that occurs between floors (especially heat energy in colder climates), plus the potential for harvesting solar and wind energy at height.

On the other hand there are disadvantages with building tall that offset, and may even negate, the benefits of concentrating people together in taller buildings. A smaller surface area per floor area may limit contact between occupier and envelope, affecting access to natural light, view and ventilation, and possibly leading to a lower quality of internal environment. Materials at height – whether primary structural systems to counteract wind loads or curtain wall systems needing to counteract greater environmental pressures – require greater sizing and performance than in the low-rise realm, further affecting the overall sustainability equation. There are also a host of other factors – societal as well as operational – which are not yet fully investigated, nor likely maximized in their potential.

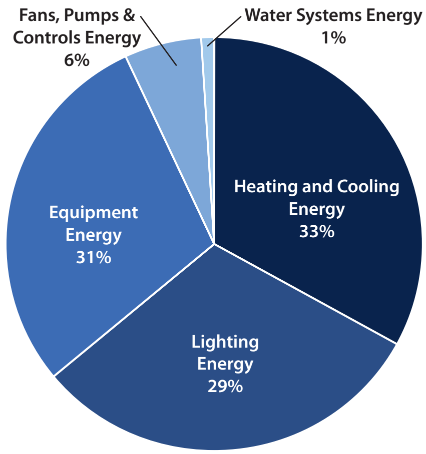
Given that the HVAC systems in tall office buildings typically account for somewhere between 30–40 percent of overall building energy consumption, the elimination of these systems with natural ventilation could be argued to be the most important single step we could take in making tall buildings more sustainable.

The general concept of "vertical" being more sustainable than "horizontal" may thus be true, especially when the larger-scale urban scenario is considered, but the myriad factors that contribute to this scenario need to be better researched and understood. Building owners, developers and consultants need to be able to understand the "sustainability threshold" for height – that height or floor count figure beyond which additional height would not make sense on sustainable grounds (and likely cost grounds as well). Of course this figure will never be an exact science and will differ not only from city to city, but from site to site and building to building. It is, however, a measure of extreme importance – and one which the global building industry needs to urgently strive toward.

Objectives of this Guide

The CTBUH Tall Buildings and Sustainability Working Group has set out to determine this "sustainability threshold" for height, despite the complex and varying nature of the equation, initially through a series of guides that analyze each aspect of the tall building in turn. Often there is disagreement and debate on what constitutes the most sustainable principles and systems for a tall building – indeed any building – but, irrespective of the final solutions, it is generally accepted that we need to reduce the energy equation – in both operating and embodied terms – of every component and system in the building as part of making the entire building more sustainable. Each guide in this expected series then seeks to establish best-practice and beyond for each system.

Though the exact percentage will vary based on climate, the HVAC (heating, ventilation and air-conditioning) systems in tall office buildings[2] typically account for 33 percent or more of overall building energy consumption (see Figure 1). Of that percentage, more than half of the HVAC energy is due to overcoming the heat gains due to occupants, lighting, miscellaneous power



▲ **Figure 1: Average energy consumption of a typical high-rise office building.** (Source: Interpreted from the US Department of Energy's reference building energy models for existing large commercial buildings built after 1980, across 16 US cities, in various climates.)

(e.g., plug loads) and solar and thermal gains and losses. The increased efficiency – or possibly even elimination – of these systems could thus be argued to be the most important single step in making tall buildings more sustainable. The reduction of this reliance on "mechanical" ventilation – through the "re-introduction" of natural ventilation systems in our buildings – is thus the focus of this guide.

It should be noted that there are numerous tall office buildings in existence (many of which are profiled in the case studies section of this report) which employ innovative natural ventilation systems, often for the greater part of the operating year. It is extremely rare, however, for a significant tall office building to be able to rely 100 percent on natural ventilation[3] – due largely to the implications of failure of the system – and this fact alone is a strong driving force for this guide. Even the best case buildings employ "hybrid" systems for ventilation (i.e., typically using natural ventilation for periods when the external conditions allow, but then full mechanical systems take over when external conditions are not optimal due to temperature, humidity, noise or pollution). Referred to as "Mixed-Mode," these hybrid systems result in significant energy

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[2] While the natural ventilation of *all* buildings is beneficial, it is generally accepted that natural ventilation in tall *office* buildings – with greater floor area sizes/depths, higher population density and higher internal heat gains through equipment, among other factors – is more difficult to achieve than in residential or hotel buildings with smaller floor plate depths, cellular "room" layouts, and greater contact with the outside envelope. This guide thus concentrates on the more difficult task of naturally ventilating tall office buildings, though many of the findings and principles could be adopted in tall residential buildings, or tall buildings of other functions.

