Adaptation of Climate-Responsive Building Design Strategies and Resilience to Climate Change in the Hot/Arid Region of Khartoum City, Sudan

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ABSTRACT

Climate change has become one of the most discussed topics of last few decades. It has inspired researchers of the built environment to develop climate-responsive design strategies. These strategies are essential for the construction sector to take advantage of abundant renewable resources in the local climate. Implementation of such strategies has the potential to reduce reliance on fossil fuels, which are considered a major cause of ozone depletion and resultant global warming.

The permanent alterations to Earth’s ecological system change have made Khartoum City in Sudan vulnerable to climate change. Significant impacts of climate change to nature, structures, and human well-being have already been noticed. Though the Sudanese government and parastatals have made efforts to address these climate-induced problems, improvements remain insufficient. Indices show the climate alterations occurring in Khartoum include irregular heat waves, increased relative humidity, drought, and extreme flooding. In addition, climate-related phenomena like intense thunderstorms and sand-dust storms have become more frequent than ever. Even though the brunt of these climatic events is primarily felt outdoors, they all result in uncomfortable and challenging to manage indoor conditions.

In this research, Khartoum’s climate data from 1981 to 2015 was analyzed and compared to identify trends in temperature, humidity, wind speed, and rainfall. This trend analysis indicates acute climate change. The Meteonorm Company created the hourly energy plus (EPW) file for Khartoum from the averages of basic climate parameters recorded and available for Khartoum from 1996 to 2015. Meteonorm 7.2.1

evaluated the city's future projected hourly energy plus (EPW) file up to 2070. To counter 2070's projected climatic conditions, resilient design strategies were evaluated to minimize energy usage and optimize thermal comfort for building users today and in the future. Contemporary design strategies of 2015 and projected design strategies for 2070 were compared and the findings revealed that design strategies must shift towards more active cooling and away from passive cooling to reduce energy usage and achieve optimal user thermal comfort in 2070. Moreover, natural ventilation and active heating will no longer be beneficial design strategies. Two-stage evaporative cooling is anticipated to become the most sustainable and effective climate-responsive design strategy for all seasons in Khartoum. Passive design strategies with increased resilience should be adapted for use with Khartoum's underutilized renewable resources to reduce future active-cooling demand and to optimize thermal comfort.

Keywords: Climate Change, Khartoum Region Climate Data, Thermal Comfort, Design Strategies

ÖZ

İklim değişikliği son yıllarda en çok tartışılan konulardan biri haline geldi. Bu konu, yapılı çevrede, iklime karşı duyarlı tasarım stratejileri geliştirmek için araştırmacılara ilham vermiştir. Bu stratejiler, inşaat sektöründe, mevcut iklimin avantajlarından faydalanıp yenilenebilir enerji kaynaklarını kullanmanın önemini vurgulamaktadır. Bu tür stratejilerin uygulanması, ozon tabakasının incelmesi ve sonuçta ortaya çıkan küresel ısınmanın önemli bir nedeni olarak kabul edilen fosil yakıtlara olan bağımlılığı azaltma potansiyeline sahiptir.

Sudan'da Hartum iklimi, bölgeyi özellikle iklim değişikliğine karşı savunmasız kılar. Günümüzde, iklim değişikliğinin doğa, yapılar ve insan sağlığı üzerindeki önemli etkilerinin farkına varılmıştır. Sudan hükümeti ve yarı resmi kuruluşlar bu iklime bağlı sorunları çözmek için çaba sarf etmiş olsalar da, gelişmeler yetersiz kalmaktadır. Düzensiz sıcak hava dalgaları, artan nispi nem oranları, kuraklık ve aşırı seller Hartum'da meydana gelen iklim değişikliklerinin belirtileridir. Ayrıca, şiddetli fırtınalar ve kum tozu fırtınaları gibi iklimle ilgili olaylar, her zamankinden daha sık ortaya çıktığı gözlemlenmektedir. Bu iklimsel problemlerin sıkıntıları öncellikle yapının dışında hissedilse de, iç mekânlarda ısıl konforu açısından rahatsız edici ve kontrol edilmesi zor iç mekan koşulları oluşturmaktadır.

Bu araştırmada, Hartum'un 1981 ile 2015 yılları arasındaki iklim verileri analiz edilmiş olup, sıcaklık, nem, rüzgâr hızı ve yağış eğilimlerini belirtilmek üzere karşılaştırılmıştır. Bu eğilim analizi, iklim değişikliğinin gerçekliğini gün yüzüne çıkarmaktadır. Meteonorm Şirketi, 1996'dan 2015'e kadar Hartum için kaydedilen ve elde edilebilen temel iklim parametrelerinin ortalamalarından, Hartum için saatlik Energy Plus (EPW) dosyasını oluşturdu. Meteonorm 7.2.1, kentin geleceği için öngörülen saatlik Energy Plus (EPW) dosyasını 2070 yılına kadar değerlendirdi. 2070 yılında öngörülen iklim koşullarına karşı mücadele edebilmek için, enerji kullanımını en aza indirmek ve de günümüzde ve gelecekte binalardaki ısıl konforu optimize etmek amacıyla esnek tasarım stratejileri incelendi. Bu kapsamda, 2015'in çağdaş tasarım stratejileri ve 2070 için öngörülen tasarım stratejileri karşılaştırıldı ve ortaya çıkan bulgular, tasarım stratejilerinin enerji kullanımını azaltmak ve 2070'de en uygun kullanıcı ısıl konforu elde etmek için daha aktif soğutmaya gereksinimin olduğunu, ve pasif soğutmadan ise kaçınılması gerektiğini ortaya koydu. Ayrıca doğal havalandırma ve aktif ısıtmanın fayda sağlayacak bir tasarım stratejileri olamayacağını göstermektedir. Hartum‘da her mevsim için en sürdürülebilir ve en etkili iklime duyarlı tasarım stratejisinin, iki aşamalı evaporatif soğutma yöntemi olması öngörülmektedir. Dayanıklı ve esnek pasif tasarım stratejileri, Hartum‘un gelecekteki aktif soğutma talebini azaltmak ve ısıl konforu optimize etmek için az kullanılmakta olan yenilenebilir enerji kaynaklarını kullanabilmek üzerine uyarlanmalıdır.

Anahtar Kelimeler: İklim Değişikliği, Hartum Bölgesi İklim Verileri, Isıl Konfor, Tasarım Stratejileri

DEDICATION

This work is dedicated to the following people:

To the memory of my late mother who I lost in 2 October 2010

My Almighty Allah (SWT) grant her with Al-Jannah

To the memory of my late father who I lost during the course of this work

My Almighty Allah (SWT) grant him with Al-Jannah

To my beloved wife Bakhita Hashim for her love and endurance during my absence

To my children Mohammed, Hashim and Fatima

To my brother Osman Mohammed Osman & Family

Who has been the source of my inspiration and for his love, support and continues encouragement

To my brothers Ahmed and Abdulgadir and sisters Zubeida, Maryam and Dar Alslam

For their love and prayers

Finally to the soul of fallen heroes of 19 December Revolution 2018 who lost their live for freedom, justice and peace for the Sudanese people.

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INTRODUCTION

1.1 Background of the Study

Climate-responsive building design has been adapting since ancient times. Its existence dates to the period when humans designed for survival, trying to protect themselves from climatic elements with clothing and shelter. This method of building is considered autochthonic because it utilized the resources of the immediate environment and responded to the prevailing climate. Depending on climatic conditions, a building has to withstand heat, cold, rain, or wind to offer safety and thermal comfort. In Polar Regions for instance, igloos were adapted to protect inhabitants from extreme cold and strong winds. On the contrary, desert inhabitants utilized the tent as a mobile shelter to protect themselves from unfavorable climatic conditions. Every climatic zone has variations that are easily distinguishable by the clothing and shelters its inhabitants used. Generally, climate-responsive buildings of ancient man evolved from locally available materials alone, without the help of architects and builders (Bilow, 2012; Behling et al., 1996). Architecture could be considered a reflection of civilization. Both civilization and its resultant architecture are influenced by various local factors and conditions. These may include community needs and wants; societal, cultural, and climatic conditions; or technological advances. All these factors mentioned are amendable except climate, which man cannot directly and immediately alter. Therefore, the different climatic conditions of countries dictate the type of architectural precautions needed to adapt and provide optimal comfort in the living environment (Ozay, 2005). Vernacular buildings – constructed in response to the climatic conditions of their location – have existed for a very long time and continue to serve their optimal purposes. Following along with that which has been successful, contemporary buildings should also emulate the same principles.

Besides adaptation to climate via building design, the significance of discussing energy issues in architecture cannot be undermined because the building sector accounts for more than 50% of the energy sources used worldwide and hold responsibility for over 60% of all waste (Bilow, 2012; Hegger et al., 2007). Moreover, climate-responsive design strategies, if appropriately applied, help designers save in energy consumption while providing optimal thermal comfort for building users. It is essential for designers to understand the complexities of local climatic conditions to which design should respond. Most designers assume to understand the climate they design for but they rarely fully recognize the implications of climate phenomena such as seasonal temperatures, wind speeds, and cloud cover trends (Van Den Wymelenberg et al., 2009). Among all the goals architects anticipate to achieve when designing a building, optimal indoor thermal comfort may be the most important. The need for comfort governs the extent to which the architect's design is able to meet this target. Since ancient times, human efforts to construct shelter have been inspired by local climate. Most architects nowadays are not competent enough to mold design to local climate; instead, they design buildings which invariably rely on active, high-energy systems for moderating the indoor climate (Daroda, 2011). Climate-responsive architecture utilize free renewable energy (Turner, 2003). Climate-responsive design benefits can be summarized as:

1-Reducing energy consumption, using abundant renewable energy instead of relying on non-renewable energy such as fossil fuels.
2-Provision of optimal interior thermal comfort in sustainable buildings (Ozay, 2005).

The world attention to the adaptation of climate change has tremendously increased in recent years. However, the contemporary climate change indices in different part of the globe agreed qualitatively with the fact that there is urgent need to implement measures and policies for the climate change mitigation in order to decrease residual warming effects (Khlebnikova & Shkol'nik, 2012).

Khartoum city is affected by increased Green House Gases (GHGS), these emissions have been invariably considered to be a major source of increasing the temperature of the city microclimate as well and negatively affect the air quality of the city (ALHUSEEN, Al Huseen, 2014). Making the situation worse, Sudanese building styles still follow the international trend of 20th century modern architecture, which put more emphasis on architectural aesthetics and function than environmental sustainability (Roaf et al., 2009; Coch, 1998). Adapting buildings from such unsustainable design strategies would increase their operational costs; therefore, this architectural setback is most economically compensated through mechanical cooling or heating systems that lead to more energy consumption. Since climate change expectations are high, it is projected that energy need for cooling will continue to increase and may render a building economically unviable in the long term. Consequently, adapting to climate-responsive strategies helps enhance the future performance of new buildings (Snow & Prasad, 2011).

Nowadays, most contemporary buildings in Khartoum City are constructed with concrete and glass for building materials without giving any attention to climatic issues. These materials create buildings that are ecologically unfriendly to the local climate. This research is an effort to provide criteria for design and construction of climate-responsive buildings in climate of the city of Khartoum, Sudan. Protection of buildings against dust and sand storms will be critically considered in order to produce sustainable design solutions that would be adaptable to climate change. Adapting climate-responsive design strategies would help decrease reliance on active cooling during the long, hot summer season that extends more than eight months.

1.2 Statements of the Problem

Khartoum City, Sudan, is within a semi-desert climatic zone that is characterized as having high temperatures which minimum and maximum are from 32 ^{O}C and 45 ^{O}C in Hot Season (March-May) and minimum maximum are 14 ^{O}C and 40 ^{O}C in Dry Season (November to February) and 21 ^{O}C and 41 ^{O}C in Wet Season (June-October). The humidity level of Khartoum is very low approximately maximum of 17% during the daytime in Dry and Hot Seasons and it reaches its peak value of 47 % after midnight. The highest humidity is achieved during Wet Season months. August is considered the most humid month and it ranges from 57% and can reach up to 99%. These climatic conditions have direct negative impacts on a building’s thermal performance because they increase heat gain, resulting in an uncomfortable interior environment. To obtain thermal comfort, people rely on air-conditioning systems during the long summer season (March to November). Together, these factors have mounted high pressure on electricity consumption. For the city Khartoum, electricity is generally generated by hydroelectricity and dependent on water supply from the nearby Twin Rivers (White Nile and Blue Nile). These rivers are the major suppliers of water to Sudan and Egypt. To make the situation worse, in recent years the water supply frequently has been disturbed during the summer season, reducing the efficiency and capacity of the electricity supply. To cover this shortage in power supply, electric generators have been utilized. The latter energy source increases the greenhouse gases emissions, further damage the natural environment. By analyzing the city of Khartoum's average climatic data from 1981 to 2015, the temperatures have increased in the city of Khartoum from March to June. October is hot and is now considered a transitional between the rainy season and winter. This research seeks to offer climate-responsive design strategies to Khartoum for tackling the following problems:

1- High cost of installation and operation of air-conditioning alongside serious shortage of electricity during long summer months. Because 70% of electricity produced in Sudan is hydroelectricity, the challenge of less water supply in summer makes the electricity supplied by the national grid unreliable.

2- High thermal load of buildings due to lack of appropriate shading of buildings.

3- Provision of design strategies that are resilient to the future climate of the city of Khartoum, Sudan.

4- Most buildings have not incorporated energy efficiency measures in their design and construction; hence, the view of air-conditioning parts have become synonymous with building façades.

1.3 Aim and Objectives of the Research

(I) Aim of the Research

This to reveal climatic conditions and design responses that affect indoor thermal comfort in the city of Khartoum, Sudan. It then suggests relevant climate-responsive design strategies that could increase the city of Khartoum's resilience to both current and projected climatic conditions. The objectives supporting these aims include identification and evaluation of climate trends projected from city of Khartoum’s 1981 to 2015 climate data; comprehension of the local climate’s effects on buildings; and introduction of enhanced ways to provide thermal comfort to current and future users of the city of Khartoum’s buildings.

(II) The Objectives of the Research

1-To develop appropriate climate-responsive strategies for passive cooling in building design in city of Khartoum, Sudan.

2-To provide building design guidelines that help architects in the early design phases to develop environmentally responsive buildings.

3-To provide strategies for saving on fossil fuel consumed for cooling and reduce negative effects of carbon dioxide, which cause climate change.

1.4 Scope of the Research

The research scope is based on the study of climate-responsive design for low-rise buildings in the city of Khartoum, Sudan. More than 90% of Khartoum’s buildings fall into this category; therefore, finding an appropriate architectural response to reduce reliance on air-conditioning systems would save a significant amount of energy and reduce pressure on hydro-electrical production and fuel fossils.

1.5 Limitation of the Research

This research is limited to climate-responsive design strategies for low-rise buildings in the city of Khartoum, Sudan. Though climate data for Khartoum is closely studied to arrive at concrete solutions, initial data was limited to the period of 1981 to 2015. The Sudanese government has rigid rules about offering climate data because it considers the sources confidential. The available climate data is in form of monthly min. and max. Average climate values. As is the case for most Third World countries, appropriate documentation of climate data is not given attention. Energy plus weather (EPW) files are also not freely available for the city of Khartoum; therefore, the EPW files were purchased from Meteonorm Company in Switzerland.

Furthermore, availability of literature covering similar research in the case study area is insufficient. Despite extensive searching, few studies in the architectural aspects of climate research have been done for Sudan to date. This constraint has tremendously enhanced the novelty of this research, since it is the first of its kind to analyze the historical climate to assess climate change in relation to building design and users' environmental comfort.

1.6 Significance of the Research

This research contributes to enrich the literature about relevant contemporary and future design strategies needed to efficiently examine, control, and use renewable energy sources and create climate-responsive building design criteria for hot and arid climates. It is not only for the city of Khartoum but also for similar climates and cities throughout the world. This study can improve the knowledge of designers, architects, urban and regional planners, civil engineers, building engineers, and municipal decision-makers, and it is anticipated to be of benefit to both cities and citizens. It may help as a good reference material to those intend to work on related research in the area or related subject.

1.7 Structure of the Thesis

This work intends to shed light on adaptation of climate-responsive building design strategies in the city of Khartoum climate zones. Climate change analysis is vital, its impact includes increase in global temperature and frequency of floods, droughts, sand-dust storms, and other climate phenomena. The historical climate data of the city of Khartoum, Sudan, for the last 34 years was evaluated for climate change. To achieve the aim and objectives, this research implemented the following data collection method:

- Intensive literature review
- Meteorological climate data for the last 34 years (1981 to 2015) from the city of Khartoum Meteorological Station to evaluate climate change
- A reliable energy plus weather (EPW) file was calculate from the 1996 to 2015 climate averages by Meteonorm 7.2.1
- A future EPW file was projected using appropriate scenarios to get future sustainable thermal comfort and design strategies.

A case study problem solving methodology was used to get climate-responsive building design strategies. Figure 1.1 illustrates the structure of the thesis.

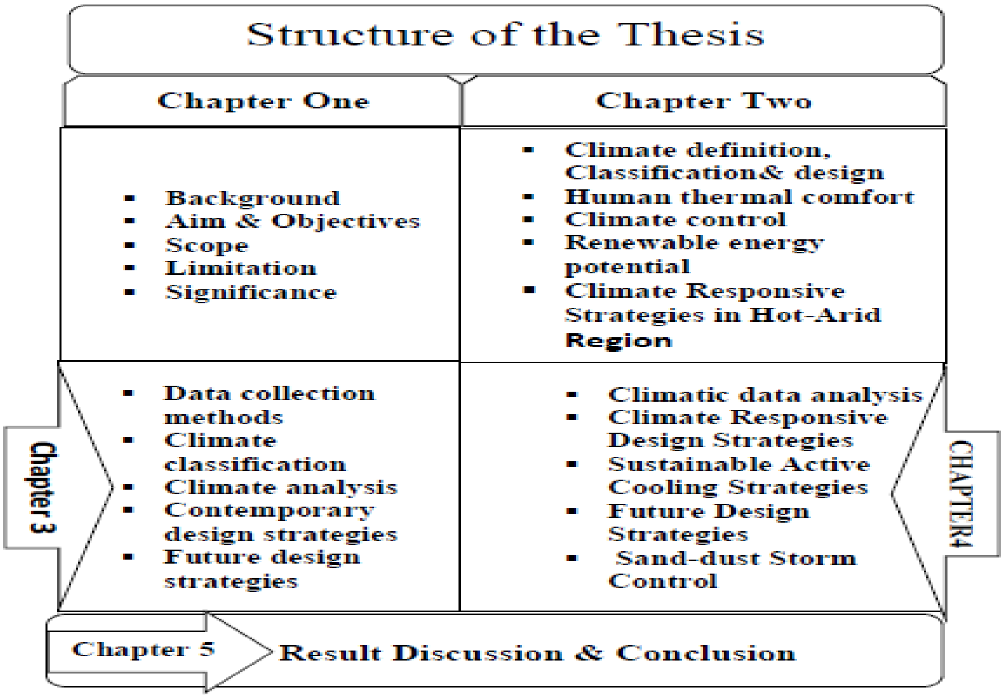


Figure 1.1: Structure of the thesis
Developed by the Author

This work is a combination of statistical calculation, computer-based software simulation, and theoretical framework supported by a thorough literature review to support the findings. This research is distributed into five chapters.

Chapter 1 gives definitions about the subject matter and explains the aims, objectives, significance, and limitations of the research. This chapter exposes the research problems and generates research questions upon which the entire thesis depends.

Chapter 2 is the literature review and it serves as a guide for this thesis. Through careful study of similar research, it tremendously helped in offering a context to the thesis. This chapter is divided into five sections which address the following:

1- Climate-responsive building design definition and its importance, the definition of climate, methods of climate classification, climatic design and its importance.
2- Study of human thermal comfort in buildings.
3- Climate control methods.
4- Energy potential in the built environment.
5- Climate considerations in a hot/arid climatic zone.

Chapter 3 describes the research methodology adopted for this thesis. It includes the data collection methods for the city of Khartoum’s historical climate data for the last 34 years, and EWP files for the city of Khartoum contemporary and future climate. Criteria for climate classification and climate-data analysis methods, which include linear trends analysis and correlation analysis methods, is intended for evaluation of climate change. Thermal comfort calculation methods and design strategies for contemporary and future climates of the city of Khartoum are also illustrated in this chapter.

Chapter 4 is about the city of Khartoum, Sudan, as the case study and includes historical background about the study area, climate classification, climate data analysis, the adapted thermal comfort approach, and architectural climate-responsive design strategies. The adaptable design strategies for the city of Khartoum include heat-loss promotion strategies, heat-gain minimization strategies, sustainable active-cooling systems, and dust-sand storm treatments for the city of Khartoum’s buildings. The future scenario of building climate-responsive design strategies for the city of Khartoum in the year 2070 was also analyzed to arrive at sustainable future resilient design strategies. Chapter 5 includes the discussion, conclusion, and recommendations of the thesis.

Chapter 2

CLIMATE-RESPONSIVE BUILDING DESIGN BASED ON CLIMATE CHANGE

2.1 Climate Responsive Building Design and Its Importance

Climate has great influences on both building design and the urban planning. Identifying, understanding, and controlling climatic effects of a location is very important prior to design process commencement. Moreover, climate has a profound effect on buildings' thermal performance. Therefore, the goal of the designer, when designing a climate-responsive building, should be towards energy saving and provision of optimum indoor thermal comfort (Manioğlu & Yılmaz, 2008; Hui, 2000). Sustainable, climate-responsive design strategies and adaptations have become necessary nowadays. Sustainability was a motive force for vernacular architecture in the past because different shapes and techniques proved to be effective climate modifiers. From Vitruvius' era until today, there have not been any fundamental changes to building design problems and precautions though the world has experienced tremendous advancement in materials and technology (Morgan, 1960). The aim of climate-responsive design is to utilize natural environment resources of the local climate for enhancement of indoor thermal comfort instead of using fossil fuels, which have relatively higher costs (Douvlou, 2004). Currently, climate factors are broadly neglected in the building design process and most buildings are built with materials that are neither sustainable nor in harmony with the surrounding environment (Krishan et al., 2001; Olgyay, 1963; Hui & Tsang, 2005). For example, it is very important for buildings to be designed in accordance with the local climate to enable them to gain minimum heat during the Hot Season of the year and lose minimum heat in the winter season of the year (Aslý, 2006). Unfortunately, most buildings constructed in the city of Khartoum are built without considering the climate. (De Carli et al, 2018). Architecture around the world, in its physical features and in terms of its climate sense, has become more generic in recent decades. It has been observed that 1960s prototypical buildings have been constructed in different geographical locations in the world without consideration of climate variations. Most ancient cities followed climate considerations in their planning and building designs; however, contemporary cities adapted their planning based on other rational principles such as optimization of infrastructure network and created irrational designs to emphasize a symbolic image of the city. The rising awareness of climate-responsive architectural design issues has great potential to gain momentum and help in making architecture more site specific. Once it considers these vital climate considerations again, architecture can regain regional relevancy (Krautheim et al, 2014).

Currently, climate change and the depletion of fossil fuels necessitate the seeking of alternative renewable energy sources to achieve sustainable development (Xu et al., 2016). Current conditions also compel the implementation of alternative means of reducing fuel consumption. Buildings consume one-third of the global energy, which has resulted in an increase of carbon dioxide emissions (Nguyen et al., 2011). The city of Khartoum, as a case of cities in most developing countries, witnessed tremendous growth in the 1990s that put more pressure on the already dilapidated services such as electricity transmission. In addition, the city’s climate is characterized as being extremely hot and dry during the summer season, which lasts approximately eight months. During this season, active cooling is currently the most commonly employed cooling strategy for achieving thermal comfort in the city of Khartoum. This limitation puts more pressure on the already insufficient electricity supply.

Adapting passive strategies is an appropriate strategy to save energy in buildings (Holmes & Hacker, 2007; Gou et al., 2015; Pacheco et al., 2012). The best passive design strategies are when the building responds to local climate resources, i.e., utilizing available renewable energy. The renewable energies are optimally utilized to enhance a building's indoor comfort level and subsidize the demand for mechanical systems (Santamouris & Kolkata, 2013; Samuel et al., 2013; Gou et al., 2015). It is interesting to note that climate-responsive strategies, which are extensively obscured in vernacular architecture globally, are passive design strategies. For this reason, numerous researchers have focused their attention on vernacular architecture (Bouillot, 2008; Du et al., 2014). This is one of the reasons climate-responsive building design has become an unavoidable option for energy saving and reducing the carbon footprint (Tzikopoulos et al., 2005). Appropriate climate-responsive design strategies should be worked with effectively, not against. Furthermore, it is important for a building's designer to make effective use of natural resources by utilizing their marvelous potential to improve buildings' indoor thermal levels. Local climate-responsive buildings should be climatically balanced. The climate-balanced building is a building that capable of withstanding undesirable stress resulting from environmental factors and utilizes natural favorable resources to enhance indoor thermal conditions. The achievement of perfect balance is possible only under exceptional environmental circumstances (Olgay, 1963).

2.2 Climate Study

2.2.1 Definition and Classification of Climate

Climate is defined as “the long-term weather conditions of a particular location based on standard average conditions over 30 years, including climatic factors such as temperature, humidity, wind, rainfall, and atmospheric pressure’’ (Daroda, 2011; Olotuah, 2015). The climate of a location on earth is determined by the following conditions: geographical location, elevation above sea level, topography, and vegetation cover. Together, certain sets of conditions dictate various climatic conditions and consequently different climate-relevant design principles emerged (Aslý, 2006). The parameters that have to be studied when classifying climate of a specific locations are precipitation, solar radiation, temperature, wind speed, relative humidity, and evapotranspiration. Evapotranspiration refers to the evaporation of water from the surface of plant’s leaves into the atmosphere; in other words, evapotranspiration is the opposite of rainfall (Bardhi & Gjongecaj, 2014). Köppen-Geiger climate classification is a well-known classification system first developed by German scientist, Vladimir Köppen (1846-1940). Köppen built his claim based on five plants groups determined by the renowned botanist De Candolle. However, Köppen includes equatorial, arid, warm, snow, and polar zones. Rudolf Geiger made enhancements to this classification in 1954 and 1961; hence the name was changed to Köppen-Geiger. Even though many classifications have been developed in recent years, the Köppen-Geiger classification remains one of the most frequent and reliable among all these classifications (Kottek et al., 2006; Wilcock, 1968; Peel et al., 2007; De Carli et al., 2018). Figure 2.1 shows the world climate classification as specified Köppen-Geiger.

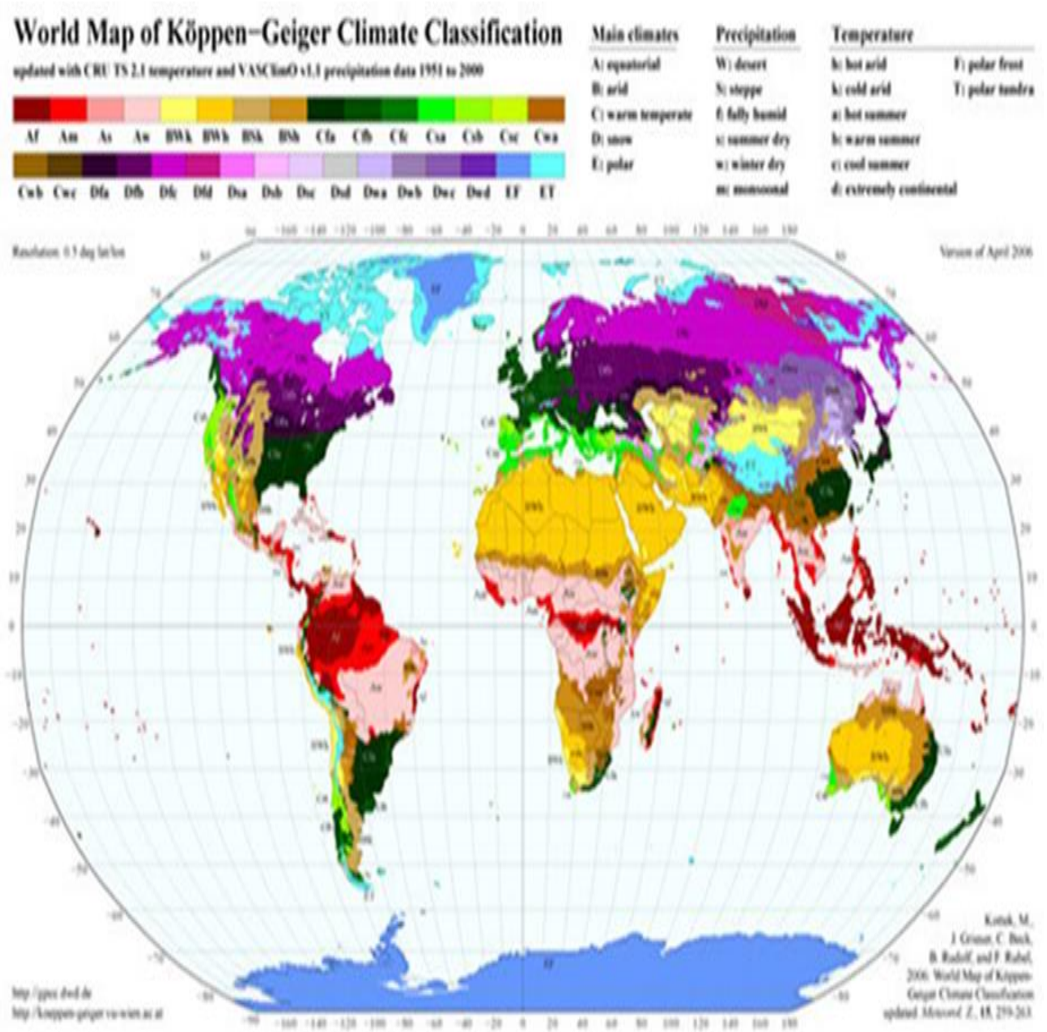


Figure 2.1: World Map of Köppen-Geiger climate classification
Source: Institute for Veterinary Public Health World Maps

The Köppen-Geiger classifies the world into desert, tropical, and subtropical, temperate, and cool climatic zones. This classification is generally used for representing climatic conditions. The classification could be used based on the thermal nature of a specific location (DouvIou, 2004). The easiest method of classifying climate is could be done with psychometrics chart. These can be classified as cool, temperate, hot/humid, and hot/dry, as in figure 2.2. However, the essence of this classification is to provide designers with general knowledge about the effects of temperature and humidity on building design strategies (Silva et al., 2008). The climatic zones in figure 2.2 were determined considering one range of temperature, between 16° and 28°C, associated with a temperate climate. The cool area in the chart locates in temperature zone of lower than 16°C. Temperatures more than 30°C combined with the air humidity, is necessary for that fact that humidity has a great influence on human thermal comfort. Hence, it is important to create two hot zones, one hot and dry with humidity less than 50% and the other hot and humidity of humidity more than 50%. At preliminary design stage, it essential to consider these two ranges because they form the first step in determining the building comfort. Material typology, opening sizes and orientations; facades design etc. these design measures are good climate design tools that help the designers to realize a responsive design without underestimating thermal comfort of building's users (Silva & Kinsel, 2006; Silva et al., 2008).

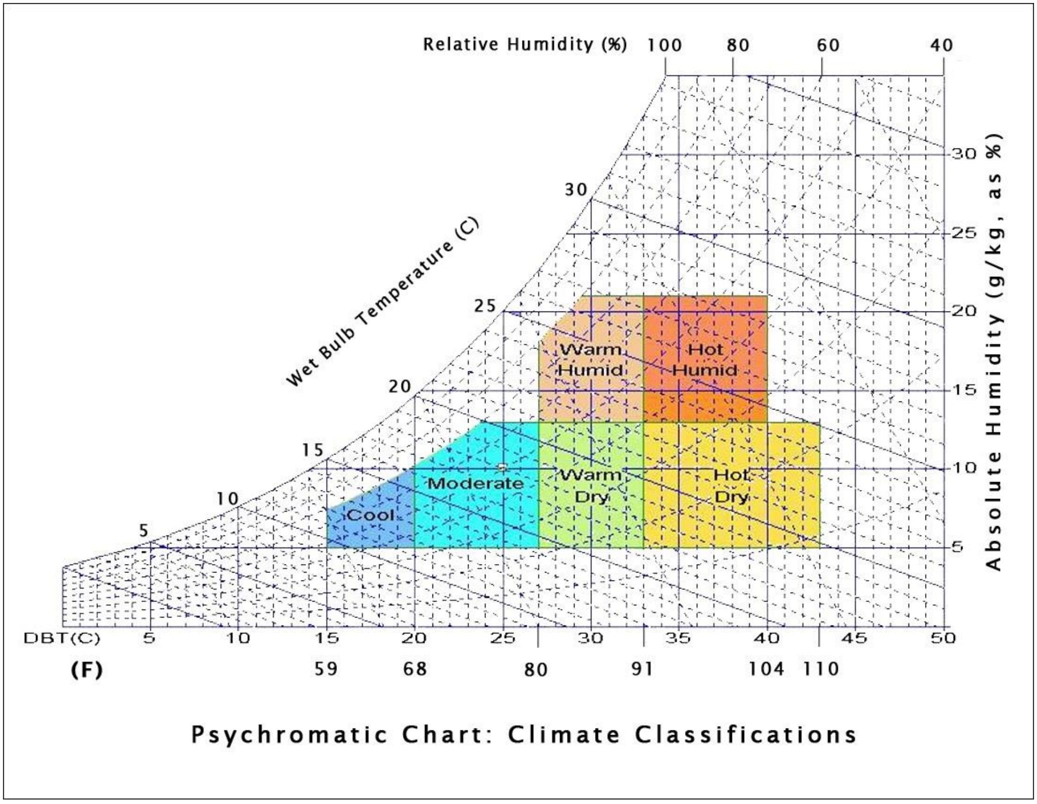


Figure 2.2: Climate classification on psychometric chart (Source: Looman, 2017)

2.2.2 Building Bioclimatic Charts

Recently, numerous design strategies that support the idea of designing environmentally friendly buildings have emerged. The best method for identifying suitable building design strategy is the bioclimatic chart method. This method uses local climate data to identify suitable design strategy. This in turn helps buildings take advantage of natural resources for low-energy cooling, heating, and lighting. Researchers, such as Olgyay and Szokolay, have conducted many studies on the utilization of natural energy resources for enhancement of indoor comfort. Furthermore, Kristinsson and Yeang among many others put these into practice (Looman, 2017; Silva et al., 2008; Giovani, 1998; Al-Azri et al., 2012). Olgyay published his book, 9Design with Climate, in 1963. It is considered to be a turning point in sustainable architecture design. According to him, building site and its local climate should be one of the determining factors of a design idea. Factors such as building orientation, form and configuration, wind pattern, and interior space quality are essential design parameters and the final design product should be a manifestation of that specific building site (Looman, 2017; Olgyay, 2015). Szokolay (2008) gave a rational explanation to architectural science saying that designers should take advantage of a building site's natural resources to provide optimal thermal comfort for building users. Szokolay advocated that the architect's target in design should be to design thermally comfortable indoor spaces that utilize less fossil fuel energy than from ambient or renewable energy sources. The architect's mission in realizing a building project progresses through four steps. First, the architect must critically analyze the building site's local climate, secondly create comfort limits, thirdly utilize the building to meet occupant comfort limits, and fourthly incorporate active means as complementary strategies when deemed necessary (Looman, 2017; Szokolay, 2008).

2.2.2.1 Olgyay's Bioclimatic Chart

The first bioclimatic chart was invented by Olgyay; its relative humidity is on abscissa and temperature on ordinate. The comfort zone is bounded by two lower and two upper fixed points. The lower temperature point is 21°C, upper temperature point of 26.7 ^{O}C and by a humidity upper boundary to form thermal comfort zone. At relative humidity less than 50%, the higher comfort boundary is 27.8 °C. The upper temperature limit descends steadily until it intersects with the lower comfort zone boundary at relative humidity (RH) of 90% figure 2.3 illustrates comfort zone in proposed by Olgyay. In situations of under-heating, the chart recommends admitting long-wave solar radiation to raise the mean radiant temperature (MRT) of a building's interior. In circumstances where there is no solar radiation then active heating would be required. During overheating periods, when temperature and humidity of a place is above comfort's upper limits, wind speed needs to be increased to extend the comfort zone. To lower temperature, evaporative cooling is needed. Olgyay assumes that indoor and outdoor temperatures are close to each other; therefore this chart is suitable for lightweight buildings (Giovani, 1998). Furthermore, it is appropriate for hot humid climates. It is inefficient for hot dry climates where the diurnal temperature between indoor and outdoor is large (Watson, 1983; Visitsak, 2007). Therefore, there is a need for further improvements to this bioclimatic chart. Giovani developed his bioclimatic chart, which works on the basis of a psychometric chart.

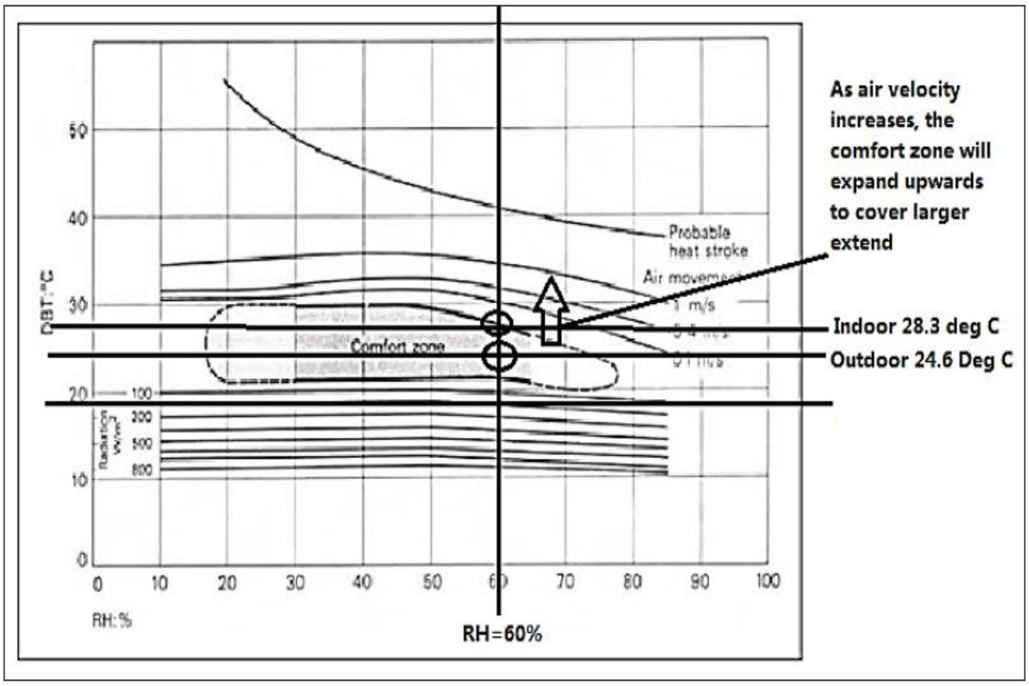


Figure 2.3: Olgyay’s Bioclimatic Chart
(Source: Watson, 1983; Visitsak, 2007)

2.2.2.2 Giovani’s Psychometric Chart

Giovani’s chart was developed by Baruch Giovani in 1969 (Giovani, 1976) as an improvement to Olgyay’s chart. The Givoni diagram in figure 2.4 is a bioclimatic diagram that comprises different zones in which it is essential to use strategies to attain human thermal comfort within a building (Morillón-Gálvez et al., 2004). In the diagram, the x-axis denotes the dry bulb temperature and the y-axis demonstrates the fresh air humidity. The psychometric curves in the graph signify the relative humidity. For instance, Ruppand and Ghisi (2014).Giovani diagram comprises 14 zones among them, zone one and two are considered to be ideal thermal comfort zones. The determination of comfort zone in this diagram depend on the dry bulb temperature (DBT) and air humidity. Giovani diagram indicates that thermal comfort can be achieved through adapting appropriate design strategy (Rupp & Ghisi, 2014; Manzano-Agugliaro, 2015).Giovani’s chart recommended some passive strategies which include heating, internal gains, natural ventilation, high mass cooling, high mass cooling with night ventilation, evaporative cooling, and shading devices (Matsumoto, 2017). Giovani's chart is more appropriate for residential building design. It offers more options for building design to enhance thermal comfort for occupants using design strategies such as natural ventilation, evaporative cooling, thermal mass, passive heating, conventional air conditioning, or dehumidification. However, many researchers around the world have used Giovani's chart to examine possible ways of incorporating passive design strategies into different world climates (Matsumoto et al., 2017). According to Lam and others (2006), Giovani's chart was used to evaluate the climate of 18 cities of China with climate ranges from cold to moderate to hot/humid to hot/dry and projected suitable passive design strategies accordingly (Lam et al., 2006; Matsumoto, 2017). Furthermore, Giovani's chart was used in Qatar's climate, which is classified as desert, to propose design strategies and good results matching characteristics of desert-climate design criteria (Saying & Marafia, 1998). This chart could be adapted for hot/arid climate of the city of Khartoum, Sudan.

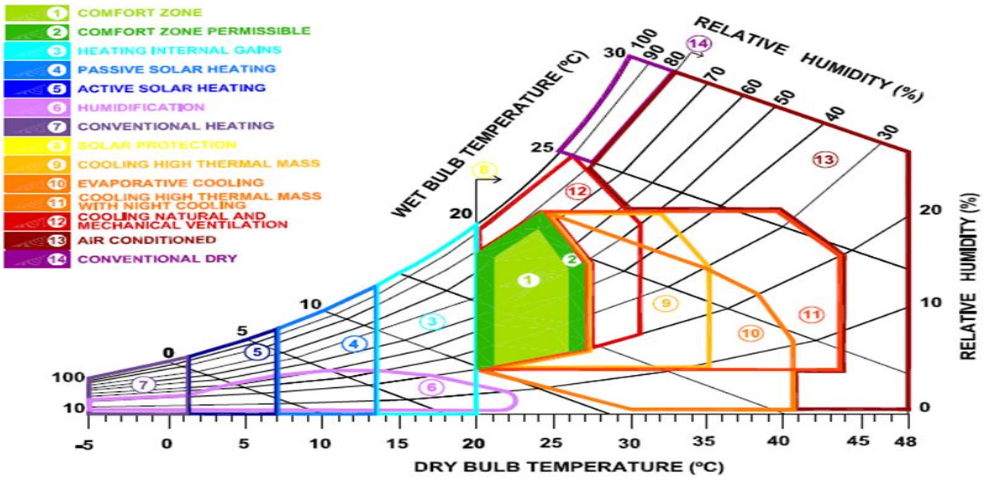


Figure 2.4: Psychometric chart adapted from Givoni, B. (1992)
(Source: & Manzano-Agugliaro, 2015)

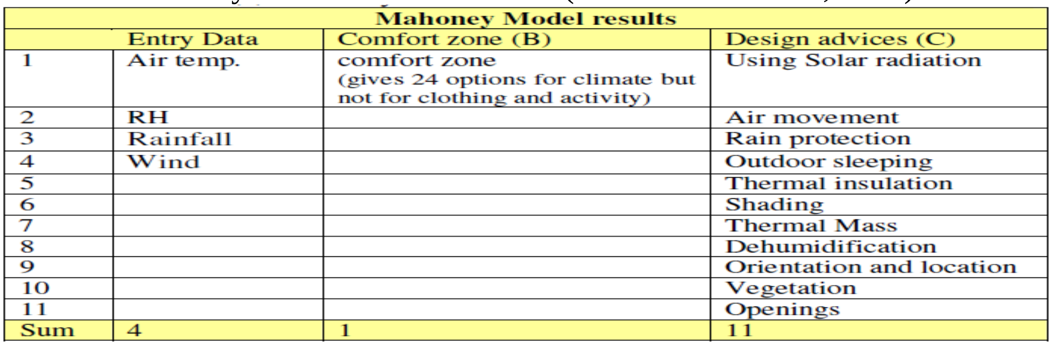
2.2.2.3 Zsokolay Control Potential Zone (CPZ) Method

Zsokolay invented this bioclimatic chart in 1986 and developed it based on thermal neutrality that was initiated by Humphreys and Auliciems. The comfort zone on this method is considered effective only in situations where the relative humidity is not more than 90% (Matsumoto et al., 2017). The Control Potential Zone (CPZ) method examines numerous strategies for working with the outdoor environment to attain indoor thermal comfort (Rabah & Tamakam, 2002; Attia, 2012). The comfort zone in Zsokolay's methodology refers to Auliciems' equation ($Tn = 17.6 + 0.31$) where thermal neutrality (Tn) is a function of outdoor mean temperature (To) and the operative temperature ranges between 17.8ºC and 29.5ºC. However, according to Szokolay, the human skin's evaporation potential variable depends on absolute humidity, and solar heating effects are influenced by solar radiation and material characteristics of the building envelope (Szokolay, 1986 & 1995; Attia, 2012). Szokolay used this method to classify the climate of 114 locations in Queensland. Moreover, Yang et al. (2005), Zain-Ahmed et al. (1998), and Upadhyay et al. (2006) employed this methodology to determine suitable cooling techniques for four different climatic regions in Cyprus, the hot-humid climate of Malaysia, and the warm-desert climate of Kathmandu valley (Attia, 2012). According to previous research, the CPZ method seems appropriate for all climatic regions.

2.2.2.4 Mahoney's Thermal Comfort Table

Architect Mahoney developed this table in 1968. It comprises a series of tables that are used for calculating the thermal comfort limits for any given location based on annual mean temperature and average relative humidity. Mahoney's tables are used to determine months in which solar shading is needed, based on buildings user's comfort preferences. Section one of the tables is used to record the extent of the data (humidity group) for each month according to the established relative humidity. The second section of the tables is used to determine months in which solar shading is required when the thermal stress exceeds a building users' comfort limits. These tables help designers to identify precautions quickly and to follow them in order to reduce any discomfort that might happen to building users. Nowadays, the necessity of using of Mahoney's table has become less important because the data is widely available for most cities around the world (El Bakkush, 2016). The shortcoming of this table is that it was originally meant for evaluation of comfort conditions in tropical climates; therefore, it does not give accurate results for cold climate situations (Xia, 2013). Mahoney Tables used to analyze the climate characteristics, from which design indicators are obtained. From these indicators a preliminary picture of the layout, orientation, shape and structure of the climatic responsive design can be obtained. The climatic data such as dry bulb temperature, relative humidity, precipitation and wind are used as entry data. Table 2.1 gives example of Mahoney's thermal comfort table

Table 2.1 Mahoney's thermal comfort table (Source: Walsh et al, 2017)



Mahoney Model results			
	Entry Data	Comfort zone (B)	Design advices (C)
1	Air temp.	comfort zone (gives 24 options for climate but not for clothing and activity)	Using Solar radiation
2	RH		Air movement
3	Rainfall		Rain protection
4	Wind		Outdoor sleeping
5			Thermal insulation
6			Shading
7			Thermal Mass
8			Dehumidification
9			Orientation and location
10			Vegetation
11			Openings
Sum	4	1	11

The following table 2.2 gives comparative studies of bioclimatic strategies approaches of Olgyay, Szokolay and Mahoney.

Table 2.2: Comparative studies of bioclimatic strategies approaches of Olgyay, Szokolay and Mahoney

	Olgyay Bioclimatic Chart	**Szokolay Bioclimatic Chart**	**Mahoney Table**
Controlled ambient variables	1-Dry bulb temperature	1-Dry bulb temperature	Monthly mean,mim.max and avrg. Temp
	2-Relative humidity	2- Wet bulb temperature	Monthly mean,min,max and average RH
		3-Relative humidity	Precipitation
		4- Absolute humidity	
Strategy proposed	Solar radiation	Natural ventilation	1 Layout
Design recommendation	Air movement	Passive heating	2 Spacing
	Shading	3 Evaporative cooling	3 Air movement
		4 Indirect evaporative cooling	4 Opening
		5 Thermal mass	5 Walls
		6 thermal mass with night ventilation	6 Roofs
			7 Outdoor space
			Rain protection
Merits	1 the chart as appropriate in hot humid areas	1 Define two comfort zones	1 Provide much design strategies as an alternative than the bioclimatic chart
	2 Suitable for residential building’s		
Demirits	1 Recommended design strategies are limited	1 The relative humidity should not exceeded 90%	2 The thermal comfort limit assumes no heat gain or loss due to ventilation or insulation

2.2.3 Factors Affecting Climatic Design

Microclimate has great influence on the design of buildings; therefore, it is necessary for designers to critically study it before embarking on design. Microclimate characteristics include natural and artificial features that affect solar access, wind patterns, and temperature. Appropriate site analysis should be performed so that designers will be able to identify ideal sustainable design strategies that function according to the local microclimate (Aminoroayaei & Shahedi, 2018).The following are very important site factors to consider when designing:

- Location and accessibility of the site.
- Soil type and condition for safe load bearing of the structure of the building.
- Topography of the site because it is always better to design buildings along the contours whether flat, sloped or hilly.
- Vegetation and natural site conditions can be integrated, highlighted, and accentuated to create a harmonious whole and sustainable environment.
- Knowledge of precipitation and hydrology of the area (annual or seasonal rainfall) is appropriate for designing drainage systems of buildings. Moreover, water bodies (e.g. ponds, rivers, and lakes) around the site should be critically examined. Relative humidity should be known since moisture content of air impacts buildings.
- Available service systems should include electricity, water, waste-disposal, and drainage patterns.
- Proximity and characteristics of neighboring buildings and surface conditions (DouvIou, 2004).

Design factors include:

- Sun path for good orientation to take advantage of the site’s potential.
- Wind patterns of the site for better utilization of wind to achieve sustainability and save energy.
- Building volume to ratio percentage or compactness
- Buildings’ windows sizes, orientations, and positions (DouvIou, 2004).

2.2.4 General Climate Control Strategies

Bioclimatic architecture strives to meet thermal comfort requirements of the building. Therefore, more attention must be given to parameters that influence human well-being such as sunshine, temperature, wind patterns, and precipitation. When designing in hot/arid climates, the designer should pay attention to the following issues:

- Protection of building occupants from solar radiation and heat gain.
- Heat gain minimization.
- Heat dissipation (Watson & Labs, 1983).

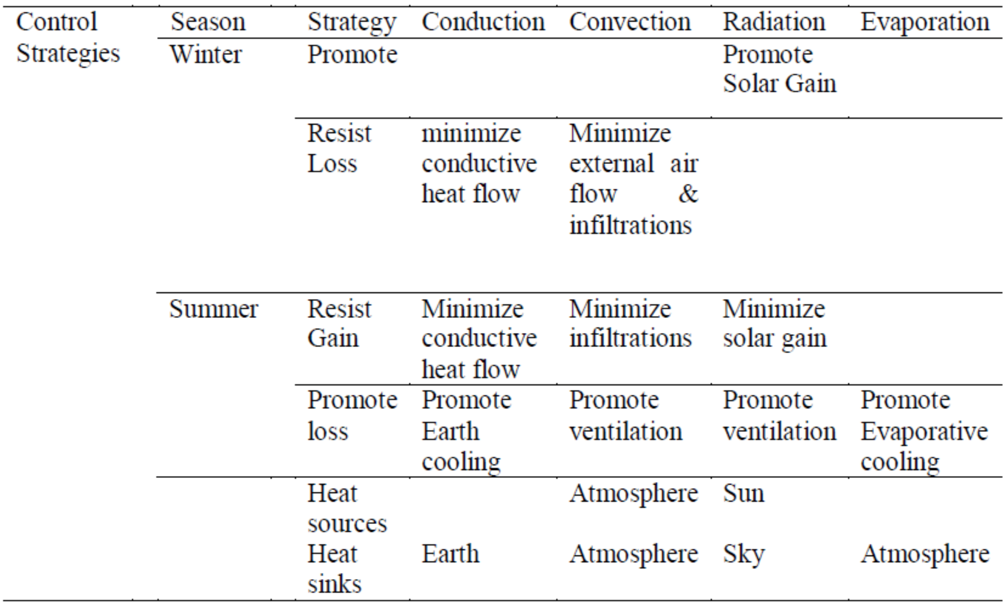
Building facade is the barrier between indoor spaces and the surrounding environment. Heat gain control via building envelope design is the most significant strategies on human thermal comfort in hot/arid climates. Hence, for adequate climate control, the following criteria should be followed:

- Thermal inertia properties of the building envelope should be appropriately selected to suit the local climate of the building
- Adapt thermal insulation for the building envelope to avoid energy loss. A research simulation on an insulated roof with reflected materials could decrease cooling load from 26% to 49% compared to one that is not insulated (Muselli, 2010). Applying thermal insulation to the building

walls and roof can decrease heat loss resulting from thermal bridges up to 25% (Bekkouche et al., 2013).

- The building form should be carefully be designed so that exposure to solar radiation is minimized to avoid heat exchange between the building in and outdoor.
- Air tightness and infiltrations of windows and doors should be controlled especially in cold climates where heating is required. See various control strategies in the table 2.3 below.

Table 2.3 Control strategies according to Watson (1983) principles



Control Strategies	Season	Strategy	Conduction	Convection	Radiation	Evaporation
	Winter	Promote			Promote Solar Gain	
		Resist Loss	minimize conductive heat flow	Minimize external air flow & infiltrations		
	Summer	Resist Gain	Minimize conductive heat flow	Minimize infiltrations	Minimize solar gain	
		Promote loss	Promote Earth cooling	Promote ventilation	Promote ventilation	Promote Evaporative cooling
		Heat sources		Atmosphere	Sun	
		Heat sinks	Earth	Atmosphere	Sky	Atmosphere

2.3 Human Thermal Comfort in Buildings

2.3.1 Thermal Comfort

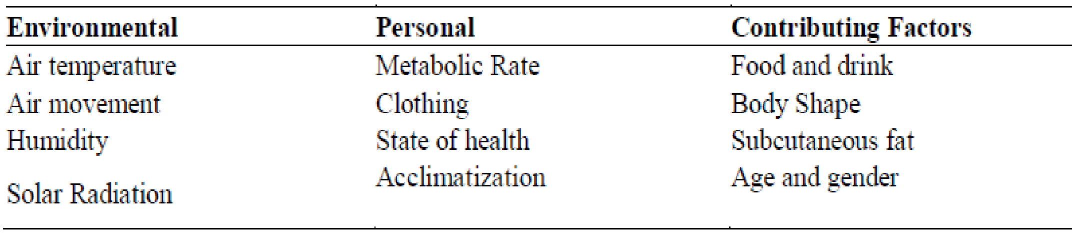
Thermal comfort is one of the essential features of building design procedure since human beings nowadays spend about 80% to 90% of their daily lives in indoor spaces. Therefore, it is imperative for architects and engineers to seek means to enhance building occupants' thermal comfort (Judson et al., 2014; Rupp et al., 2015).

ASHRAE 55 (2004) defined thermal comfort as “that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation.” Thermal comfort research has become a more dynamic field since the advent of air conditioning in the built environment (Van Hoof et al., 2010; ASHRAE 55, 2004). In previous years, numerous researchers have interpreted and combined results of factors affecting thermal comfort in buildings into a single parameter/index. This allows setting of ranges of comfort for the same parameter (Mishra & Ramgopal, 2013; Almeida, 2010). The thermal comfort index is generally defined either theoretically or through adaptive modelling (Almeida, 2010). Thermal comfort is classified in respect to environment: outdoor, semi-outdoor, or indoor (Rupp et al., 2015). Patterning indoor thermal comfort, there are two approaches that can be used for calculations.

The first one, the Fanger model (1970), applies the predicted percentage of dissatisfied (PPD) as proposed by a standard. This index was developed by Fanger on the basis of a mathematical model and he used data generated from experiments conducted on human beings in controlled climate spaces (Kuchen, 2016; Fanger, 1970). This model predicts the mean thermal sensation of a group of people in order to know the individual’s dissatisfaction with the thermal environment. It is expressed as the predicted mean vote (PMV) minus the predicted percentage dissatisfied (PPD). PMV was a basis of ASHRAE 55, and can be obtained through parameter such as; metabolism, clothing, indoor air temperature, indoor mean radiant temperature, indoor air velocity, and indoor air humidity (Rupp et al., 2015).

The second approach used for calculating thermal comfort is the adaptive model. It is more advantageous than the first approach because it is suitable for helping a building’s occupants achieve thermal comfort with strategies such as natural ventilation or clothing types that are suitable to the climate and sun exposure. The adaptive model approaches in appropriately modelled building design can reduce energy usage for mechanical ventilation and heating to 50% (Albatayneh et al., 2017). Thermal comfort influences factors that are a combination of environmental and individual variables. Finger used these factors in his equation. The environmental variables are air temperature, mean radiant temperature, relative air velocity, and relative humidity (Hensen, 1990; Ekici, 2013). Table 2.4 shows categories of factors that influence thermal comfort.

Table 2.4: Thermal comfort influencing factors.



Environmental	Personal	Contributing Factors
Air temperature	Metabolic Rate	Food and drink
Air movement	Clothing	Body Shape
Humidity	State of health	Subcutaneous fat
Solar Radiation	Acclimatization	Age and gender

Thermal comfort is a very significant concept influencing human comfort in the aspect of temperature, and is one of the most important parameter to consider in building design. Frontczak and Wargocki (2011) acknowledged that thermal comfort is both a fundamental condition and contributor to people’s comfort in building interiors (Frontczak & Wargocki, 2011). Rupp et al. (2015) carried out thoughtful research on thermal comfort in the built environment with a thorough literature survey on over 466 research articles discussing human thermal comfort aspects in the built environment. With their intensive research, they evaluated thermal comfort impacts and variables to enhance indoor environment thermal comfort (Rupp et al., 2015).

2.3.2 Thermal Comfort Parameters

It is difficult to give the exact values for the seven thermal comfort parameters, which would provide a suitable thermal environment for all people. The relations between these parameters are defined by numerous thermal indices such as the optimal operative temperature, comfort zones, the predicted mean vote, and predicted percentage of dissatisfied. These can be utilized to create the circumstances under which some inhabitants in a building tends to be comfortable though others many not be. (URL. 1). This study aimed is not to explain all the factors affecting thermal comfort; explanations that are more detailed are given for air temperature, radiant temperature, relative humidity, and air speed in the following subsections.

2.3.2.1 Air Temperature

Among all the environmental factors mentioned above, air temperature is the most influential one in determining thermal comfort (Parsons, 2010). Air temperature is also referred to as dry bulb temperature (DBT) and is measured with dry bulb thermometer. Griffith advocated that having a suitable temperature level was the one issue people deem to be the most vital in a building. The temperature for indoor comfort should be in the range of 16^{o}C to 30^{o}C for a room during the daytime and usually lower for sleeping times. However, people also encounter heat sensation through walls, windows, et cetera because of solar radiation from the surrounding environment. When the temperature increases or decreases beyond the comfort range, it may be necessary for people to increase or decrease their activity levels, adjust closures, or create air movement to restore thermal comfort (Gabril, 2014).

2.3.2.2 Radiant Temperature

Solar radiation has influences on thermal comfort. These effects can be illustrated in terms of thermal exchange between the body and the air surrounding it. The radiant temperature for a body invariably depends on the temperature of the surface that surrounds it. To examine the effect of the radiant temperature, mean radiant temperature (MRT) is measured. MRT refers to the temperature of a sphere. It is measured by an infrared scanner or it can be calculated as a function of global temperature, air temperature, and air velocity (Nicol, 2008; Fanger, 1970; Goulding et al., 1992; Foruzanmehr, 2017). Global temperature is generally used in thermal comfort survey research and has become one of the basic variables. According to Nicol (2008), global temperature has been suggested for measuring the joint impact of air and radiant temperature on the human body (Nicol, 2008; Foruzanmehr, 2017).

2.3.2.3 Relative Humidity

Relative humidity is a very important environmental parameter and has a great impact on thermal comfort in buildings. The effect was first documented a long time ago. Nowadays, it is incorporated into the effective temperature (ET) scale for calculation of thermal comfort zones (Jing et al., 2013. In warm climatic regions, high humidity levels compound discomfort when the temperature level is above the comfort zone. In buildings, the tendency of humidity change is not as significant as air temperature; peoples’ sensitivity to humidity change within the range of 40% to 70% is negligible. This indicates that humidity does not receive much attention when air temperature, air speed, and radiant temperature are within the comfort zone. However, with increased temperature and metabolic rate of the human body, the effect of increased humidity on thermal comfort becomes more noticeable (Kong et al., 2019). Numerous researchers have shown that the skin’s humidity is a main cause of discomfort for human beings. The current ASHRAE standard 55 recommends decreasing the opportunity of discomfort resulting from low humidity by keeping the dew point temperature in occupied spaces above 3˚C (Berglund, 1998; Gagge, 1971; Berglund & Cunningham, 1986; Jing et al., 2013).

2.3.2.4 Air Speed.

Air speed has an influence on individual thermal comfort because it promotes heat loss through the process of convection. As air moves closer to the skin, it increases the evaporation. However, in circumstances where the air temperature is lower than the skin's temperature, air movement can result in additional heat loss through convection (Nicol, 1974 & 2008; Foruzanmehr, 2017). In hot/arid climatic regions, air movement has a great influence on thermal comfort of the human body. The impact of air movement in this climatic region has been projected to be equal to a 3˚Cdrop in temperature (Nicol, 2008; Foruzanmehr, 2017). Figure 2.15 illustrates the amount that air movement can offset the operative temperature (ISO 7730 Standard, 2005; Foruzanmehr, 2017). As demonstrated in figure 2.15, in a situation where air speed within a building is 0.2m/s or less, no offset will occur in operative temperature. However, in cases where air speed within a building is 0.3m/s or more, then operative temperature will offset up to 1.5°K. Notably, air movement, radiant heat, and relative humidity have effects on comfort level, but have no effects on the air temperature (Sassi, 2006; Foruzanmehr, 2017). Air speed is required to offset operative temperature; the horizontal dotted line in figure 2.5 signifies an air speed above which papers might be disturbed.

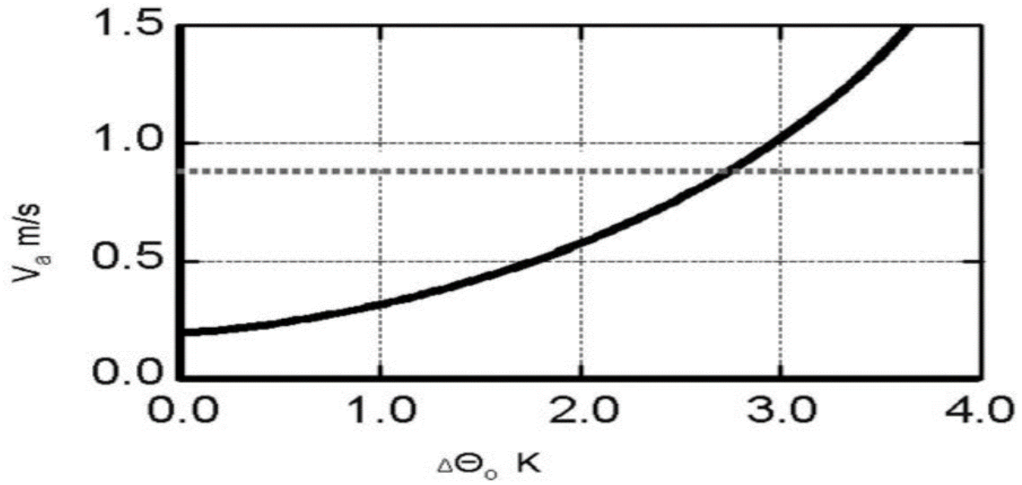


Figure 2. 5 Air speed influence on individual. Source: CEN Standard (EN15251)

2.3.3 Health and Comfort in Buildings

Buildings play a vital role in human health issues. The most essential characteristics of a healthy building is to provide an optimal healthy interior environment for inhabitants. Naturally ventilated buildings are considered the most suitable for human beings from a human health point of view. Most airborne allergens and infection diseases are linked with poor indoor air quality of buildings (URL.2). According to Health Optimization Protocol for energy-efficient building (HOPE). A healthy building is “the one that does not aggravate or cause illness to its own occupants. Grants high thermal comfort levels to its own occupants in performance of their normal daily activates for which the building was designed to host, and minimizes the use of industrial heating, ventilation, and cooling (HVAC) systems” (Roulet et al., 2006). This means that building users’ comfort can be achieved by creating a static, ideal thermal environment (Looman, 2017). In this research, thermal comfort is addressed for both occupant well-being and energy efficiency, but more emphasis is laid on energy saving issues.

2.3.3.1 Occupant Well-being

The World Health Organization’s (WHO) definition for health now includes more than the mere absence of illness; it has been extended to include a state of complete physical, mental, and social well-being (URL.3). Nowadays, the meaning of human health has changed and become more complex than ever. It includes the interrelationship between psychology, social life, and health. The manner in which an individual lives and interacts in society can be viewed as part of the definition of health alongside biological and physiological symptoms; therefore, heath is no longer merely having access to medication but related to the quality the buildings (URL.4).

Research shows that there is complexity in the relationship between human well-being and a building’s interior air quality. Factors such as thermal, visual, and chemical issues of building interiors can negatively affect building users’ well-being (Arif et al., 2016). These relationships are complicated and multidimensional and invariably have long-term and short-term effects on individuals (Babisch, 2008; Fisk et al., 2006; Lewtas, 2007; Arif et al., 2016). Major cases of indoor pollutant concentrations result from the use of newly invented materials which are not properly tested and closing building fenestrations for the purposes of saving energy but causing poor air exchange. As these factors continue to exist in buildings, they eventually lead to sick-building syndrome (Edwards et al. 2001; Helmis et al., 2009). The term, sick-building syndrome, become popular in the 1970s to describe a state in which the building inhabitants experience severe health problems or symptoms which are triggered when people stay longer in a particular building (Babatsikou, 2011).

Users’ health indicates that building design is a significant issue in providing heathy interior living environment. Although healthy environments can be realized through various healthy architectural design strategies, contaminants still causing symptoms should be adequately tackled. In the case of the city of Khartoum, where sand-dust storm particles are the major cause of respiratory diseases, this work is poised to find a solution (Osman & Sevinc, 2019).

2.3.3.2 Metabolism and the Thermal Balance of the Human Body

Metabolism can be defined as a process performed by the human body, which entails transformation of chemical substances to grow and respond to its environment. Generally, metabolism comprises two stages. The first stage is catabolism in which a human body gathers the necessary nutrition from foods and beverages. The second stage is anabolism that is derived from the Greek *ana*, which means up. The process involves a build-up and breakdown of substances into usable forms of energy (Looman, 2017). The body releases, transfers, stores, or utilizes the energy produced during metabolism. The energy converted through this process is invariably less than half that needed for work; therefore, it is transferred to heat energy and increases body temperature (Ji et al., 2018). The human body has tools to regulate its own thermal balance. To what extent the human body's regulatory system can work is influenced by factors such as body heath, shape, age, and gender. As well, there are personal factors (clothing and adaptive behaviour) which function alongside the environmental factors (temperature, humidity, and wind speed) to influence thermal comfort. These environmental factors are very essential for building designers to be aware of because they have enormous impacts on building design criteria (Looman, 2017).

2.3.3.3 Adaptive Thermal Comfort Approach

Thermal comfort depends wholly on environmental, physical, physiological, and psychological factors. People living in same environment might have different thermal sensations (Nematchoua et al., 2018). Thermal comfort is relatively complex and differs according to the subject (CIBSE & CIBSE guide A, 1999). Though various standards have been established about comfort levels, researchers are still in debate (Yau, 2008). Currently, scientists are concentrating more on energy efficiency issues in buildings (Nematchoua, Tchinda, & Orosa, 2014). Thermal comfort research is mostly conducted using two methods. The first method is rational in which thermal comfort strive for describing the response of people to the thermal environment in terms of the physics and physiology of heat transfer. The shortcoming of the rational indices approach, when it is used for field surveys, is that they involve knowledge of clothing insulation and metabolic rate which might be difficult to estimate and they are not accurate in predicting the comfort vote (Humphreys & Nicol, 2002). The second method is based on standards such as ISO7730 and ASHRAE 55 (ISO 7730, 2005 & ASHRAE 55, 2004). Considering the adaptive comfort model approach, whenever human's thermal comfort sensation is altered or changed, they react in a manner to restore their comfort. This approach links field surveys performed in a wide range of environments, hence supporting the comfort survey criteria of Humphreys (1976, 1978), Auliciems and deDear (1986), and deDear and Brager (1998) (Humphreys and Nicol 2002).

The adaptive comfort model is used in naturally-ventilated buildings where neither air-conditioning nor mechanical ventilation systems are used. This model is expressed by Humphrey and Nicol's (1998) principles which said, "if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort." This model assumes that a person is not just a passive receiver of thermal sensations but actively participates in restoring personal thermal equilibrium by adjusting clothing and/or opening or closing windows (Humphrey & Nicol, 1998). The type of adaptive comfort model is defined in ASHRAE 55-2010. The model assumes that the indoor temperature will be favourable when the average outdoor temperature is in the range of 23.3 to 33.5°C and the indoor temperature can be held within a specified 10 degrees. Therefore, thermal comfort is invariably dependent on outdoor climatic conditions (URL.5).

2.4 Climate Control Strategies for Buildings

Increasing fossil fuel burning and removal of plant cover contributes to great extent to increasing greenhouse gases. In particular, carbon dioxide (CO2), methane (CH4), and nitrogen dioxide (N2O) have caused global temperature increases. Which in turn led to climate change. The main features of climate change includes increases in average global temperature – which is called global warming, variations in precipitation, melting of ice caps, increases in ocean temperatures, and increased ocean acidity which occurs when sea water absorbs heat and carbon dioxide from the atmosphere (URL.6). If appropriate environmental control strategies are not taken, climate change will certainly hinder development processes and compromise the safety and comfort of contemporary and future generations. Moreover, climate change effects may be more adverse in developing countries (Ashwill et al., 2011).

2.4.1 Climate Change

Human activities on the planet are projected to have increased the global temperature 1°C above pre-industrial levels, and it is expected to reach 1.5°C between the year 2030 and 2052 if appropriate environmental measures are not taken (URL.7). The reason behind the occurrence of climate changes is generally related to the increase of man’s intervention into the natural environment, particularly during the pre and post industrial revolution. During this period, humans are accountable for the production of large quantities of carbon dioxide emissions. These factors contributed to great extent in increasing the frequency of climate extreme events during recent decades (Alzahrani et al., 2018). Climate change has become a reality, and its risk to buildings and human life has become apparent.. For instance, the global temperature will increase the tendency of floods and dust-storms and other severe events of climate change (Midgley et al., 2005; Berz, 1997; Alzahrani et al., 2018). Tschakert et al. (2010) documented extreme climate impacts in Africa. They discussed mainly the drought incidents and they disregarded the several incidences of heavy rainfall which invariably resulted in tremendous damage to the built environment (Tschakert et al., 2010). The most important feature of the effects of global warming is that for a given change in global temperature, the regional changes can vary immensely. Consequently, a "moderate" global warming of about 2°C beyond the pre-industrial temperatures can lead to great changes in different climate subsystems and sensitive regions (Trenberth et al., 2007; Lorenz, 2012). In contemporary years, climate change imposes a tremendous danger to the built environments performance (Crawley, 2008). The exhaustion of energy resources and the danger of climate change necessitate adapting sustainable development in building industry through proper utilization of renewable energies and energy efficiency approaches (Robert & Kummert, 2012; Rubio-Bellido et al., 2015). This research work is poised to analyze the climate of the city of Khartoum, Sudan, to evaluate climate change and to provide design strategies that are adaptable to the contemporary climate and resilient for future climate.

Sudan, as is the case for most developing countries in Africa, is highly vulnerable to climate change and climate variability (Zakieldeen, 2009). Sudan is considered among countries with variable rainfall Africa (Zakieldeen, 2007; Zakieldeen, 2009). The city of Khartoum suffers considerably from greenhouse gases (GHGs). Recent temperature increases were attributed to GHG emissions. The first effort to analyze climate change for the entire country of Sudan was sponsored by the United Nations Framework Convention on Climate Change (UNFCCC). UNFCCC revealed that there will be increases in average temperature, between 1.5°C - 3.1°C during August (Wet Season), and between 1°C and 1.1°C during January (Dry Season) by 2060. Moreover, a 6 mm reduction in rainfall during the Wet Season in the city of Khartoum is expected. Hazard and vulnerability assessments carried out in 2007 predicted that the city of Khartoum will be exposed to risky weather events because of climate change (URL.8). Figure 2.6 shows climate change progressions, indices, and dangers.

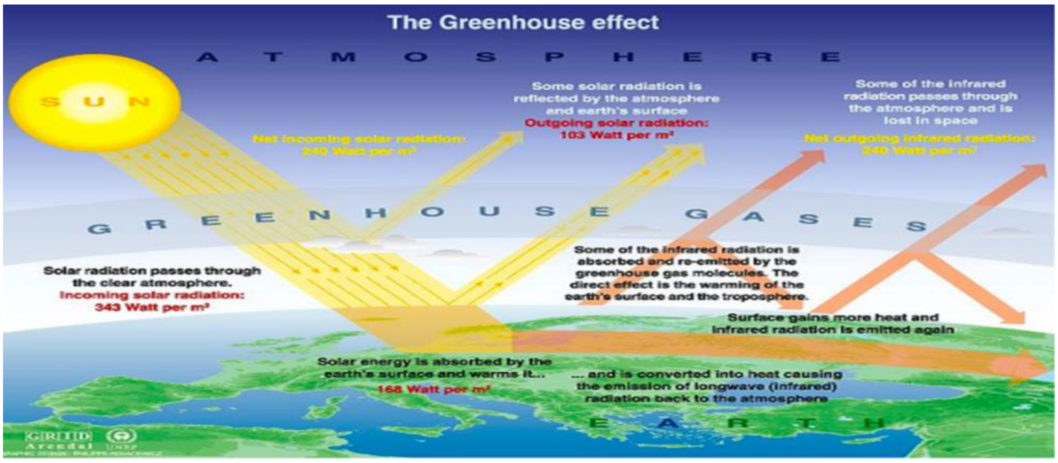


Figure 2. 6: climate change progressions, indices, and dangers
(Source: Zakieldeen, 2009)

Sudan is considered one of the countries with high vulnerability to climate change. This was confirmed by IPCC's 4th assessment report of 2007, which also revealed that Sudan is the most susceptible country among all African countries to climate change. The United Nations Environment Programme's (UNEP) 2007 report demonstrated that there have been shifts of 50km to 200km of the semi-desert and desert boundary southward since 1930. Furthermore, this boundary shift is expected to continue to move southward until 2050 because of the drought in the entire region (Sayed and Abdala, 2010).

2.4.2 Effects of Climate Change on the Environment

2.4.2.1 Temperature Increase

Researchers have proved that the Earth's surface temperature has risen by approximately 0.8^{o}C since the 19th century. Similarly, the recent increases in greenhouse gases emissions resulted from rising demand on fossil fuels consumption which is one of the genuine reasons for global warming. However, natural factors such as volcanoes and changes in solar irradiance may be contributing factors to this dilemma (Ring et al., 2012).

Comprehensive studies of global climate in the previous 15 decades revealed that the world had witnessed climate change in two subsequent phases in 1919 and 1940; during this period of time, an average temperature rise of about 0.35°C was observed. The second phase is from 1970 until today; this period exhibits a temperature rise of 0.55°C. Moreover, records demonstrate that the previous 25 years are considered the warmest time of the previous five centuries. Global warming has caused warming of the oceans, rising of sea levels, melting of glaciers, and reduced snow cover in the northern hemisphere. The recent climatic disasters such as heavy floods in Pakistan and India, Hurricane Katrina in the United States, and prolonged droughts in Australia, China, Pakistan, India, and Texas, USA, are all attributed to global warming. The 21st century has witnessed numerous extreme climatic events. These destructive climatic events are expected to continue in the future if appropriate measures to mitigate global warming are not adopted (URL.9). Figure 2.7 shows the annual global surface temperature from1880 to 2014 which indicate that global warming have happened and will continue unless serious measures are taken.

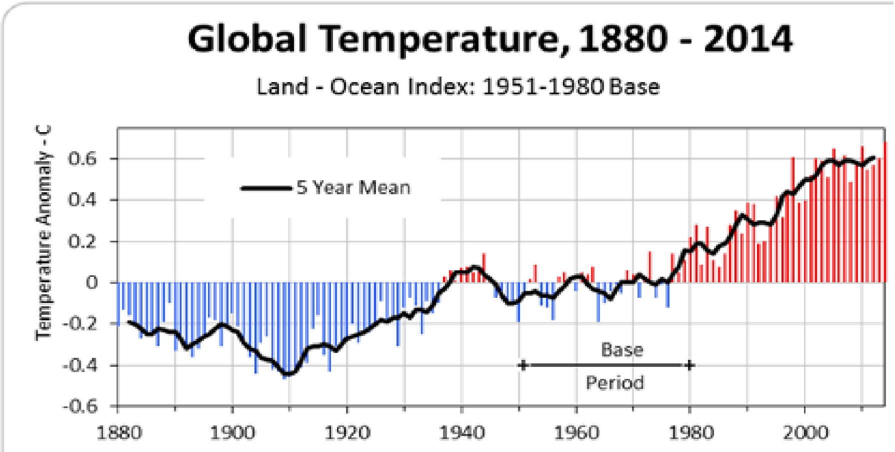


Figure 2.7: Global Temperature, 1880-2014.
Source: Goddard Institute for Space Studies (GISS) and Climate Research Unit (CRU).

Sudan, as an example of most developing countries of the world, is subjected to climate change. This is expressed in the United Nations Environment Programme (UNEP) report. Sayed and Abdala (2010) advocated that a trends analysis of temperature of the city of Khartoum, Sudan, between 1901 and 2009 revealed increases in temperatures. Figure 2.8 shows the trend of increase in temperature for the city of Khartoum of Sudan from 1901 to 2009.This in line with this research work, which hypothesis to analysis trend variation of Khartoum city climatic data.

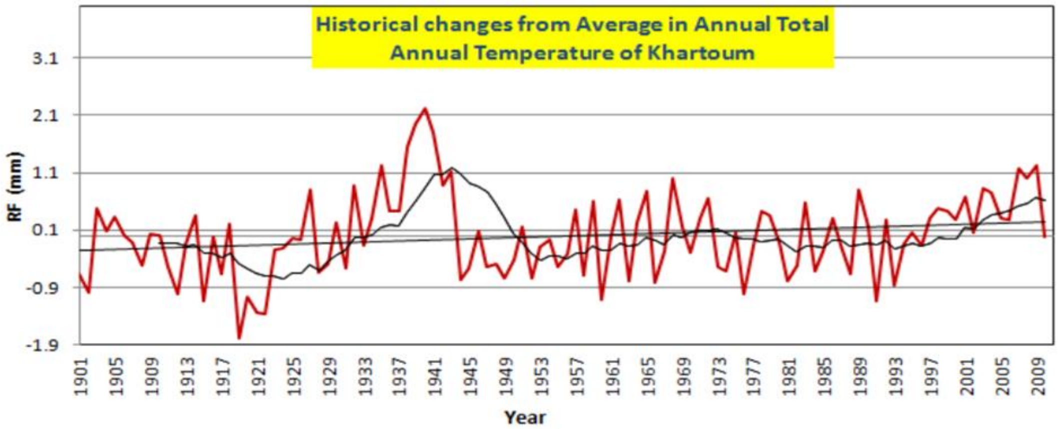


Figure 2.8: Historical changes in temperature of the city of Khartoum Meteorological Station. (Source: Sayed and Abdala 2010).

2.4.2.2 Raising Sea Level

Discussing the effects of climate change on the sea is a very important since it has been estimated that by the year 2100 the mean sea level is expected to rise only 0.1m lower if the global temperature increases only by 1.5°C instead of 2°C. However, sea level will continue to rise until 2100 and the amount and rate of rise is governed by the future emissions scenario (URL.7). The rising sea level effects are observed as increased occurrences of heavy storms. If carbon dioxide and greenhouse gases continue to increase in their contemporary phase, sea level may be projected to rise from more than 0.5m to up to 1m by the year 2100. It is uncertain to predict the manner in which to predict the manner in which sea rising will happen in the future. Recent satellite data shows that global sea level is rising in the last two decades by 3.2cm per year and the overall observed rise since 1901 is estimated to be up to 20cm (Cicerone & Nurse, 2014). Figure 2.9 shows global average sea level rise since 19th century.

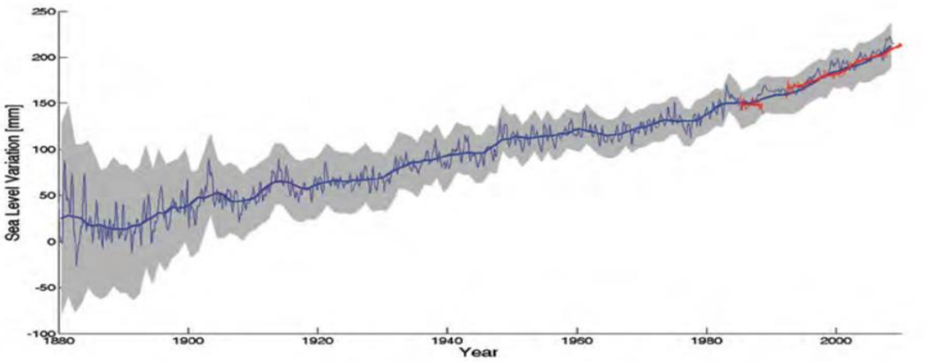


Figure 2. 9: Global average sea level rise in 19th century. Source: (Cicerone & Nurse, 2014).

2.4.2.3 Wind and Storm

Climate researchers predict that wind speeds, extreme rainfall incidents, and intense local storms will generally increase all over the world if appropriate mitigation measures are not taken. The major concerns with tornados and tropical storms are the impacts of extreme winds, dust storms, coastal storm surges, and heavy rain. For these reasons, it is necessary for architects to design their buildings in ways that reduce wind loads on new buildings by adapting more aerodynamically efficient structures, like for example, curved corners and reduced roof eaves. However, these design strategies should be adapted and balanced with a need to protect buildings in circumstances of severe flood and controlling solar radiation (Sanders & Phillipson 2003; Snow & Prasad, 2011). Majority parts of Sudan have been experiencing numerous sand-dust storm events throughout the year. Because the Sahara Desert has covered part of the country, it is considered a major source of dust in the region. Sudan experiences massive dust storms that at times lead in to reduction of visibility. These storms are locally called *Haboob*. The city of Khartoum witnessed severe sand-dust storm events in the years 2007 and 2009, which completely disturbed movement in the city and resulted in many traffic accidents and the cancellation of flights (Sayed & Abdala, 2010). Figure 2.10 is provided by the World Meteorological Organization, the graph provide information about global atmospheric sand-dust storms distribution in order give researchers’ idea about sand-dust storm movement pattern.

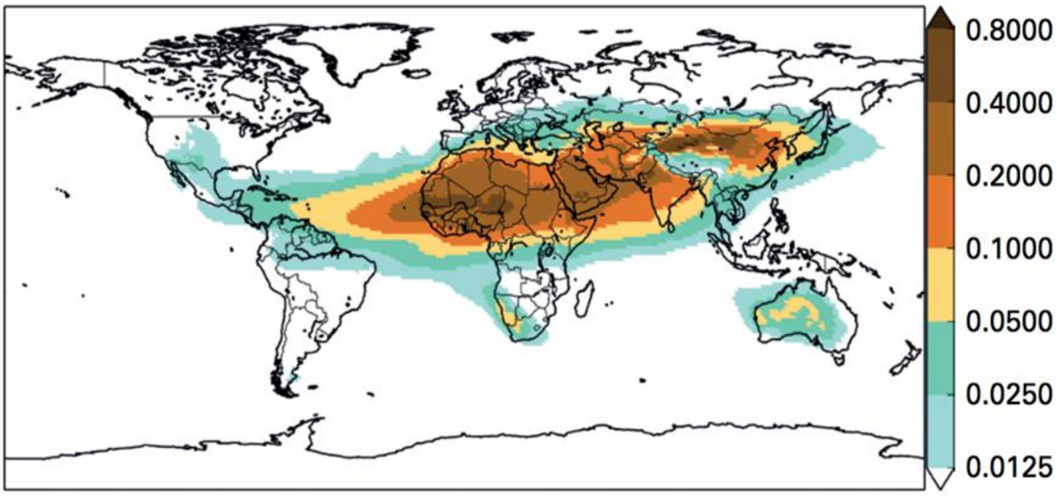


Figure 2.10: Annual mean distribution of dust aerosol optical depth (AOD) in 2016 (Source: World Meteorological Organization).

Figure 2.11 shows pictures of typical sand-dust storms in the city of Khartoum, Sudan. The frequency of sand-dust storm events is more than ever. This may be a result of climate change that occurred in the city of Khartoum (Osman & Sevinç, 2019). This research, in response to these sand-dust storms, proposes adaptive solutions at building scale.

Figure 2.11: A typical event of sand-dust storm in the city of Khartoum (Source: Osman & Sevinç, 2019).

2.4.2.4 Drought and Precipitation

Researchers have advocated that most of the recent and more frequent incidences of climate extremes in previous decades can be attributed to climate change. However, most general circulation models predict a noticeable change in precipitation (Loukas et al., 2008). The movement of water into the atmosphere from the Earth (from evaporation from water bodies and transpiration from plants) is due to temperature increases and is expected to lead to increased drought in dry areas. In drier regions, evapotranspiration may produce periods of drought (URL.10). Drought is defined in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) as "a prolonged absence or marked deficiency of precipitation', a 'deficiency of precipitation that results in water shortage for some activity or for some group' or a 'period of abnormally dry weather sufficiently prolonged for the lack of precipitation to cause a serious hydrological imbalance'' (Trenberth et al., 2014). Drought extremes and frequency is projected to increase in the future due to climate change, which will lead to a general reduction in regional precipitation and an increase in evaporation. Previous evaluations of historical changes in drought toward the end of the 20st century and the beginning of the 21st century reveal that drought may be happening globally (Sheffield et al., 2012). Figure 2.12: shows twelve-month running-mean time series of precipitation rate (mm/day) of the world cotenants (North America, South America, Europe, Africa, Asia and Australia) from January 1979 to May 2017.

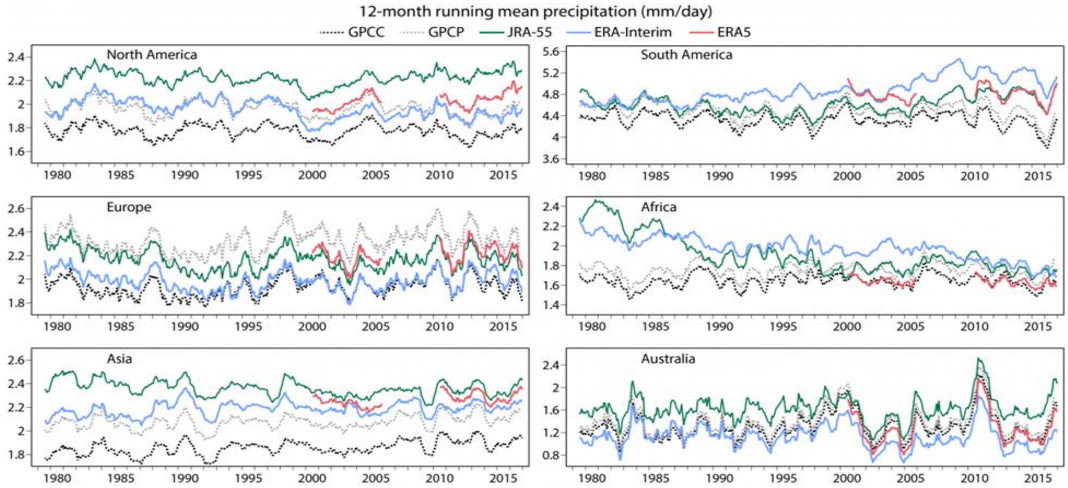


Figure 2.12: Precipitation rate (mm/day) of the world six continents (Source: Sheffield et al., 2012).