[3] There is only one completed building included as a case study in this guide – the Torre Cube, Guadalajara – which is fully naturally ventilated without any mechanical plant for heating, cooling or ventilation. The building, however, is only 17 stories tall and takes great advantage of the compliant Guadalajara climate. The transferability of its systems and approaches to other locations would thus be difficult at best.

savings over the year when natural ventilation is enabled instead of mechanical systems; however, the true potential of natural ventilation is not delivered since a mechanical plant needs to be provided to cope with the peak load (worst case scenario) conditions. The embodied energy required for the mechanical plant equipment, not to mention the loss of floor space and impact on other aspects of the building, can be significant. The ideal scenario then – and one which this guide strives toward – is for tall buildings which deliver acceptable internal conditions throughout the whole year through natural ventilation alone.

Content Overview

The term "re-introduction" of natural ventilation systems is used intentionally to remind us that, for many centuries, buildings relied on natural ventilation strategies alone. In the post-World War II period when "cheap" energy liberated architecture from its connection with the natural environment, the advent of the sealed, air-conditioned Modernist box proliferated around the world. Prior to that period, all buildings were naturally ventilated as a matter of necessity since mechanical ventilation systems were not yet advanced enough to sufficiently condition the space. Further, the systems to achieve natural ventilation differed from place to place according to climate and, sometimes, culture. Ultimately, much of what this guide proposes – buried though it may be beneath layers of modern solutions and technical systems – is a re-learning of the principles upon which the ventilation of buildings were based for many hundreds of years.

It is perhaps fitting then that a brief historical overview of ventilation in tall office buildings forms the first section to this guide, followed by a brief outline of the generic principles of natural ventilation as a background to the more advanced systems outlined later. The majority of the guide is focused on the analysis of a number of seminal case studies that employ natural ventilation systems to a greater or lesser degree – buildings ranging in completion from 1996 to 2011, and locations from Frankfurt to Guadalajara. Fifty percent of the case studies are located in Germany. This is the result of the relatively moderate climate of the region, which allows for natural ventilation systems to be implemented, combined with Germany's generally ambitious commitment to the development of these systems.

Before embarking on the following pages, the reader should note that we began the compilation of this guide fully intending to deliver detailed performance data on each case study, which would allow a direct analysis of the effectiveness of each system and strategy employed, for the benefit of those considering such strategies in other buildings. That we have fallen somewhat short of this high ideal reflects, in the authors' opinion, perhaps the single biggest barrier facing the industry in the true adoption of sustainable design principles moving forward, i.e., the lack of hard data verifying what is working effectively, and what isn't.

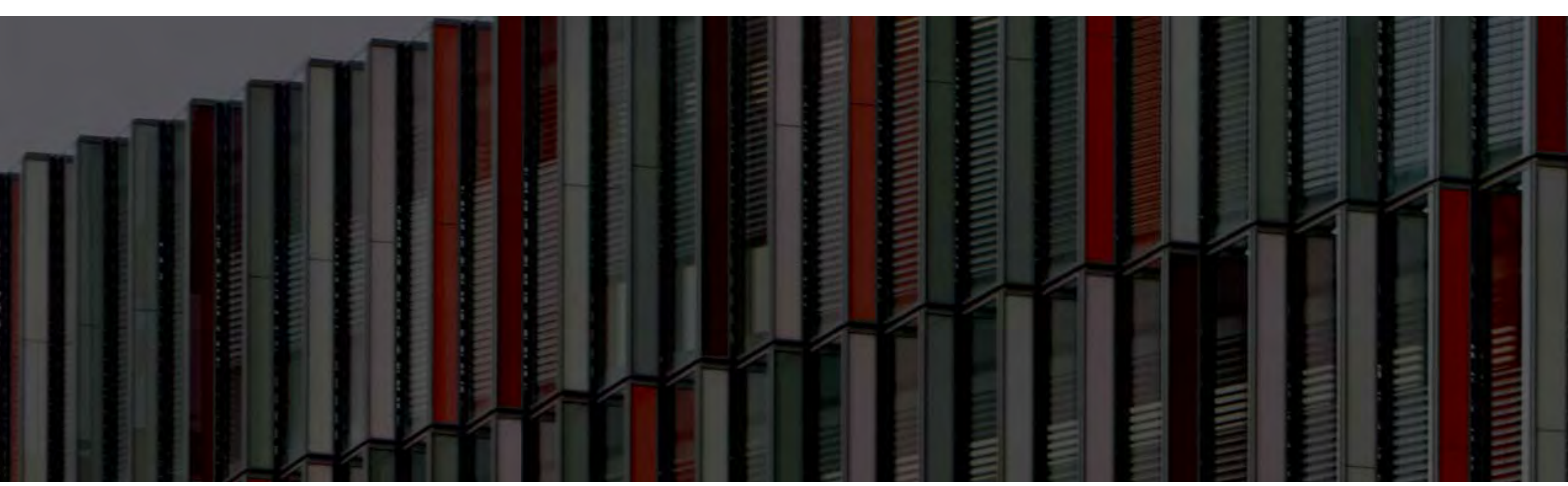
Though there have been moves in recent years to address this – sustainability ratings systems insisting on energy reporting, for example – the reality is that we are still a long way from the open sharing of reliable information on building energy performance, or even the agreed metrics to allow a fair and accurate comparison across buildings and building types. Even where the data does exist there is still a general reluctance to release it into the public domain – especially for high-profile buildings. Some of the case studies in this guide were completed relatively recently, complicating any attempt to build up reliable and consistent data within the time frame of this publication. Other buildings included, however, have been in operation for a decade or more, and yet the data still was not available.

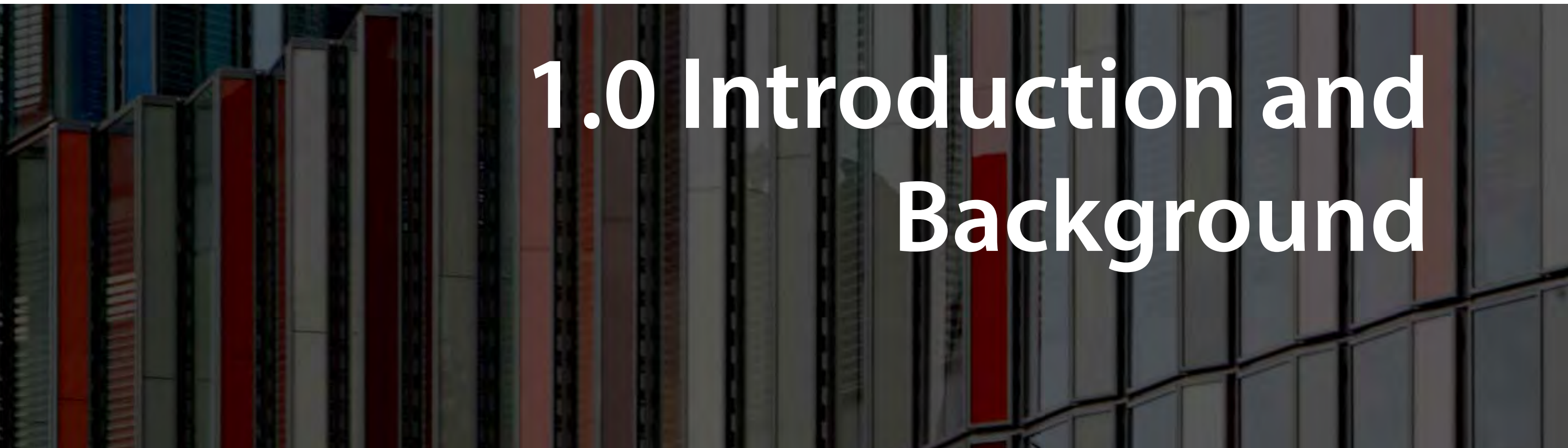
Where any information on building performance was obtained, it has been included to give the reader the best possible understanding and assessment of the systems employed. However, it should be noted that, in many cases, even this information is estimated based on predictive analysis studies that were undertaken at the design stage.

A qualitative analysis of the strengths and limitations of each system – often developed in conjunction with the consultants connected with each case study – has been included. A comparative analysis has also been drawn between the different case studies in order to determine the key parameters which influence the prospects of natural ventilation in high-rise office buildings. This analysis is drawn together into a set of considerations and recommendations which conclude this guide, together with suggested areas for further necessary research in the field.

The guide is aimed primarily at the typical building owner or professional who wants a better understanding of the options available for naturally ventilating a tall office building. It does not pretend to portray any radical new knowledge that previously did not exist. Rather, it aims to bring together disparate strands of information and put them together, with analysis, into one publication. This is intended as the first of several guides from the CTBUH Tall Buildings & Sustainability Working Group that, when taken together, will provide a tool kit for the creation of tall buildings with a much-reduced environmental impact, while taking the industry closer to an appreciation of what constitutes a sustainable tall building, and what factors affect the "sustainability threshold" for tall buildings.

Even the best case buildings employ "hybrid" systems for ventilation, typically using natural ventilation for periods when the external conditions allow, but then full mechanical systems take over when external conditions are not optimal.





1.0 Introduction and Background

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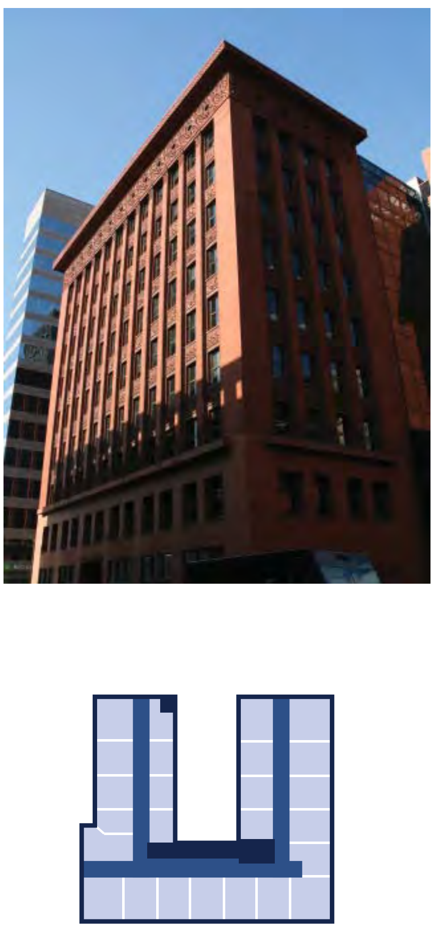
1.1 Historical Overview of Natural Ventilation in High-Rise Office Buildings