Figure 2.13 illustrates decreased trends in the city of Khartoum rainfall between the years 1900 and 2002. Even though general decreases in rainfall were observed during this time period, the years such as the early 1920s, 1993, the mid-1960s, and 1988 witnessed excessive increases in rainfall, which resulted in great damage to some parts of the city of Khartoum. However, this reveals uncertainty of rainfall, the city has witnessed excessive flood in recent years, and 1988 flood was the most notable one. Therefore, designers should take persuasions to avoid this. In otherward, this figure provide a good theoretical frame work for this research.

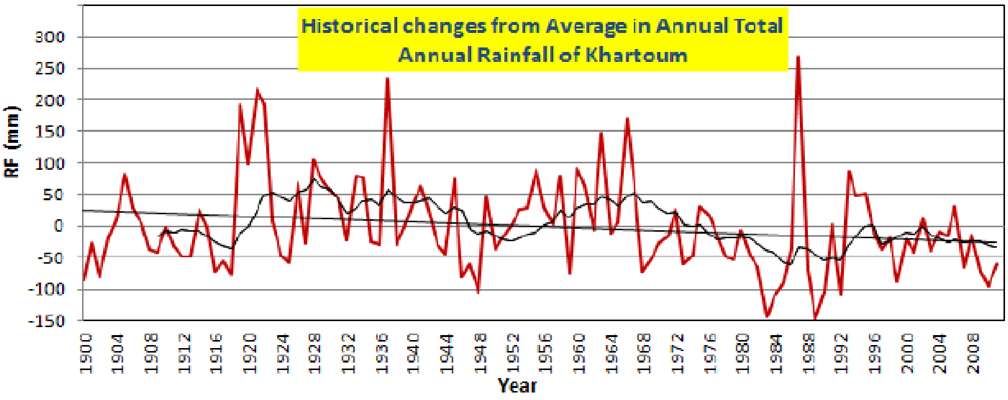


Figure 2.13: Historical changes in total annual rainfall of the city of Khartoum (Source: Sayed and Abdala 2010).

2.4.3 Effects of Climate Change on Hot/Arid Climate Zone Buildings

Climate has a great influence on man’s life in urban areas. Buildings are highly affected by climate change. This research addresses the climate challenges which both contemporary and future buildings in hot/arid climatic regions will face. Climate change indices that affect a building occupants’ thermal comfort should be addressed before the beginning of the building design process. These indices include temperature rise, drought, sea temperature rise, sand-dust storms, higher wind speeds, and increased precipitation (El Basyouni, 2017). Climate change imposes greater responsibilities on architects and planners of the built environment. It is essential to take into consideration the minute temperature increases that may be in some instances outside the normal range and can increase hazards dramatically, such as the strength of storms, wind movements, and floods (Snow & Prasad, 2011). Adaptation of building design strategies to climate change entails controlling and handling the effects of unavoidable extreme climate events. Although the climate researchers are arguing about the extent of adaptation needed, there is increasing consciousness that the design profession is required to consider predictions about the uncertainty of extreme climate events. This necessitates increased resilience by using appropriate and sustainable building materials and design strategies’ (Stephen S. Szoke et al., 2014; El Basyouni, 2017).

Research work conducted in hot/arid climates has revealed a rising trend of temperatures and summer discomfort in previous years and it was disclosed that the predicted temperature increase could lead to escalation of cooling load for achieving thermal comfort (Lam et al., 2008; Lam et al., 2010; Li et al., 2012). Electricity is generally used for air conditioning and will lead to excessive emissions, in turn damaging the ozone layer and causing more climate change (Kahrl & Roland-Holst, 2009; Li et al., 2012). Most buildings in hot/arid climates are susceptible to excessive climate and extreme incidents, such as increased precipitation, melting snow, more frequent fire events, severe storms, and floods. In order to mitigate such hazardous events, resilient design strategies should be appropriately adopted. The challenges the construction sector encounters in hot climates include:

1. Excessive precipitation could extend construction duration which leads to increased costs.
2. Global warming hazards change the length of building seasons.
3. Extreme climate events necessitate more frequent maintenance of buildings.
4. Increased heat fluctuation events have the consequences that building design shifts away from contemporary architectural design pattern towards new design approach which might increase the building's cost.
5. Temperature rise will put more pressure on energy demand. For instance in poor developing countries, as the climate gets hotter increased fortune will be the motivating factor of increased energy consumption, particularly for air conditioning. Without adopting mitigation strategies, the world energy demand for air-conditioning systems is predicted to increase from approximately 300TWh in the year 2000 up to 4000TWh in the year 2050 (Chalmers, 2014).

2.5 The Renewable Energy Potential Used in the Built Environment

Nowadays, buildings depend on energy to provide the required comfort for occupants. Energy is used as a substantial primary and secondary source for heating, cooling, and ventilation of buildings. Energy is also a secondary source for operating buildings and it is used for hot water supply and vertical transportation systems. The building's energy consumption depends on its construction and operational systems. During prehistory, man exhibited much evidence of climate-responsive design strategies when fossil fuels were not even available. In many parts of the world, ancient man was able to provide a design that utilized available local materials in a manner to gain maximum benefit from the local surroundings (Baird, 2017). Improving building occupants' indoor air quality and thermal comfort in buildings, and reducing carbon dioxide emissions from buildings during their life cycle requires appropriate climatic design strategies that consider a building's local climate. Much effort has been done globally to reduce energy consumption in buildings. The American Institute of Architecture (AIA) and the United States federal government formed year 2030 challenges and passed the energy independence and security law that stressed that by the year 2030 all newly constructed buildings should be net-zero energy (Street, 2013). According to UN reports for the year 2011, it is expected that by the year 2030 nearly 60% of the world population will be living in cities; therefore, most building construction is expected to take place in urban centres (URL.11). The bioclimatic design approach, as a determinant of design criteria for urban buildings, is essential to tackle the escalated demands of dwellings that would accommodate tremendous population influxes (Street, 2013). Nowadays, the world energy supply depends primarily on fossil fuels which cannot meet the total demand of the built environment (Cullen & Allwood, 2010; Broersma, 2013). Realizing built environment energy demand can be through appropriate design that considers local and regional renewable energy sources. This can be achieved through smart design strategies that make appropriate use of local renewable potentials (MacKay, 2008; Broersma, 2013).

2.5.1 The Climate Elements Considered in Building Design

The building site's accessibility to climate resources is influenced by its location. The quantity and quality of resources the building can benefit from to achieve thermal balance for its occupants depends on the adopted building design strategies. Climatic elements that are available in nature include air, geothermal energy from the earth, and sun location in the atmosphere, sky cover, solar radiation intensity, wind pattern, humidity, vegetative cover, and water bodies (Looman, 2017).

2.5.1.1 Sun and Sky

It has been estimated that 99.8% of the earth energy comes from the sun (Dickinson & Cheremisino, 1980). Solar energy is obtained from direct solar radiation and indirect solar radiation (Dickinson, 2018). Solar radiation comprises two basic components: direct radiation that directly reaches the ground without any obstacles and indirect radiation that reaches the ground after several reflections. Figure 2.14 represents energy balance of the earth's atmosphere under the influence of solar radiation.

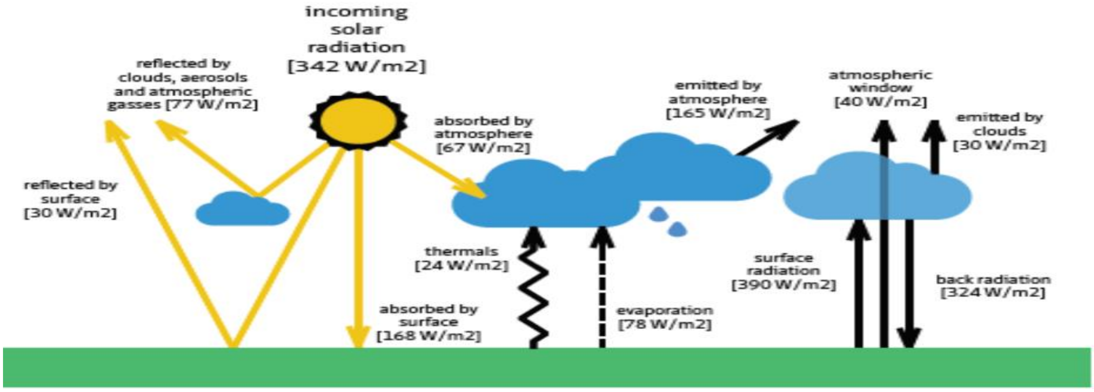


Figure 2.14: Energy balance mechanism of the earth's atmosphere (Source: Cherri, 2015).

Solar radiation is a renewable energy source of heat and light and a determining factor in enhancing indoor built environment sustainability. A buildings' accessibility to solar radiation is determined by the status of active and passive solar potential for buildings. In some circumstances, the insulation of building openings affects their use and designated activities. Solar goals are numerous and may be depending on the time of day and seasons according to thermal comfort requirements. This is especially true in tropical climates (Chatzipoulka, 2017). Because of energy crisis during the 1970s, much attention was paid to energy saving in buildings. Appropriate design and use of solar energy help in conserving energy and in improving human health and thermal comfort. Understanding the characteristics of solar radiation is essential for building designers to make rational use of solar radiation and reduce energy consumption in buildings. Sky luminance distribution is essential for describing sky types and calculating daylighting performance. Sky luminance distribution varies with the time of the day and depends on weather conditions such as sun position and availability and distribution of clouds (Luo et al., 2015). The quantity of global solar radiation on a specific place on earth varies according to factors such as sun position in the sky. When the sun's latitude angle is high, the solar radiation's distance to earth becomes shorter; hence solar radiation's occurrence of reflection is reduced. Consequently, solar radiation intensity of the location on earth increases. This indicates that maximum global solar intensity is achieved in areas closer to equator. When further from the equator, the travel distance of solar radiation increases during the year due to the earth's orbit around the sun and its axial tilt. This phenomenon causes seasonal variations of climate (Looman, 2017).

2.5.1.1.1 Global Radiation

Global radiation refers to the quantity of solar radiation that passes through the atmosphere and falls on earth. During this process, it loses part of its radiation through absorption, diffusion, and reflection. The absorption happened by ozone, atmospheric water vapor, clouds, and oxygen. The reflection results from clouds that play a principal role in the reduction of solar energy received by the earth (Exell, 2000; Poudyal et al., 2012). However, global solar radiation is one of the important climatic element for building design (El-Sebaii & Trabea, 2005; Sukhera & Pasha, 1987; Poudyal et al., 2012).

2.5.1.1.2 Solar Geometry

Thermal climatic design of buildings depends solely on the sun as a main influencing factor. Solar radiation penetration through building openings provides desirable warm effects during the winter season. However, if the building's form and openings are not appropriately oriented and sized it could lead to excessive overheating in the summer season. Therefore, assessment of its utilization and control is a vital strategy for design to be sustainable and thermally comfortable for building users (Szokolay, 1996). Solar architecture is the most effective design strategy for gaining and preserving energy in buildings (Schittich, 2003).

To monitor the sun angle and how it moves in the sky it is very important to take information about sun altitude and azimuth angles. Altitude angle β, as in figure 2.15, is the angular distance above the horizon measured perpendicular to the horizon. It reaches its peak when the solar radiation is at 90° to ground surfaces. Azimuth angle α , is the angular distance measured along the horizon in the clockwise direction. It begins at zero degrees and increases clockwise (Mumtahana et al., 2016). Figure 2.15 gives an illustration of the sun's path in the sky. It is very important for designers to properly understand sun movement in the sky for them to appropriately orient buildings in relation to sun movement.

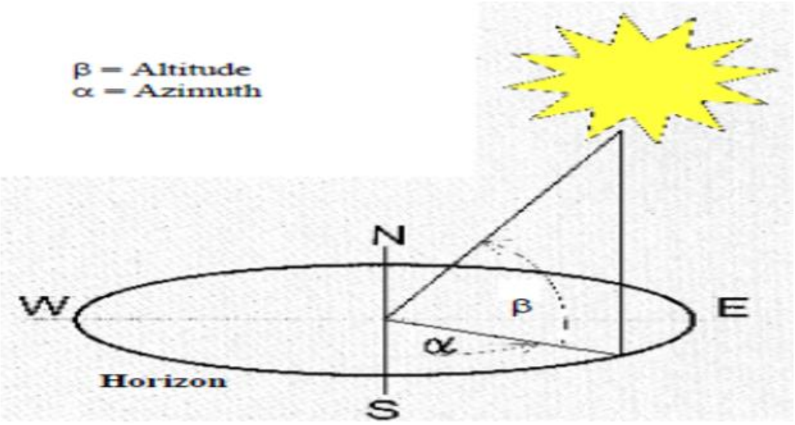


Figure 2.15: Sun motion in the. (Source: Mumtahana et al, 2016).

Figure 2.16 illustrates this phenomenon. On 21 December, the winter sun's altitude angle is at its lowest point; this is called the winter solstice. In summer, on 21 June, the sun's attitude angle is at its highest position; this is called the summer solstice. The equinoxes are situated half way between the solstices and when the sun is at an equinox, the day is the advent of the spring or fall season (URL.12).

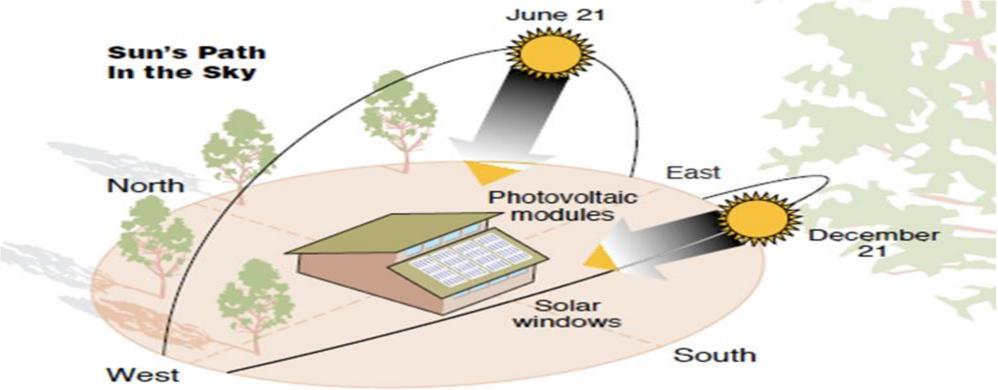


Figure 2.16 summer and winter solstice. (Source: Mumtahana et al, 2016).

2.5.1.1.3 Sunshine Duration

Sunshine duration, or solar shine duration (SSD), is a vital climatic parameter has been used for centuries and it has been used in many disciplines such as tourism, public health, agriculture, and solar energy (Kothe et al., 2017). Knowing the availability and variation of solar radiation energy is very important for researches in atmospheric modelling and climate studies. Much research has been done in recent decades on solar shine duration (SSD) in different climatic regions of the world either with clear sky conditions or after the removal of cloud effects (Founda et al., 2014). There is a noticeable relationship between sky cloudiness and SSD because higher cloud intensity reduces SSD. However, air pollution, emissions coming from industrial sites, other sources of SSD reduction include increased may also contribute in reducing SSD.

Sand-dust storm, industrial pollutants and cloud reduced SSD this reduction effect will be clearer in winter season (Matuszko, 2012). Solar altitude, angle variations during the year, global climate irregularities, topography, and atmospheric weather conditions such as air pollutants affect SSD reaching the earth. These invariably accounted for inconsistency of SSD in short periods of time (Fernandez et al., 2018). Long-term trend analyses for a period of 50 years was done for SSD, total cloud cover (TCC), and low cloud cover (LCC) in China for 618 meteorological stations. The result revealed a significant decrease in the trends of SSD and TCC, while LCC exhibited a significant level of 95% (Xia, 2010). This indicates that climate change has a great influence on SSD quantity and quality. As for the city of Khartoum, Sudan, it receives about 8.7 hours per day of sunlight in July and 10.5 hours in February. This averages to about 9.92 hours per day of sunlight and approximately 3600 hours per year (Widatalla & Zinko, 2011).

2.5.1.1.4 Sky Cover

Sky cover, also known as cloud cover, is the most complex metrological parameter because it is difficult to evaluate and ambiguously defined (Gerth, 2013). According to Arking (1964), the debate over sky cover started after the first satellites were launched. Sky cover can be defined as the percentage of opaque clouds to the area of clear sky during a period of one hour. Moreover, area of sky or sky view is usually defined as the part of sky that is visible to an observer when standing in a particular location (Gerth, 2013). For a designer to utilize daylight appropriately in building design to save energy, it is important to consider sky cover. In order for the designer to realize energy efficient design it is essential to comprehend the potential extremes of sky conditions from clear sky to overcast sky. Clear sky is the sky condition when there are no clouds that hinder solar radiation from reaching the ground. Overcast sky is the condition when a thick layer of clouds completely covers the sky and prevents radiation from reaching the earth. All radiation is diffused in the latter condition and it is invariably difficult to determine the sun’s location. The figure 2.17 below shows the difference between clear sky, overcast sky and illustrate the horizon and zenith to the right.

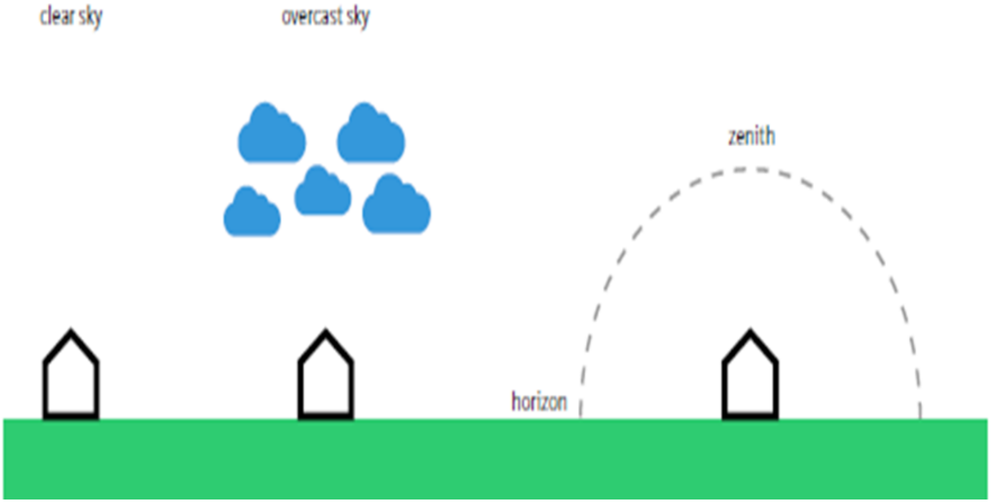
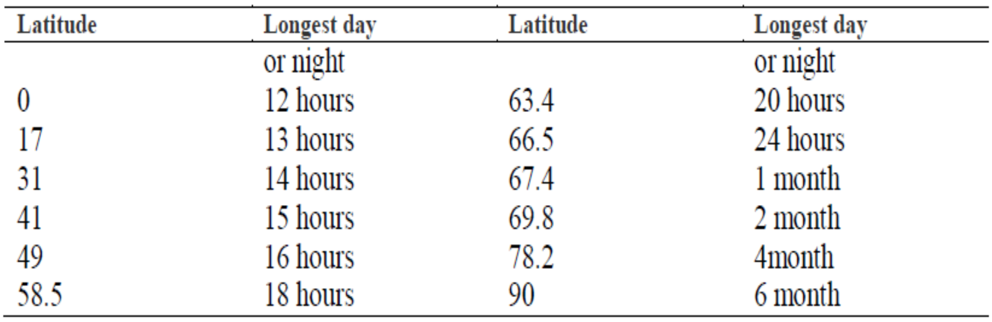


Figure 2.17: Difference between clear sky & overcast sky
(Source: Looman, 2017).

The length of the day is determined by sunshine duration, which also contributes to the quantity of solar energy the earth's surface received. Solar latitudes also have great control over SSD since this controls the length of the day. Earth's angular rotation on its axis and its revolution around the sun brings about day/night and seasonal variations. At the equator, the length of the day is 12 hours; therefore, it has the potential to receive the greatest amount of solar radiation. A location's length of day reduces the further it is from the equator (URL.13). Table 2.5 shows monthly variations in length of day according to the latitude.

Table 2.5: Length of monthly variations in length of days according to latitude.



Latitude	Longest day or night	Latitude	Longest day or night
0	12 hours	63.4	20 hours
17	13 hours	66.5	24 hours
31	14 hours	67.4	1 month
41	15 hours	69.8	2 month
49	16 hours	78.2	4month
58.5	18 hours	90	6 month

2.5.1.1.5 Ambient Temperature

Large cities experience high temperature fluctuations resulting from paved surfaces, lack of trees, and heat released from large concrete buildings. Plant cover in urban areas helps in reducing ambient temperature and urban heat island effects through the process of providing shade and evapotranspiration. These can reduce the energy needed for cooling and heating buildings (Yousif & Tahir, 2013). Utilization of plants' cooling effects has been mentioned in a lot of research (Nowak et al., 2002). Nowak (1995) enumerated that planting deciduous trees outside the north and east façades of buildings in the southern hemisphere or the south and west façades in the northern hemisphere provides cooling effects in the summer season and warms buildings in winter (Yousif & Tahir, 2013). The temperature of the troposphere closer to earth's surface is heated by solar radiation absorbed, reflected, or diffused from the sun (Looman, 2017). Shakurov et al. advocated that soil temperature where covered with grass in the city of Khartoum, Sudan, is 15-20°C lower than uncovered loamy soils and paved areas. Until now, there is not any evidence that shows the impacts of the White Nile and Blue Nile Rivers on ambient temperatures in the city of Khartoum (Shakurov et al., 2016).

2.5.1.1.6 Solar Energy Potential Estimation in a Built Environment

Sudan is one of the promising countries that have great potential for solar energy technology. Sudan is blessed with solar insolation of 6.1 kWh/m^2.With radiation reaching horizontal surfaces ranges from 4.9 to 6.7 KWh/m^2/day. The total potential over a year has been estimated to be 10.1 GJ/m^2 . Furthermore, Sudan is characterized by having abundant land and low cloud cover most of the year; this makes it possible to generate appreciable amounts of energy from photovoltaic systems. Another advantage is the minimum of 8.5 sunshine hours are received daily in the city of Khartoum (Al-Haj & Sopian, 2018). Figure 2.28 shows monthly global and diffuse solar radiation in the capital Khartoum. Figure 2.29 shows the average number of annual sunshine hours calculated by Meteonorm7.0. Photovoltaic technology, despite its viability in Sudan, still faces some challenges such as dust storm that reduce photovoltaic (PV) efficiency. Similarly, high temperatures also causes decrease the efficiency of PV modules and increase radiation thermal losses (Al-Haj & Sopian, 2018).

2.5.1.2 Energy Potential Estimation of Wind Energy in A built Environment

Wind energy can be one of sustainable means for enhancing indoor thermal comfort. This can be achieved by directly using the prevailing winds to ventilate buildings or by harvesting renewable energy through the use of wind turbines. The latter has become common nowadays. In order to make maximum use of wind energy, appropriate knowledge of wind movement patterns in the designated area is very important.

Utilization of wind energy dates back to many years ago in Sudan. Wind has been used as a source of energy in rural areas for water pumps, corn grinding, and small industries (Omer, 2002). Sudan is blessed with abundant renewable wind energy of approximately 5m/s in 50% of the country that can be utilized to generate electricity (Omer, 2000).

2.5.1.2.1 Natural Ventilation Potential

Natural ventilation is one of the most efficient strategies in providing cooling and ventilation for the built environment. Appropriately, natural design provides amicable and healthy indoor living condition for building occupants and subsequently reduces the money used for active cooling (Yu et al., 2015). Natural ventilation denotes the mechanism of air exchange between indoor and outdoor environments. This mechanism depends on wind effects, thermal buoyancy, or both (Cheng & Bahnfleth, 2016). Natural ventilation that occurs because of temperature differences is called stack effect. This ventilation plays a vital role as it increases natural ventilation vertically through buildings. A good ventilation strategy is an atrium. Used in large-scale buildings, atriums have high ceilings coupled with operable openings and function like solar chimneys (Yu et al., 2017). Despite the fact that stack effect is a means of providing thermal comfort via natural ventilation, it has disadvantages (Lovatt & Wilson, 1995). These may be malfunctioning lifts doors or aggravating noise emanating from lift’s halls (Tamura, 1994; Klote; Evans, 2007; Yu et al., 2017).

To solve the problems associated with stack effects when it rises in a high-rise open plan office, for instance, the highest-pressure differences across the lift doors are usually measured at the first floor and the last floor as in figure 2.18. In situations where the upper floors of the offices are pressurized by HVAC systems then the wind floor rate from the lift to the building spaces on the upper floors will be decreased. Therefore, the wind flow rate from the lobby space of the first floor to the lift shaft would eventually reduce as in figure 2.19 (ASHRAE Standard, 2009; Yu et al., 2017).

Figure 2.18: Highest-pressure differences measurement
(Source: Looman, 2017)

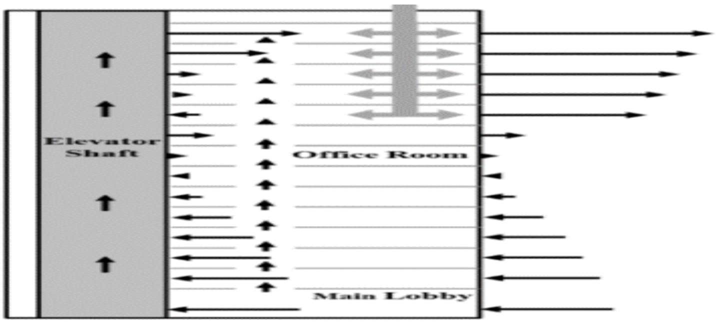


Figure 2.19: Wind flow rate from the lobby space
(Source: Looman, 2017).

Wind-driven ventilation uses external wind and thermal buoyancy as a driver to admit fresh, cool air to the indoor environment (Wang et al., 2014; Yang & Li, 2015;

Prueksakorn et al., 2015). In order to take maximum advantage of these driving forces, building openings should be appropriately sized, shaped, and oriented (Evola & Popov, 2006; Kim et al., 2007; Prueksakorn et al., 2015). It is essential for these ventilation devices to provide the required indoor thermal comfort level for building users without any need for mechanical systems. It is generally difficult and more complex to design a naturally ventilated building than to design a mechanically ventilated system for the same building (Fontanini et al., 2013; Prueksakorn et al., 2017). Optimal ventilated building design involves intervention of researchers who have knowledge of climate, topography, orientation, and environmental impact assessments (Kleiven, 2003; Prueksakorn et al., 2015). Designers should consider factors that affect energy saving potential by natural ventilation strategies such as orientation, location, form, and building envelope from preliminary design stage (Jin et al., 2012; Mora-Pérez et al., 2016).

Wind towers are another sustainable cooling strategy that is very popular in the history of the Middle East. It was used in combination with courtyards and atriums. It uses the principles of wind-driven and stack effect ventilation. The wind enters into the tower of the building creating positive pressure on the windward side and negative pressure on the leeward side. This pressure difference pushes inside air to exit and replaces it with fresh cool air from outside; the cycle becomes continuous (Lien & Ahmed, 2011). Figure 2.20 illustrates wind tower utilization in hot/arid climates.

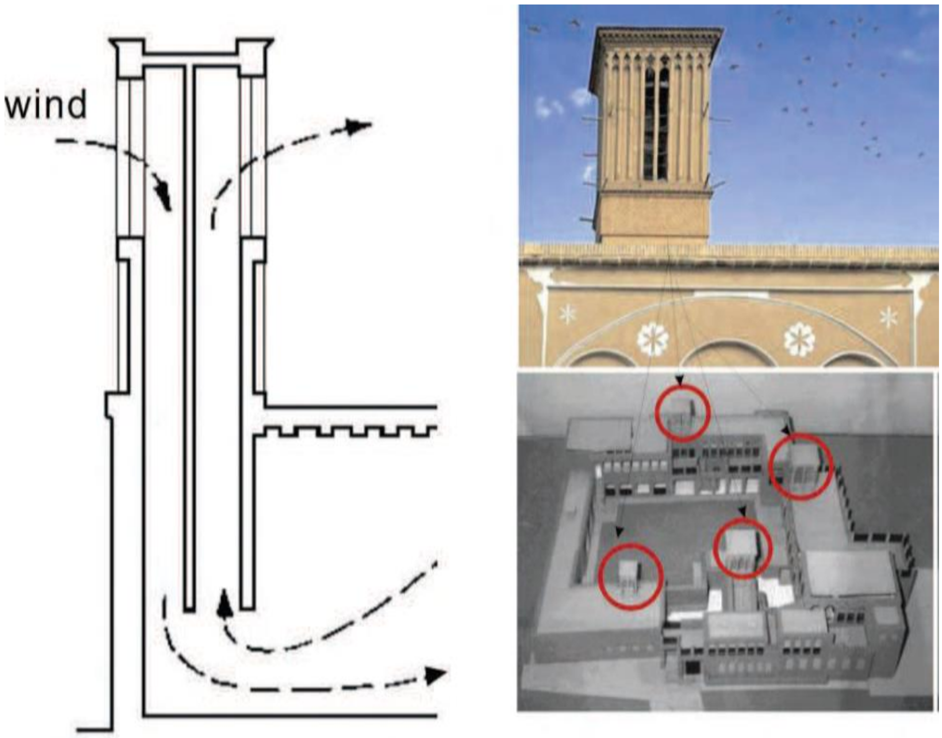


Figure 2.20: Wind tower design in Middle Eastern building
(Source: adapted from Lien & Ahmed, 2011).

2.5.1.2.2 Cooling Potential of Outdoor Air

Ambient temperature in the city of Khartoum, Sudan, is higher than thermal comfort most of the time since the Hot Season (March - May) and the Wet Season (June - October) last so long. The high temperatures are accompanied by high solar radiation and sand-dust storms, which have become a normal phenomenon in the city because of climate change. In addition, climate analysis conducted in this research work proved that natural ventilation is not applicable in most months of the year except during the nights of the Wet Season. Night ventilation is an effective cooling strategy in the Hot and Wet Seasons of the city of Khartoum. It is possible to improve outdoor temperatures by utilizing appropriate landscaping. Because the phenomenon of sand-dust storm has become more frequent than ever, there is a need to plant a buffer zone around the city of Khartoum to intercept the excessive storms that blow in from the greater desert in Dry Season. The ambient temperature is within the comfort zone during the daytime in the Dry Season (November-February) and below the comfort level at night. With appropriate passive solar design strategies, the ambient temperature can be improved. As buildings in the city centre absorb much solar heat radiation during the daytime, this releases at night. Then the city's ambient temperature can be reduced through the mechanism of urban heat island effect.

2.5.1.3 Water

It has been estimated that about 70% of the earth is covered with water. Consequently, the entire climate is deeply affected by water in all forms. Most of what appears as climate (rain, vapour, humidity, and snow) is highly dependent on water. This phenomenon is called the hydrologic cycle and it is defined as the migration of water particles from the earth's surface to the atmosphere and back again. During this process, the water frequently transforms between different states (solid, liquid, and gas) and between different locations on earth (ocean, atmosphere, and land) (Berlatsky, 2011). Water is a source of energy and it could be utilized to achieve a sustainable built environment (Rendall, 2017). Water evaporates from ocean and land surface into the stratosphere, where it is diverted across the earth's surface in the form of water vapour. Water vapour condensates to form clouds, rain, snow, or other forms of precipitation that fall back to the ground. This precipitation falls on water bodies, is taken up and transpired by plants all over the earth, and become surface runoff and/or recharges groundwater. Groundwater infiltrates deep into the ground and some parts combine with saline ground water in coastal areas. In this last stage, water returns back to the ocean from where it will eventually evaporate again, finishing the hydrologic cycle (Pagano & Sorooshian, 2002). Figures 2.21 illustrate the hydrologic cycle phenomenon.

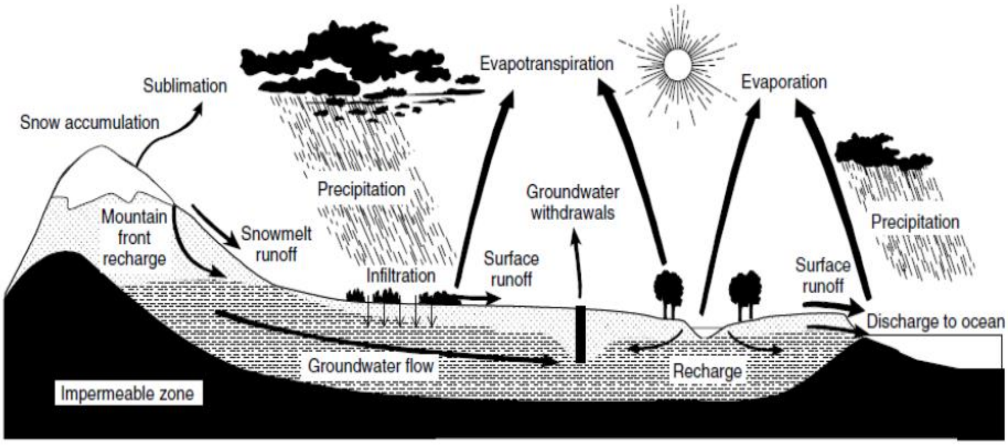


Figure 2.21: Hydrologic cycle phenomenon.
(Source: Pagano & Sorooshian, 2002).

2.5.1.4 Precipitation and Evaporation

Precipitation is the term described in climate science as rainfall, snowfall, and any other frozen or liquid falling from clouds. It differs from year to year and over decades, and varies in quantity, intensity, occurrence, and types. It effects the environment and people. Moderate rainfall is more beneficial because it penetrates into soil and provides better irrigation to plants. Heavy rain that falls within short periods causes floods and can cause soil erosion and damage to plants. Heavy rains can result in dry soils after short periods (Trenberth, 2011). Precipitation is an important climate element, which could be enhanced through appropriate landscaping (Collins & Avissar, 1994).The characteristic of arid climates such as the city of Khartoum is, low relative humidity and less rainfall, in this climate the ability of soil to absorb water is significant. The city of Khartoum soil is characterized as being tenacious clay and has the characteristics of supporting less trees and bushes than silts and finer sand soil types with same rainfall quantities. Evaporation is high in the city of Khartoum because of uninterrupted solar radiation, high wind movement, low relative humidity, and high soil temperature (Oliver, 1965). Many studies were conducted since 1940s on the analysis of annual and daily rainfall for central Sudan. These studies utilized various techniques in order to arrive at accurate outcomes. However, the obtained results indicated that there was a decrease in the amount of rainfall resulting in the existence of distinct wet and dry sequences (Elagib, 2010). The city of Khartoum, Sudan, experiences an average of 10 hrs of sunshine per day, solar radiation of 3.05-7.62 kWh/m2/day, and an average temperature of 32 to 40 ^{O}C. These climatic conditions promote the evaporation phenomenon (Abdelmajeed et al., 2009).

2.5.1.5 Surface Water and Ground Water

Water surface temperature behaves the same as soil surface temperature and can vary extremely according to daily and seasonal time scales and owing to atmospheric conditions and hydrological factors (Bolduc, 2015). The thermal capacity of water is higher than that of soil because solar radiation increases water temperature more slowly and evaporation occurs on water surfaces which in turn reduce the air temperature. These evaporative cooling effects can be utilized for cooling buildings (Looman, 2017).

The incidents of global warming, which have become more profound than ever before, necessitate utilization of renewable energy sources. Groundwater is viewed as a sustainable energy source (Arola, 2015). The utilization of groundwater for heating and cooling of buildings in China, North America, and Europe is well known in the past (Banks, 2009; Ferguson and Woodbury, 2005; Banks, 2012; Arola, 2015). A groundwater cooling system needs the presence of an aquifer from which water can be removed through a borehole. As illustrated in figure 2.22, cold water is extracted from the borehole at a temperature of 6-12°C and then piped through a heat exchanger to cool the building. The subsequent heated water is discharged into the aquifer through a hot borehole. In areas where the water table is close to the earth's surface, the resultant hot water can be reused as gray water or discharged into the sewer (ADe Saulles, 2004; Ampofo et al., 2006).

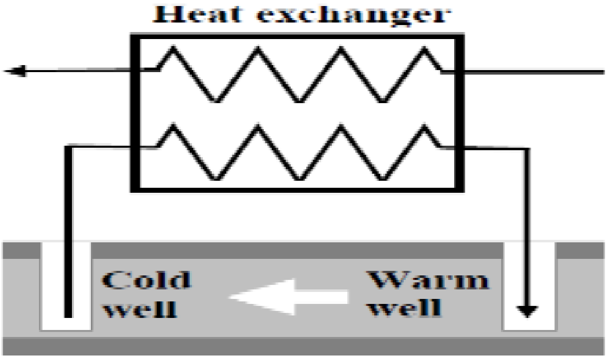


Figure 2.22: Ground water for cooling
(Source: Ampofo et al, 2006)

2.5.1.6 Water in an Urban Context

Urban surface-water bodies have a great influence on the climate of the built environment; therefore, they are considered very essential components of the urban centre environment (Yang et al., 2018). In urban areas, water bodies greatly enhance microclimates of the surroundings with appreciable cooling effects. They facilitate evaporative cooling. Evaporative cooling is considered one of the most efficient cooling strategies that can be used in hot/arid climates. Research has proved that water bodies are one of the most significant methods of reducing a city's temperature. Water can reduce urban temperatures by approximately 2 to 6°C (Manteghi, et al., 2015). In many cities, water plays a vital role in people's daily lives, especially in cities situated near rivers, seas, oceans, and lakes. Xu et al (2009) conducted research on the effect of water on thermal comfort in cities that experienced summer-day temperatures of more than 35C°. Their results demonstrated that water contributed heavily to cooling cities. Concurrently, a modelling research work was done by Robitu et al (2006) that proposed that some small water ponds have appreciable cooling effects on their surrounding environments. Moreover, research work on the cooling influence of water holding pavement proved a temperature reduction of several degrees (Theeuwes et al., 2013; Nakayma & Fujita, 2010; Manteghi, et al., 2015).

2.6 Climate-Responsive Building Design Considerations for Hot/Arid Climatic Region

Climate change has become one of the main concerns of most building designers nowadays due to the ethical issues associated with the concept of sustainability and the need for providing uncompromised living facilities for the future generation. This necessitates the need for adapting climate-responsive design strategies through appropriate utilization of renewable technologies for passive cooling of buildings. Certainly, building space cooling has intensely increased energy consumption and creates a vicious cycle, being, at the same time, a reason for and an effect of the anthropogenic overheating of the Earth (Ascione, 2017). In less developed countries located in hot/arid climates, excessive heat events create problems in cities because of buildings' heat retention, especially in situations where building ventilation for cooling at night is inappropriate (Weihe, 1984; Akande, 2010). Nowadays, many designers are shifting their focus toward adapting sustainability in design and construction through the use of passive and low energy strategies. The intention is to achieve optimal thermal comfort especially in hot/arid climatic regions (Akande, 2010).

Approximately a quarter of the planet is estimated to be located in hot/arid areas mostly between 50°N and 50°S, but mainly found in the 15-30° latitude in both the southern and northern hemispheres. Daytime temperatures ranging between 40 and

45°C are common. During the night, temperature may drop as low as the freezing point. It should be noted that not all hot/arid zones are continuously hot. For instance, the Gobi Desert located in central Asia experiences hot summers but has a very cold winters with temperature as low as -30°C. Cold/arid zones exist in the polar climatic region of the Arctic and Antarctic (Ashrafian et al., 2011). Variations in desert climatic regions are independent of factors such as proximity to coast and geographical location. However, there are a major difference in temperature, humidity, and wind speed in summer and winter during the course of the day and season (Hausladen et al., 2013). The amount of solar radiation received in hot/arid climates is considered to be the highest. The quantity of solar radiation reaching the ground depends on the climate of the lower layers of the atmosphere as well as the presence of clouds and earth surface characteristics, such as albedo, emissivity, temperature, humidity and thermal properties of the underlying soil (Santillán-Soto et al., 2015). In hot/arid climates such as the city of Khartoum, high cooling load is required for building users to achieve thermal comfort. Evaporation level is very high in hot/arid areas except for areas close to coastal areas. In such areas, dehumidification is strongly recommended to achieve thermal comfort.

2.6.1 Heat Loss Promotion Techniques

In order to design a climate-responsive building in hot/arid climates, the following criteria should be adapted. Heat loss promotion techniques could be achieved through evaporative cooling, natural ventilation, solar chimneys, and wind towers.

2.6.1.1 Evaporative Cooling

Cooling is highly required in hot/arid climatic zones to achieve thermal comfort, especially in the summer. Evaporative cooling is one of the most favourable sustainable cooling strategies, which have incredible advantages, such as easy to construct, low initial and maintenance costs, and high-energy efficiency. Evaporative cooling serves as a basis for simple air-conditioning systems, and it is suitable in hot regions characterized as having low humidity levels. Basically, evaporative cooling can be divided into two types: direct and indirect. In both types, the minimum temperature at which air can be cooled is the wet-bulb temperature of the inlet air (Jain, 2008; Qureshi & Zubair, 2006). Building protection from excessive heat is one of the most challenging processes in cooling strategies. It requires utilization of evaporative cooling pads, misting, or fogging systems together with mechanical ventilation. However, in hot/arid climatic regions such as that of the city of Khartoum, Sudan, evaporative cooling is considered the best and most energy efficient and economical strategy to use over conventional air-conditioning systems (Alodan & Al-Faraj, 2005; Abbouda & Almuhanna, 2012).

2.6.1.1.1 Direct-Evaporative Cooling

Direct evaporative cooling is the process of converting sensible heat into latent heat. The non-saturated air is cooled through heat and mass transfer with a fan that blows air through a liquid’s surface. Some of the sensible heat is absorbed by the liquid and becomes latent heat when some of the water evaporates. The latent heat flows with the water vapour and is liberated into the air (Brown & Watt, 1997; Camargo et al., 2005). Figure 2.23 shows a diagram on how direct evaporative cooling systems work. In direct evaporative cooling, the heat and mass transferred between water and air reduces the air-dry bulb temperature (DBT) and increases its humidity, keeping the enthalpy level constant (Camargo et al., 2005).

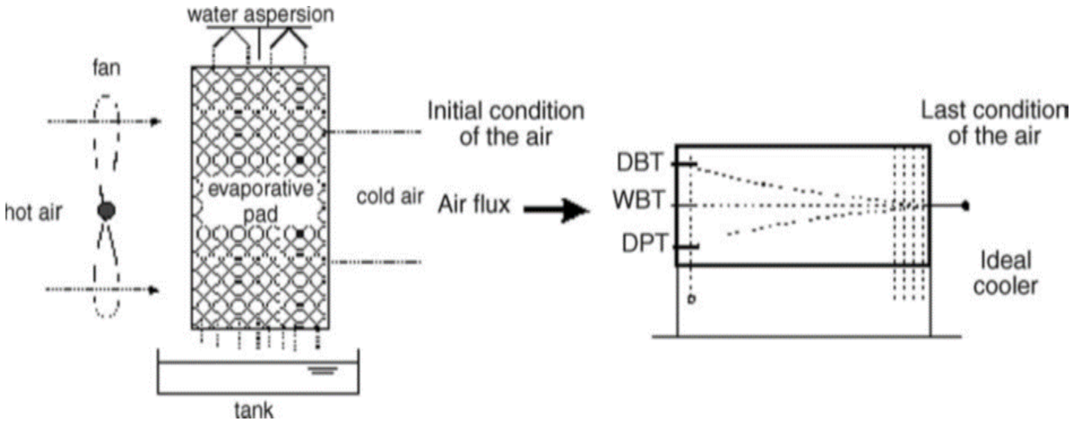


Figure 2.23: Direct evaporative cooling (DEC).
(Source: Camargo et al, 2005).