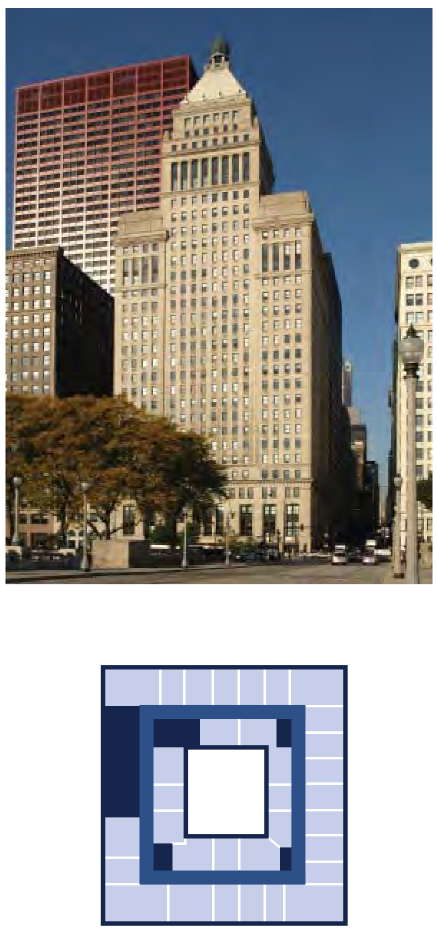
The 19th century marked the emergence of the office building typology as we know it today. Controlling the indoor environment in these early office buildings was achieved by passive means. In most US and European cities, operable windows were used for natural ventilation and for keeping cool, while stoves and radiators were the main sources of heat energy when it was cold. The high cost of electricity and the need to conduct tasks under natural lighting conditions had a profound impact on the design of office buildings. The need to provide adequate daylight limited the depth of office floor plans, and consequently enabled natural ventilation by means of operable windows.

Although keeping cool was not a major concern for architects at the time, natural ventilation was considered necessary for sanitary purposes and for the elimination of excessive humidity. Furthermore, many of the large office buildings during that period were influenced by the classical styles of architecture, which involved the use of central open courts, or light-wells, that limited plan depths to allow natural light and air into the interior.

This building type became particularly common in Chicago during the office building boom that followed the Great Fire of 1871. The building type was referred to as the "Chicago Quarter Block" because it employed open courts and occupied the plot of the entire city block between streets. This building type was also exported to many other US cities, where it was used as a model for emerging office buildings.



▲ Figure 1.1: View of the 1891 Wainwright Building, St. Louis (top); and typical floor plan (bottom). © Antony Wood/CTBUH



▲ Figure 1.2: View of the 1924 Straus Building, Chicago (top); and typical floor plan (bottom). © Marshall Gerometta/CTBUH

▲ Figure 1.3: View of the 1930 Chrysler Building, New York (top); and typical floor plan (bottom). © Steven Henry/CTBUH

Light courts were integrated into the buildings in E, H, and U-shaped plan arrangements (Arnold 1999a, pp. 40–54). Louis Sullivan's Wainwright Building in St. Louis, which was completed in 1891, is a good example of the adoption of this classical style (based on the Uffizi in Florence) through the use of a U-shaped plan to provide light and air to every office (see Figure 1.1). It is also worth noting that external sunshades were integrated into the design of the Wainwright Building as a passive means of controlling solar gains and providing thermal comfort.

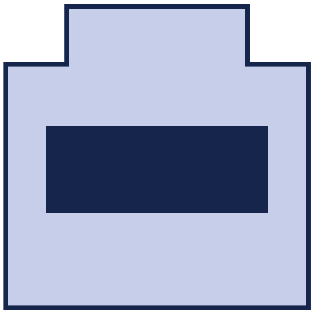
Built in 1924, the Straus Building in Chicago (a 21-story building with a nine-story tower) set another example of how the classical style was adopted through the use of a large central light court (see Figure 1.2).

At the beginning of the 20th century, architects started to design many of the most prominent skyscrapers in New York on the same basis. Iconic buildings such as the Chrysler Building (1930), and the Empire State Building (1931) reached unprecedented heights while still relying on natural ventilation and lighting. The form of these skyscrapers and the depth of their plans (see Figure 1.3) were still driven by the need to provide natural light for office interiors, with no particular emphasis given to the development of a natural ventilation strategy.