2.6.1.1.2 Indirect Evaporative Cooling (IEC)

Alternatively, indirect evaporative cooling (IEC) is another sustainable cooling method that has a bright future. It can provide a low cost and energy efficient cooling system. The system comprises two separate air passages. In the primary passage, the airflow from outside is sensibly cooled without adding water to it. Secondary air and water flow concurrently together. The secondary passage surfaces are wetted with a water sprayer, and in this way, the water film will evaporate into the secondary air, making the passage surface temperatures drop. Cold surfaces extract the heat from the outdoor air as it passes through the primary passage. Subsequently, the air leaving the primary passages has lower WBT and DBT than it had when entering (Alonso et al., 1998; Erens, 1993; Farmahini-Farahani et al., 2012). Figure 2.24 illustrates how indirect evaporative cooling operates.

Figure 2.24: Indirect evaporative cooler
Source: Alonso et al., 1998).

2.6.1.1.3 Two-Stage Evaporative Cooling

Two-stage evaporative cooling, also known as indirect-direct evaporative cooling, is introduced as an improvement over the previous direct and indirect evaporative cooling. It has numerous advantages over the previously mentioned ones, most especially in hot/arid climatic regions. Two-stage evaporative cooling comprises indirect evaporative cooling in stage one, which provides pre-cooled air to the direct evaporative cooling system in stage two (Sharag-Eldin, 1988). The ASHRAE Standard revealed that two-stage evaporative cooling could use between 60% and 70% less power than a normal air conditioning system. This makes two-stage evaporative cooling an effective and sustainable energy efficient cooling strategy. The success of this cooling strategy is influenced by the depression that occurs between wet bulb temperature and dry bulb temperature (Ambade, 2015). Figure 2.25 shows how two-stage evaporative cooling operates.

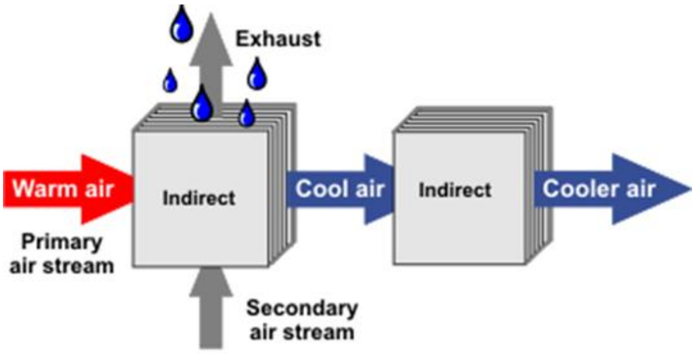


Figure 2.25: Two-Stage Evaporative Cooling
(Source: Ambade, 2015).

Hot/arid climatic zones are characterized as having low relative humidity; therefore, this cooling strategy is suitable for providing thermal comfort to building users. In order for this cooling strategy to function appropriately, 100% external air movement should be granted otherwise relative humidity may increase beyond the indoor comfort level. According to Sharag (1988), during the Hot Season, two-stage evaporative cooling strategy may reduce dry bulb temperature to $29^{O}C$ and increase relative humidity to 60%, provided that the air entering the building blends with the air already inside. The advantages of two-stage evaporative cooling are:

1. It is energy and cost-efficient and more appropriate in areas where direct evaporative cooling is insufficient.
2. It consumes half of the energy that an air conditioning system uses and its construction cost is low.
3. It provides better comfort than compressor-based systems; hence it can replace mechanical refrigeration cooling.
4. It provides 100% cooling with fresh air; therefore, internal air quality problems do not arise in such cases. This cooling strategy is designed for 25 to 40 air changes per hour which makes it similar to natural ventilation.
5. This cooling strategy uses refrigeration which makes it environmentally friendly.

The disadvantages of two-stage evaporative cooling are:

1. It is inefficient in coastal areas where relative humidity is high.
2. There is a significant temperature variation in the cooled space year round depending on the prevailing ambient dry and wet bulb temperatures (Ambade, 2015).
3. It requires frequent maintenance throughout the year.
4. The entire system fails in situations when there are water and power failures which are common in hot dry areas.

2.6.1.2 Natural Ventilation

Natural ventilation is the process of delivering fresh air to a building's indoor space in order to make comfortable and favourable indoor environment. This helps in saving energy. Normally, a naturally ventilated building is approximately 40% less cost that of an air-conditioned building (Guide, 1993; Castillo & Huelsz, 2017). Natural ventilation is achieved as a result of air pressure difference around buildings. Pressure differences promote air movement from higher-pressure zones to lower-pressure zones. Pressure difference occurrence attributes to wind or buoyancy force that result from the variation of air density at different temperatures. Ventilation uses outside or inside the building air, and can result from a temperature difference, stack effect, a solar chimney, wind towers, inside versus outside air movement, and cross ventilation (Aboul Naga, 1990). In hot/arid climatic zones, night ventilation is found to be most suitable cooling strategy for providing optimal thermal comfort conditions to building occupants. Because of the large temperature swings in this climate, the night cooling refreshes the building's indoor spaces. But, for hot and humid climates, a whole day of ventilation would be more efficient to stimulate indoor thermal comfort. Air movement speeds up sweat evaporation, cooling the building's occupants. That is why it is necessary to evaluate the building indoor natural ventilation in relation to thermal comfort of the users (Castillo & Huelsz, 2017).

In order to take maximum advantage of natural ventilation, designers are recommended to consider the following precautions:

- The longer part of the building should be oriented to take benefit of prevailing wind direction; the appropriate orientation is zero to 30 degrees, without losing any benefits of the cool breeze.

- Building orientation and opening sizes should be appropriately designed according to climate type. Daytime ventilation is important in hot/humid climates and nighttime ventilation is important in hot/dry climates which have significant differences between day and night temperatures.
- Raising a building's level exposes it to more winds.
- Hedges should be planted at distances of at least 8 meters from the building in order for them not to prevent windows from utilizing prevailing winds.
- Cross-ventilation can be promoted by limiting building depth to enable inward airflow from one facade and outward flow through another. Introducing architectural elements such as wing walls and parapets can promote cross-ventilation by creating negative and positive pressure zones.
- Large windows and doors can provide appropriate ventilation provided they are well protected from solar radiation.
- For appropriate ventilation, it is recommended to use nearly equal inlet and outlet openings.
- For rooms having only one wall exposed to the outside, it is more appropriate to provide two windows than a single one.
- A single-sided opening provides ventilation to a depth of between 6 and 7 meters. While cross-ventilation can provide up to 15m depth. However, a deeper space plan can be better ventilated with an atrium or chimney (Butera et al, 2015).

The factors that determine the way in which the building ventilation works are building form, building position, and location of openings. Building ventilation principles include single-sided ventilation, cross-ventilation, and stack effect ventilation (Kleiven, 2003).

2.6.1.2.1 Single Sided Ventilation

Single-sided ventilation depends on airflow through openings on only one side of an enclosed space. The air enters through one window and exits from the same window or from another window in the same wall, as demonstrated in the figure 2.26. In a situation where the room operates with a single-sided window ventilation principle, wind turbulence will be the only driving force. Therefore lower ventilation rates are created and the tendency of achieving efficient ventilation in the space is restricted. Stack effect ventilation can be used to improve the space ventilation by using two different windows at different heights. Stack effect ventilation can be further enhanced by separating the two windows in the horizontal dimension. Because of wind pressure differences created at the position of each window (URL.14), A single-sided corridor is another natural ventilation principle that is usually used in hospital buildings. In this system, the corridor is located on one side of the hospital ward figure 2.27. Airflow is in one direction from corridor to ward or from ward to corridor, according to prevailing wind direction. This ventilation system has the advantage of preventing cross-infections. Therefore, designer should be careful with the window design, sizing, and locations in order to address any cross-infection that might occur (Allard, 1998; Chartier & Pessoa-Silva, 2009).

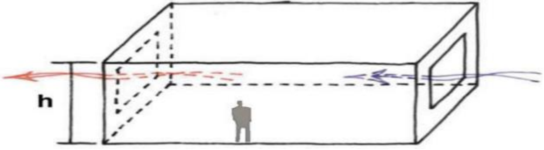


Figure 2.26: Single sided ventilation
(Source: (Allard, 1998).

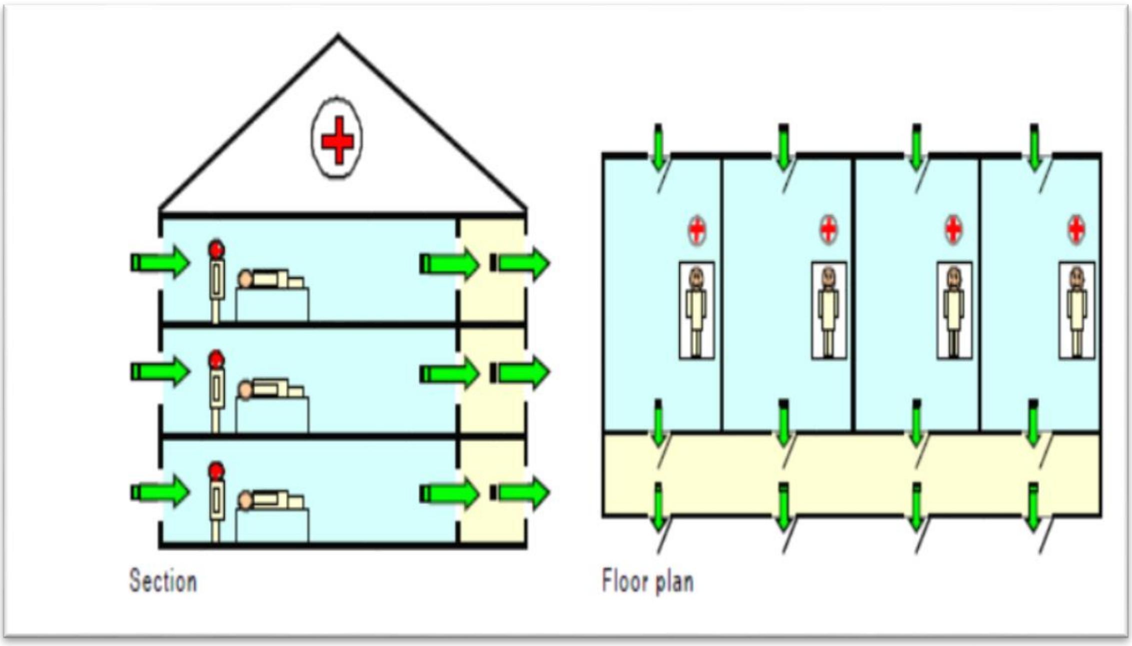


Figure 2.27: Wind-driven natural ventilation
(Source: Chartier & Pessoa-Silva, 2009).

2.6.1.2.2 Cross-Ventilation

Air movement results from pressure difference between indoors and outdoors in naturally ventilated buildings and the airflow is influenced by unstable parameters such as wind velocity and direction, turbulence characteristics in the wind, heat sources, solar radiation, and the form and location of windows (Liu et al., 2013). One of the most vital types of ventilation is cross-ventilation; it is defined as the situation whereby the air moves through two sides of the building façade because of wind-induced pressure differences between the two sides of the façade. The air penetrates and exits normally through windows or openings integrated in the building façades. Ventilation operates as the air flows from the windward side to the leeward side. Figure 2.28 is a typical cross-ventilation system where air moves through several rooms passing through doors or overflow grills. Cross-ventilation is also achieved in buildings when considering a single space where air penetrates from one side of the space and exits from the opposite side as in figure 2.29. In this circumstance the ventilation principle can be called cross-ventilation or stack effect ventilation. When the airflows across the space it picks up warm air. However, the effectiveness of this system is limited, since as space depth increases the cross-ventilation effectiveness decreases (Kleiven, 2003).

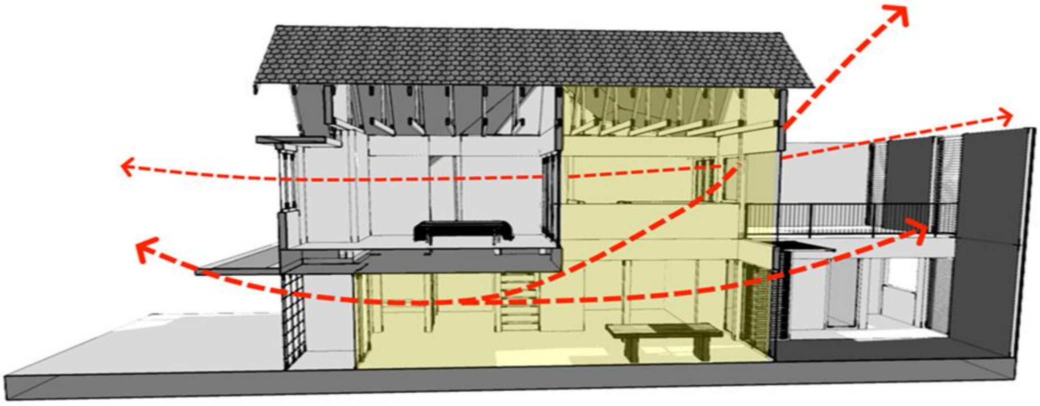


Figure 2.28: Typical cross-ventilation system.
(Source Liu et al., 2013).

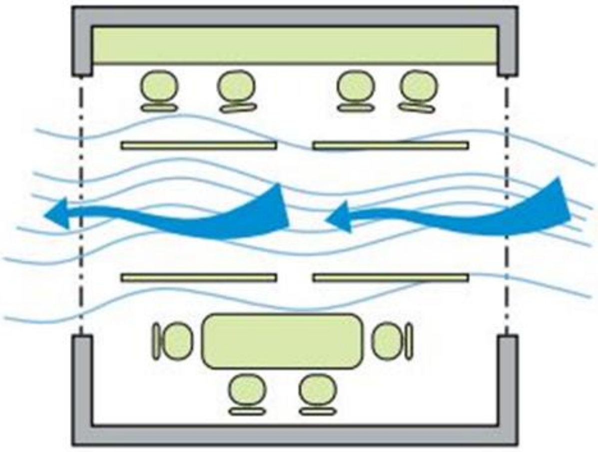


Figure 2.29: Cross-ventilation for a single space
(Sources: Kleiven, 2003)

2.6.1.2.3 Stack Effect Ventilation

The stack-effect ventilation occurs as the result of air density difference between indoors and outdoors, which are caused by temperature fluctuations. The direction and velocity of prevailing winds have a great impact on the efficiency of this ventilation principle. The most favourable circumstances in which this system operates efficiently are when a light air flows in a way that the exhausted air is drawn out through the outlets of ventilation openings or ducts. Fresh air moves through the inlet vents or opening inside the rooms, which increases the rate of air movement. This ventilation strategy is very suitable in hot/arid climatic zones where the humidity is low and the temperature difference between day and night is relatively high compare to other climatic zone (Gładyszewska & Gajewski, 2012). Figure 2.30 shows a diagram of stack-effect ventilation in a building.

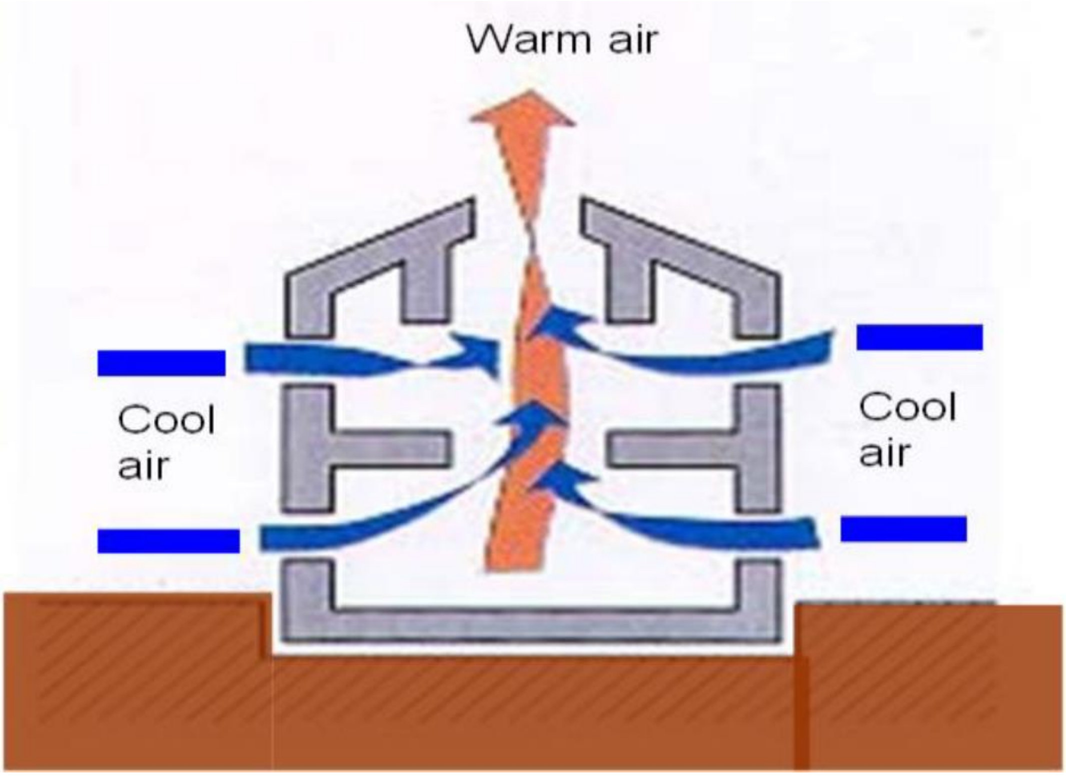


Figure 2.30: Stack Effect in a Two Storey House
(Source: Wahab & Ismail, 2012).

Since stack effect ventilation performance efficiency depends on the temperature difference between the indoor and outdoor environment, it is important for the building designer to understand clearly the characteristics of the climatic zones of the design.

For instance, hot/humid climates are characterized as having high temperature, high solar radiation intensity, high humidity levels, and much rainfall throughout the whole year. This necessitates insulating the indoors to provide adequate thermal comfort for building users. This can be achieved by using proper building materials coupled with good design. Maintaining lower building indoor temperatures compared to outdoor temperatures can promote the stack ventilation principle in buildings (Wahab & Ismail, 2012).

2.6.1.3 Wind Towers

Fossil fuel burning is one of the major sources of gas emissions. Active cooling systems consume significant amounts of a building's energy demand. The negative impact on the environment can be significantly reduced by utilization of sustainable and renewable ventilation and cooling strategies. Winds, being a renewable resource, can be appropriately used to provide adequate cool fresh air through adoption of wind towers, solar chimney, et cetera. Wind towers have been used for more than three thousand years to provide thermal comfort in the Persian Gulf and Middle East regions (Saadatian, Haw, Sopian, & Soulaiman, 2012; Abedini, 2014). Montazeri and Azizian defined wind tower "as a device which facilitates the effective use of natural ventilation in a wide range of buildings in order to increase the ventilation rates" (Fathy, 1986; Montazeri, 2011; Hughes et al., 2012). Wind towers project from the top of a building's roof. They have openings placed towards prevailing wind direction in order to catch warm air, cool it down, and pass it to a buildings indoor to provide thermal comfort for building users. The air moves through the tower to the building is as result of wind flowing or the temperature difference between indoor and outdoor. The wind blow creates positive pressure on the windward side and negative pressure on the other side of the wind tower. In windless areas the wind tower works as a chimney or stack effect; where by hot and less dense air rises and flows out from the wind tower opening (Ahmadikia, Moradi, & Hojjati, 2012; Abedini, 2014). The left part of figure 2.31 describe how wind towers work during the day and the right side of the figure represents how it operates at night. During the daytime, the prevailing wind is the driving engine of the entire system's operation because it creates a pressure difference between the inlet and outlet which promotes air movement between the inside and outside of the building the wind tower operation methods at night the outside, lower air temperature cools down the building's thermal mass; this provides additional cooling the next day (Hughes et al, 2012).

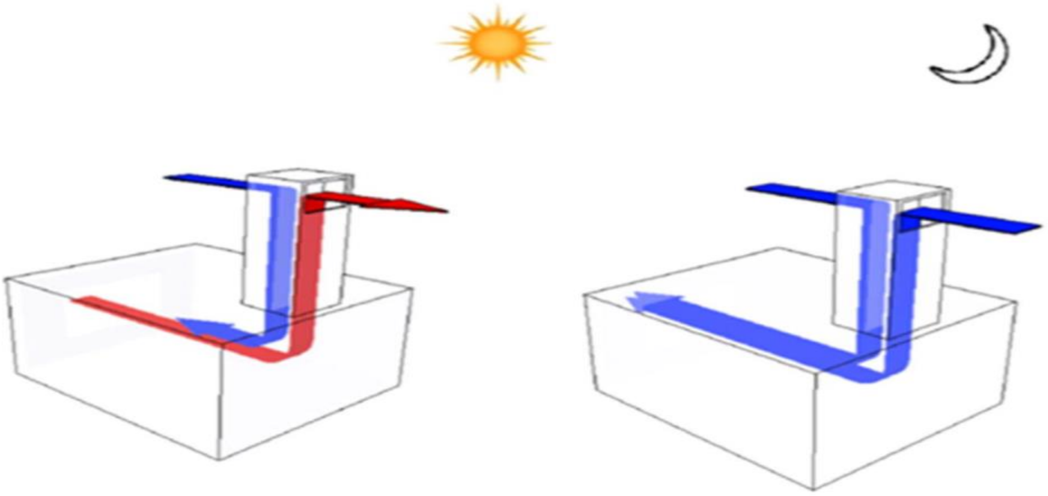


Figure 2.31. Left side represents day time operation and right side represents night time operation. (Source: Hughes et al, 2012)

2.6.1.4 Wind tower Cooling Techniques

2.6.1.4.1 Using Evaporative Strategy for Wind Tower

Due to some problems associated with traditional wind towers such as insect penetration and sand-dust storms, which have become more frequent than ever in hot/arid regions, researchers have made improvements on the old ones. The world trend of sustainable development also necessitated these improvements in order to save energy. Numerous scholars suggested new designs of wind towers for hot/arid zones to enhance the performance of traditional wind towers (Bahadori, 1985; Dehghani-Sanij et al., 2015; Khani et al., 2017). Bahadori presented two new models of wind towers, named “wind tower with wetted columns” and “wind tower with wetted surfaces.” These two new models have made tremendous improvements to the traditional wind tower.

2.6.1.4.2 Wind Tower with Wetted Columns

Wind towers with wetted columns are a building cooling strategy that has thick curtains or clay conduits installed inside the wind tower column. Water is sprayed on the clay screen or conduit in order to moisten them. The water that is being sprayed is collected at the bottom of the tower in a sink and recirculated by pumping it up. The hot air from outside that flows through the wetted column is cooled by evaporative cooling process. Ultimately, the cooled and moistened air with lowered temperature is delivered indoors through the tower’s outlet (Bahadori et al., 2014; Bahadori, 1985; Bahadori & Pakzad, 2002; Bahadori et al., 2008; Khani et al., 2017). This cooling strategy is suitable in hot/arid climatic zones because the humidity level is very low and the sand-dust storm problem is also well addressed. The fear of discomfort as a result of high humidity and dust does not arise here. Figure 2.32 illustrates how wind towers with wetted columns operate.

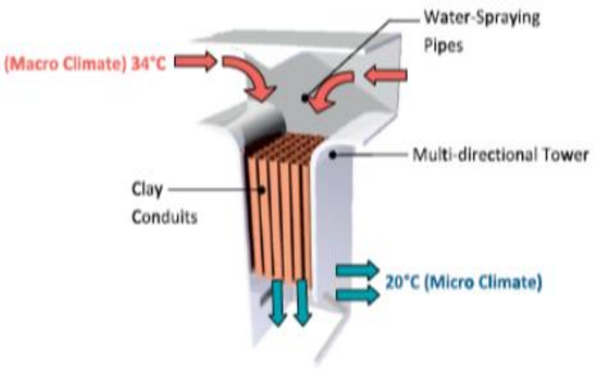


Figure 2.32: Wind tower integrated with wetted column
(Source: Hughes et al, 2012).

2.6.1.4.3 Wind Tower with Wetted Surfaces

The operation system of wind towers with wetted surfaces is the same as that of wetted columns. At the inlet opening of each wind tower, wetted cooling pads are placed so that passing air induces evaporation. The pads can be rewetted intermittently or at scheduled intervals by spraying water from an outlet at the top of the tower. This type of cooling system is most efficient and predominantly employable in arid regions that frequently have winds of sufficient speed. Figure 5.33 shows the wetted surface wind tower operation system (Hughes et al., 2012). Bahadori (1994) conducted experimental research on wind-wetted surface wind towers equipped with evaporative cooling pads on the outside of the air inlet, the research revealed that the air entering the living space through the wetted surface of the tower has a temperature much lower than the air temperature exiting the traditional wind tower. This evaporative system is more suitable in hot/arid climatic zones that have less wind or are practically windless (Bahadori, 1994; Hughes et al., 2012).

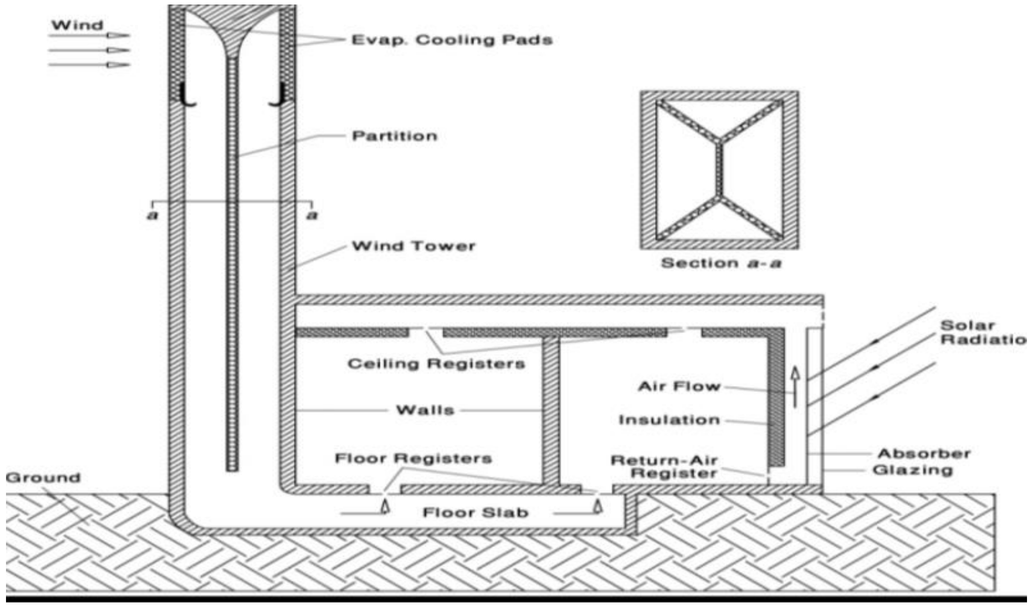


Figure 2.33: Cross-sectional view of a wind tower with wetted surfaces
(Source: Bahadori, 1988).

2.6.1.4.4 Solar Chimney Effects Ventilation

Solar chimney strategies have been used to promote the buoyancy effect in order to achieve adequate air movement rates to acceptable thermal comfort levels for indoor environments.

Numerous approaches have been suggested in the literature to boost the buoyancy effect for attaining suitable airflow rates and a desired level of thermal comfort for a building’s indoor spaces. Solar chimneys are a suitable example. They are designed to take full advantage of the ventilation effect while maximizing solar gain (Bansal et al., 1993; Khanal & Lei, 2011). In that way, adequate temperature differences will be created between the indoor and outdoor of the building. It will be enough to derive acceptable airflow rates. Generally, there is a temperature difference between the indoors and outdoors of a building during a summer day. As a result of that, ordinary chimneys operate by stack effect principle and do not provide acceptable air movement. This necessitates the use of solar chimneys to maximize the solar gain.

The combined radiation and convection in the solar chimney leads to air movement effects that improve ventilation. Solar chimney is a suitable ventilation strategy in windless climatic regions where stack effect ventilation is inadequate due to the insufficient temperature difference between indoors and outdoors (Gan, 2006; Khanal & Lei, 2011). Figure 2.34 shows a schematic of a solar chimney with vertical absorber geometry and Figure 2.35 is a schematic of an inclined-roof solar chimney. Solar chimneys can also be integrated into wind towers in hot/arid climatic regions in order to enhance indoor and outdoor air movement. They are especially useful in areas with very low wind speeds (Hughes et al., 2012). This strategy is illustrated in Figure 2.36.

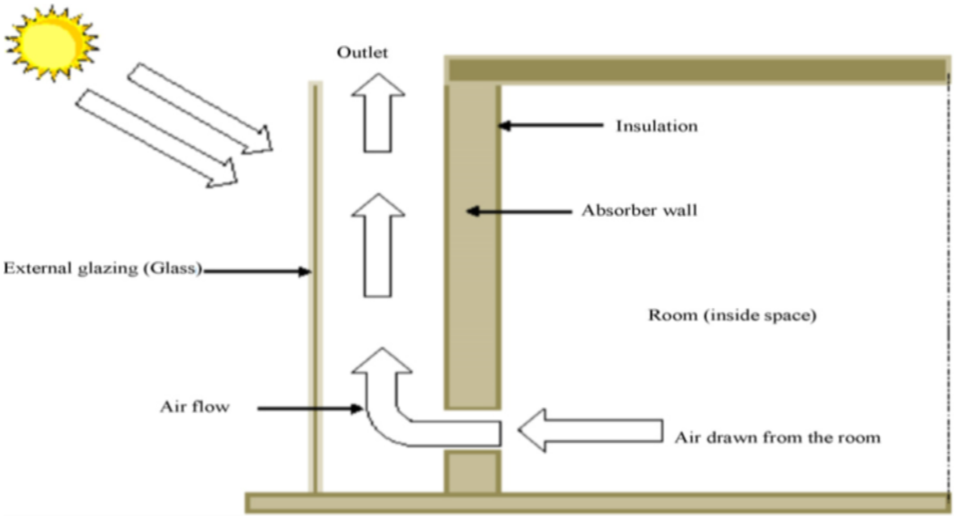


Figure 2.34 Schematic diagram of a solar chimney with vertical absorber geometry (Source: Khanal &Lei, 2011).

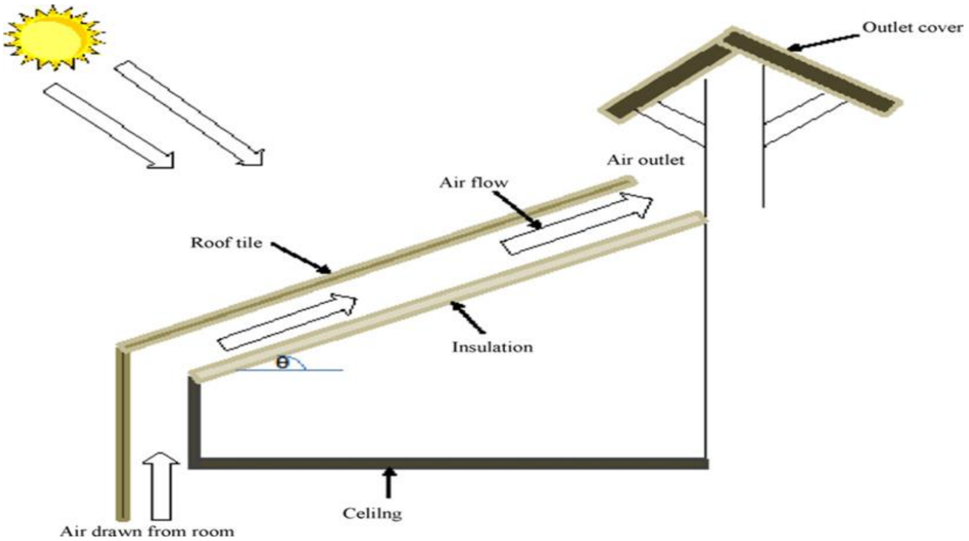


Figure 2.35: Schematic of inclined roof solar chimney
(Source: Khanal &Lei , 2011).

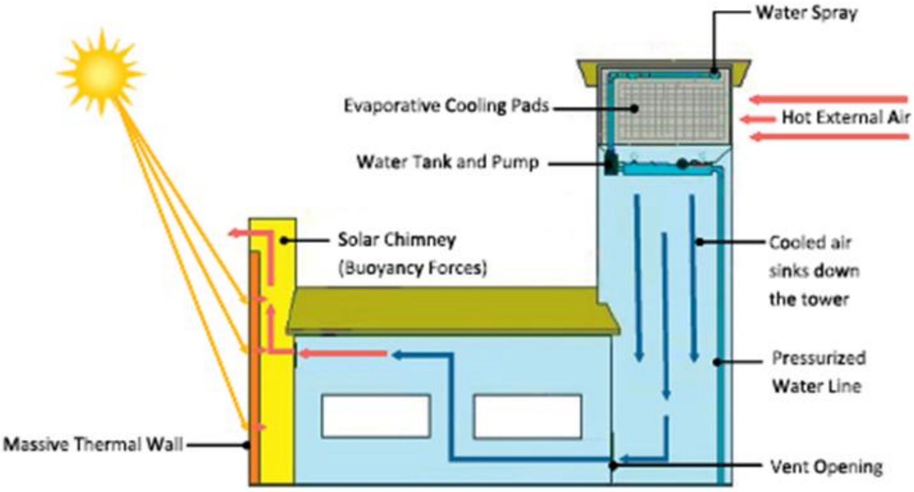


Figure 2.36: Concept of wind tower integrated with solar chimney
(Source: Hughes et al, 2012)

2.6.2 Heat Gain Prevention

When adopting this strategy, the first step to take is to prevent the penetration of any unnecessary thermal load that might pass to the building interior. This includes:

1. External thermal loads resulted from direct, indirect solar radiation, outside air infiltration, et cetera.

2. Internal loads that emits from people’s body are a results of cooking, and other activates, lighting, and appliances (Sharma et al., 2003). All these problems can be addressed through the following climate-responsive strategies.

2.6.2.1 Solar Control

Nowadays, various types of shading devices for the purpose of controlling solar radiation have been proposed. The type of shading devices to use depends on building orientation, location, and window type. Solar control strategy is one of the most important design strategies in hot/arid climatic zones, shading devices contribute to a greater extent to enhancing the building’s indoor thermal comfort if they are appropriately designed and sized. Furthermore, if shading devices are not ideally designed, they will worsen the indoor environment’s thermal comfort conditions and therefore lead to increases in energy consumption (Bellia et al., 2014). Building designers in hot/arid climates always compromise the adoption of natural light in their design in order to avoid excessive heat penetration to the building’s interior. Instead, shading devices and small windows are considered appropriate in this climatic region to control excessive solar radiation that leads to heat gain and glare problems (Edmonds & Greenup, 2002; Freewan, 2014). The function of a building’s openings in hot/arid climatic regions is to promote thermal comfort during the summer season. Good design and oriented window permit solar radiation admission to building indoor when heating is required in winter season (Greenup & Edmonds, 2004; Bellia et al., 2014). The hot/arid climate is characterized by clear sky conditions, giving a good chance for utilization of daylighting and natural ventilation for a building’s interior. This high level of solar radiation results from permitting direct solar radiation to penetrate indoors, which in turn, results in overheating and occurrences of discomfort glare. To resolve this problem, solar screen shading could be used in the form of external perforated panels fixed in front of the windows figures 2.37 and 2.38 (Sheriff et al., 2012). South-facing façades are exposed to solar radiation in the winter season; therefore, south windows should be protected from low altitude solar radiation in the mornings and evenings. Solar radiation striking east and west façades at low angles should be intercepted with adjustable slats.

Figure 2.37: Exterior detail, Mashrabeya bay window (Source: Alden and Willia, 1977).

Figure 2.38: Interior photo of a house in old Cairo, Egypt. (Source: Bugarin, 2005).

For appropriate shading of buildings, the shading devices should depend on solar movement of a particular building façade. This could be achieved through monitoring the sun's movement throughout the day. It is appropriate to use simple overhangs to shade the south façade window-wall in summer when sun angles are high. This may be adapted for hot/arid climate of the city of Khartoum, Sudan. Moreover, the same horizontal shading elements are appropriate for intercepting low afternoon solar radiation from penetrating the west façade openings of a building during the peak heat-gain period. The following are possible shading elements:

- Using landscape elements such as mature trees or hedge rows;
- Using exterior elements such as overhangs or vertical fins;
- Using horizontal reflecting surfaces for instance light shelves;
- Using low shading coefficient (SC) glass; and,
- Using interior glare control elements such as Venetian blinds or adjustable louvers (URL.43). Figure 2.39 shows some shading techniques.

Figure 2.39: Aluminium horizontal sun control device
(Source: Source: Bugarin, 2005).

According to Donald Watson (1983) and Lava pour and Surat (2011), research work entails monitoring solar radiation angles for different locations in hot/arid climates between 30° and 50° latitudes. They disclosed that a horizontal overhang of 76cm located 40cm above the top of the opening can provide appropriate solar control for south façade windows as in figure 2.58. However, in a situation where long windows or glass doors are used then it is preferable to increase the overhang to offer more shade (Donald Watson, 1983; Lavafpour & Surat, 2011). See figure 2.40 shows that 76/40 cm overhang is appropriate for south elevations in 30° to 50° latitude.

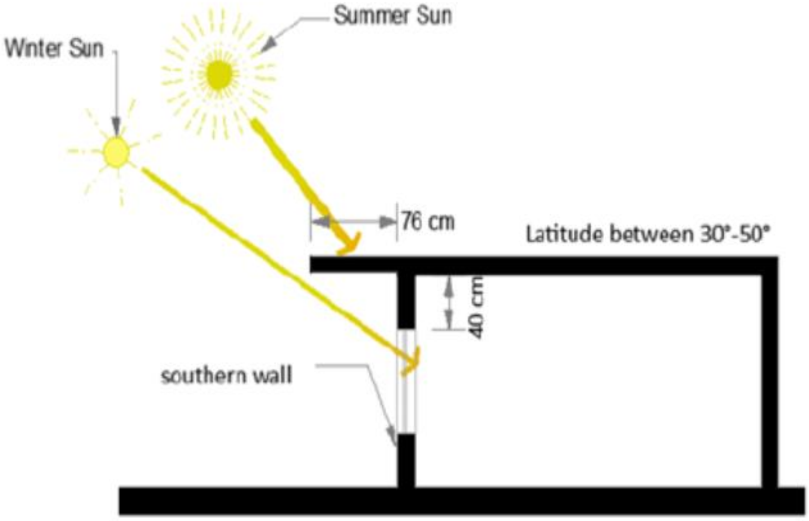


Figure 2.40: Roof overhang for south façade shading
(Source: Donald Watson, 1983).

2.6.2.2 Thermal Mass Lacking

Thermal mass is a substantial characteristic of a material, and can be defined as the ability of the material to absorb, store, and release heat when it is needed. High thermal mass generally is considered having high thermal mass and could act to appropriately regulate the temperature fluctuations in buildings. Thermal mass is considers to be preferably suitable for hot/arid regions. For instance, in the summer, night coolness can be stored in the building’s thermal mass and used during the daytime to stabilize indoor thermal comfort. During winter, heat radiation from lower solar angle can be stored in walls and floors and released during nighttime to improve indoor thermal comfort (Meir & Roaf, 2002; Ghoreishi, 2015). In such climate type and strategy of storing energy is very beneficial in controlling and regulating the building’s indoor environment and helps in reducing energy demand. As people’s living standards have risen in recent decades and environmental challenges such as climate change demand alternative means of enhancing indoor thermal comfort, high thermal capacity in a well-shaded and insulated building could serve as an appropriate alternative. It has the potential to reduce indoor energy demand by 35% to 45% (Givoni, 1994; Lavafpour & Surat, 2011). Thermal mass in some circumstances may be the only cooling option, particularly in most developing countries where power interruptions, because of increase peak load, commonly occur. When such events happen, for example in winter, the heat stored in the thermal mass can be utilized to enhance indoor thermal comfort levels (Meir, 2000; Lavafpour & Surat, 2011). Thermal mass is applied in design and construction to provide passive heating through direct solar gain or roof pond strategies in the winter season. Through these strategies, the stored heat is released at night in the wintertime to help provide acceptable indoor thermal comfort the figure 2.41 demonstrates, direct gain systems utilization of thermal mass in Hot/Arid climate zones. Trombe wall strategy is another good example. In this strategy, the indirect solar gain technique is used to improve indoor thermal comfort (Mazria, 1980; Ghoreishi, 2015). Figure 2.42 illustrates indirect gain - masonry thermal storage utilization for enhancement of indoor thermal comfort in Hot/Arid climate zones.

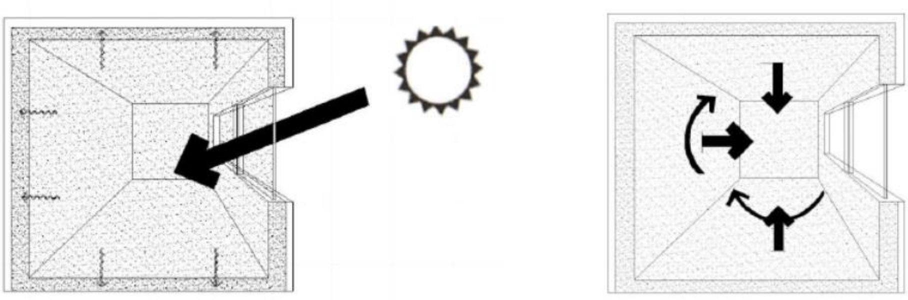


Figure 2.41: Masonry heat storage, direct gain systems
(Source: adapted from: Mazria, 1980).

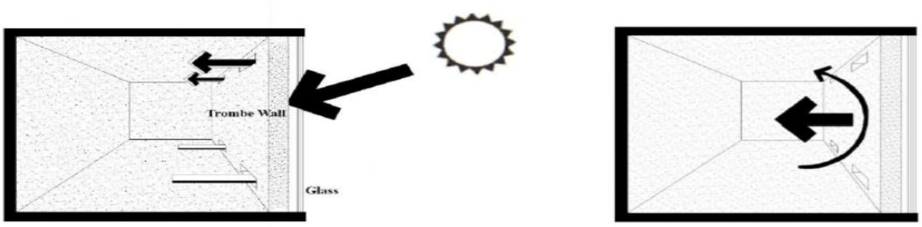


Figure 2.42: Indirect gain - masonry thermal storage wall
(Source: Adopted from: (Mazria, 1980).

2.6.2.3 Building Form

Buildings located in hot climatic zones face a greater challenge of internal heat gain because of high solar radiation intensity. The radiation penetrates the building directly through openings or building envelope. This results in an increased demand for air conditioning (AC) in summer to maintain indoor thermal comfort in warm and temperate climatic zones (Caruso & Kämpf, 2015). The building form plays an important role in energy loss minimization (Catalina et al., 2011); therefore, it is important for building designers to adapt the approaches optimising the form of the building envelope to save energy. The problem of building form optimisation has been analysed in various research articles (Caruso et al., 2013). Designing an energy efficient building requires careful choosing of building's form. The designer's choice for compact building form is invariably based on rules of thumb. The rule states that when designing; consider passive solar building design strategies for the building form and orientation. This is the most appropriate thermal performance of the building (Hemsath & Bandhosseini, 2015).