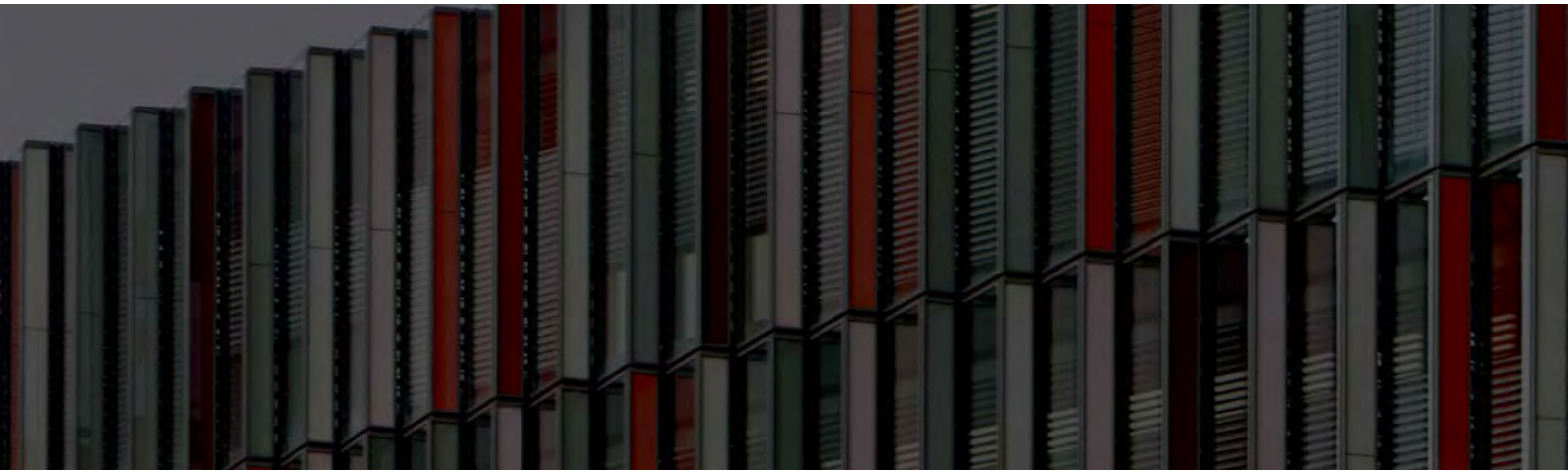
By the 1950s, the availability of cheap energy and the widespread use of air-conditioning had a profound impact on the form and planning of office buildings. The ability to control indoor temperature and humidity by mechanical means eliminated the restrictions architects faced with regards to plan form, plan depth, and window fenestrations. In other words, the consideration of passive measures to provide comfortable indoor environments were no longer a central concern for architects and engineers at that time. The dependence on air-conditioning allowed the emergence of deep-planned, transparent office buildings with curtain-walled windows. The heavyweight stone or brick-clad skyscrapers of the early 1900s were replaced by the light, fully-glazed office buildings of the 1950s and 1960s. Renowned architect Mies van der Rohe's work in high-rise buildings exemplifies this era of the all-glass-box style of architecture, from his 1958 Seagram Building in New York (see Figure 1.4), to his 1972 IBM Building in Chicago. The increased transparency and lightness of the structure, as well as the lack of solar shading devices, placed a higher load on air-conditioning systems to cool down buildings during the summer and to heat them during the winter (in temperate climates).

The oil crisis of 1973 marked another turning point in the development of office buildings. As a result of this crisis, western countries aimed to reduce global energy consumption – mainly by reducing the energy used in buildings for heating, cooling, and ventilation. The proposed solutions mainly focused on increasing the insulation level of building envelopes and reducing the air infiltration level by sealing the building. In other words, the main goal was to reduce the consumption of fuel by reducing heat loss through ventilation. The introduction of these increasingly sealed office buildings impacted negatively the comfort and health of the occupants. This resulted in the deterioration of indoor air quality and the spread of diseases due to humidity condensation and the growth of mold (e.g., "sick building syndrome"). The lack of fresh air and the overheating problems in summer affected the productivity and performance of office workers.