Several scholars have deliberated on the issue of efficiency of building form for energy saving (Olgyay, 2015). Vector Olgyay advocated the connectivity of building form and orientation with the passive solar energy efficiency of buildings. This suggestion helped in the construction of some passive solar buildings projects (Allen & Iano, 1989). The 2004 ASHRAE Standard recommends that building form and glazing should be oriented along an east-west direction to take advantage of natural ventilation and lighting (Ross, 2009). Current research on building geometry's effects on building energy can be categorized into two indictors: The first indictor is the energy performance of building, this include the shape coefficient and relative compactness. The second indictor is analysing the impact of form typology, such as orientation, plane and shape; configuration and layout, the window-to-wall ratio, and other physical characteristics. The first category seeks to find a simple indictor or direct correlation for the energy performance of the building (Liu et al., 2017). Numerous efforts have been made to find the effect of building form on building energy consumption. Ourghi et al. (2007) introduced a method for predicting the effect of the shape of an air-conditioned office building on its annual total cooling load. He simulated buildings from four different locations in different climatic zone including Rome, Tunis, Cairo, and Gabes. The simulation's result revealed a strong interdependency between total annual cooling loads and various building parameters such as building form, opening size, and glazing type (Ourghi et al., 2007; Pathirana et al., 2019). Caruso and Kampf (2015), in their effort to find optimized building form, investigated the optimal three-dimensional form of buildings that minimise energy consumption as a result of solar radiation using the evolutionary algorithm. The research finding is that the optimal building form is the one that is compact and oriented to a particular direction in the sky that depends on the site adapting self-shading pattern (Caruso & Kampf, 2015; Pathirana et al., 2019).

The impact of form in hot/arid climates, for air-conditioned office buildings in Kuwait was investigated by AlAnazi et al (2009). They analysed several building shape and form types including rectangular, L shaped, U shaped, T shaped, cross-shaped, H shaped, and cut shaped. The research revealed that buildings with less wall/window ratio tends to consume less energy compared to the one with high wall/window ratio. This indicates that compactness ratio is an influential factor in terms of energy consumption in the tropical climate zones (AlAnzi et al., 2009; Pathirana et al., 2019). This indicates that form has a great influence on the energy efficiency of buildings in hot/arid zones; therefore, it is important to use compact and appropriately oriented, sized, and positioned windows for buildings in Hot/Arid regions.

As in figure 2.43, a compact building form has a positive impact on reducing the cooling load during the summer season in hot/arid climates. A reduced building surface area to volume ratio, location of building on east-west axis, and away from building self-shaded walls can help in reducing energy demand for cooling (Hausladen et al., 2014).

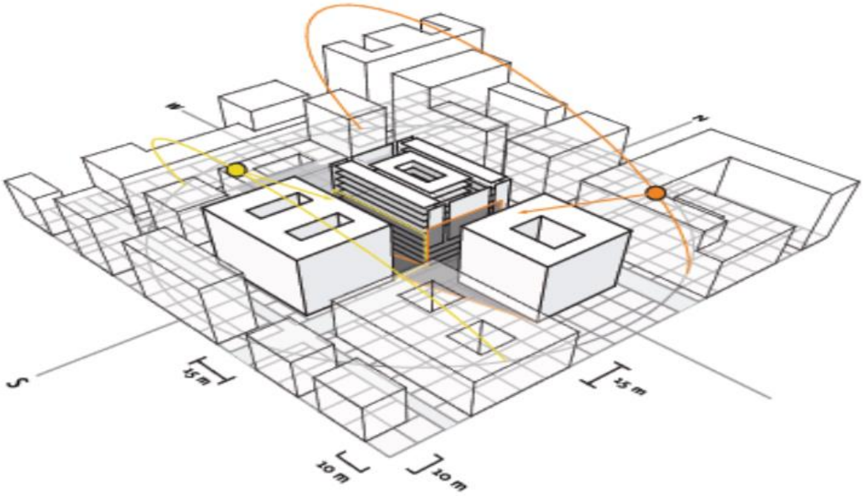


Figure 2.43: Utilization of compact buildings form, courtyards and self-shading to reduce heat gain in Hot/Arid climate zones. (Source: Hausladen et al., 2014).

2.6.2.4 Thermal Insulation

Thermal insulation types are fibrous, particulate, film, and sheet, block open, or close cell. Thermal insulation materials are generally used for building envelopes to protect building interiors from thermal discomfort. If the appropriate type and size of thermal insulation is used it will help in reducing energy consumption for air conditioning most especially in hot/arid climate where cooling load is relatively large. Thermal insulation equally increases the thermal comfort without dependence on conventional air-conditioning system. The amount of saving that could be achieved when thermal insulation is used depends on the building typology, climatic conditions where is building located, type, thickness, and location of insulation material used (Al-Homoud, 2004). It is generally recommended that in hot/arid climates, the building envelope should be insulated with a continuous coating of thermal insulation. It is important for building ducts and shafts to be within the vicinity of the insulated part of the building for them not to create a thermal bridge. A continuous coating or layers of thermal insulation reduces the tendency of thermal bridges (URL.15). Currently, people’s awareness about the need for energy conservation has tremendously increased because of their realization of its long-term benefits. In the future, the trend of using thermal insulation and other energy efficiency techniques may likely be more enthusiastically followed for reducing buildings running cost (Abdelrahman and Ahmad, 1991; Al-Homoud, 2004 & Hughes et al., 2012).

The Gulf Countries Council (GCC), which is located in hot/arid climatic zones, has set building regulations for using thermal insulation in buildings. The minimum level of thermal resistance specified for this region is R-values of 1.35m2K/W and 1.75m2K/W for walls and roofs, respectively. The choice of using insulation for building envelopes relies on the application types and the desired insulation level for the designated (Al-Homoud, 2004).

2.6.2.5 Building Orientation

The energy crisis of the 1970s motivated researchers' interest in climate-responsive design strategies. Nowadays, as most buildings are constructed with unsustainable building materials which consume more energy to provide acceptable thermal comfort level, the world researcher's attention is shifting now towards sustainable architecture. This principle of sustainability requires first a suitable building location and orientation and then cooling and heating requirements. Moreover, building orientation can maximize chances for passive solar heating and cooling when it is needed. The building orientation dictates the quantity of solar radiation received (Bekkouche et al., 2013). Building orientation depends invariably on the type of the climate where it is located. The hot/arid climatic zone is located between latitudes 15° and 30° North and South of the equator. In the summer season, temperature rapidly increases and reaches its peak at noon; temperature may fall up to 20°C at night. In the winter season, the mean maximum temperature might reach approximately 30°C and falls at night up to

20°C and precipitation is very low. The relative humidity is very low in continental climate zones and ranges from 10% to 55%. It might reach up to 90% in coastal areas such as Dubai City together with the higher temperatures, makes the climate to be uncomfortable. A building's orientation significantly influences the impact of the sun and wind on the dwelling. In hot/arid climate orienting the longest part of the building towards the north and south can significantly reduce a building's solar exposure. The openings should face the prevailing winds; this in turn helps in maximizing cross-ventilation of the rooms. Generally, the north and west directions of the house offer the most breezes and ventilation. Appropriate orientation of a building will therefore provide occupants comfortable living spaces for the whole year and even under unfavorable weather conditions (Gut & Ckerknecht, 1993). Figure 2.44 shows the building form and orientation in relation to sun movement in the hot/arid climate.

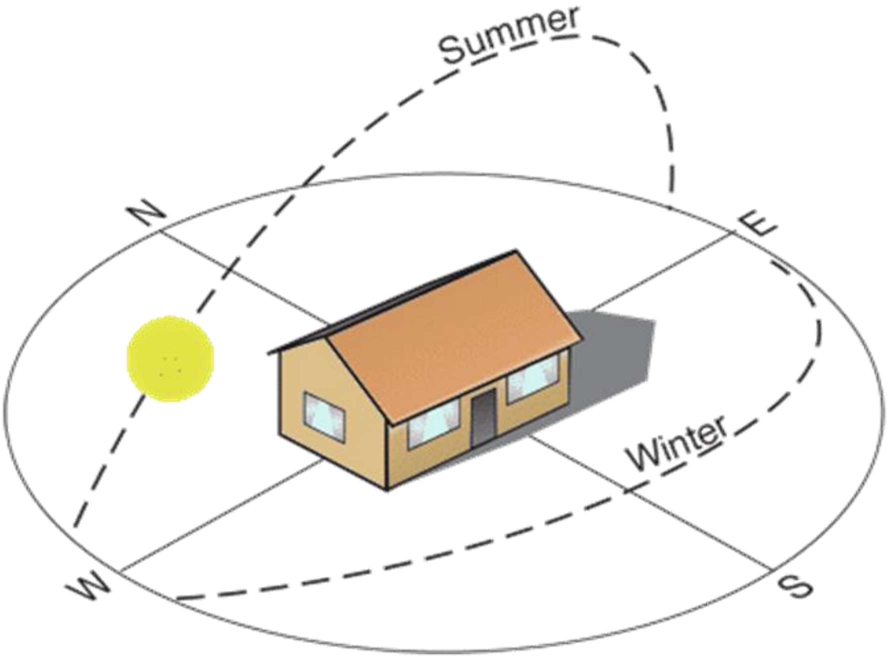


Figure 2.44: Orientation of building in relation to sun movement
(Source: Gut & Ckerknecht, 1993).

2.6.2.6 White Paint Roof

When the solar reflectance increase in cities, it will lead to the increase of short-wave solar radiation, which in turn leads to reduced quantity of solar heat energy absorbed by exterior building surfaces. Lower temperatures and reduced outflow of thermal radiation into the atmosphere will be released. This strategy can help in mitigating climate change effects. Similarly, cool roofs and cool pavements save energy in buildings that are used for active cooling and enhances unconditioned buildings (Akbari & Matthews, 2012; Akbari et al., 2009). Research has revealed that improving roof thermal performance helps make major energy savings in buildings. For instance, high reflective roof (cool roof) has been extensively adapted to increase roof thermal performance by reducing cooling energy demand (Algarni & Nutter, 2015). Due to low cost, considerable energy savings, and lack of aesthetics conflict, it is possible to encourage building owners to adapt this strategy (Akbari & Matthews, 2012; Akbari et al., 2009). Moreover, pavements and roof constitute more than 60% and roof between 20-25% of urban surfaces. Applying reflective surface materials on pavements and roof can increase albedo up to 0.25 and 0.15 respectively, leading to an overall increase of 0.1 on the total net albedo for the entire city (Akbari et al., 2009). Accumulation of sand-dust storms are one of the challenges in hot/arid climates zone in the city of Khartoum, Sudan. It can drastically affect the performance of reflective surfaces because of the increased frequency of its occurrence in recent decades (Ghazi et al., 2014). This effect is illustrated in figure 2.45, which presents two types of roofs, a fully dusted and an undusted one (Algarni & Nutter, 2015).

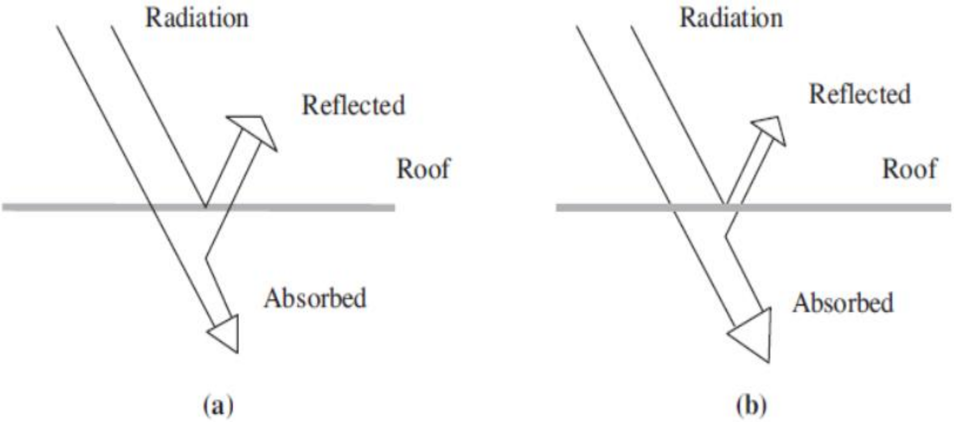


Figure 2.45: Variation of absorbed solar radiation under clean (a) roof and (b) dusty roof (Source: Algarni & Nutter, 2015).

2.6.2.7 Building's Envelope Design

The building's envelope is the principal climate mediator between the indoor and outdoor environments, and it is exposed to environmental climate elements and required to moderate air exchange, solar radiation, and sound in order to provide healthy and comfortable living environments (Reid, 1988; Bahaj et al., 2008). The building envelope may increase building costs for thermal insulation, highly efficient glass, the need for triple glass, and measures to avoid thermal bridges (Hausladen et al., 2014). Therefore, it is crucial for architects and engineers to make suitable selections of envelope material in order to make use of renewable energy such as daylighting and winds. Building function is the second most important factor in envelope design. In situations where activity and equipment in the space generate heat, the thermal loads may be primarily internal rather than external. However, this invariably affects the level at which the building losses or gains heat. Furthermore, building form, orientation and volume have a great impact on energy efficiency measures of the building envelope. In hot/arid climates, the most appropriate design strategy is to reject solar absorption through prevention of direct solar radiation penetration into the building's indoor space while still permitting a reasonable quantity of daylighting for visual efficiency. Heat loss reduction is a very important strategy in cold climates; this however, helps in maintaining desired thermal comfort through accumulation of solar radiation in the building envelope (Straube & Straaten, 2001; Bahaj et al., 2008). The following criteria should be adapted for sustainable building envelopes:

1. Building envelopes should provide appropriate control of direct solar radiation through self-shading strategies or shading devices to protect the building interior from external heat gain.
2. Façades should be appropriately designed to control any heat gain that might occur through infiltration through using well-sealed opaque façade components.
3. Provide natural ventilation means to the building interior where deemed necessary.
4. Provide adequate natural lighting while still minimizing any occurrence of solar gain by using appropriate shading devices and light shelves (URL.16).

Building envelopes should incorporate filters that control sand-dust storms in hot/arid climates. Because sand-dust storm events have become more frequent than ever before. Figure 2.46 shows a concept of south façade in Hot/Arid climate.

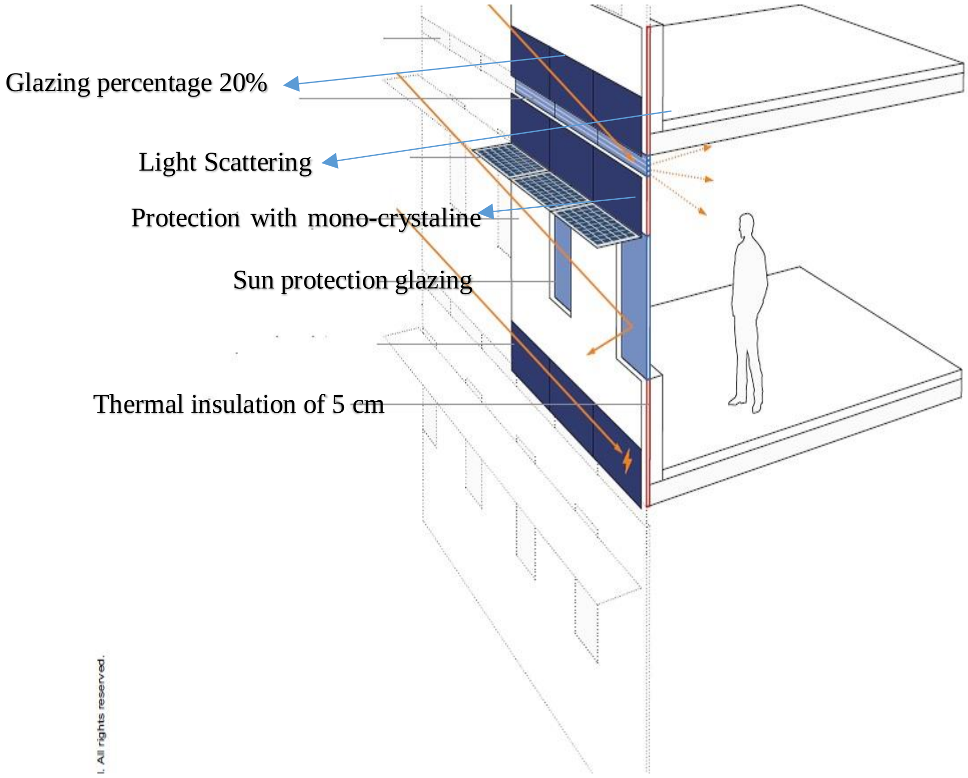


Figure 2.46: South façade design of buildings in Hot/Arid climates zone size.(Source : (Hausladen et al., 2014)

2.6.2.8 Glazing Façade Design Consideration

Glazing façades utilization in buildings have gained more attention in recently years (De Gracia et al., 2013; Iyi et al., 2014; Nasrollahi & Salehi, 2015). Its use has become the most widely used façade system worldwide due to the increased demand for building façade transparency and their good characteristics of acoustic and energy efficiency (Fuliotto et al., 2010; Nasrollahi & Salehi, 2015). With good design and appropriately selection glazing material, a considerable energy saving can be achieved in HVAC systems in buildings by accepting solar energy in the winter season and rejecting overheating in the summer (Shameri et al., 2011; Nasrollahi & Salehi, 2015). In hot/arid climatic zones, which are characterized as harsh environments, using larger glazing material increases the heat gain. Excessive penetration of direct solar radiation is undesirable and may affect visual comfort of building users (Sadek & Mahrous, 2018). It is more beneficial to use double-glazed windows in hot/arid climate because it reduces cooling load in hot season where active cooling is needed (Banihashemi, et al, 2015). Therefore it is appropriate to apply double glazed system in Khartoum since active cooling is needed from June up to October in order to save energy.

Using thin ceramic film electrochromic glazing is more appropriate for desert climate buildings. It can save considerable quantity of energy when used under clear or partly cloudy sky conditions (Lee et al., 2006; Sherif et al., 2015). Using glazed façades has become very common nowadays. It has its own advantages in terms of energy efficiency and psychological benefits, which are summarized as follows:

1. It is a lightweight, flexible, and fast construction system that has aesthetics values and is suitable for high-rise buildings.
2. Visual connection between the inside and outside helps improve occupants' productivity rates. It also adds aesthetics value to the surrounding environment during daytime by using optical properties of glass such as reflection. At night the interior lighting could possibly provide a beautiful night scene.
3. Provides appropriate daylighting, hence reducing artificial lighting.

In addition to glazing material's transparent nature, it is imperative to raise designer's awareness about the implication of using glazing materials in desert climatic zones. The most commonly addressed concerns are listed as:

1. Increasing building energy consumption as a result of increased overheating hours.
2. Elevating thermal discomfort because of increased mean radiant temperature (MRT) of the surrounding environment.

3. Escalating infiltration rates due to air leakage are caused as a result of low level of workmanship.
4. Excessive glare.
5. Dilapidation of furniture as a result of their exposure to the ultra-violet rays for longer hours of the day.
6. A need for adapting to continuously maintain culture (Assem & Al-Mumin, 2010).

The type of glazing appropriate for hot/arid climates should contain sun protection coating so as to control diffuse solar radiation, which causes excessive overheating irrespective of glazing orientation. The g-value was defined by Hausladen et al (2014) as “the permeability of the glazing to energy occasioned by solar radiation.” It is one of the most important factors for choosing the appropriate type of glazing. It is recommended that the g-value of glazing types should be adapted and should not be less than 0.3 in all cases. Furthermore, any façade glazing should not be more than 30% because of the high illumination level in the city of Khartoum’s climate (Hausladen et al., 2013).

Chapter 3

DEVELOPMENT OF A NEW METHODOLOGY FOR THE CLIMATE-RESPONSIVE BUILDING DESIGN STRATEGIES FOR THE CITY OF KHARTOUM, SUDAN

3.1 Methodology

This research entails addressing the scientific knowledge gap in adaptation of climate-responsive building design for hot/arid climatic zones in the case of the city of Khartoum, Sudan. This research problem has been identified as a challenge because most researchers in recent decades have neglected adapting climate into their designs. Climate change is a serious issue facing the entirety of humanity in the 21st century. It is expected to have serious consequences on the built environment globally (Parry, 2007). This research adapted a case study problem solving method in which accurate energy plus weather files were created from the averages of Khartoum’s 1996 to 2015 weather data. The city’s climate for the years between 1981 and 2015 was analysed through linear trend analysis to find climate change on the seasonal basis. All of the achieved results are supported with outside references. Climate Consultant 6.0 software was used for analyzing contemporary thermal comfort and climate-responsive building design strategies for the city of Khartoum. Moreover, this research predicts future resilience, thermal comfort, and design strategies for the city of

Khartoum in 2070 according to appropriate scenario. Figure 3.1 the Methodology Adapted in the Research.

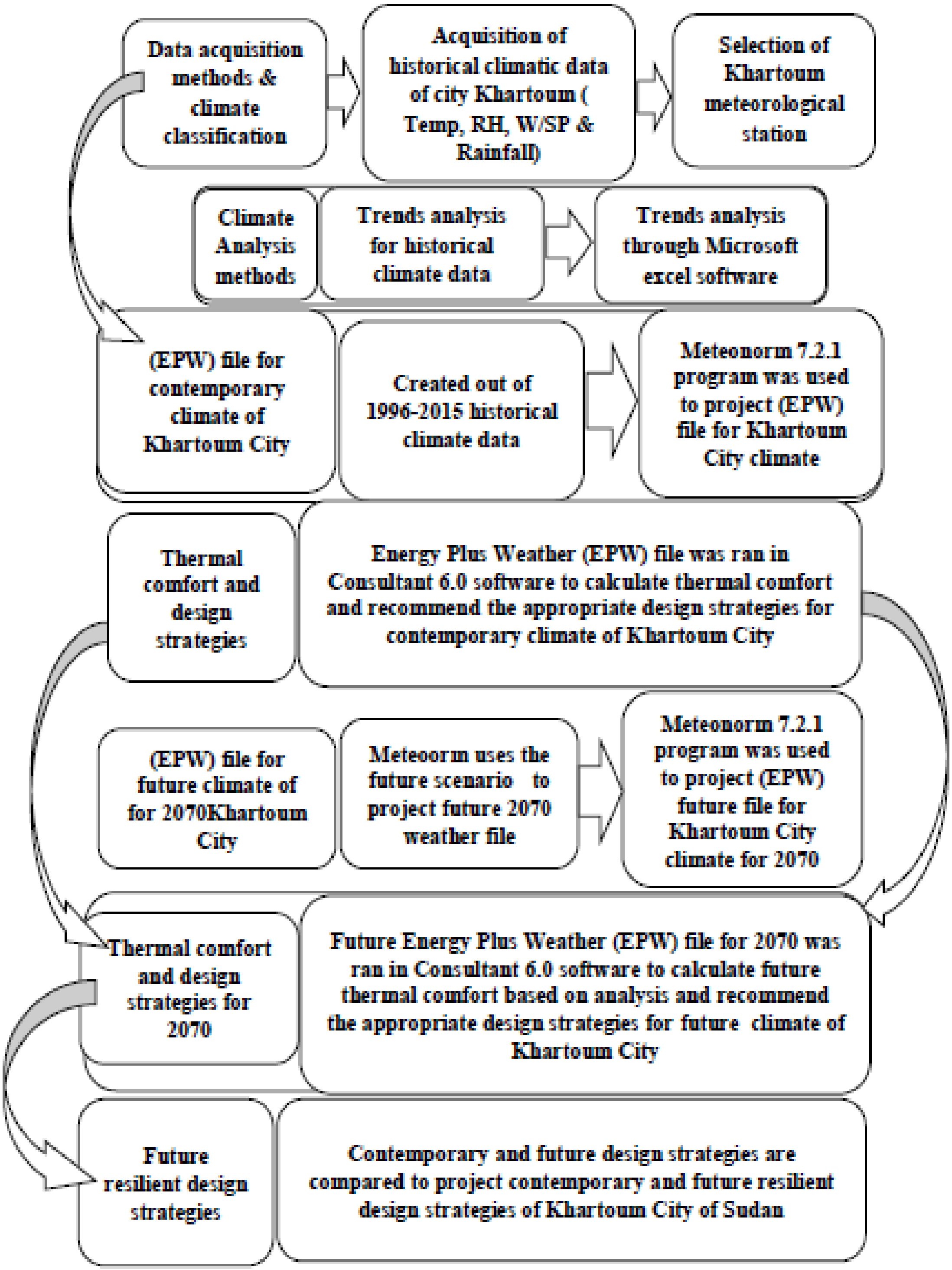
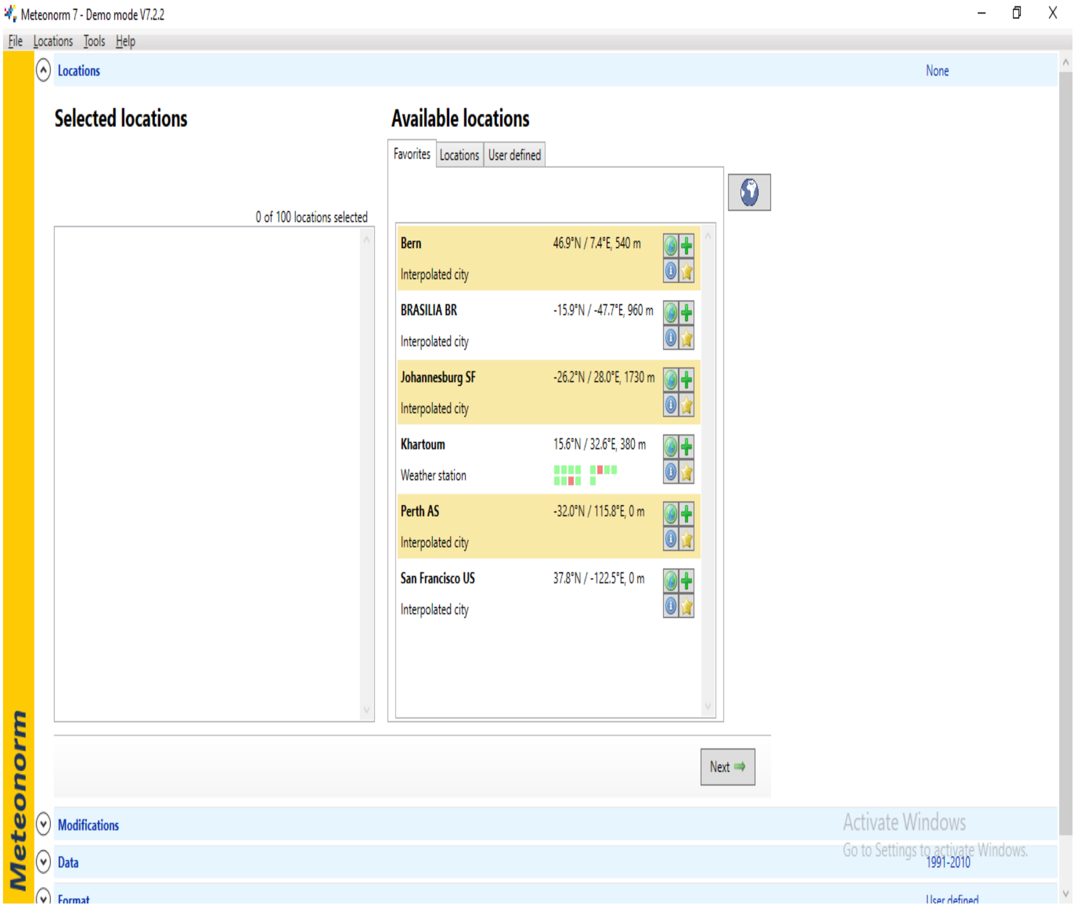


Figure 3.1: Diagram of research methodology adapted in the research
Source: Developed by the Author.

3.2 Data Accusation Methods

The data used for this research was acquired from the Khartoum Metrological Station located at Khartoum International Airport in the capital city (latitude 15°36’N, longitude 32°33’E, altitude 380m) (Elagib, 2011). Since this research focuses on climate-responsive building design, it became essential to analyze the climatic data for the years 1981 to 2015 to determine to what extent the city has witnessed climate change during these period. The climatic data used in this research included minimum and maxim monthly data for temperature, humidity, wind speed, and rainfall, in order to know the extreme condition for cooling and heating requirement for buildings. This analysis helped provide appropriate climate-responsive design strategies for contemporary and near future buildings in the city of Khartoum. Additionally, due to the lack of more detailed climatic data for this research, some missing but necessary data was acquired from Meteonorm 7.2.

Meteonorm is a unique combination of reliable data sources and sophisticated calculation tools. It provides access to typical years and historical time series. Meteonorm generates accurate and representative typical years for any place on earth. You can choose from more than 30 different weather parameters. The database consists of more than 81000 weather stations, five geostationary satellites and a globally calibrated aerosol climatology. On this basis, sophisticated interpolation models, based on more than 30 years of experience, provide results with high accuracy worldwide Meteonorm, 2018).All what the user need is to know the latitude and longitude and elevation over sea level of the location for him to download the EPW file. Figure 3.2 shows the software interface



Bern Interpolated city	46.9°N / 7.4°E, 540 m
BRASILIA BR Interpolated city	-15.9°N / -47.7°E, 960 m
Johannesburg SF Interpolated city	-26.2°N / 28.0°E, 1730 m
Khartoum Weather station	15.6°N / 32.6°E, 380 m
Perth AS Interpolated city	-32.0°N / 115.8°E, 0 m
San Francisco US Interpolated city	37.8°N / -122.5°E, 0 m

Figure 3.2: Meteonorm working environment
(Source: Meteonorm 7.2.1 software)

Meteonorm is well-known and reliable software. The software can provide full details of climatic data for any location on Earth (Douvlou, 2004). The new software version of Meteonorm 7.2.1 has improved accuracy and can provide more parameters than the previous versions 6.0 version .It can also provide accurate future predictive weather files up to 2100 (URL.17). For this research, a 2070 future predictive weather file was calculated from this software.

3.3 The city of Khartoum Climate Classification

According to research, the city of Khartoum is characterized as a hot and arid climate with Hot Season (March- May) with the maximum temperature may reach up to 45.4

^{O}C at late afternoon and may drop up to 16.6 ^{O}C after midnight. Moreover, the minimum humidity level is 10% in the afternoon to may reach its maximum value of 46% after mid night. The Dry Season (November- February) is cold and dry with minimum temperature of 12.5 ^{O}C in early morning hours of January and can be as high as 40 ^{O}C at noon. The humidity level ranges between 10% and 59%. Nadir and Martin (2000) also classify the climate of central Sudan, in which the city of Khartoum is located, as hot and arid. They further categorized the city's climate as summer (Hot), winter (Dry) and the autumn (Wet). The has approximately 95% of annual rainfall received by the city of Khartoum and it includes the months of June, July, August, September, and October. The month of August is the wettest month of the season. The Hot season extend through March, April, and May when the city experiences the highest temperatures. Finally, the Dry Season is in the months of November, December, January, and February when the city of Khartoum experiences the lowest temperature levels (Nadir & Martin, 2000). Generally, there is agreement between the classifications by Köppen–Geiger, ASHRAE Standard, and Nadir and Martin (2000); the climate of the city of Khartoum is considered hot and arid. For the purposes of this study, the climatic seasons for the city of Khartoum will be adopted from the categorization by Nadir and Martin (2000).

3.4 Analysis Methods

This research used three different analysis methods that rely on climate classification and climatic data in order to arrive at climate-responsive building design strategies that conform to the contemporary and future climate. The adapted analysis methods are trend analysis, and thermal comfort design strategies analysis.

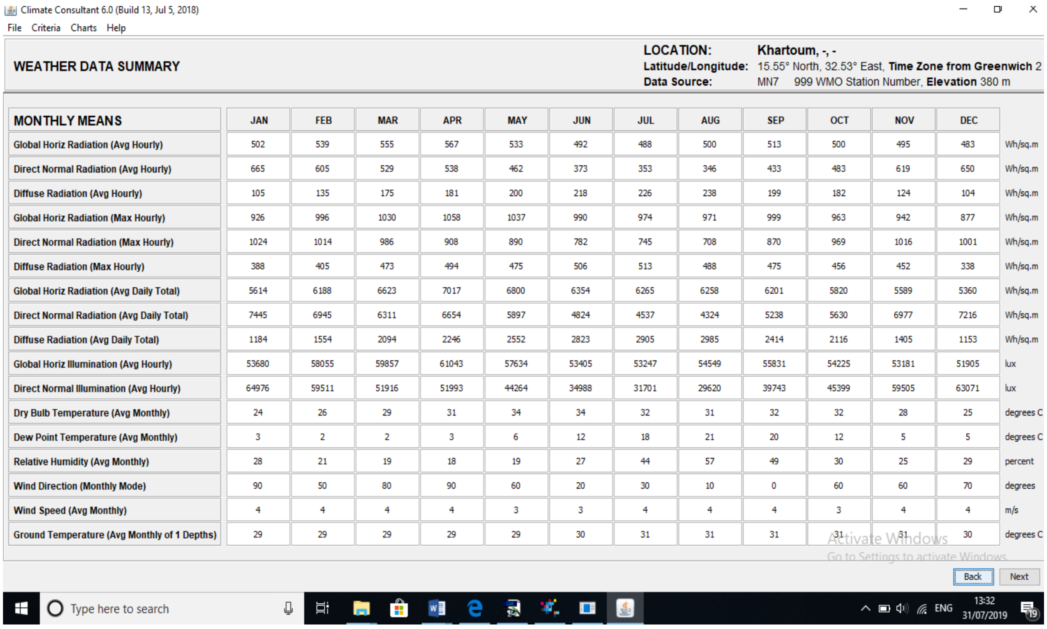
3.4.1 Trends Analysis

Time series analysis has a profound benefit when studying hydrology in previous years. It has been used for numerous hydrological parameters such as rainfall and temperature analysis (Mirza et al., 1998; Astel et al., 2004; Ahmed et al., 2014). A trend is a substantial change that occurs to the time-series value of a parameter or variable and is recognized through statistical parametric or non-parametric means. Trend is normally represented as a decreasing or increasing (i.e. monotonous) data. In previous years, many researchers have identified a climatic trend (Ahmed et al., 2014). In this research about the city of Khartoum's climate, linear trends is used to hypothesis the variation effect of monthly average data of relative humidity, temperature, wind speed, and rainfall in order to predict future forecast . Linear trends for all climatic parameters considered in this study were drawn based on seasons of the year of the mentioned parameters from 1981 to 2015.

3.4.2 Thermal Comfort and Design Strategies Analysis Used for the Contemporary Climate of the city of Khartoum

The world population has witnessed tremendous growth combined with an increase in urban densities which resulted into a substantial thermal stress and health hazards. These conditions necessitate a need for developing a sustainable measure of thermal comfort conditions. Such a measure can help a building's designers provide appropriate climate-responsive buildings in order to reduce the reliance on fossil fuel (Hirashima et al., 2018). To evaluate thermal comfort in the city of Khartoum, Climate Consultant 6.0 software was used.

Climate consultant is a free, easy-to-use, graphic-based computer program that displays climate data in dozens of ways useful to architects, builders, contractors, and homeowners, including temperatures, humidity, wind velocity, sky cover, and solar radiation in both 2-D and 3-D graphics for every hour of the year in either Metric or Imperial units. Climate Consultant 6.0 also plots sun dials and sun shading charts overlaid with the hours when solar heating is needed or when shading is required. The psychrometric chart analysis shows the most appropriate passive design strategies in each climate, while the new wind wheel integrates wind velocity and direction data with concurrent temperatures and humilities and can be animated hourly, daily, or monthly. Because energy codes require slightly different types of buildings in each climate zones, it is important for people who are designing, constructing, or maintaining these buildings to understand the unique attributes of their climate and how it impacts their building’s energy consumption. Climate Consultant reads climate data in the EPW format that the Department of Energy makes available at no cost (in fact there are more than 1300 stations from around the world available in this format). The psychrometric chart analysis leads to a rank ordered list of Design Guidelines which in turn are supported by graphic illustration of the architectural implications. An automatic link to the Architecture2030 Swatches is also provided (Energy design tool, 2017). Figure 3.3 shows climatic 17 parameters included in Khartoum weather file. Moreover, figure 3.4 demonstrates the ASHRAE Standard type which climate consultant 6.0 should use in order to analyze thermal comfort and design strategies. Once the suitable Standard is chosen, the software can give reliable thermal comfort and design strategies of the location.



WEATHER DATA SUMMARY

LOCATION: **Khartoum, -, -**
Latitude/Longitude: 15.55° North, 32.53° East, **Time Zone from Greenwich** 2
Data Source: MN7 999 WMO Station Number, **Elevation** 380 m

MONTHLY MEANS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Global Horiz Radiation (Avg Hourly)	502	539	555	567	533	492	488	500	513	500	495	483	Wh/sq.m
Direct Normal Radiation (Avg Hourly)	665	605	529	538	462	373	353	346	433	483	619	650	Wh/sq.m
Diffuse Radiation (Avg Hourly)	105	135	175	181	200	218	226	238	199	182	124	104	Wh/sq.m
Global Horiz Radiation (Max Hourly)	926	996	1030	1058	1037	990	974	971	999	963	942	877	Wh/sq.m
Direct Normal Radiation (Max Hourly)	1024	1014	986	908	890	782	745	708	870	969	1016	1001	Wh/sq.m
Diffuse Radiation (Max Hourly)	388	405	473	494	475	506	513	488	475	456	452	338	Wh/sq.m
Global Horiz Radiation (Avg Daily Total)	5614	6188	6623	7017	6800	6354	6265	6258	6201	5820	5589	5360	Wh/sq.m
Direct Normal Radiation (Avg Daily Total)	7445	6945	6311	6654	5897	4824	4537	4324	5238	5630	6977	7216	Wh/sq.m
Diffuse Radiation (Avg Daily Total)	1184	1554	2094	2246	2552	2823	2905	2985	2414	2116	1405	1153	Wh/sq.m
Global Horiz Illumination (Avg Hourly)	53680	58055	59857	61043	57634	53405	53247	54549	55831	54225	53181	51905	lux
Direct Normal Illumination (Avg Hourly)	64976	59511	51916	51993	44264	34988	31701	29620	39743	45399	59505	63071	lux
Dry Bulb Temperature (Avg Monthly)	24	26	29	31	34	34	32	31	32	32	28	25	degrees C
Dew Point Temperature (Avg Monthly)	3	2	2	3	6	12	18	21	20	12	5	5	degrees C
Relative Humidity (Avg Monthly)	28	21	19	18	19	27	44	57	49	30	25	29	percent
Wind Direction (Monthly Mode)	90	50	80	90	60	20	30	10	0	60	60	70	degrees
Wind Speed (Avg Monthly)	4	4	4	4	3	3	4	4	4	3	4	4	m/s
Ground Temperature (Avg Monthly of 1 Depths)	29	29	29	29	29	30	31	31	31	31	31	30	degrees C

Activate Windows
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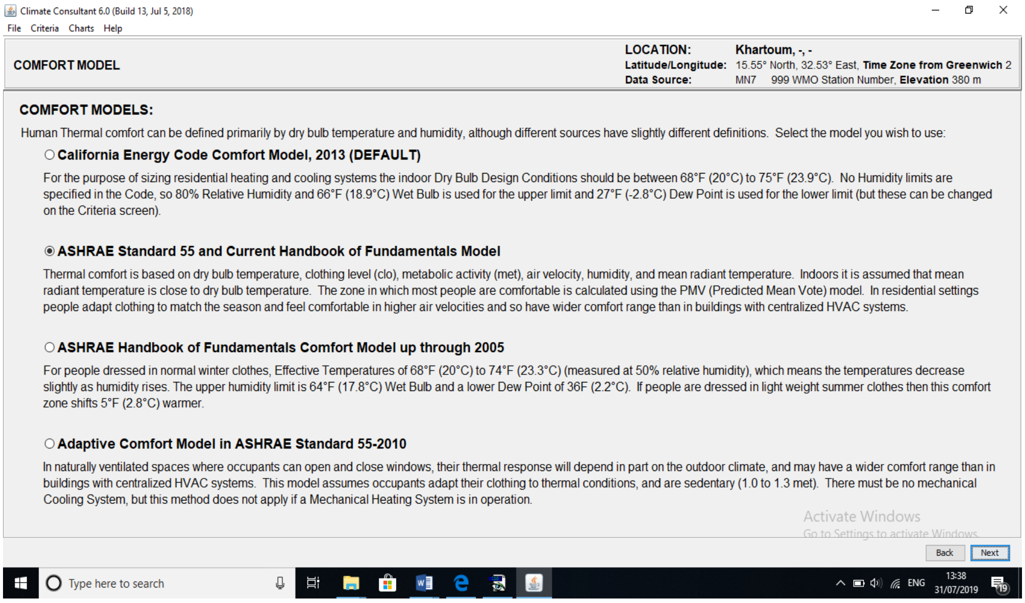
Figure 3.3: Climatic parameters used in the climate analysis
(Source: Climate consultant 6.0)



COMFORT MODEL

LOCATION: **Khartoum, -, -**
Latitude/Longitude: 15.55° North, 32.53° East, **Time Zone from Greenwich** 2
Data Source: MN7 999 WMO Station Number, **Elevation** 380 m

COMFORT MODELS:

Human Thermal comfort can be defined primarily by dry bulb temperature and humidity, although different sources have slightly different definitions. Select the model you wish to use:

○ **California Energy Code Comfort Model, 2013 (DEFAULT)**

For the purpose of sizing residential heating and cooling systems the indoor Dry Bulb Design Conditions should be between 68°F (20°C) to 75°F (23.9°C). No Humidity limits are specified in the Code, so 80% Relative Humidity and 66°F (18.9°C) Wet Bulb is used for the upper limit and 27°F (-2.8°C) Dew Point is used for the lower limit (but these can be changed on the Criteria screen).

● **ASHRAE Standard 55 and Current Handbook of Fundamentals Model**

Thermal comfort is based on dry bulb temperature, clothing level (clo), metabolic activity (met), air velocity, humidity, and mean radiant temperature. Indoors it is assumed that mean radiant temperature is close to dry bulb temperature. The zone in which most people are comfortable is calculated using the PMV (Predicted Mean Vote) model. In residential settings people adapt clothing to match the season and feel comfortable in higher air velocities and so have wider comfort range than in buildings with centralized HVAC systems.

○ **ASHRAE Handbook of Fundamentals Comfort Model up through 2005**

For people dressed in normal winter clothes, Effective Temperatures of 68°F (20°C) to 74°F (23.3°C) (measured at 50% relative humidity), which means the temperatures decrease slightly as humidity rises. The upper humidity limit is 64°F (17.8°C) Wet Bulb and a lower Dew Point of 36F (2.2°C). If people are dressed in light weight summer clothes then this comfort zone shifts 5°F (2.8°C) warmer.

○ **Adaptive Comfort Model in ASHRAE Standard 55-2010**

In naturally ventilated spaces where occupants can open and close windows, their thermal response will depend in part on the outdoor climate, and may have a wider comfort range than in buildings with centralized HVAC systems. This model assumes occupants adapt their clothing to thermal conditions, and are sedentary (1.0 to 1.3 met). There must be no mechanical Cooling System, but this method does not apply if a Mechanical Heating System is in operation.

Activate Windows
Go to Settings to activate Windows.

Figure 3.4: ASHRAE Standard adapted for analysis
(Source: Climate consultant 6.0)

This computer software requires the energy plus weather (EPW) file for the city of Khartoum. The weather file was calculated using the average climatic data for the city between the years 1996 and 2015. Weather files are usually based on hourly values of climatic parameters. The Khartoum Metrological Station has no records of hourly climatic data. Therefore the average data was imported to the Meteonorm 7.2 program to obtain EPW file through the following procedure:

Meteonorm takes the long-term monthly averages of the parameters. With a stochastical process (Markov Chains), daily and then hourly values are synthetically generated. For the derived radiation parameters diffuse and direct irradiance, are calculated using Perez model to split the global radiation value into the diffuse and direct part (Meteonorm, 2018). In order to calculate thermal comfort zone for the city of Khartoum two adaptive thermal comfort models are used in this research. They are the adaptive comfort model and the ASHRAE Standard 55 with its current handbook of fundamentals.