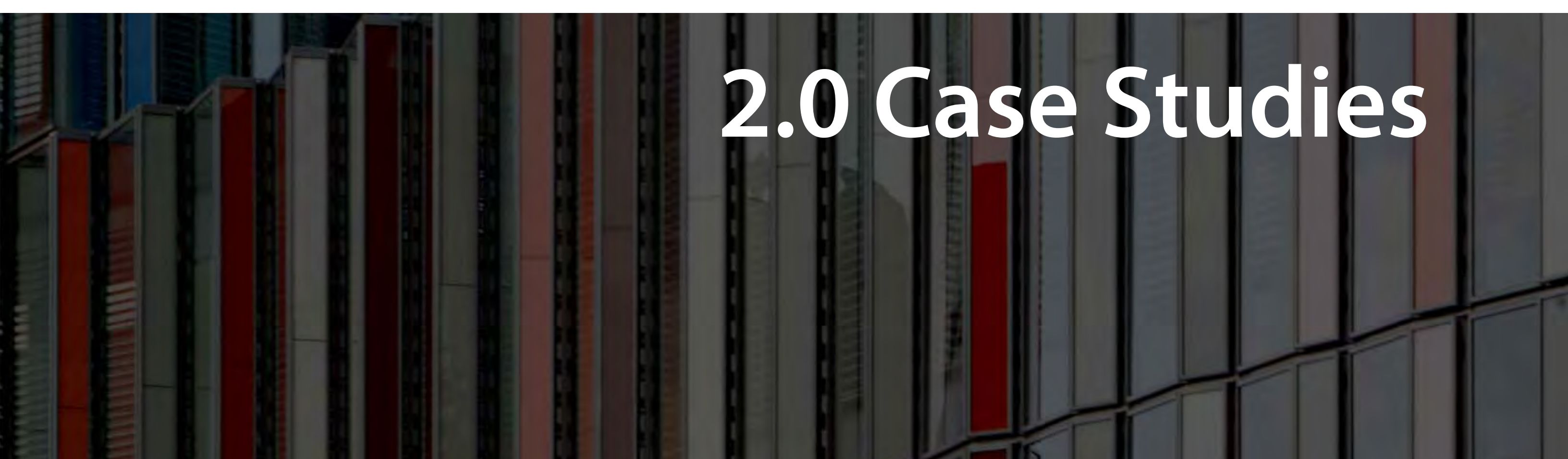
As a response to the oil crisis and the development of building-related illnesses, designers started to consider energy conservation measures that provided healthier and more comfortable working environments. The 1980s and 1990s thus marked the start of greater building energy efficiency and a return to considering the benefits of natural ventilation in buildings, as well as passive heating and cooling strategies in office building designs. This report will focus on the most advanced strategies adopted to naturally ventilate high-rise office buildings during the late 20th and early 21st centuries.



▲ **Figure 1.4: View of the 1958 Seagram Building, New York (top); and typical floor plan (bottom).** © Antony Wood/CTBUH



2.0 Case Studies



Project Data:

Year of Completion
- 2002

Height
- 163 meters

Stories
- 42

Gross Area of Tower
- 65,323 square meters

Building Function
- Office

Structural Material
- Composite

Plan Depth
- 12 meters (from central void)

Location of Plant Floors:
- 20

Ventilation Overview:

Ventilation Type
- Mixed-Mode: Zoned / Complementary-Changeover

Natural Ventilation Strategy
- Cross and Stack Ventilation (connected internal spaces)

Design Strategies
- Double-skin façades
- Full-height central atrium divided into 9-story sky gardens
- "Wing Wall" extensions
- Aerodynamic external form

Double-Skin Façade Cavity:
- Depth: 1.7 meters (south façade), 1.2 meters (north façade)
- Horizontal Continuity: Fully Continuous (along entire length of façade)
- Vertical Continuity: Approximately 32 meters (height of sky gardens)

Approximate Percentage of Year Natural Ventilation can be Utilized:
- Unpublished

Percentage of Annual Energy Savings for Heating and Cooling:
- 79% compared to a fully air-conditioned German office building (measured)

Typical Annual Energy Consumption (Heating/Cooling):
- 75 kWh/m^2 (measured)

Case Study 2.7

Post Tower Bonn, Germany

Climate

The climate and temperature of Bonn are often influenced by the nearby Rhine Valley and strong westerly maritime winds which blow in from the North Sea. In general, the weather is characterized by four distinct seasons and cloudy skies are usually the norm. Winter temperatures average around 3 °C, climbing to 10 °C by springtime. Snowy weather is light with rainy days being more likely. Summer temperatures regularly top 20 °C, rising to more than 25 °C at times, with long spells of sunshine. However, rainy weather occurs often with quick, unexpected showers (see Figure 2.7.1).

Background

The Post Tower in Bonn, Germany, was completed in 2002 (see Figure 2.7.2). The Tower's form consists of two offset elliptical segments separated by a 7.2-meter-wide atrium that faces west toward the City of Bonn, and east towards the Rhine River. This full-building-height atrium is segmented into four sky gardens; three are nine stories high and the top is 11 stories high. In each elliptical segment of the building, cellular offices hug the perimeter, with conference rooms and core functions located toward the center of the ellipse (see plan and section, Figures 2.7.3 & 2.7.4). The two elliptical halves of the tower are connected at every level across the atrium by steel and glass bridges that access the elevator lobbies. The two main façades of the office segments face north and south, respectively, while the façades of the sky gardens have east and west orientations.

Natural Ventilation Strategy

From the onset of planning, there was a strong desire to give all office staff direct access to the outside air, including individual control of this access. Other key client criteria included transparent, floor-to-ceiling glazing and natural light in all office spaces. The natural ventilation strategy of the building is based on a double-skin façade system which supplies air to the

Climatic Data:[1]

Location
- Bonn, Germany

Geographic Position
- Latitude 50° 43' N, Longitude 7° 5' E

Climate Classification
- Temperate

Prevailing Wind Direction
- West-northwest

Average Wind Speed
- 2.4 meters per second

Mean Annual Temperature
- 10 °C

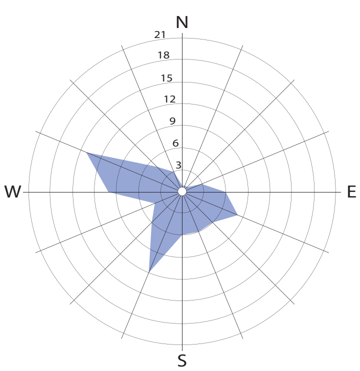
Average Daytime Temperature during the Hottest Months (June, July, August)
- 17 °C

Average Daytime Temperature during the Coldest Months (December, January, February)
- 3 °C

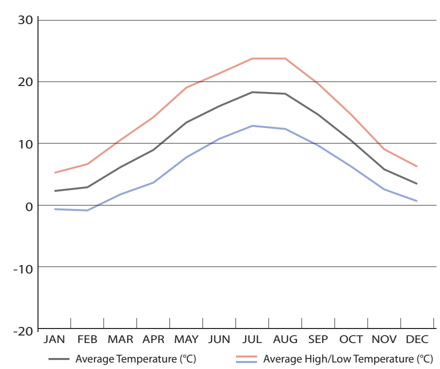
Day/Night Temperature Difference During the Hottest Months
- 11 °C

Mean Annual Precipitation
- 796 millimeters

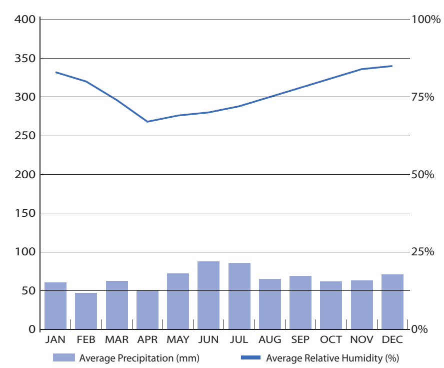
Average Relative Humidity
- 72% (hottest months); 83% (coldest months)



Wind Rose



Average Annual Temperature Profile (°C)



Average Relative Humidity (%) and Average Annual Rainfall

▲ Figure 2.7.1: Climate profiles for Bonn, Germany.[1]
◀ Figure 2.7.2: Overall view. © Murphy/Jahn Architects

[1] The climatic data listed for Bonn was derived from the World Meteorological Organization (WMO) and Deutscher Wetterdienst (German Weather Service).

Project Data:

Year of Completion
- 2008

Height
- 115 meters

Stories
- 22

Gross Area of Tower
- 64,567 square meters

Building Function
- Office

Structural Material
- Concrete

Plan Depth
- 11.5 meters (from central core)

Location of Plant Floors:
- B1, Roof

Ventilation Overview:

Ventilation Type
- Mixed-Mode: Complementary-Concurrent

Natural Ventilation Strategy
- Cross and Stack Ventilation (connected internal spaces)

Design Strategies
- Double-skin façades
- Segmented atria/sky gardens act as a thermal buffer zone
- 115-meter solar chimney

Double-Skin Façade Cavity:
- Depth: 1.3 meters
- Horizontal Continuity: Fully Continuous (along entire length of façade)
- Vertical Continuity: 4 meters (floor-to-floor)

Approximate Percentage of Year Natural Ventilation can be Utilized:
- 35%

Percentage of Annual Energy Savings for Heating and Cooling:
- 73% compared to a fully air-conditioned Manitoba office building (measured)
- 81% compared to Canadian MNECB energy code (measured)

Typical Annual Energy Consumption (Heating/Cooling):
- 39 kWh/m^2 (measured)

Case Study 2.12

Manitoba Hydro Place Winnipeg, Canada

Climate

Winnipeg experiences extreme variations in climate, with a temperature swing between a −35 °C extreme in winter and a +35 °C extreme in summer. From December through February the temperature typically remains below freezing, with an average daytime high of −10 °C. Despite the harsh winter, Winnipeg is known for year-round sunny weather. Snowfall is regular, with an annual average of 1,150 millimeters and can continue through springtime. By April, temperatures begin peaking at 10 °C. Summertime experiences hot weather with plenty of sunshine and the temperature often peaks at 30 °C between July and August (see Figure 2.12.1).

Background

Careful consideration was given to the new location for the Manitoba Hydro headquarters, including a study on proximity to public transport options for the 1,800 employees. The project was seen as an opportunity to build up downtown Winnipeg and the local transit system. Prior to relocating from the suburbs, 95 percent of the employees drove to work. After relocation and a corporate incentive program, 68 percent of the employees use public transport to get to and from work (Linn 2010). In addition to the city's local restaurants and shops benefitting from 1,800 new patrons, the new building offers a three-story, light-filled galleria which is open to the public.