3.4.3 Thermal Comfort and Design Strategies Analysis Used for the Future Climate of the city of Khartoum

Climate change's effects on buildings have become one of the most prominently deliberated issues; therefore, it is important that researchers of buildings and the built environment consider the effects of climate change on long-term building performance. Most building simulation programs need hourly-based meteorological data to give information about the indoor thermal environment and total energy consumption. However, the simulations in this research used regional and average weather data of contemporary or past weather conditions. In order to design sustainable, climate-responsive buildings that are adaptable to contemporary conditions and resilient to the future climate, this simulation incorporates climate change predictions (Guan, 2009; Kikumoto et al., 2015; Keller et al., 2016). The Intergovernmental Panel for Climate Change (IPCC) has made tremendous effects to create reliable weather files that can be used to predict the future resilient design strategies for buildings worldwide. In line with this, IPCC has analyzed climate change using many possible alternative future emissions scenarios. These scenarios were formed using various rates of greenhouse gas production following socio-economic scenarios (Herrera et al., 2017). Future EPW file for predicting climate-change scenarios for the city of Khartoum in the year 2070 is calculated through Meteonorm Software .From the IPCC report 2007 ("AR4", Meehl et al, 2007) the average of all 18 models has been included in Meteonorm. Three different scenarios B1 (low), A1B (mid) and A2 (high) are available. The anomalies of temperature, precipitation, global radiation of the periods 2011–2030, 2046–2065, 2080–2099 were used for the calculation of future time periods (Gregory et al, 2007 & Meteonorm, 2018). Moreover, due to improvements in building and construction technologies, building lifespans can extend from 80 up to 100 years or more. Therefore, predicting the next 55 years of climate-responsive building strategies is rationalized. Together with Meteonorm Software results, these make it possible to calculate the 2070 weather file for the city of Khartoum in order to evaluate how the future predicted climate-responsive design strategies for the city of Khartoum would perform.

3.5 Summary of the Chapter

This chapter described the way this thesis work was carried out. The first step was data accusation from the meteorological weather station in the city of Khartoum and formulation of the energy plus weather (EPW) files for the city of Khartoum today and for 2070. These helped in calculating contemporary and future thermal comfort and design strategies. The second step was to identify climate classification criteria. The third step included the data analysis methods for contemporary and future thermal comfort and design strategies. This helped in predicting near-future climate-responsive building design strategies that are resilient to both known and anticipated climate change in the city of Khartoum.

Chapter 4

ADAPTATION OF THE METHODOLOGY OF THE CLIMATE RESPONSIVE BUILDING DESIGN STRATEGIES FOR THE CITY OF KHARTOUM, SUDAN

4.1 Case Study Area: the City of Khartoum, Sudan

The city of Khartoum, Sudan, was founded in 1820 CE and later became the capital of this northeastern African country. The city’s name derives from its shape which resembles an elephant trunk (Al Khartoum in Arabic). Its development is focused around 15°33′06″ N latitude, 32°31′56″ E longitude and it averages 380 meters above sea level. The city’s location in the center of the country coupled with its strategic position at the confluence of the Blue and White Nile Rivers made it one of the most important cities in the Sudan. (Shakurov et al., 2016; Awad and Hussein, 2006). The Central Bureau of Statistics of Sudan (CBSS) estimated the city of Khartoum’s population at 6.5 million in 2013 with a 2.7% rate of annual increase (URL.50).The study area of the city of Khartoum shows in figure 4.1.

Figure 4.1: Geographical location of the city of Khartoum Centre.
(Source: Map adapted from: Google Earth)

In the Köppen classification system of climate, the city of Khartoum is located in a hot arid desert zone. According to Elagib and Mansell (2000), the city of Khartoum's three seasons are winter (Dry Season covering November through February), summer (Hot Season starting in March and extending to May), and autumn (Wet Season lasting from June to October) (Elagib and Martin, 2000). A notable phenomenon of the city of Khartoum's climate is sand-dust storms which prevail throughout central Sudan. These storms are categorized into three distinct types. A *haboob* is a dust storm associated with clouds, as in figure 4.2 and is caused by winds moving from north-northeast to south-southwest. They usually occur in desert regions of the northern hemisphere between April and September, and reach maximum intensity during June. Each haboob can last from 30 minutes to several hours. A second dust storm occurring in the city of Khartoum involves steep pressure gradients caused by south-southwest winds from intertropical fronts. These prevail from May to October. The city of Khartoum's third type of sand-dust storm is caused by north-northeast trade winds crossing the greater desert between February and April. These winds are accompanied by fine particles (Bakr, 1988; Miller et al., 2008). Which create sincere design challenges addressable through filtration of the air entering buildings.

Figure 4.2: Sand-dust-storm-Khartoum-Sudan
(Source: Osman & Sevinc, 2019)

Omondi et al., 2014) explain how environmental degradation attributed to climate change has happened in the city of Khartoum, during the past decades. However, Omer et al. (2015) also indicated that vegetative cover of the city of Khartoum was reduced by human activity after climate-induced urban migrations starting in 1993 as a result of drought in some areas in Sudan. Activities associated with urbanization and reductions in vegetation include housing development and increases in seasonally-fallow or nutrient-poor agricultural lands due to food-production pressures (Omer et al., 2015). Secondly, trends analysis of the city of Khartoum rainfall data collected from the city of Khartoum Meteorological Station between 1900 and 1980 shows a significant decrease in rainfall, an indication of climate change (Altahir, 1988).

4.2 Climate Study

Climate data analysis, meant to formulate building design guidelines, often involves presentation of the annual patterns of the main climatic factors affecting human comfort and the thermal performance of buildings in various forms, such as graphical monthly patterns of the local temperatures, humidity, wind speed, cloudiness, etc., as well as bioclimatic charts (Givoni,1992). Since the building life span may extends 50-100 years, it is worthy to evaluate their energy performance relative to current weather and throughout their life cycle with respect to the climate change (Beckett & Dan Sudeyko, 2018). Climate-responsive design strategies take several factors into account: seasonality, sun direction, solar position, readily available natural shading via topographic features around the site, and climatic elements like prevailing winds, rainfall, and humidity. Moreover, it is essential to analysis climate history of a place and predict its future climate in order to achieve a sustainable design strategies.

4.2.1 Climatic Elements

Climate elements are the most significant factors that decide the characteristics of the climate and impact the architectural typology which is adaptable in that climate. These climate elements include solar radiation, air temperature, air humidity, precipitation, and wind (Hausladen et al., 2013).

4.2.1.1 Solar Radiation

Hot climate areas like the city of Khartoum are characterized as having abundant solar radiation. Solar radiation design and control has a great influence on building cooling load calculations (Ahmed & Ahmed, 2011; Abed et al., 2018). The quantity of solar radiation (R) falling on a surface can be categorized by three components; direct solar radiation from the sun (DR); diffused radiation from the sky (DIF_R), and reflected radiation from the earth (REF_R). Therefore $R= DR+DIF_R+REF_R$ (Sharag-Eldin, 1989). Figure 4.3 illustrates solar radiation rates. These include average hourly, maximum hourly, and average daily respectively. The city of Khartoum climate reaches its maximum solar radiation in the Hot Season (March, April, and May). It reaches its minimum solar radiation during the Dry Season (November, December, and January) due to the low solar angle. It is observed that the relative uniformity is similar for average hourly, maximum hourly, and average daily global radiation over the whole year.

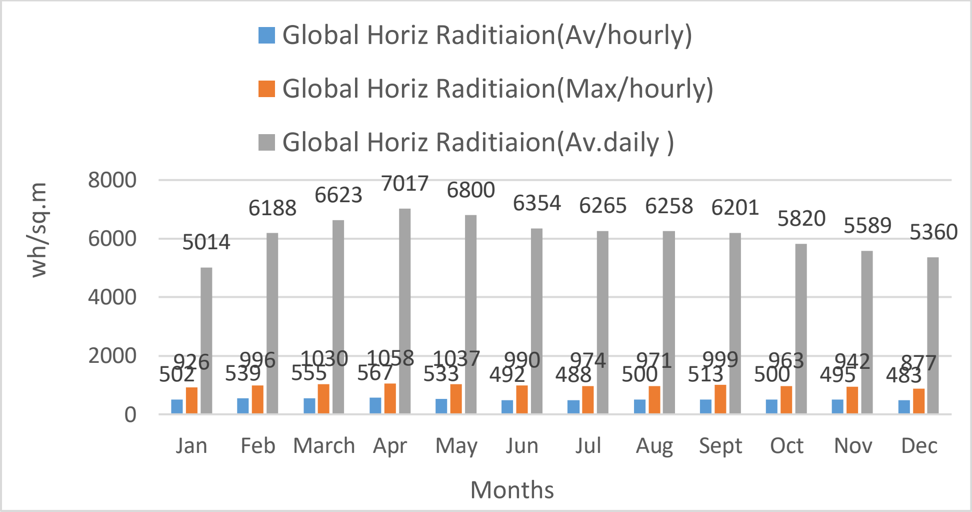


Figure 4.3: Global horizontal radiations for the city of Khartoum, Sudan (Source: Data Source Meteonorm 7.2.1)

The diffused solar radiation distribution follows a different pattern because of cloud cover and variations of sunshine throughout the day. As demonstrated in figure 4.4 the diffuse radiation (average daily and maximum hourly) reaches its maximum value in August 2985 Watt/h/square and minimum value of 1153 Watt/ h/meter square in December , and average hourly reaches its highest values in July 226 watt/hour per meter square. The diffuse radiation reaches its minimum value in January and December which coincide with the Dry Season of the city of Khartoum.

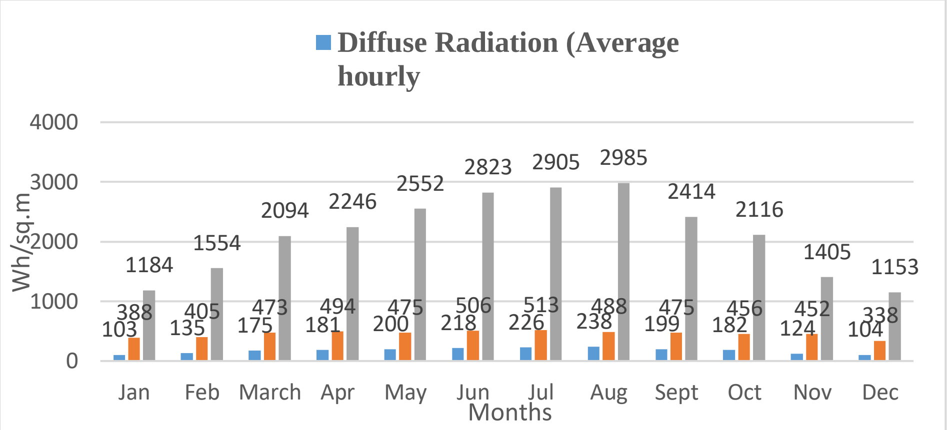


Figure 4.4: Diffuse solar radiation (Av hourly, max hourly and Avg daily)
(Source: Data source Meteonorm 7.2.1)

The sun illumination of the city of Khartoum is affected by cloud cover and monthly sun brightness duration doesn’t vary much in Sudan. The cloud cover is affected by southeast trade winds, which are accompanied by moisture and cause rainfall in most parts of central Sudan from June to September. The highest solar radiation received in the city of Khartoum is in March and April, which coincides with the Hot Season in which the city experiences the highest temperatures and lowest humidity as in the figure 4.5.

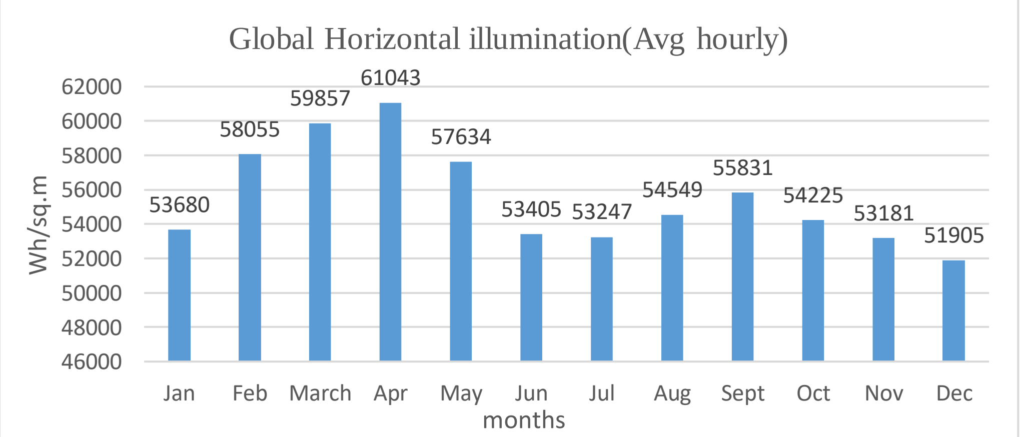


Figure 4.5: Global Horizontal Illumination (Avg Hourly)
(Source: Data Source Meteonorm 7.2.1)

For controlling the solar radiation, there is a need for architects and designers to monitor the sun's movement throughout the year and to provide appropriate shading of windows (Sharag-Eldin, 1989). The quantity of solar radiation penetrating into a building determines the energy demand for air-conditioning of the building (Inanici & Demirbilek, 2000).

4.2.1.2 Temperature

The quantity of annual mean temperature of the city of Khartoum makes it one of the hottest cities in the world (Tahir & Yousif, 2013), temperature normally exceed 40°C during summer. The city of Khartoum's average annual temperature is about 37.1°C. Six months of the year average temperatures might exceed 38°C. Moreover, never in the year does the city of Khartoum's average temperature drop below 30°C. During December and January (Dry Season), temperatures are moderate during the day while at night they may be below 15°C .The average temperature data of the city of Khartoum constitutes mean, high average, and low average temperatures between 1981 and 2015. Figure 4.6 demonstrates that the highest temperature recorded is in May and coincides with the Hot Season. However, it has been mentioned in literature that the city of Khartoum was one of the hottest cities in the world in 2009. The diurnal temperature difference of the city of Khartoum is high in Hot Season exceeding 12°C in the Hot Season, increasing the potential of night ventilation. The Dry Season (November, December, January, and February) of the city of Khartoum has warm daytimes and cool nights that may drop below comfort levels.

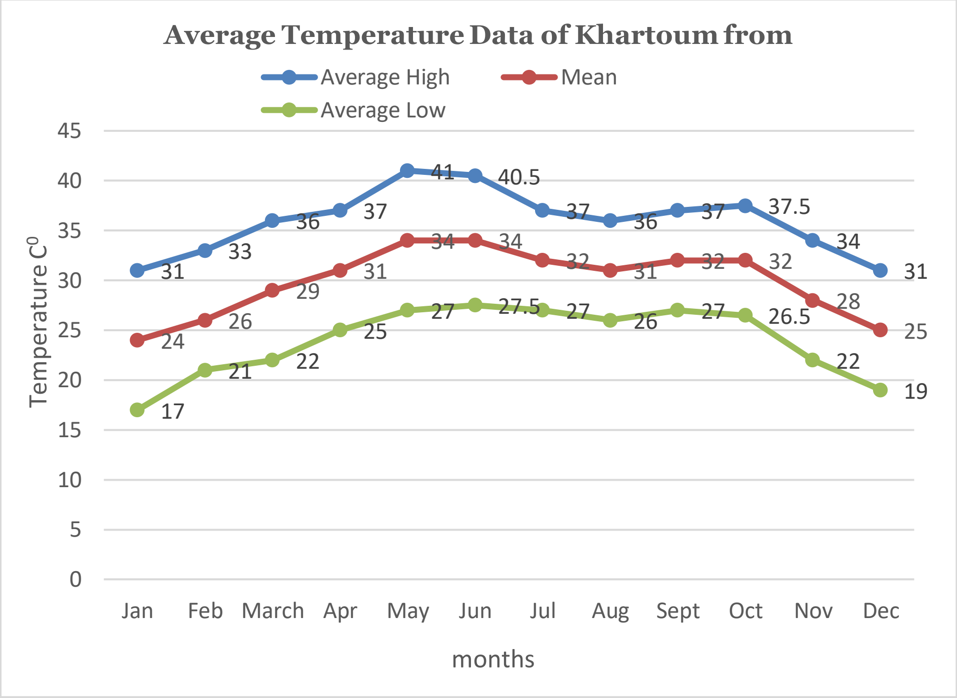


Figure 4.6: Average temperature data of the city of Khartoum
(Source: Data source is Meteonorm 7.2.1)

4.2.1.3 Air Humidity

Air humidity can be measured by one of two methods: relative and absolute air humidity. Absolute humidity of a place is affected by its proximity to large bodies of water and precipitation levels. It is considered a very important factor for indoor and outdoor airflow patterns. Relative humidity (RH) is a ratio of the percentage of water vapor in the air to the air’s moisture saturation level at the same temperature and pressure (Hausladen et al., 2013; Perry et al., 2015; Tahir & Yousif, 2013). Furthermore, absolute air humidity changes as the day progresses and relative humidity is affected by temperature. Minimum absolute humidity values are attained on especially cold days, while maximum values occur when temperatures are highest (Hausladen et al., 2013). The figure 4.7 is a graph representing the average humidity data for the city of Khartoum which shows that humidity is very low during the Hot Season (March-May). The average minimum humidity value can be as low as 9% in April and the maximum average high value in this season is still below the comfort level. Furthermore, humidity in the Dry Season (November, December, January) is still low, the same as in the Hot Season. This indicates that there is a good potential of utilization of evaporative cooling for the city of Khartoum in these two seasons to boost occupants’ thermal comfort. The highest achievable humidity is in the Wet Season (June-October) and the month of August has the highest humidity level among all Wet Season months.

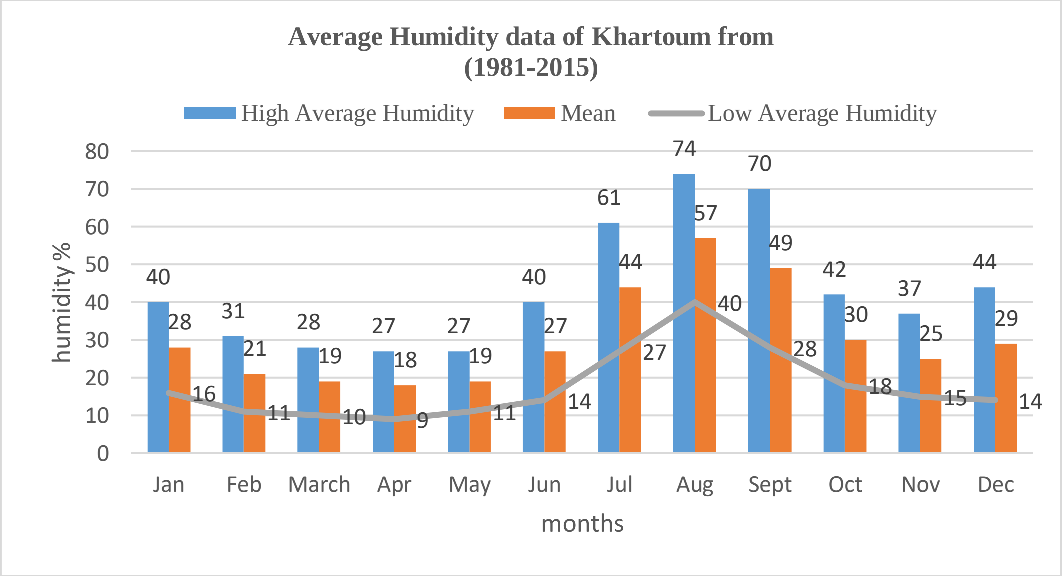


Figure 4.7: Average Humidity data of the city of Khartoum (High Avg, Mean and Low Avg).(Source: Data source is Meteonorm 7.2.1)

4.2.1.4 Wind

It is very important for an architect designer to know about regional wind directions. Knowledge about prevailing wind movement helps to identify appropriate building orientation. However, having the knowledge of wind speed patterns is also necessary because in situations of high-speed winds, there is potential for destruction of various parts of buildings. Therefore, knowledge about the wind speed distribution patterns are important for designer to know. (Zareaian & Zadeh, 2013). As the wind flows through urban areas it is influenced by many factors that may force it to change its speed and direction such as building form, sizes, and other local obstructions such as trees. Wind flow patterns around a building invariably affect the building's interior and environmental quality. Therefore, adapting aerodynamically efficient building's form with rounded corner helps in controlling and suppressing wind's load or reducing wind turbulence (Krautheim et al., 2014).

Monthly average wind data of the city of Khartoum is plotted as in the figure 4.8 illustrates the wind speed behaviour throughout the year and indicates that the wind attains its peak high average in three seasons of the year in the city of Khartoum. In the Dry Season (November, December, January, and February) wind speed average is high in all months of the season, and it is more than 6 meters per second. This attributes to the prevalence of the north and north eastern trade winds crossing from the Sahara Desert and carrying dust (sometimes via sand storms). It modifies daytime temperatures. For the Hot Season (March, April, and May) the average maximum high wind speed is more than 6 meters per second in March and April. It reduces in May but is usually accompanied by dust storms. When considering the Wet Season (June, July, August, September, October), the highest wind speed is in July and August, which are the rainiest months of the season. The southwestern wind is accompanied by moisture and causes rainfall.

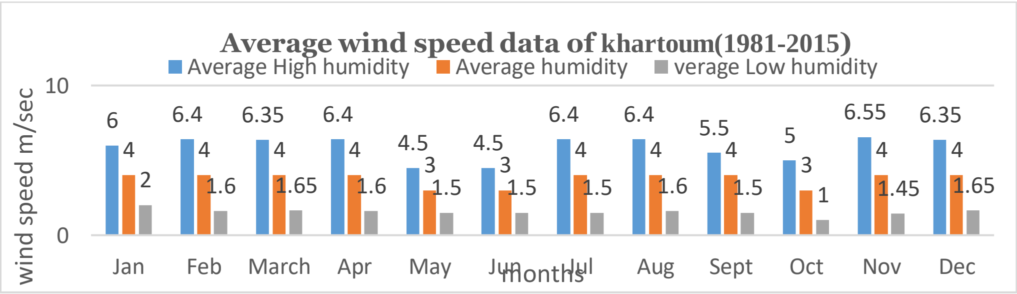


Figure 4.8: Average Monthly Wind speed Data of the city of Khartoum
(Source: Data Source is Khartoum Metrological Station)

Figure 4.9 shows the average hourly wind speed of November, April, and August along with the approximately constant wind speed during the night hours. In the period between 8am to 10 am, the wind speed shows a sharp increase reaching an absolute maximum around 2pm. In the period between 7 pm and 9 pm the wind speed shows a sharp decrease to about 0.8 m/h.

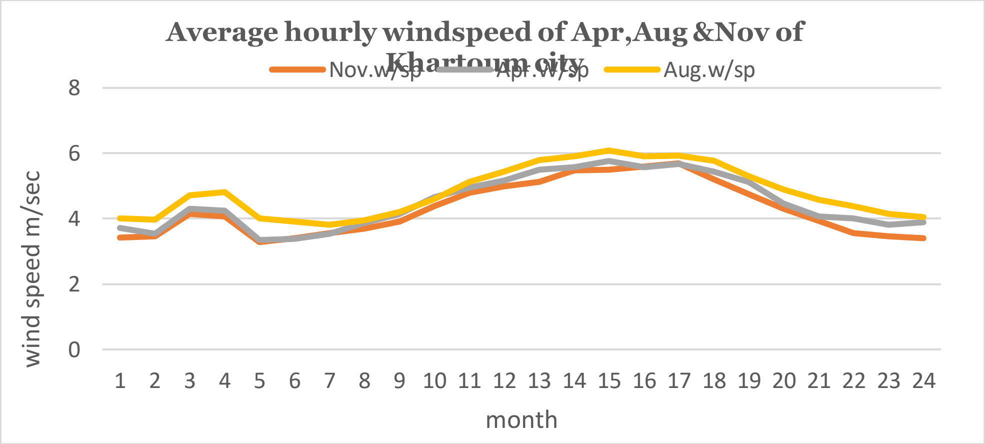


Figure 4.9: Average Hourly Wind speed of April, August and November for the city of Khartoum (Source: Data source Meteonorm 7.2.1)

4.2.1.5 Rainfall

Rainfall in Central Sudan, where the city of Khartoum is located, is caused the domination of dry northern and northeastern winds and humid southwestern winds. The rainfall increases from the northern part of the country to south which is considered dry to the sub-humid south of the country (Mohammed et al., 2014).The Wet Season of the city of Khartoum is between June and October, with the month of August considered the wettest month of the season. More than 80% of the annual rainfall is received between July and September with August averaging 50% of the rainfall received in the 2000s. Although climate warming causes rapid evaporation, the city of Khartoum has experienced frequent rainstorms during the last two decades. These rainstorms resulted in a series of floods in 2003, 2007, and 2009 (Mahmoud et al., 2014; Elagib, 2009; Elagib & Elhag, 2011; Davies & Walsh, 1997; Tschakert et al., 2010). Average rainfall data of the city of Khartoum is plotted in figure 4.10 there are incidences of rainfall in the Dry and Hot Seasons, these are attributed to climate change (Mahmoud et al., 2014).

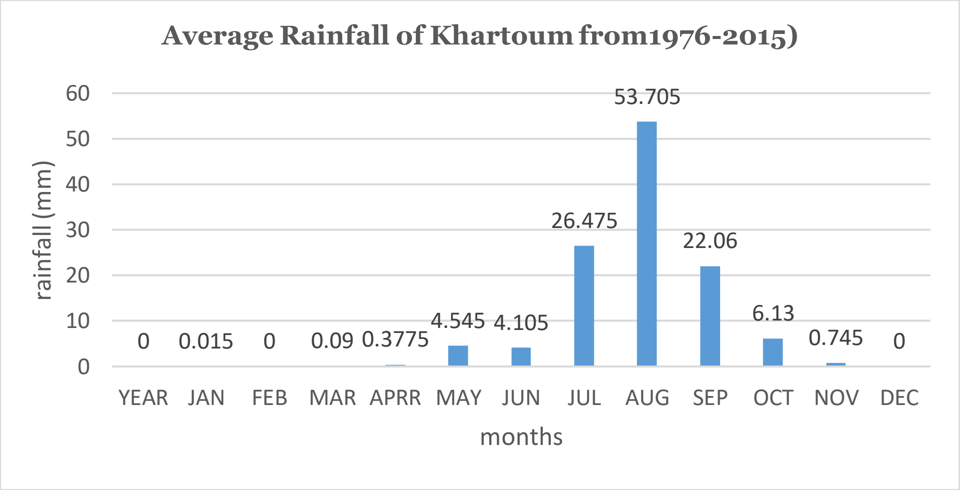


Figure 4.10: Average rainfall in the city of Khartoum
(Source: Data source is Meteonorm 7.2.1)

4.2.1.6 Sand-dust Storm

A dust storm is defined by the World Meteorological Organization (WMO) as " the result of surface winds raising large quantities of dust into the air and reducing visibility at eye level (1.8 m) to less than 1000 m " (McTainsh & Pitblado, 1987; Middleton & Kang, 2017). Sand and dust storms are common climatic hazards in desert and semi-desert regions their occurrence have become a normal phenomenon in recent years in the city of Khartoum. It has been estimated that approximately 40% of aerosols in the troposphere are dust particles from wind erosion. The arid regions in North Africa, the Arabian Peninsula, Central Asia, and China are the main supplier of dust particles in the world. Relatedly, Australia, America, and South Africa make slight contributions .Sand-dust storms generate numerous risks for human society

(Goudie & Middleton, 2006; Middleton & Sternberg, 2013; Middleton, 2017). Sand-dust from these storms accumulates on building roofs, imposing a negative impact on the roof's thermal performance in hot/arid climates region. Many researches have been done on the impact of dust on roofs' thermal performance over long time intervals. Suehrcke et al. (2008), examined the impact of weathering on building solar absorbance for a time span of eight years. They found that weathered white paint with a low initial absorbency of 0.2 exhibited an increase of 15% (Berdahl et al., 2008; Algarni & Nutter, 2015). According to Osman and Sevinç (2019), Sudan is among countries that have been witnessing sand-dust storms. The occurrences of sand-dust storms in recent decades are more frequent than ever (Osman & Sevinç, 2019). Statistics show that more than 0.5% of the time visibility is less than 1km in the north, west, and central regions of Sudan because of sand- dust storms (Ghobrial et al., 1985).

4.2.2 Climate Data Analysis of the city of Khartoum, Sudan

For climate parameters from 1981 to 2015, linear trend analysis was evaluated in order to observe variations which occur in trend equations of climate parameters on a seasonal basis. Monthly averages of the relative humidity, temperature, wind speed, and rainfall were considered and the results are shown in (table 4. 1).

Table 4.1: Trends Equation for Relative Humidity, Temperature, Wind Speed & Rainfall for the City of Khartoum from 1981 to 2015

Parameter	Season	Equation	Comment
Humidity (%)	Dry	y = -0.0163x + 57.349	Decrease
	Hot	y = -0.0669x + 149.86	Decrease
	Wet	y = 0.1792x - 320.14	Increase
Temperature (^{O}C)	Dry	y = 0.0619x - 96.268	Increase
	Hot	y = 0.005x + 23.999	Increase
	Wet	y = 0.0094x + 11.418	Increase
Wind speed (m/s)	Dry	y = 0.0023x - 0.106	Increase
	Hot	y = -0.0094x + 23.08	Decrease
	Wet	y = -0.0018x + 7.6367	Decrease
Rain Fall (mm)	Dry	y = 0.002x - 3.999	Increase
	Hot	y = 0.0079x - 13.873	Increase
	Wet	y = -0.0041x + 30.474	Decrease

4.2.2.1 Season-based Trends Analysis

In this section linear trend analysis is being analyzed for average monthly humidity, temperature, wind speed and rain fall on seasonal basis for Khartoum city of Sudan.

4.2.2.1.1 Dry Season (Nov, Dec, Jan and Feb)

The winter (Dry Season) in the city of Khartoum is characterized as being war at day time, cool from midnight to early hours of the morning with a very low relative humidity (RH); RH minimum values between 8% and 10% are common. The trend analysis indicates that RH has been decreasing annually by 0.02% and temperatures during the Dry Season exhibit an annual increase of 0.1 °C. Reductions in plant cover, as revealed by Mohamed and Babiker (2015), account for both the decrease in RH and the seemingly contradictory increase in rainfall (Omer et al., 2015). Rainfall’s annual increase during the Dry Season is not a normal phenomenon for the city of Khartoum and therefore invariably a sign of climate change.

Variations in climate parameter’s for the Dry Season are shown in table 4. 1. Trend analysis of the city of Khartoum climate data from 1981 to 2015 shows that climate change has occurred. While the in the city of Khartoum is historically characterized by northern winds which pass through the greater desert and are accompanied with dust and sand storms, proven climate change will also make the occurrence of dust and sand storms more frequent than ever before.

4.2.2.1.2 Hot Season (March, April and May)

The hot summer season in the city of Khartoum has low relative humidity with the minimum temperatures value of 16.6 ^{0}C after midnight and maximum is often above 40 ^{0}C at afternoon .Trend analysis of climate parameters displays an annual decrease of RH by 0.07%, an annual increase of temperature by 0.010°C, an annual decrease of wind speed by 0.002 meters per second, and an annual increase of rainfall by 0.01 mm. These results reveal climate changes during the 1981 to 2015 s and projections mean more extreme temperatures and lower RH and wind speeds in the city of Khartoum's future s. Relatedly, Yousif and Hashim (2013) disclosed that the city of Khartoum was the hottest city in the world during 2009. Moreover, Sayed and Abdala, (2010) have already revealed that Khartoum city temperature has witnessed an increase between 1901 and 2009.

4.2.2.1.3 Wet Season (June, Jul, Aug, Sept and Oct)

Khartoum's autumn (Wet Season) is characterized as being hot and maximum temperature is above 40 ^{O}C at noon and can reduce up to 12.5 ^{O}C after midnight. This could provide appropriate condition for the operation of night ventilation. Among Wet Season months August is wettest month. Trend analysis of Wet Season parameters from 1981 to 2015 provides four findings. Even though there was an annual reduction of rainfall by 0.004 mm during this season, the city witnessed severe flooding due to extreme rainfall events in 1988, 2003, 2007, and 2009. Despite the reduction in rainfall, an annual increase of RH by 0.2% was observed. These alone could be considered as sign of climate change but the city of Khartoum also experienced an annual increase in temperature of 0.02^{0}C and an annual reduction in wind speed by 0.002 meters per second. The trend analysis' decrease in wind speed, increase in temperature, and decrease in rainfall shows that climate change has happened during the period from 1981 to 2015. This is in line with the work done by Althir (1988) and Yousif and Hashim (2013) (Altahir, 1988; Tahir, Abdala and Sayed, 2010 & Yousif et al., 2013).

4.3 Climate-Responsive Building-Design Strategies Adapted

4.3.1 Comfort Model

The adaptive comfort model used in this study assumes that buildings are naturally ventilated and occupants can close and open windows according to their thermal desires. Hence, building users' thermal response will depend in part on the outdoor climate and may have a wider comfort range than those in buildings with centralized heating ventilation and air-conditioning (HVAC) systems. For the ASHRAE Standard 55 model, there must not be any mechanical cooling system nor does this method apply if a mechanical heating system is in operation (Rubio et al., 2015). Furthermore, the model assumes that occupants can adapt their clothing according to expected thermal conditions.

This comfort model is suitable for application in the hot and arid climate of the city of Khartoum, Sudan. Comfort zone plotting in a psychometric chart is a well-known design tool used to plan in the early design stages for optimum thermal comfort of building occupants. Numerous researchers in the field of building and sustainable environment have undertaken these issues (Nguyen and Reiter, 2014). Meteonorm Company calculated climatic hourly weather files for 1996 to 2015 from average climatic data of the city of Khartoum. Subsequently, the files were processed through Climatic Consultant 6.0. ASHRAE Standard 55 model was selected in order to calculate contemporary thermal comfort for the city of Khartoum. When ASHRAE Standard 55-2010 adapted for natural ventilation in the city of Khartoum, annual thermal comfort is achieved in (2119 hours) out of the total hours of the year which is (8760 hours) and these constitute (24.2%)of the year as in the table 4.2. Based on monthly thermal comfort values, it was observed that it is most difficult to achieve thermal comfort using this model during the city of Khartoum's Hot Season. In the month of May the minimum temperature is about 23.5 ^{0}C after midnight and reach its peak value of 45.5 at afternoon and the minimum relative humidity at noon is 10% and after reach its highest value at midnight 40%, this drastically reduce thermal comfort to 6.3% (47 hours), however, since the diurnal temperature is above 20 ^{0}C then night ventilation could be utilized. Moreover, in June which coincide with Hot season temperature ranges from 43.9 to 24.3 and the relative humidity is between 53% to 12% and it is not possible to achieve thermal comfort without using active cooling . The highest thermal comfort from natural ventilation is achieved in the dry winter season with November having the highest thermal comfort 32.9% (237 hours) of all Dry Season months.

Table 4.2: Adaptive Comfort Model in ASHRAE Standard 55—2010 applied in the city of Khartoum, Sudan for the year 2015

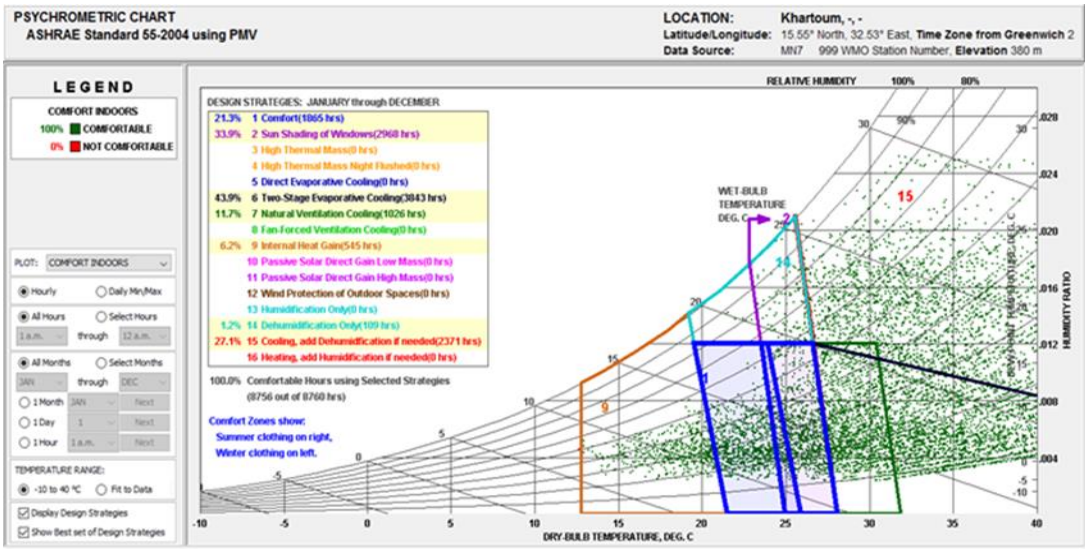
Months	Comfort	Comfort (Hours)	Total Hours
Jan	28.4%	211	744
Feb	27.8%	187	672
March	28.1%	209	744
Apr	26.4%	190	720
May	6.3%	47	744
June	0%	0	720
Jul	18.1%	135	744
Aug	33.2%	247	744
Sept	30.8%	222	720
Oct	30%	223	744
Nov	32.9%	237	720
Dec	28.4%	211	744
Annual	24.2%	2119	8760

4.3.2 ASHRAE Standard 55 and Current Handbook of Fundamental Model

The adaptive comfort model used in this study is based on American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 55 and its current handbook of thermal comfort. This model considers dry bulb temperature, clothing level (clo), metabolic activity (met), air velocity, humidity, and mean radiant temperature (MRT). It is assumed that MRT and dry bulb temperature are similar. The zone in which most people are comfortable is calculated using the Predicted Mean Vote (PMV) model. Moreover the adaptive comfort model reflects that in residential buildings, which are predominantly naturally ventilated and people adapt clothing in a way to match seasonal conditions and feel comfortable in higher air velocities. So, they have wider comfort ranges than those in buildings using central air-conditioning systems (Altahir et al., 2013).

In accordance with these specifications, solar control is one of the most valuable strategies in modifying thermal comfort in climates like the city of Khartoum's.

Sudanese vernacular architecture provides excellent techniques for managing solar heat gain: the design of a roof to shade itself; and rotational use of space where open and semi-open spaces are used for instance for relaxation and sleeping during different periods. Besides the mentioned strategies, other commonly adapted design strategies are two-stage evaporative cooling, natural ventilation, humidification, and active cooling. It is not possible to achieve 100% thermal comfort without using mechanical cooling systems which increase thermal comfort by 27.1% of the total comfort. Through combination of these thermal-comfort strategies with a mechanical cooling system 72.9% (6385 hours out of 8760 hours) of thermal comfort can be achieved, see figure 4.11. The comfort range without using any design strategies is reduced to 21.3% and 24.2% thermal comfort is achieved by using the adaptive comfort model. The little variations achieved through this research contributed to global horizontal solar radiation control and relative humidity modification with adoption into the thermal comfort model. Reduction in relative humidity as a result of plant cover reduction in the city in recent decades may also be influential factor.


PSYCHROMETRIC CHART
ASHRAE Standard 55-2004 using PMV

LOCATION: Khartoum, -, -
Latitude/Longitude: 15.55° North, 32.53° East, Time Zone from Greenwich 2
Data Source: MN7 999 WMO Station Number, Elevation 380 m

DESIGN STRATEGIES: JANUARY through DECEMBER
21.3% 1 Comfort(1865 hrs)
33.9% 2 Sun Shading of Windows(2968 hrs)
3 High Thermal Mass(0 hrs)
4 High Thermal Mass Night Flushed(0 hrs)
5 Direct Evaporative Cooling(0 hrs)
43.9% 6 Two-Stage Evaporative Cooling(3843 hrs)
11.7% 7 Natural Ventilation Cooling(1026 hrs)
8 Fan-Forced Ventilation Cooling(0 hrs)
6.2% 9 Internal Heat Gain(545 hrs)
10 Passive Solar Direct Gain Low Mass(0 hrs)
11 Passive Solar Direct Gain High Mass(0 hrs)
12 Wind Protection of Outdoor Spaces(0 hrs)
13 Humidification Only(0 hrs)
1.2% 14 Dehumidification Only(109 hrs)
27.1% 15 Cooling, add Dehumidification if needed(2371 hrs)
16 Heating, add Humidification if needed(0 hrs)

100.0% Comfortable Hours using Selected Strategies
(8756 out of 8760 hrs)

Comfort Zones show:
Summer clothing on right,
Winter clothing on left.

Figure 4.11: Psychometric chart with climate responsive Design strategies applied in the city of Khartoum. (Source: Climate Consultant tool 6.0. (Source; Author)

When appropriate shading of windows is applied it increases thermal comfort by 33.9% (zone 2). The strategies of internal heat gain (zone 9), active cooling (zone 15), and natural ventilation (zone 7) improve thermal comfort by 6.2%, 27.1%, and 11.7% respectively. Although two-stage evaporative cooling has no direct impact on thermal comfort and it contributes up to 43.9% and it is suitable in all seasons of the year and its efficiency is reduced only in Wet Season. If evaporative cooling is not used, it would increase active cooling rate from 27.1% to 59.5%. In otherward two- stage evaporative cooling should be adapted to reduce any discomfort that may occur and to reduce active cooling load. The combined use of both active cooling and two-stage evaporative cooling (Indirect-Direct evaporative cooling) is valuable in the city of Khartoum because together they can improve thermal comfort up to 59.5%.

A classification of design strategies for each season is shown in table 4.3. A thermal comfort of 41.7% can be achieved in the Dry Season, 22.9% in the Hot Season and 4.3% Wet Season.

Table 4.3: Classification of design strategies on seasonal basis for the city of Khartoum, Sudan for the year 2015

Design Strategies	Dry Season	Hot Season	Wet Season
Comfort	41.7 % (1200 hrs)	22.9% (506 hrs)	4.3% (159 hrs)
Sun shading	30.1% (867 hrs)	35.9% (792 hrs)	35.8% (1313 hrs)
2 stage evaporative cooling	40.9% (1179 hrs)	72.8% (1608 hrs)	28.8% (1056 hrs)
Internal heat gain	17.3% (498 hrs)	-	-
Active cooling	-	-	63.3% (2324hrs)
Natural Ventilation	-	-	7.7%(282 hrs)

In the Dry Season, two-stage evaporative cooling is the most influential strategy. It has directs impacts on thermal comfort and contributes about 40.9% (1179 hours out of 8760 hours). Window shading is most important from 10:30 AM to 3:00 PM during this season. Using thermal mass could enhance indoor thermal comfort when outdoor temperature is below comfort level after midnight.

In the Hot Season about 22.9% thermal comfort can be achieved without adapting any design strategies, and this constitute 506 hours out of 8760 hours of the whole year. To achieve optimal thermal comfort, window shading from 9:00 AM to 5:00 PM is needed to protect building interiors from overheating. A combination of active cooling and two-stage evaporative cooling is better even though two-stage evaporative cooling contributes 72.8% (1608 hours out of 8760 hours) because it doesn’t have direct effect on thermal comfort in this season. If not used it would increase active cooling demand from 2.1% (47 hours) to 75% (1655 hours). Moreover internal heat gain is another strategy that should not be neglected because it help in enhancing indoor thermal comfort in Dry season from midnight to 6am it can contribute to up to 41.4% (348 hours) comfort.

The Wet Season is one of the hottest seasons in the city of Khartoum, the minimum temperature is 12.5 ^{0}C and the maximum temperature can reach up to 43.9 ^{0}C; as a result a thermal comfort of only 4.3% can be achieved without using any strategy. Window shading is most advantageous from 8:30 AM to 5:00 PM to avoid overheating. Active cooling is the most important strategies to achieve thermal comfort during the Wet Season; they constitute 63.3% (2324 hours) and directly affect thermal comfort. It should be used congruently with two-stage evaporative cooling. If two- stage evaporative cooling is not used, the cooling demand would increase from

63.3% (2324 hours) to 85% (3122 hours). Dehumidification only contributes about 3% to thermal comfort in the Wet Season but directly affects thermal comfort. Natural ventilation is an applicable design strategy only in the Wet Season.

Finally, precautions should be taken to control sand-dust storms which occur at different times of day throughout the year. Miller et al. (2014), after observing *Haboob* in the city of Khartoum's central district for eight years, found that dust-storm wall height could exceed one kilometer and each storm could last from 30 minutes to several hours. Moreover, these storms occurred 50% of the days between May and June and 70% of days from July to September during these period of time the maximum temperature is often above 40 ^{0}C at noon and may drop after mid-night till 20 ^{0}C (Miller et al., 2008). For these reasons, when air is admitted into buildings it should pass through a series of filters. This can be done at the urban scale by planting trees in a buffer surrounding the city, and at building scale by installing a series of filters in air inlet locations.

4.3.3 Passive Cooling Strategies Adaptable in the city of Khartoum, Sudan

Adapting passive cooling measures in building design and construction denotes utilizing any design techniques or feature that help in providing optimum living condition for building dwellers without the need for using energy **(**Taleb, 2014). Passive strategies using in building has become more popular after 1970s energy crisis. In order for the passive cooling strategies to operate effectively climate should critically be analyzed. The board strategies that are to be discussed in this research are heat-loss promotion and heat removal strategies.

4.3.3.1 Heat-loss Promotion Strategies

Heat loss-promotion can provide optimal thermal comfort for buildings occupants if properly applied. For this strategy to function best, the industry needs more developed techniques related to heat dissipation. Heat dissipation utilizes naturally-existing air pressure and the pressure differences between inside and outside a building to move hot air away when outside air is cooler than outside. This technique can be broadly categorized into; natural ventilation and natural cooling.

4.3.3.1.1 Evaporative Cooling

Evaporative cooling is a heat and mass transfer process that uses water evaporation for air cooling. In this process a large amount of heat is transferred from air to water and consequently the air temperature decreases. The three types of evaporative coolers are direct evaporative coolers, in which the working fluids (water and air) are in direct contact; indirect evaporative coolers, where a surface/plate separates the working fluids; and a combined system of direct and indirect evaporative coolers with or without other cooling cycles. Evaporative cooling, as the name implies, depends on climatic conditions more than active cooling. By their very nature, Evaporative Cooling Systems are more dependent on climatic conditions than mechanically cooled systems that is why to study the characteristics and performance of ECSs, local climate analysis is very important (El-Refaie and Kaseb, 2009).

4.3.3.1.1.1 Wet Bulb Depression (WBD)

Wet Bulb Depression (WBD) is one of the most influential parameters determining the efficiency of evaporative cooling. It is defined as the difference between Dry Bulb Temperature (DBT) and Wet Bulb Temperature (WBT). As WBD increases, the efficiency of evaporative cooling increases (Hui and Cheung, 2009).

4.3.3.1.1.2 Major Properties of Wet Bulb Depression in the city of Khartoum, Sudan

Analysis of average monthly Wet Bulb Depression of the city of Khartoum data (plotted in figure 4.12 shows that wet bulb depression (WBD) is highest in the months of April and May thus evaporative cooling is a very effective strategy during these months. The month of August has the lowest WBD paired with low efficiency of evaporative cooling strategies, therefore active cooling is the more effective strategy recommended by Climate Consultant 6.0 for August.

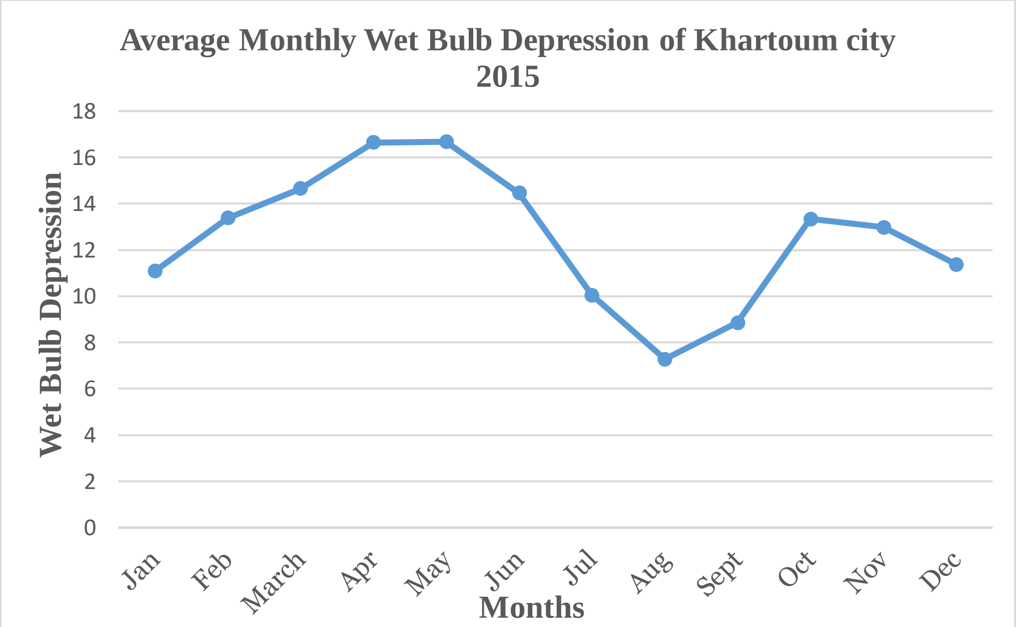


Figure 4.12: Average Monthly Wet Bulb Depression (WBD) in the city of Khartoum (Source: Meteonorm)

Furthermore, by comparing evaporative cooling efficiency of 2015 and 2070 (plotted in figure.4.13) and table 4.4 show that there might be a decrease of 5.57% in the efficiency of evaporative cooling in the Dry Season of 2070 compared to 2015, while efficiency in Hot Season of 2070 is projected to be slightly higher than 2015 by 0.3%. Pertaining Wet Season, evaporative cooling efficiency will be more efficient in 2070 than 2015 by 3.5%. Increased efficiency of evaporative cooling in Wet Season in 2070 indicates the weather of Khartoum in Wet Season is projected to be dryer that it used to be, therefore this an indication of climate change. Moreover, comparing the annual efficiency for 2015 and 2070 show that there is 0.64% decrease in 2070 compared to 2015.

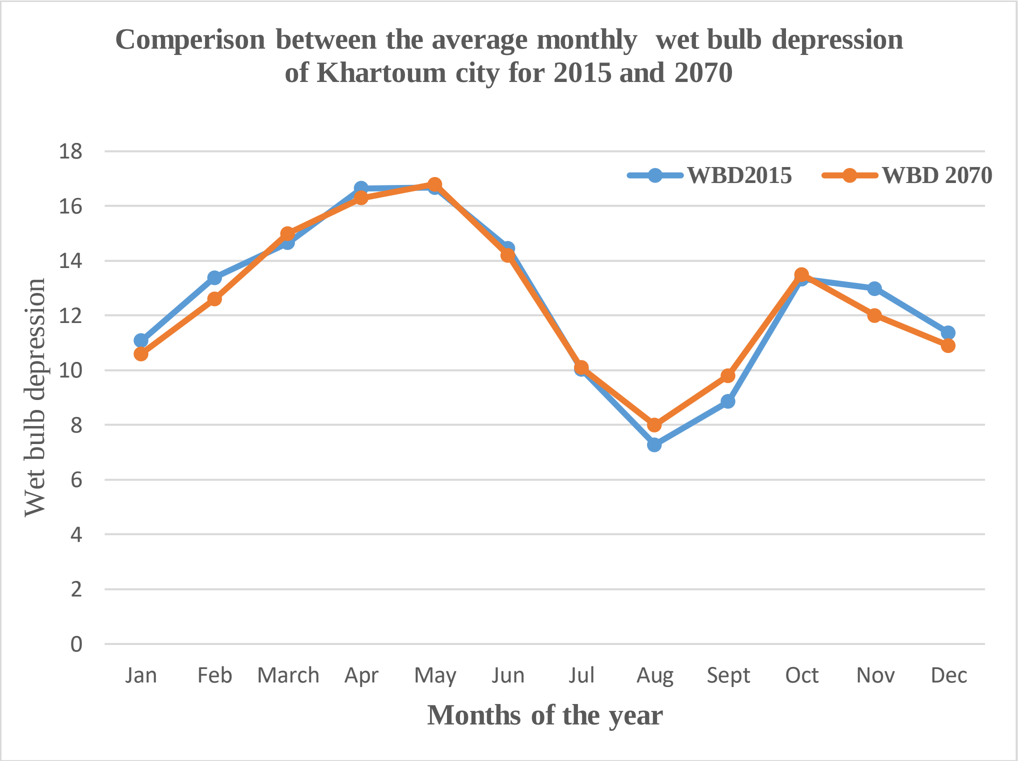


Figure 4.13: Average Monthly Wet Bulb Depression (WBD) in the city of Khartoum, Sudan (Source: Meteonorm)

Table 4.4: Comparison between WBD in 2015 and 2070

Season	Months	2015 ^{O}C	Average Seasonally	2070 ^{O}C	Average Seasonally	Change Seasonally %
Dry	NOV	12.98	12.2	12	11.52	-5.57
	DEC	11.37		10.9		
	JAN	11.07		10.6		
	FEB	13.38		12.6		
Hot	MAR	14.65	15.98	15	16.03	+0.31
	APR	16.64		16.3		
	MAY	16.67		16.8		
Wet	AUG	14.46	10.79	14.2	11.12	+3.05
	SEP	10.04		10.1		
	OCT	7.28		8		
	NOV	8.85		9.8		
	DEC	13.33		13.5		
Annual Average		12.56		12.48		-0.64

Also in figure 4.14 the analysis of hourly Wet Bulb Depression for the month of May, which is one of the hottest months and it can reach maximum of 45.4 ^{0}C at afternoon. However, this indicate that WBD changes over the course of the day and is higher between 8:00 am and midnight (14.7^{0}C). As such, evaporative cooling works more efficiently during these times of the day.

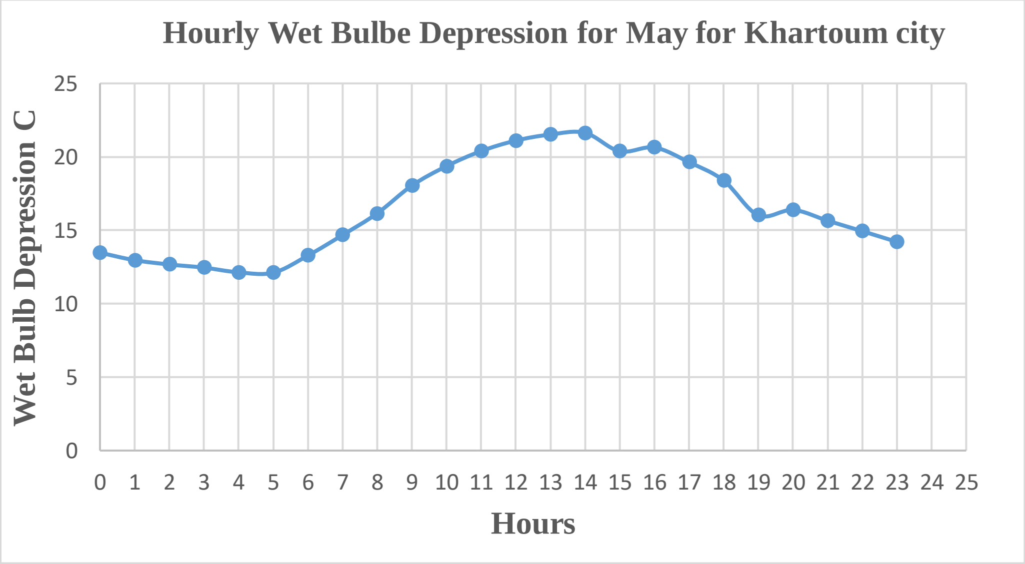


Figure 4.14: Average Hourly Wet Bulb Depression (WBD) for the city of Khartoum for Month of May (Meteonorm).

By comparing the efficiency of 2015 and 2070 as in figure 4.15 below, there is general decrease of 1.5 and 1.4 ^{O}C in the WBD at 3 pm and 9 pm respectively for 2015 year series compared to 2070. This give indication that active cooling is highly needed in 2070 compared to 2015.

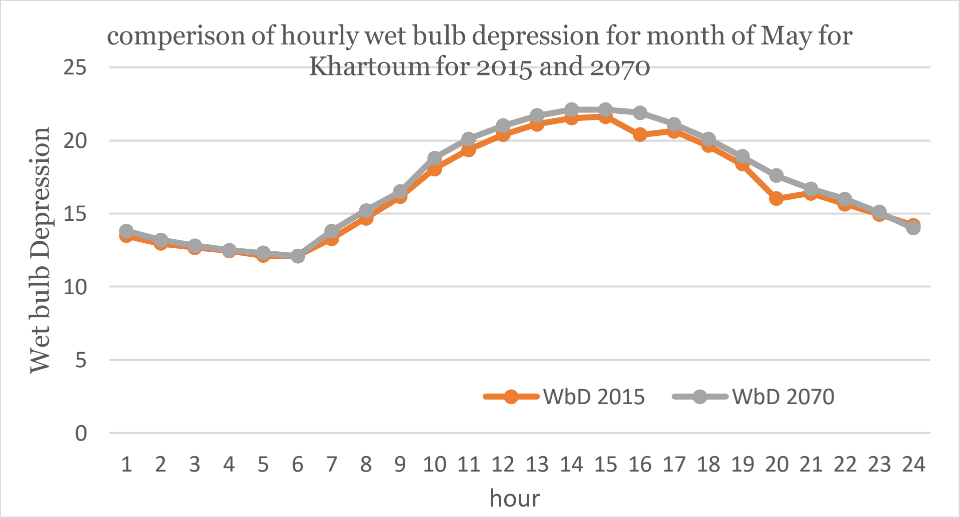


Figure 4.15: Comparison between Hourly Wet Bulb Depression (WBD) for the city of Khartoum for the Month of May 2015 and 2070. (Source: Data acquired from Meteonorm)

4.3.3.1.1.3 Two-stage Evaporative Cooling

Several suitable passive and active cooling strategies can be applied to buildings in the city of Khartoum. Based on Climate Consultant 6.0 analysis, two-stage evaporative cooling seems the most suitable cooling strategy for the city of Khartoum in both Dry and Hoy Seasons of the year. Two-stage evaporative cooling comprises indirect evaporative cooling in stage one which provides precooled air to the direct evaporative cooling system in stage two (Sharag-Eldin, 1988). ASHRAE makes it known that two-stage evaporative cooling can use 60% to 70% less power than a normal air-conditioning system. This makes two-stage evaporative cooling an effective, sustainable, and energy-efficient cooling strategy. The success of this cooling strategy is dependent on the WBD that occurs between wet bulb temperature and dry bulb temperature (Ambade, 2015). The way two-stage evaporative cooling systems operate shows in figure.4.16

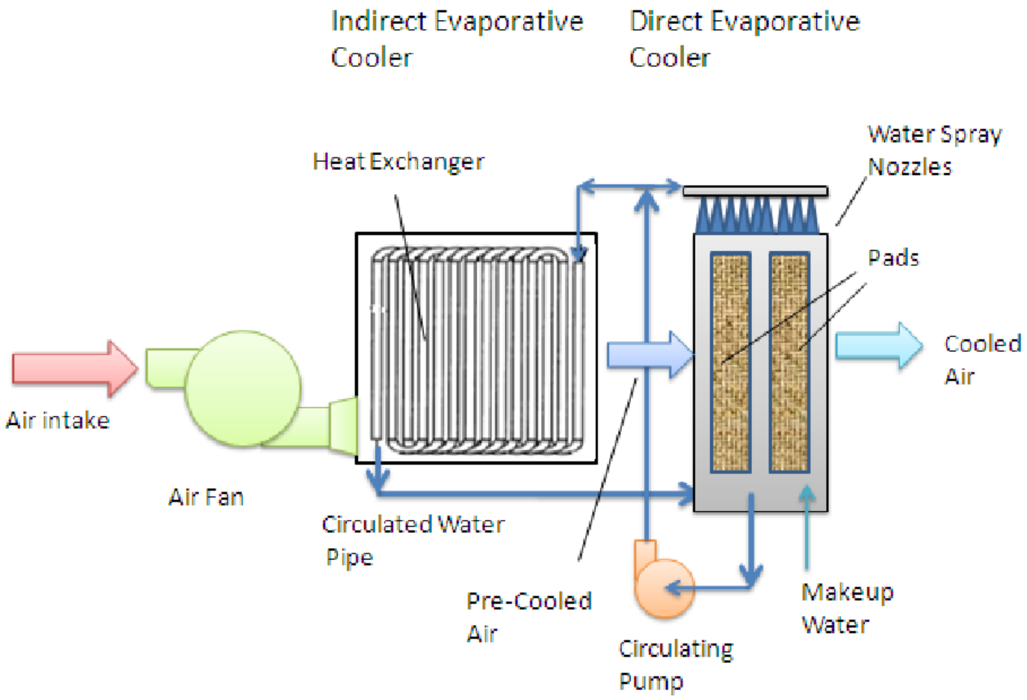


Figure 4.16: Two-stage Evaporative Cooling System
(Source adapted from Al-Juwayhel, et al. (2004)

As noted before, the city of Khartoum's climate is characterized as having low relative humidity; consequently, this cooling strategy can provide thermal comfort for building users. In order for this cooling strategy to function best, 100% external air movement should be guaranteed. Without external air movement, indoor relative humidity would increase beyond the comfort level of building users. According to Sharag-Edin (1988), during the Hot Season of the year in the city of Khartoum when used in afternoon, two-stage evaporative cooling can reduce dry bulb temperature from 43.9 ^{O}C up to 29 ^{O}C and increase relative humidity for the same period of the day from 10% up to 60% provided outside air blends with inside air upon entry. Furthermore, two-stage evaporative cooling is an appropriate design strategy in the city of Khartoum during its Dry Season. When building envelopes are insulated, it increases thermal comfort by 17.3% (498 hours). See matrix table 4.6

During the Hot Season, buildings with appropriate thermal insulation may improve comfort zones by 2.1% (47 hours) reducing the demand for active cooling (Table matrix 4.6). The Wet Season has the least efficient use of two-stage evaporative cooling among the seasons due to relatively high humidity; natural ventilation is the best strategy for increasing the comfort zone during this season (Table matrix 4.6).

4.3.3.1.1.4 Advantages of Two-stage Evaporative Cooling

There are five advantages of two-stage evaporative cooling. It is energy and cost efficient and more appropriate in areas where direct evaporative cooling is insufficient. It consumes half as much energy as air-conditioning systems use and its construction is more cost efficient. It provides better thermal comfort than compressor-based systems and can replace mechanically-refrigerated cooling systems. It provides 100% cooling and internal air quality is improved through the insertion of fresh air; 25 to 40 air changes per hour makes it similar to natural ventilation. This cooling strategy uses evaporation which makes it environmentally friendly.

4.3.3.1.1.5 Disadvantages of Two-stage Evaporative Cooling

There are four disadvantages of two-stage evaporative cooling. It is inefficient in coastal areas where relative humidity is high. There are significant temperature variations in the cooled space throughout the year depending on the prevailing ambient dry and wet bulb temperatures (Ambade, 2015). It requires frequent maintenance. The entire system may fail in situations when there are water shortages and power failures such as are common in hot dry areas like the city of Khartoum (Ambade, 2015).

4.3.3.1.2 Natural Ventilation

Natural ventilation is one of sustainable cooling strategies relied upon to achieve thermal comfort. In hot and dry climates when outside temperature is beyond tolerable levels, it is more appropriate to close windows until temperatures decrease to more acceptable levels (Aynsley, 2014). The potentiality for using natural ventilation strategies depends significantly on the local climate (Chen et al., 2017). Natural ventilation is not a best practice for all seasons in Khartoum but is appropriate during the Wet Season. In hot-arid climates, however, natural ventilation should be avoided during the day, and night ventilation should be favoured for cooling the structure. The most efficient way to optimise these contrasting needs is provided by adapting courtyard system (Butera and Adhikari, 2015). Night ventilation strategies function well with appropriate building thermal mass in the city of Khartoum. Night coolness occurs as a result of increased wind movement and humidity rising from the Nile River. Figure 4.17 illustrates night ventilation.

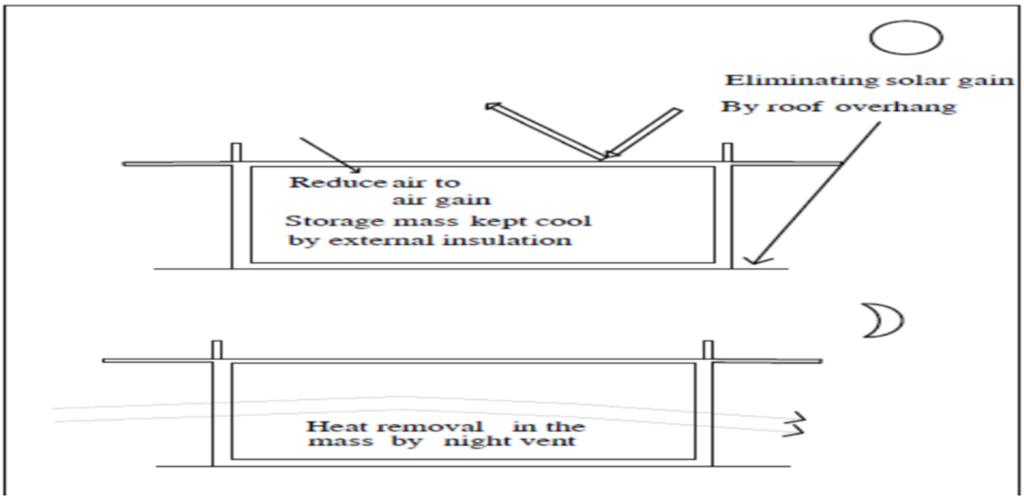


Figure 4.17: Night Ventilation in the city of Khartoum City

Natural ventilation in the city of Khartoum is utilized in the daytime during Dry Seasons and during the night. However, the best season to use natural ventilation is the Wet Season. The best time of the day to employ natural ventilation in the Wet Season is from midnight until 6:00 AM because of increased humidity and wind speed. Natural ventilation is also efficient though less so from 6:00 AM until noon as illustrated in table 4.3.

Building form and position and size of windows dictate operational efficiency of natural ventilation. Single-sided ventilation, cross-ventilation, and stack ventilation are the most common ventilation principles providing thermal comfort for the city of Khartoum's building users (Kleiven, 2003). Furthermore, Shakurov et al. (2016) on his research on Khartoum city climate promoted simultaneous exposure of microclimate effects of natural ventilation on temperature, humidity and wind speed. The temperature difference between 8:00 AM and 5:00 PM in green areas of sandy-soil regions minimum temperature ranges from 15°C to 20°C while those in loamy-soil and asphalt regions can reach maximum temperature of 45°C (Shakurov et al., 2016). Appropriate architectural and urban design strategies help improve microclimate conditions of the city. Finally, for natural ventilation, Sudan is blessed with abundant renewable energy sources in the forms of wind, solar, and water. When adequately utilized, these provide prime cooling solutions for buildings. However, in order to achieve maximum benefit from natural ventilation there are various building design elements such as solar chimneys, wind towers that stimulate air movement (Brager and de Dear, 2000).

4.3.3.1.3 Solar Chimneys

Utilization of passive-solar strategies in building design is a sustainable solution capable of reducing energy usage as much as 25% (Godoy-Vaca et al., 2017). Solar chimneys are one passive-solar strategy that exploits renewable energy to improve a buildings’ interior air quality (Mehani and Settou, 2012). It uses a combination of solar stack-assisted and wind-driven ventilation. The solar chimney is most appropriate for low-rise buildings which include about 80% of buildings in the city of Khartoum. Double-skin façade are a more appropriate solar strategy for high-rise buildings. In both cases, air inside the chimney or gap expands as a result of solar heating and become less dense. The lighter, hotter air rises out of the top vent dragging cooler breezes from the bottom through windows. These strategies can be complemented further by outside wind pressure, by pressure differences between the interior and exterior air temperature, and by inducing greater pressure difference via temperature differences and increased stack height (Tan and Wong). These strategies are appropriate in almost all season of the year if located and designed in accordance with location and direction of solar radiation.

The following figure 4.18 illustrates how the solar-chimney strategy when used for cooling can be enhanced when used in combination with trombe walls. Together they can encourage hot air removal from indoor spaces and promote air exchange between the built-up, hot indoor air and the cool outdoor air at night. This strategy operates as the cool air flows in to buildings through tunnels located within the floor or foundation. The double-layer floors together with double-layer walls form a thermal-siphon Diurnal temperatures differences in the city of Khartoum are large enough that cool, night air can be stored in the floor and wall cavities and as building interior spaces warm up during the day, the siphoning effect can draw the cooled air into the interior spaces without the need for mechanical cooling systems. This strategy may perform better in the city of Khartoum if the building's interior spaces are well protected from direct solar radiation and the fenestrations are designed and positioned to take advantage of cool outdoor air which cooled by underground pipes and landscaped patio with sun protection sails and shading trees. Furthermore, the manner in which the architect adjusts the exterior landscape, courtyards, and building's interior space determines the extent of this strategy's success.

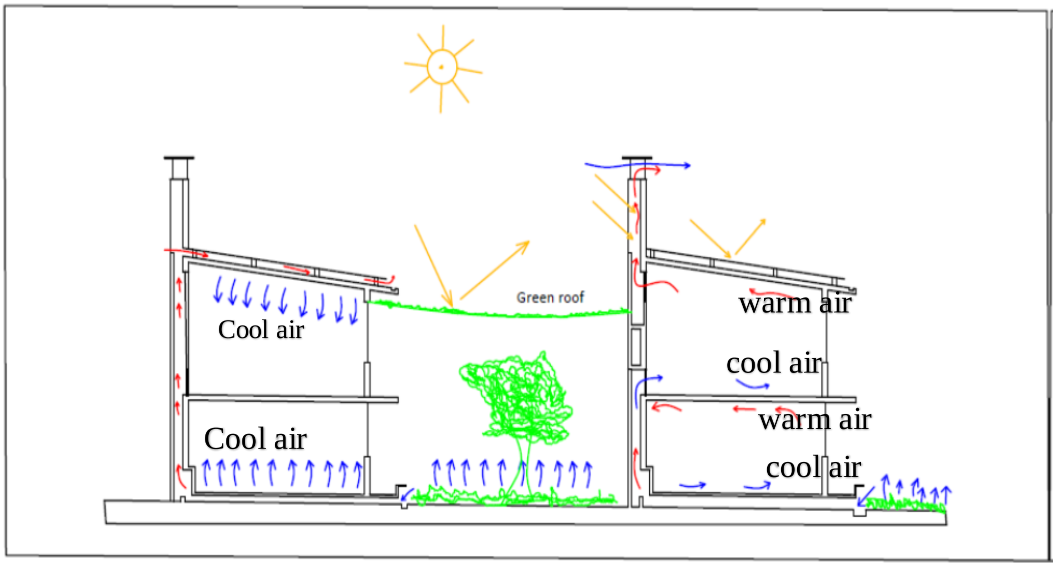


Figure 4.18: Solar chimneys with Trombe walls for natural ventilation promotion

4.3.3.1.4 Wind Towers

Wind towers have been used to provide cooling effects on building interiors in hot, arid regions for centuries. Wind towers face challenges when used in dense urban areas where local airflow is invariably affected by the arrangement of buildings. In desert regions, wind towers face dust-sand storm phenomenon and their heights should be adjusted to rise above the level where winds carry most of the sand and dust. With the latter adaptations, construction and maintenance costs increase (Calautit et al., 2013).

Wind towers shows in figure 4.19 operate in three ways. First, they direct prevailing winds downward from up high and toward building-interior spaces. The efficiency of enhancing building air quality with this strategy depends on exterior airflow rate and temperature. Second, wind-assisted temperature gradient strategy connects an underground tunnel to a tower with an opening facing away from the prevailing wind direction. When the tower is open, air is sucked upward and downwind by stack effect. The efficiency of wind-assisted temperature gradient strategy can be enhanced with evaporation cooling. Third, wind towers can work like solar chimneys when heated air in the tower rises through the opening encouraging cool air to move into building interiors from other fenestrations or vents (Ahmadikia et al., 2012). However, in situations where by there is high diurnal temperature difference, wind towers of mud-brick are cooled by radiation and convection (Ahmadikia et al., 2012).

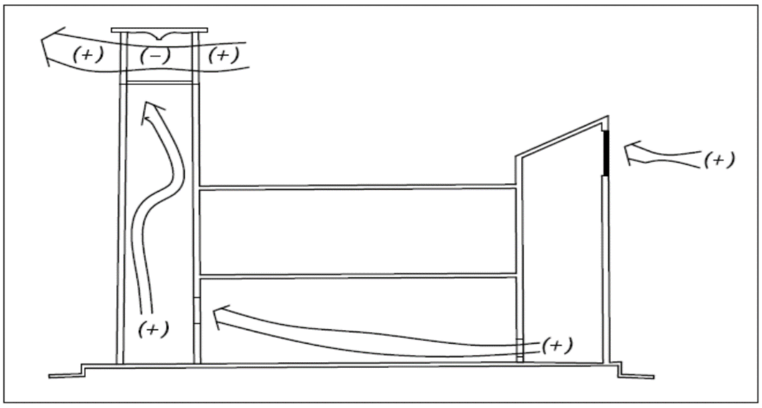


Figure 4.19: Wind Tower in Sudan according to prevailing wind direction.

Wind towers operate well in Sudan’s Hot Season when temperatures exceed 40°C and wind movement in the city is from south to southwest. Filtration of airborne particles should be controlled then because hot-season winds carry fine dust. Wind speeds increase during the night and help cool the air. In the Wet Season, the wind movement is from southwest to north-northeast, probability of sand-dust storms is higher, and thermal comfort is least achievable. For this season, wind towers can offer adequate cooling from late evening to the early-morning hours.

4.3.3.1.5 Sudanese Adapted Wind Tower

The type of wind tower traditionally used in Sudan is the one open-side type that has challenges associated with sand-dust storm and insect penetration. These challenges have been addressed in the adapted-Sudanese wind tower. This wind tower adaptation is employed on the Emergency NGO Pediatric Clinic, a low-rise building in the city of Nyala in western Sudan. The wind tower operates by capturing air from an 8-meter high tower, as in figure 4.20, and channeling air into the basement through a labyrinth. The labyrinth helps reduce air speed, the air is further cooled through the earth's thermal mass, and airborne sand and dust are deposited as the air slows. Finally, before entering the building's interior spaces, the air is treated by an industrial cooler dimension of (1.2x1.2.1.2) meter as in figure 4.21. This cooling strategy helps reduce air temperature by 10°C and reduces usage of conventional air-conditioning by 70%. This cooling strategy could also be utilized in the city of Khartoum in low-rise residential buildings except that it is not cost efficient for use in the center of the city where land prices are high; it can be better used away from the city center. Furthermore, wind towers could be enhanced for future buildings of the city of Khartoum by adding evaporative cooling effect and using filters to control sand-dust storm, this way a reduction in cooling load could be achieved.

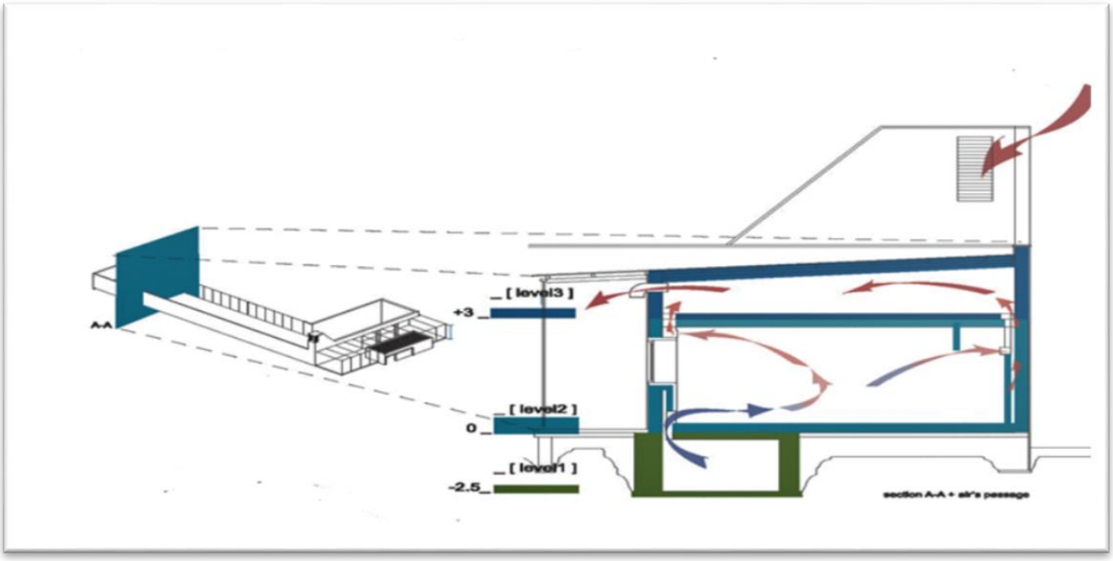


Figure 4. 20: Sudanese tower at Nyala clinic Sudan
(Adapted from studio tamassociati)

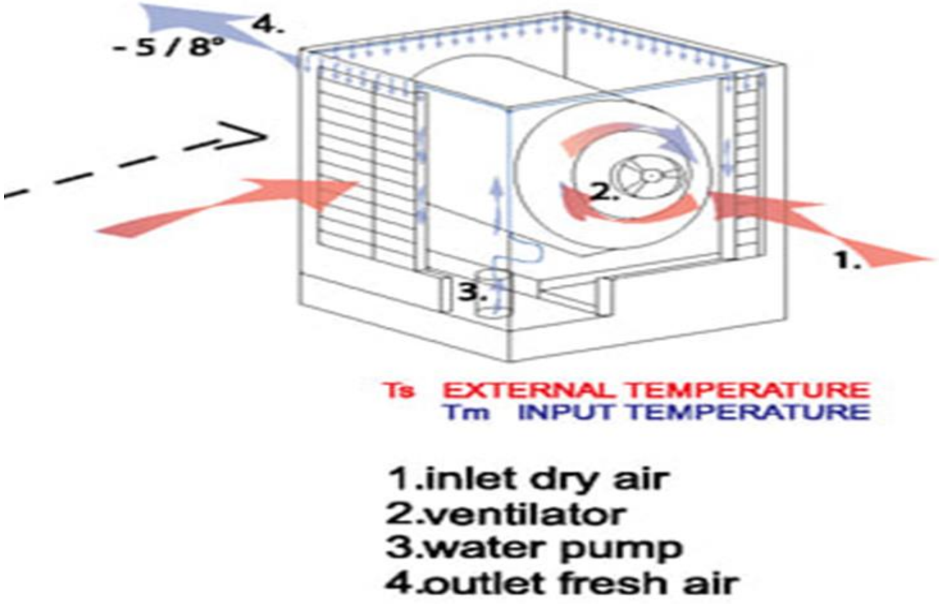


Figure 4.21: Air treatment by an industrial cooler
Source: (courtesy of studio tamassociati)

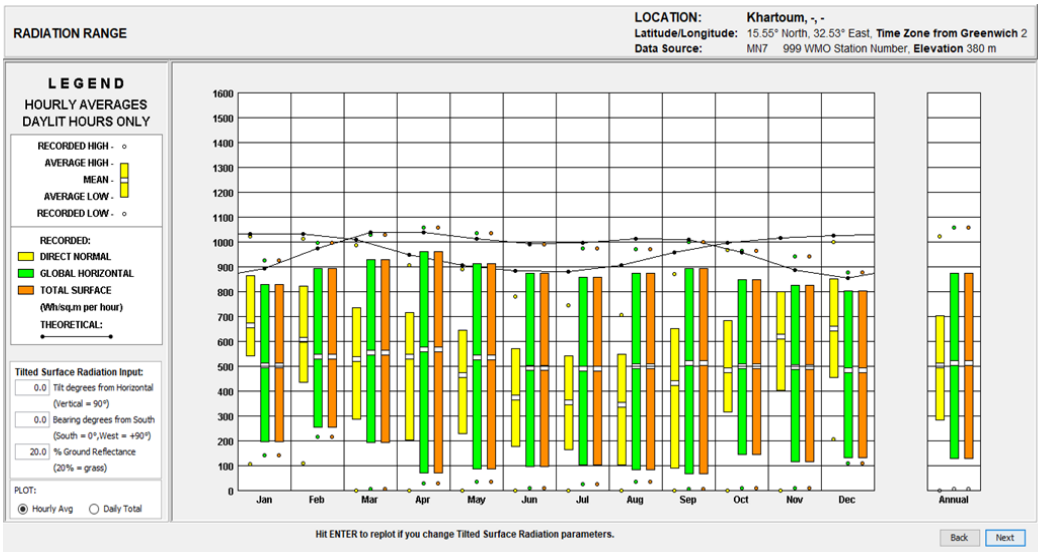
4.3.3.2 Heat-gain Minimizing Strategies

4.3.3.2.1 Solar Control

Khartoum, Sudan is located in a region characterized by high solar-radiation intensity during its Hot and Wet Seasons (Elagib and Martin, 2000). These characteristics should be considered in order to control sun exposure and avoid uncomfortable building-interiors during its eight-month-long hottest period. The city of Khartoum has average monthly solar radiation of 27.55MJ/m^2; it is considered to be the highest in the world (Omer, 1997). In the city of Khartoum, horizontal surfaces receive maximum solar radiation in the months of March, April, and May, coinciding with the Hot Season in which temperature exceed 40°C during most of the time. During the Dry Season, the city receives less solar radiation (Sharag-Eldin, 1989). According to Onsa (2015) and others, when building penetration of solar radiation is reduced by 20% to 40%, it leads to reductions in building thermal running costs by the same percentage (Onsa et al., 2015). Consistent with Sharag-Eldin (1989) and supported by Climate Consultant's sun shading calculator figure 4.22 ,the city of Khartoum buildings need appropriate shading from 9:00 AM to 5:00 PM during the Hot and Wet Sesons. While in the Dry Season, shading from 10:30 AM to 3:00 PM is adequate (Sharag Eldin, 1989).

Table 4.5: Solar Angles for the city of Khartoum on Monthly basis (Source: Climate consultant 6.0)

Month	Jan	Feb	March	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Solar angle in degrees	58	66	74	82	90	98	90	82	74	66	58	50


RADIATION RANGE

LOCATION: Khartoum, -, -
Latitude/Longitude: 15.55° North, 32.53° East, Time Zone from Greenwich 2
Data Source: MN7 999 WMO Station Number, Elevation 380 m

Tilted Surface Radiation Input:
0.0 Tilt degrees from Horizontal (Vertical = 90°)
0.0 Bearing degrees from South (South = 0°,West = +90°)
20.0 % Ground Reflectance (20% = grass)

PLOT: ● Hourly Avg ○ Daily Total

Hit ENTER to replot if you change Tilted Surface Radiation parameters.

Figure 4.22: Solar radiation component ranges for the city of Khartoum, Sudan
Source: Climate consultant 6.0

Based on the shading calculator analysis and the city of Khartoum seasonal solar angle shows in table 4.5 south-facing windows receive direct solar radiation from August to April. Therefore, horizontal shading devices are required to obstruct inclined radiation at angle $51^{0.}$ Furthermore, there is a need to obstruct inclined radiation through vertical fins from East and West at angle 43 ^{0} and 45^{0} respectively during morning and hot afternoon. Because of the city of Khartoum's location at 16° north, it receives solar radiation from the north between May and July; a little effort is encouraged to shade northern windows with roof overhangs. East and west side façade windows can be shaded with vertical, moveable fins. To address high solar intensity, a combination of both vertical and horizontal (egg-crate) shading patterns is most appropriate. Again, the Emergency NGO Pediatric Clinic in Nyala exhibits good examples of solar control strategy. South façade window are design to be small and recessed to intersect morning and afternoon hot inclined solar radiation to avoid overheating as figure 4.23. Automated or smart shading devices can more efficiently respond to solar angle. Unfortunately, though functionally better at reducing solar gain, these technological shading devices are not cost efficient. To conclude solar control as the most important strategy in the city of Khartoum, windows should be appropriately sized and designed to achieve optimal thermal comfort.

Figure 4.23: Vernacular solar control system.
Source: (courtesy of studio tamassociati)

4.3.3.2.2 Thermal Mass as Time Lack

Thermal mass moderates diurnal temperature differences between day and night as a suitable cooling strategy in arid regions (Meir and Roaf, 2002). The efficiency of thermal mass to enhance building-interior thermal comfort depends on the material's ability to store energy and release it when needed. This process is governed by the properties of the materials which include its specific heat capacity, density, thickness, and conductivity (Ghattas et al., 2013). Usually, massive-wall construction succeeds in maintaining building interior temperature, reducing cooling load. However, the thermal mass achieved from brick, concrete block, and stone, etcetera also have the ability to hold and transmit heat gained from exterior surroundings to indoor spaces. For thermal mass to function properly, effective ventilation strategies need to remove deposited heat from the building and stimulate the mass for further thermal moderation (Brambilla et al., 2018). The city of Khartoum experiences Dry Season temperatures lower than comfort levels especially from 6:00 PM to 6:00 AM. Using high thermal mass could increase comfort levels (see matrix table 4.6). Furthermore, nowadays with the advancement in building construction technology innovative light weight phase change materials could be adapted for future buildings of the city of Khartoum to enhance thermal mass without a need to add extra load on buildings. The benefits of using high thermal mass includes reduction in annual energy demand, adequate indoor quality, good acoustic and insulation properties , enhancing fire resistance of buildings, reducing insulation costs and reducing maintenance cost respectively (Ahmed et al, 2014).

4.3.3.2.3 Use of Thermal Insulation

Thermal insulation systems are used on building to reduce heat flow through buildings fabric. The performance of thermal insulation material is measured through thermal conductivity and thermal transmittance of the material also known as U value. For the material to serve as a thermal insulation its conductivity should be lower than 0.07 W/mK (Asdrubali et al, 2015). The introduction of sustainability notions in recent decades necessitates utilization of thermal insulation as building envelope accounts for 40-45% of the building total heating loads (Mujeebu, 2016; Hasan et al., 2014). Using thermal insulation for walls and roofs helps reduce heat gain through the building envelope (Bhikhoo et al., 2017). According to Sharag-Edin (1989), using 5 cm thickness of expanded Polystyrene thermal insulation on exterior walls in the city of Khartoum helps reduce radiated heat transfer between the two lines of brick wall. A great reduction in total heat flow can be achieved this way.The following figure 4.24 shows a typical exterior insulated brick wall. The city of Khartoum buildings receive intense solar radiation between April and September and the greater part of the radiation falls on horizontal surfaces. For this reason it is very important to use thermal insulation on roofs to reduce cooling load. East- and west-facing vertical walls also receive a substantial portion of radiation therefore exterior thermal insulation should be used on exterior walls as well.