The mass of Manitoba Hydro Place consists of two converging 18-story office wings separated by a service core, resting on a three-story podium (see Figure 2.12.2). The two column-free office blocks face west and east-northeast respectively, with north- and south-facing atria fusing the two masses together. Private office spaces such as workstations and glass-enclosed meeting areas are organized into "neighborhoods" around each atrium. The form and mass of the towers were generated in response to solar orientation, prevailing wind conditions, and other unique climatic conditions that characterize the city of Winnipeg.

Climatic Data:[1]

Location
- Winnipeg, Canada

Geographic Position
- Latitude 49° 54′ N, Longitude 97° 7′ W

Climate Classification
- Cold

Prevailing Wind Direction
- South

Average Wind Speed
- 4.7 meters per second

Mean Annual Temperature
- 3 °C

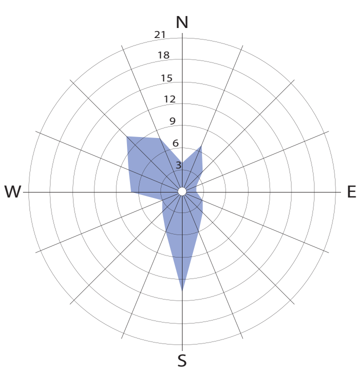
Average Daytime Temperature during the Hottest Months (June, July, August)
- 25 °C

Average Daytime Temperature during the Coldest Months (December, January, February)
- −10 °C

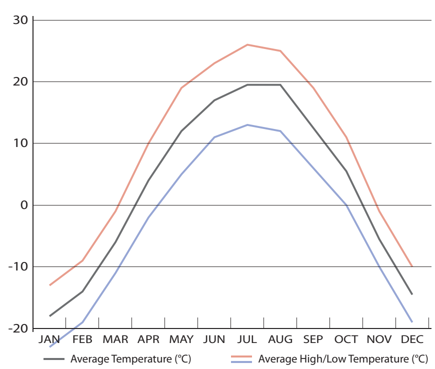
Day/Night Temperature Difference During the Hottest Months
- 13 °C

Mean Annual Precipitation
- 514 millimeters

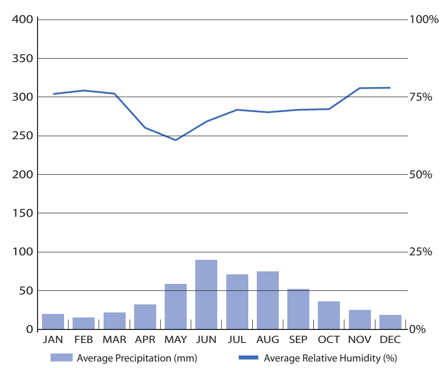
Average Relative Humidity
- 69% (hottest months); 77% (coldest months)



Wind Rose



Average Annual Temperature Profile (°C)



Average Relative Humidity (%) and Average Annual Rainfall

▲ Figure 2.12.1: Climate profiles for Winnipeg, Canada.[1]

◀ Figure 2.12.2: Overall view from northwest. © KPMB Architects

[1] The climatic data listed for Winnipeg was derived from the World Meteorological Organization (WMO) and the Meteorological Service of Canada.

Tall buildings are not the only solution for achieving sustainability through increased density in cities but, given the scale of current population shifts, the vertical city is increasingly being seen as the most viable solution for many urban centers. However, the full implications of concentrating more people on smaller plots of land by building vertically – whether for work, residential or leisure functions – needs to be better researched and understood.

It is generally accepted that we need to reduce the energy equation – in both operating and embodied terms – of every component and system in the building as an essential element in making it more sustainable. Mechanical HVAC systems (Heating, Ventilation and Air-Conditioning) in tall office buildings typically account for 30–40 percent of overall building energy consumption. The increased efficiency (or possibly even elimination) of these mechanical systems – through the provision of natural ventilation – could thus be argued to be the most important single step we could make in making tall buildings more sustainable.

This guide sets out recommendations for every phase of the planning, construction and operation of natural ventilation systems in these buildings, including local climatic factors that need to be taken into account, how to plan for seasonal variations in weather, and the risks in adopting different implementation strategies. All of the recommendations are based on analysis of the research findings from richly-illustrated international case studies.

Tried and tested solutions to real-life problems make this an essential guide for anyone working on the design and operation of tall buildings anywhere in the world. This is the first technical guide from the Council on Tall Buildings and Urban Habitat's Tall Buildings & Sustainability Working Group looking in depth at a key element in the creation of tall buildings with a much-reduced environmental impact, while taking the industry closer to an appreciation of what constitutes a sustainable tall building, and what factors affect the sustainability threshold for tall.

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