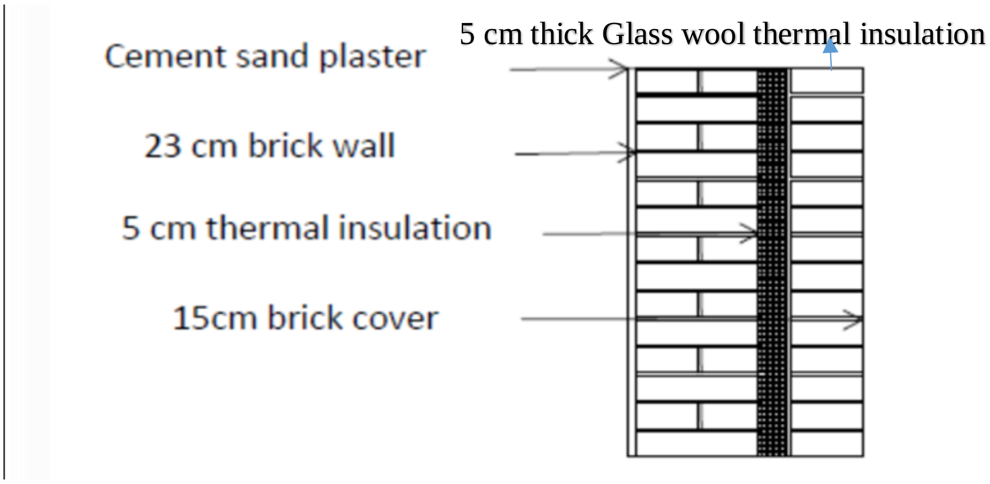


Figure 4.24: Typical brick wall in the city of Khartoum
Adapted from Sharg-Edin (1989)

There is not much research about thermal insulation in Sudan; the only known application shows thermal insulation as in figure 4.25 used at the Slam Center for Cardiac Surgery in the city of Khartoum This building is a renowned climate-responsive, low-rise building. Most of high-rise buildings are designed and constructed without accounting for thermal insulation, therefore, air conditioning is frequently required to achieve thermal comfort.

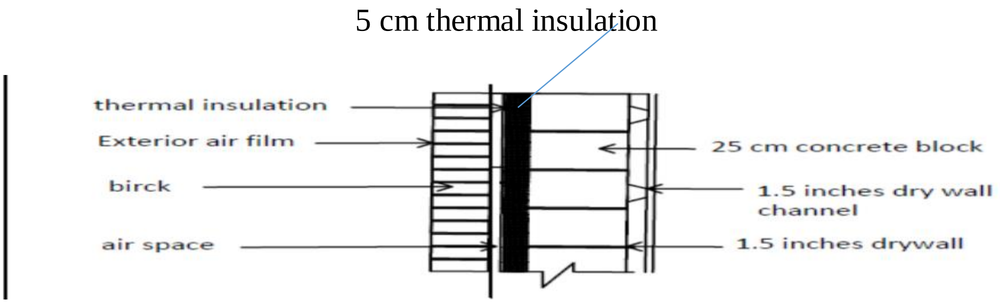


Figure 4.25: Thermal insulation adapted in Slam Center for Cardiac Surgery, the city of Khartoum. Source: (courtesy of studio tamassociati)

4.3.3.2.4 White Roof

The use of high –albedo materials on major urban surfaces is one of the ways to mitigate urban heat island in cities. High-albedo materials can save cooling energy use by directly reducing the heat gain through a building's envelope (direct effect) and also by lowering the urban air temperature in the neighborhood of the building (indirect effect) (Taha et al, 1992). In many urban centers, roofs constitute form 20% to 25% of the total urban area. If appropriately utilized can increase the net urban albedo up to 0.1(Akbari et al, 2007). These coatings for buildings represent easy and cost effective solutions and may be applied to horizontal or vertical surfaces though rooftop application is most common. This strategy is most appropriate for low-rise buildings of the city of Khartoum which receive maximum solar radiation on their horizontal surface from March to November. Santamouris et al. (2007) advocated use of this strategy in the city of Khartoum’s residential buildings to save 25.4% of the cooling load (Santamouris et al., 2007). Urban areas tend to reduce the overall effective albedo through two mechanisms. The first one is as a result of larger absorption on darker building and urban surfaces whereas the second results from the effects of multiple reflections inside urban canyons producing significantly lower effective albedos (Aida, 1982).

Although highly-reflective roof coatings reduce interior cooling loads, they bring the disadvantages of increased heating demand in the cooler, drier winter season; and reflectivity on low-rise buildings can cause visual discomfort (glare) for occupants of adjacent high-rise buildings (Dabaieh, 2014; Hosseini, 2014; Taleghani et al., 2014). In the case of the city of Khartoum, the cool-season disadvantage is minimized due to the fact that the dry (winter) season is relatively short. Furthermore, these strategy could be innovatively used for the city of Khartoum high rise and low rise building's roof and walls to reduce cooling load.

4.3.3.3 Sustainable Active-cooling Systems

Dabaieh et al. (2015) calculated that about half of power usage is for air conditioning to meet cooling demand in hot and arid regions and Tong et al. (2014) pointed out that power consumption for air-conditioning reaches its maximum load during the summer period. These researchers and others acknowledge the fact that decreasing demand for air-conditioning is one of the greatest means of saving energy (Dabaieh et al., 2015).

Besides the use of passive-design strategies to reduce demand, it is expected that sustainable active-cooling systems will continue to increase their energy and cost efficiency until 2070 while simultaneously reducing their carbon footprint. Because Sudan has abundant solar energy potential with average daily sunshine lasting 8.5 to more than 11 hours, sustainable active-cooling systems using renewable energy are a viable option (El- Zein, 2017). Such systems may have desiccant solar assisted cooling and heat pumps appropriate for the city of Khartoum's hot (summer) season. Conventional air conditioning requires steady and large quantities of power and should be paired with clean energy sources for sustainability. While Sudan's solar energy supply can adequately meet cooling demands using conventional systems during its 11-plus hour summer days, Magzoub and Osman (1998) conducted research in the city of Khartoum demonstrating more efficient power usage for solar cooling of a brick building using solar simulation programs. Their finding shows it is possible to achieve up to 65% cooling of the brick building (Maqzoub, 1998).

4.3.3.3.1 Desiccant Air Conditioning

Desiccant air conditioning can be used as a substitute for conventional vapor compression air-conditioning systems. Desiccant-system advantages over the later include its accessibility, cost effectiveness, and sustainability. This cooling system can be powered by solar energy, such that appreciable operating costs will be achieved (Concina and Sadineni, 2011). Research conducted on solar-powered desiccant cooling utilization proves savings in all climate types (Daou et al., 2006). A research done by Abdalla and Osman (2017) on desiccant air conditioning powered by solar energy from evacuated-tube solar collectors can provide cooling load demand for the building for about 10 hours (Abdalla and Osman, 2017). However, as in table 4.7, active cooling is also demanded in the city of Khartoum’s Wet Season to achieve optimal thermal comfort. Figure 2.26 is a diagram of desiccant air conditioning powered by solar energy.

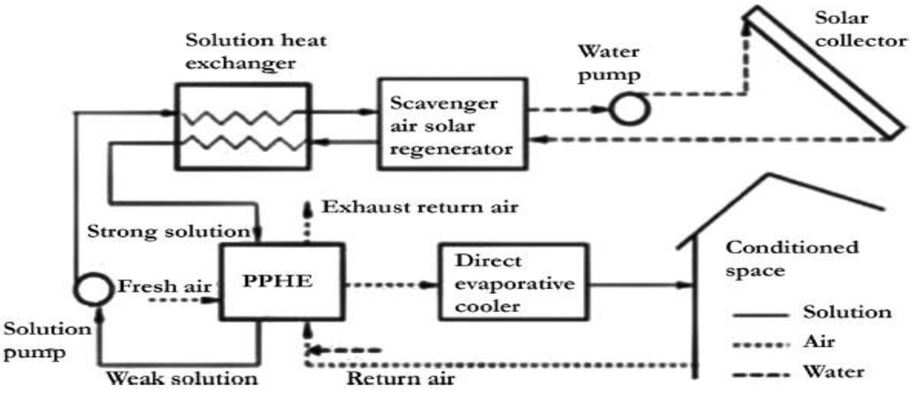


Figure 4.26 : Solar liquid desiccant air conditioning system.
(Source: Alizadeh, 2008)

4.3.3.3.2 Heat Pumps

Heat pumps can be used to provide heating, cooling and hot water for domestic use in all types of buildings. As well, they can be used in all climates because they take on earth’s constant temperature for operation. There is a need to control and minimize refrigerant leakage through appropriate installation for environmental and appliance-maintenance purposes (Greening and Azapagic, 2012). The efficiency of heat pumps is expressed as the Energy Efficiency Ratio (EER) (Manzella, 2017). Besides the efficiency of the appliance, heat pumps depend on other factors which greatly contribute to the overall system efficiency. These factors include temperature level of the heat source and heat dissipation, and appropriate design and installation in accordance with the unique conditions of the area (Forsén, 2005).

Heat pumps can be divided into ground-source heat pumps (GSHP), groundwater-source heat pumps (GSWHP), and air-source heat pumps (ASHP) (URL.18). A ground-source heat pump (GSHP) is an adequate solution for heating and cooling residential and commercial buildings due to its energy efficiency compared with conventional air-conditioning systems (Jiang, 2017). These systems are refrigeration machines that provide cooling and heating using stable underground or water temperatures (El sheikh, 2011). GSHPs shown in figure 4.27 can be divided into four systems.

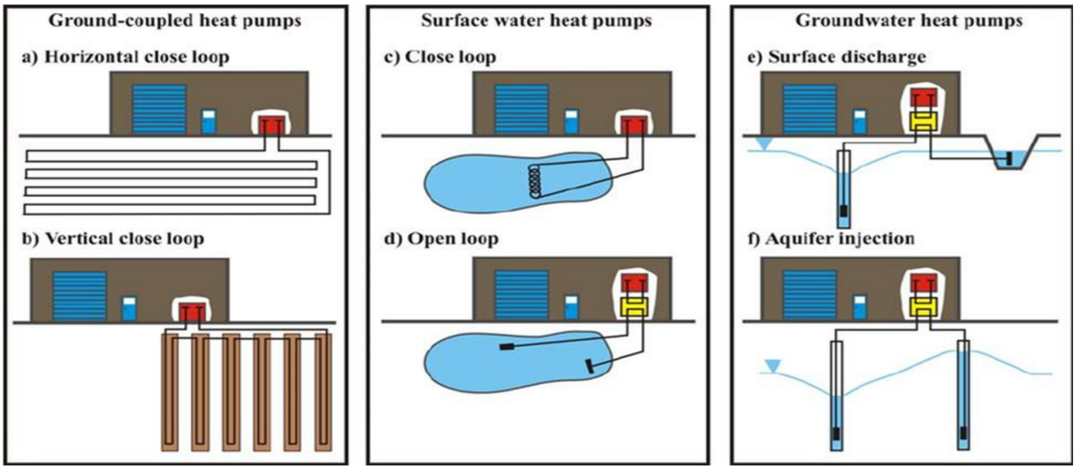


Figure 4.27 : Ground source heat pumps (GSHP) and their ground heat exchangers (Source:Wright and Colvin ,1993)

4.3.3.3.2.1 Close loop

This system uses a buried loop containing water or a glycol solution to transfer the coolness to heat pumps and then to the building in hot areas (Valizadeh, 2013; Goetzler et al., 2009).

4.3.3.3.2.2 Vertical loop

This system involves bore-hole drilling to reach cool groundwater and transfer the coolness to the surface heat pump for distribution throughout a building. Vertical loop systems may be expensive in the city of Khartoum due to the deep level of the water table (Valizadeh, 2013; Goetzler et al., 2009). Horizontal loop: This system is less expensive because installation occurs only four to five feet below ground. Major disadvantages of this system are that it requires much land than the others, and it is more affected by seasonal temperature fluctuations (Valizadeh, 2013; Goetzler et al., 2009). This system may not be appropriate for the city of Khartoum’s climate.

4.3.3.3.2.3 Hybrid System

This system is normally used in large buildings where cooling load is more than the heating load. In this system, the ground heat exchanger is replaced by a conventional cooling tower to cope with peak cooling load. This system has a reduced initial capital cost.

4.3.3.3.2.4 Groundwater-Source Heat Pumps (GWSHP)

Groundwater-source heat pumps (GWSHP) are considered environmentally friendly and economically wise to use for heating and cooling buildings, and consequently have great potential to moderate greenhouse gas emissions (Kim and Nam, 2015). This system exchanges groundwater coolness by draining heat from the pumps into the aquifer. This cooling system is efficient where groundwater is reliable and available without interruption throughout the year (Liu, 2017). This cooling system is very effective for the city of Khartoum because of availability and reliability of groundwater. The only disadvantage is the initial capital cost is relatively high. See figure 4.28 shows different types of GWSHPs.

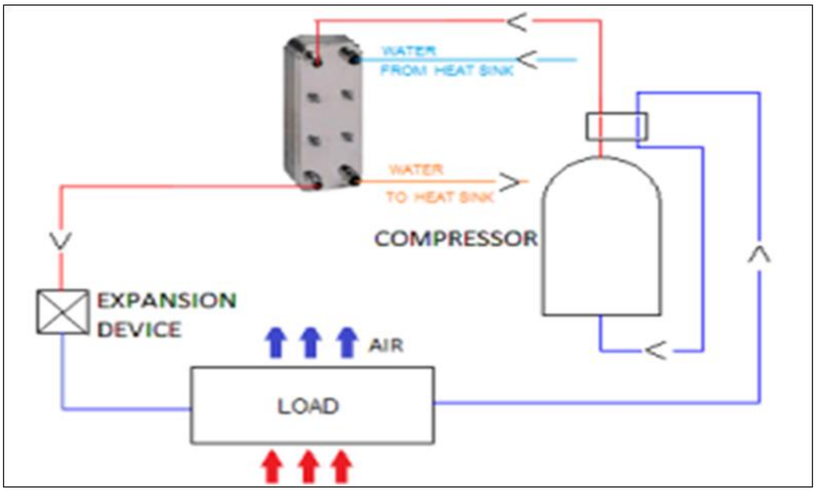


Figure 4.28 :Water source heat pump (Source: Water Source Heat Pump)

4.3.3.3.2.5 Air-Source Heat Pumps (ASHP)

Air-source heat pumps (ASHP) are categorized based on their placement outside the heat exchanger by air to air and air to water (Staffell et al., 2012). An air-source heat pump pull its heat indoors from the outdoor air in the winter as it functions as a heater and pushes indoor air out in the summer as a cooling system (URL. 19). ASHP technology has witnessed tremendous growth in recent years due to efficiency and reliability of pumps being used in the refrigeration cycle. Air-to-water heat pumps are efficient and environmentally friendly in reducing global warming. Air-to-air heat pumps are efficient in compact urban areas (Lukanov, 2019). But their efficiency is less than ground-source and groundwater-source heat pumps (Ross, C, 2008).

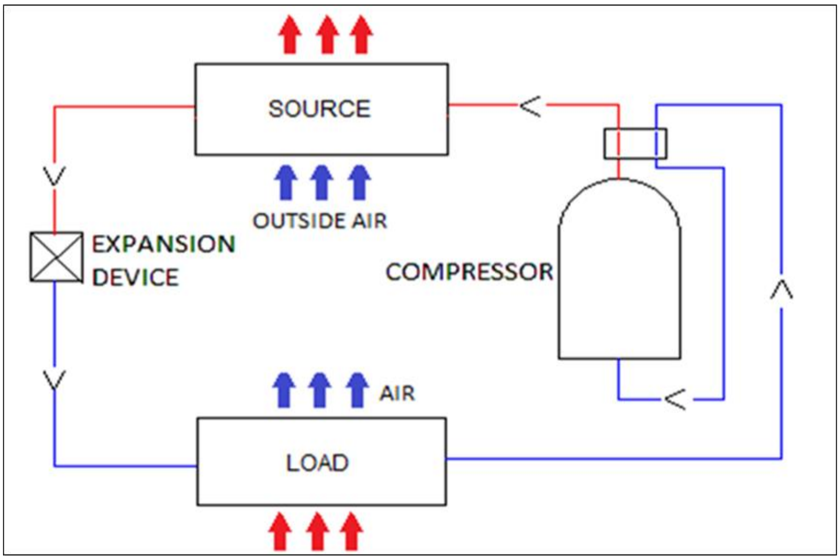


Figure 4.29: Air source heat pumps (ASHP) works
Source: (Staffell et al., 2012)

Figure 4.29 above shows ASHPs. Table 4.6 shows the advantages and disadvantages of heat pump types'. Heat-pump technology is a promising and sustainable technology, and if appropriately utilized would reduce the need for conventional air-conditioning systems which damage the environment. This technology is not introduced in Sudan yet, and there are not enough experienced with its installation or use in the city of Khartoum. From a literature survey on this subject matter, a reduction in capital cost can be achieved with hybrid and groundwater-source heat pump systems compared to ground-source heat pumps systems.

Table 4.6: The advantages and disadvantages of heat pumps types

Heat pump type	Advantages	Disadvantages
Ground source heat pumps (GSHP)	-Energy efficient -Cost effective with pay back of 2-10 years -have no visible sense -silent make no noise -low maintenance cost -pipes lasted for 40-50 years -adaptable in all climates -fire resistant -few moving part	- lack of confidence in the technology - inadequate information about it -lack of adequate supply and services -uncertainty about actual average efficiency and published confidence of performance
	-more expensive than (GWSHP) &(ASHP but more efficient than them[URLQ].	
	-has better seasonal efficiency than (ASHP) [URLQ].	
Water source heat pumps (GWSHP)	-Suitable in all climates -cost effective -environmentally friendly -if properly designed can reduce cost -consumes less power if ground and water temperature remain constant throughout the year [Kim & Nam, 2015]. -few moving part	-depend on ground water temperature -more power used for pumping -local legislation -lack of knowledge -can effectively be used only where ground water is grantee [Kim & Nam, 2015].
Air source heat pumps (ASHP)	-energy efficient -economically wise -easy to retrofit in to existing buildings -does not need much external land for installation -appropriate in high dense urban areas -good for heating, cooling and water heating -long life span -easy maintenance	- need highly trained expert for installation -any leakage of refrigeration system hazard to the environment and can also damage the entire system -Less efficient than (GSHP) & (GWSHP)

4.3.3.4 Feasibility Study of the Selected Design Strategies for the city of Khartoum Buildings

For this research to be more valuable for building designer it is imperative to provide a cost analysis (feasibility) of the selected strategies for a simple residential building on the basis of thermal comfort matrix table 4.7

Table 4.7: Thermal comfort matrix

Seasons (months)	Time schedule	Temperature (min-max °C)	Humidity (min-max %)	Thermal comfort before applying design strategies (hours/ year; %)	Thermal comfort due to Design Strategies							
					Shading	2-stage evaporative cooling	Direct evaporative cooling	Active cooling	Natural / night ventilation	Dehumidification	Internal heat gain	Passive solar heating
Dry (November to February)	6am-12noon	12.7- 38.5	18 -56	43.5%	48% 403 hr	36.6% 299 hr.					20.7% 175 hr	
	12 noon 6pm	19.2 – 40.6	10 - 59	15.7%	69% 580 hr	84% 706 hr.						
	6pm-12 midnight	13.5 – 36.3	10 - 34	52.6		39.4% 331 hr.						
	12 midnight-6am	12.5 – 30.3	13 - 47	53.8%			4.5% 38 hr.				41.4% 348 hr	28.2% 237 hr
Hot (March to May)	6am-12noon	17 – 43.5	17 - 46	23.4%	65.4% 421 hr	70.2 452 hr.						
	12 noon 6pm	20.2 – 45.4	10 - 43	0.2%	71.4 %	97.5% 628 hr.						
	6pm-12 midnight	20.2 – 41.2	10 - 20	13.7%		84.5% 5436 hr.						
	12 midnight-6am	16.6 – 35.1	11 - 34	53.9%		39.6% 255 hr.						
Wet (June to December)	6am-12noon	22.7 – 43.9	20 - 99	4.6%	70.1% 655 hr.	28.7% 307 hr.		63.1 % 676 hr.	7.4% 79 hr.			
	12 noon 6pm	26.3 – 43.9	12 - 93	0%	71.3% 764 hr.	29.8% 319 hr.		70.1% 751 hr.				
	6pm-12 midnight	24.9 – 43.9	11- 88	1.1%		29.8% 852 hr		66.7% 725 hr.	4.9% 53 hr.			
	12 midnight-6am	21.5 – 42.4	18 - 84	13.2%		25.6% 274 hr.		51.3% 549 hr.	17.7%% 190 hr.	8.6%% 92 hr.		

4.3.3.4.1 The Application of the Design Strategies in an Exemplified Building in Khartoum City as Case Study

The study is to show how the architectural design can be affected by implementing some of the passive cooling strategies discussed in the previous chapters. The example house is a one - bed room flat meant to accommodate a small family, the built area is 78 m2, ceiling height of 3.25 m and raised 0.6 m above ground level. The structural system is loadbearing wall of one and half exterior brick wall with 30 cm thickness. The roof is reinforced concrete slab of 15 cm thickness. Figure 4.30 see the building plan.

4.3.3.4.2 The Use of Passive Cooling as Design Strategy

1-The ratio of length to width is 1:1.3 by which minimum heat gain is maintained as suggested in Section 2.6.2.5

2-West orientation is avoided for bedroom and cross ventilation has been provided.

3-The walls project beyond building corners to provide shading against low early morning and late afternoon sun angles

4- Window on East direction is designed as high level window and shaded with roof overhang to avoid any overheating at morning time.

5- The walls project beyond building corners to provide shading against low early morning and late afternoon sun angles.

6- White paint was used for roof top because the city received high solar radiation because horizontal surfaces received maximum solar radiation as mentioned in section 4.3.3.2.1

7- Night ventilation can be of benefit at night in Wet Season through the use of thermal mass

8- Passive solar heating in Dry Season constitute 41% of thermal comfort from midnight till 6 am this can be achieved in this building through using walls and floors.

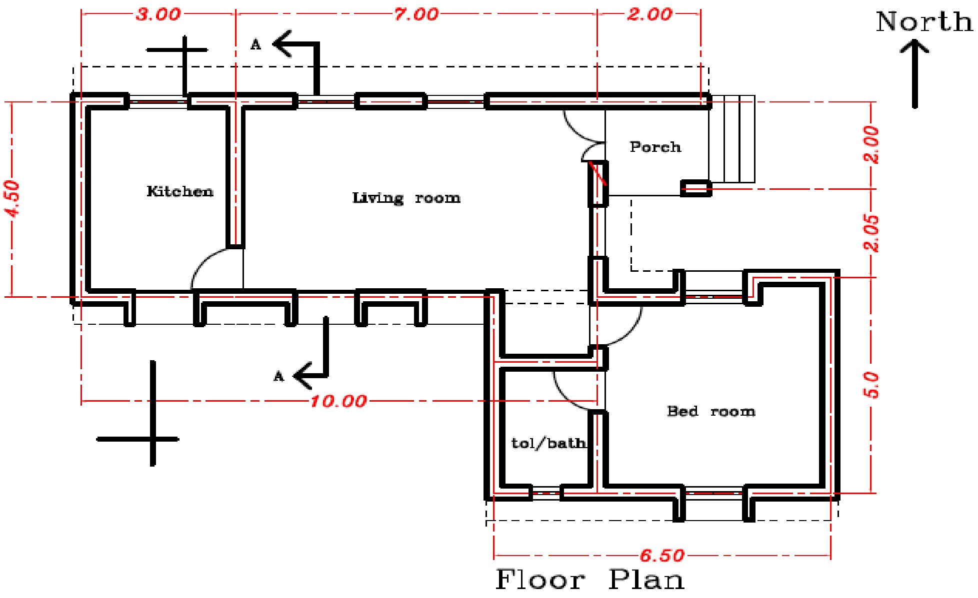


Figure 4.30: Floor Plan of a one-bedroom flat in Khartoum city

9- Cross ventilation is used in this building, according to matrix table natural ventilation is suitable in Wet Season (June- October). Building height is important for creating indoor environment that is thermally comfortable. The following precaution have been considered in the design as in figure 4.31;

(i) Floor to ceiling height is 3.2 meter and a trap for hot air under the ceiling. When this air layer gets thick it flows to the chimney without mixing with cooler air at the living area.

(ii) Building is elevated up to 0.6 meter above ground level this protect the building floor from both soil movement and serve as a thermal insulation

(iii) Daylight was appropriately controlled to avoid any visual discomfort that might occur as a result of Khartoum high solar radiation.

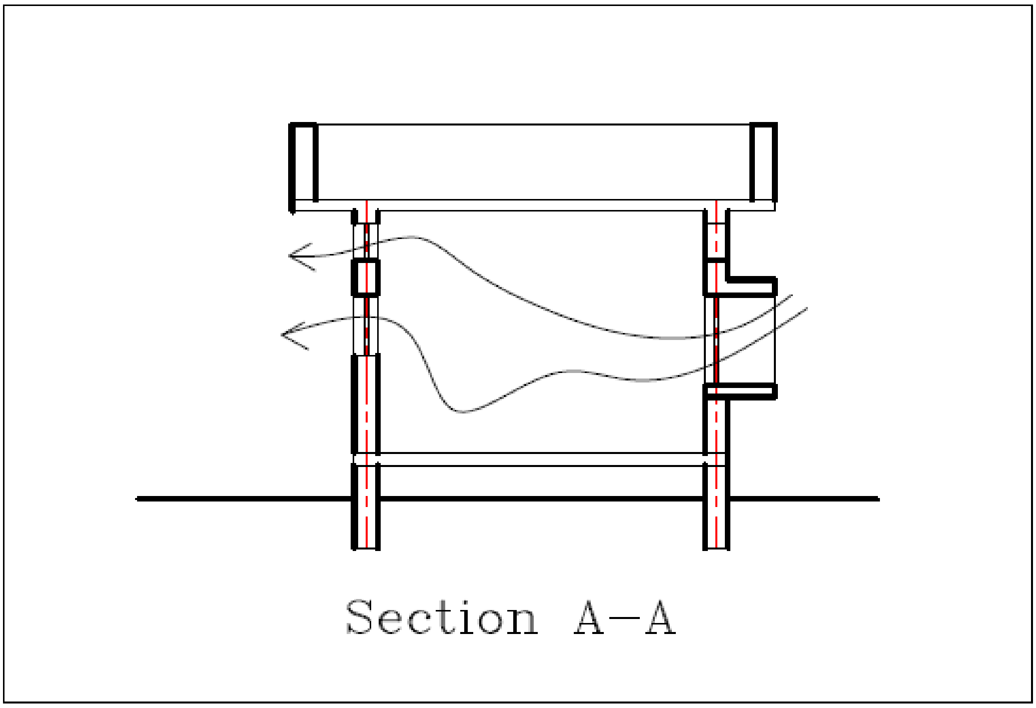


Figure 4.31: Section A-A of a one-bedroom flat showing natural ventilation potential

10- Shading devices: The shading analysis in Section 4.3.3.2.1 suggested horizontal shading devices for south window and vertical fins to obstruct early morning and late afternoon solar radiation at angle 43° east and 45° west, see figure 4.32. As a result of the city location near Equator roof overhang can control north window, see figure 4.33. There are no windows on east and west side

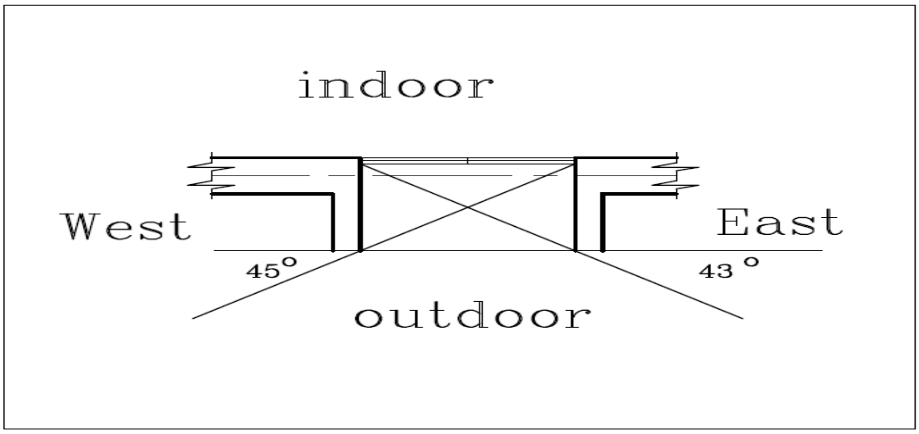


Figure 4.32: South window shading proposed configuration

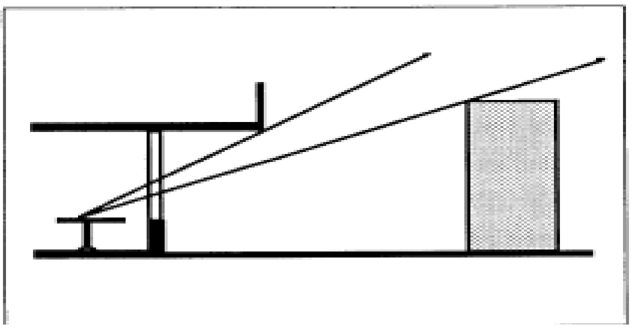


Figure 4.33 Cantilever or roof overhang used for shading of north facing window in Khartoum City

11- Thermal insulation: From the research conducted in chapter four, using thermal insulation on roof is a reasonable to reduce heat gain. However, wall insulation is added to the architectural details to minimize the heat gain and to decrease the radiant heat flow from the internal surfaces. This enhance thermal comfort because the effect of the mean radiant temperature is more sensed than air temperature (4.3.3.2.3). Moreover, painting roof and wall with white colour could also be an alternative in case of the increased cost of thermal insulation. But one of the disadvantages of white paint is they tend to loss their efficiency as dust accumulate on roof since Khartoum city is nowadays is subjected to more frequent sand-dust storm than ever(Section 4.3.3.2.4)

4.3.3.4.3 Cost Analysis of the Selected Cooling Strategy

Cost analysis for cooling strategies for Khartoum city building as in table 4.8 gives the following results:

1- Shading devices is the most cost efficient strategies since it is needed in all seasons.

2- Roof insulation and white painting are more cost efficient than wall insulation since roof received more solar radiation it best to apply. However for insulating west façade only could be of benefit since it receives radiation more than the other facades

3- Applying evaporative cooling through water evaporative cooler are adequate even though their initial cost is relatively high, but they are energy efficient and their spar part are few and easily replaceable.

4- The best way to achieve optimum thermal comfort is by appropriately design shading devices with well insulated roof and west façade, and the use of water evaporative coolers in Hot and Wet Seasons.

5- According to the cost analysis, these design strategies are more expensive than shading devices windows and white paint roof. For this reason, Hot and Wet season need these design strategies, which is not very cost efficient. Alternatively, thermal insulation material (polystyrene glass wool) can be replaced by sheep wool, which is affordable. Active cooling (water evaporative cooling) cannot be replaced by natural ventilation only.

Table 4.8: Cost analysis for selected Design Strategies in Khartoum City

Strategy	Material cost	Labour Cost (m)	Economic Efficiency		
			High	Medium	Low
Shading devices	Reinforced concrete shading devices per metre square 300 Sudanese pound (SDG)	100 SDG	+		
Windows for natural ventilation	Standard size (1.2x1.2) material 3000 SDG	900 SDG	+		
Thermal insulation for roof	Glass wool for roof insulation 350 SDG	50 SDG		+	
Thermal insulation for wall	500 SDG	350 SDG			+
Painting roof white	White paint application for roof 60 SDG	40 SDG	+		
Active cooling	Water evaporative cooler unit price 15000 SDG	2000		+	

The exchange rate is 1 USD = 65 SDG

4.3.3.5 Dust-sand Storm Treatment for the city of Khartoum's Buildings

Air filtration issues have become more pronounced than ever before due to concerns about respiratory health. Air filters are designed to remove dust concentrated in air where dust content of air does not exceed 2 mg (up to 0.2 mg) per cubic meter of air before entering HVAC systems (URL.20). The most common filter type used today is fibrous and is characterized as being 80 to 90% porous material with low resistance to air movement (Podgórski et al., 2006).

4.3.3.5.1 Artificial Air Filters

According to Ahn et al. (2006), air filters can be categorized according filtration particulate efficiency as pre-filter, medium filter, high-efficiency particulate air (HEPA) and ultra-low particulate air (ULPA)(Ahn et al., 2006). Pre-filters capture larger sand particles. Medium filters have an efficiency of 60 to 90%. HEPA filters are most sought after for air filtration in the building industry because of their 99.99% efficiency and their ability to trap air impurities of different diameter sizes. This filter type is appropriate for use in most public buildings like theatres and hospitals (Brincat et al., 2016). ULPA filters have 99.999% efficiency (Ahn, Brincat et al., 2016). These days, as air pollution rates increase, researchers are developing innovative new non-woven nano-fiber material that can perform even better in instances where the air contains smaller particle sizes (Wang et al., 2013). Glass fiber is another excellent air filter which has efficiency of 99% (John and Reischl, 1978). A trombe wall filter, shown in figure 4.34, is an efficient filter and can provide qualitatively healthy ventilation for building interiors, especially in dense and contaminated urban centers like that of the city of Khartoum (Imbabi, 2006).

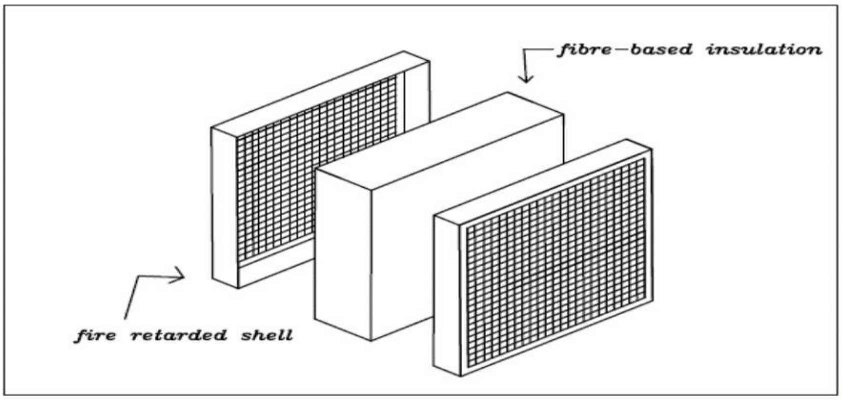


Figure 4.34: Modular breathing panels in framed construction. (Source: Imbabi, 2006)

4.3.3.5.2 Natural Air Filters

An active living wall (ALW) is a technology appropriate for buildings in which mechanical and natural ventilation is incorporated as in figure 4.35. The system operates by forcing air to pass through the ALW, taking on the benefits of the AWL's biological capacity to cool, purify, and humidify air (Podgórski et al., 2016; Liu et al., 2017).

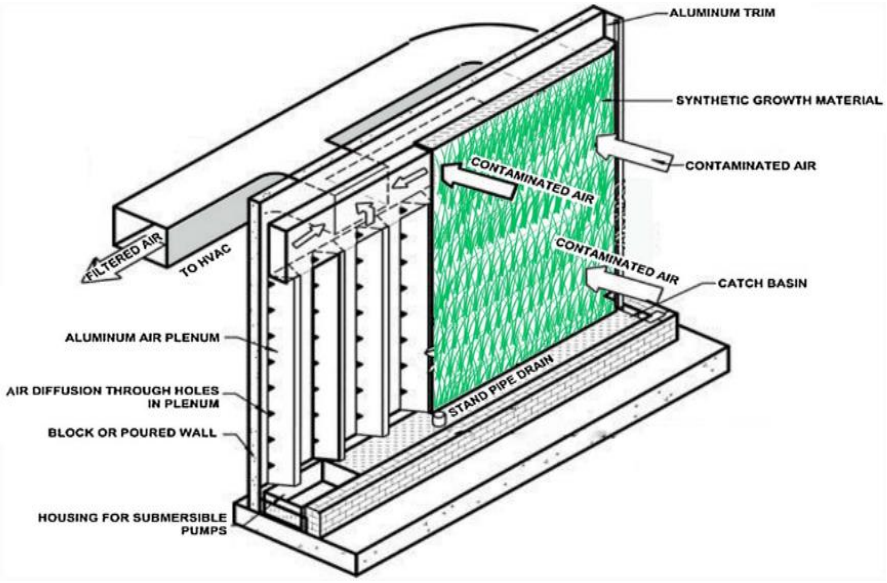


Figure 4.35 : Schematic of indoor biofiltration system.
(Source from:Soreanu et al. (2013)

Bio façades in figure 4. 36 is a new, innovative filtration strategy. This filtration system could pave the way to more sustainable and environmentally friendly cites. According to Antony Wood et al. (2014), bio façades have numerous advantages at both the city and the building scale which are listed in (table 4.9) (Wood et al., 2014).

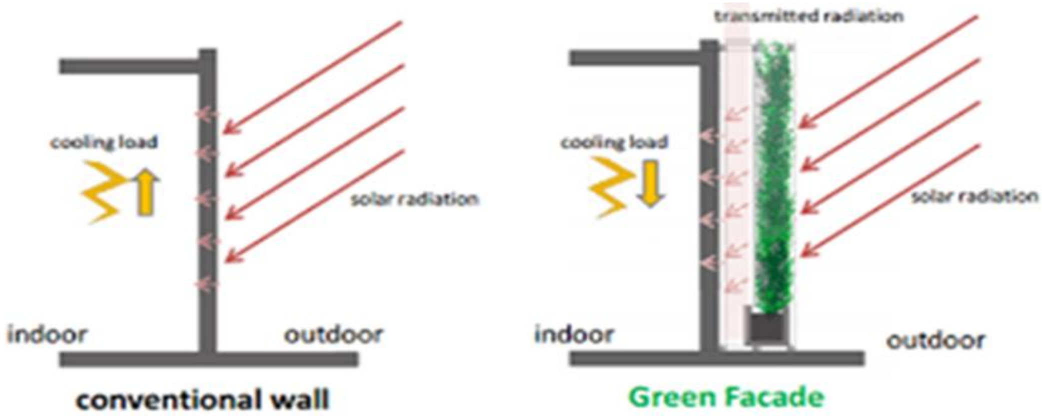
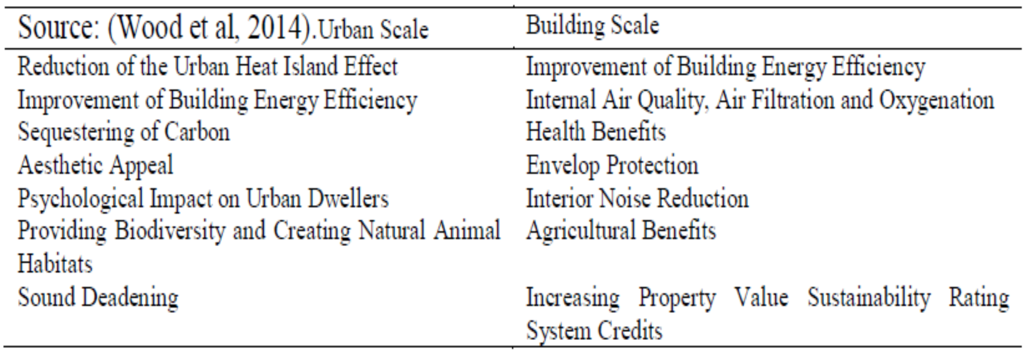


Figure 4.36: Bio facade used as innovative filtration strategy.(Source: Suleiman, 2013)

Table 4.9: Advantages of bio facade system both at city and building scale



Source: (Wood et al, 2014).Urban Scale	Building Scale
Reduction of the Urban Heat Island Effect	Improvement of Building Energy Efficiency
Improvement of Building Energy Efficiency	Internal Air Quality, Air Filtration and Oxygenation
Sequestering of Carbon	Health Benefits
Aesthetic Appeal	Envelop Protection
Psychological Impact on Urban Dwellers	Interior Noise Reduction
Providing Biodiversity and Creating Natural Animal Habitats	Agricultural Benefits
Sound Deadening	Increasing Property Value Sustainability Rating System Credits

4.3.3.5.3 Contemporary Control Systems for Dust and Sand Control in Sudan

Currently, only two methods are used to control dust or sand from storms in Sudan’s buildings. First, an adaptation to wind towers is derived from Iranian vernacular architecture where sand and dust fall out of the air when air shifts direction in the system. Here, fine particles are captured by the spraying of water. Second, air is allowed to pass through long underground tunnels constructed in labyrinthine ways to reduce airspeed and allow large particles to settle out of the air. Later, sprays of water control fine dust particles and cool down the air.After review of these dust-control strategies, the following results are obtained. Non-fibrous filters (HEPAs and ULPAs) are valuable for their high efficiency but their disadvantage is high initial cost. Trombe walls, active living walls, and bio-façade filtration systems are good for their numerous advantages and adaptable for the city of Khartoum buildings. Wind towers and underground tunnel systems have high initial cost and their construction requires additional land therefore they are not an economical choice for the city of Khartoum.

4.3.4 Future Scenario of Building Climate-Responsive Design Strategies for the city of Khartoum in the Year 2070

Climate change is one of the greatest challenges facing humanity currently. It is widely accepted that the effects of greenhouse gas emissions on global climate indicate that energy consumption in buildings should be reduced and building should be able to resist climate change effects for a long time. However, this requires contemporary and future buildings to cooperatively function under extreme changing weather conditions (Guan, 2009). Future projections of climate are inevitable and beneficial to achieving sustainable development for the current and future buildings.

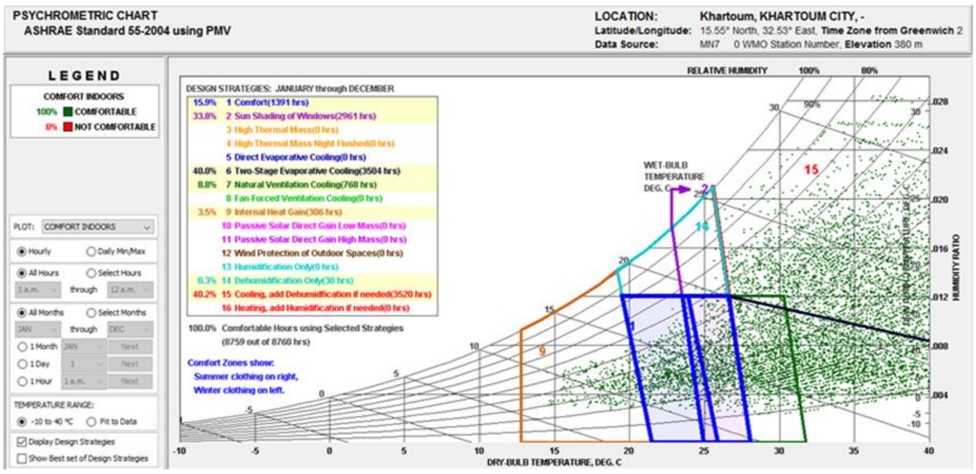
4.3.4.1 Comfort Model as Applied in the Year 2070

Climate change poses a significant challenge to human existence especially in hot, arid regions. It is imperative for architects to know about predicted future thermal performance of buildings; however, there is scarcity of climate data in most developing countries that is suited for prediction models (Jentsch et al., 2010). This data scarcity was resolved through the use of building energy simulation (BES) program (Jentsch et al., 2008; Khalfan and Steve, 2016). The program uses hourly weather file data to calculate thermal comfort and thermal performance of buildings

(Remund et al., 2010). The most common weather file format is the Energy Plus Weather (EPW) file which can be either freely downloaded or obtained from Meteonorm Company. Future weather files can be obtained from weather generator software such as Meteonorm (Remund, 1999).

Future climate-change scenarios for the city of Khartoum in the year 2070 is chosen on the basis of appropriate scenario. Due to improvements in building and construction technologies, building lifespans can extend to 80 and 100 years or more. So, predicting the next 55 years of climate-responsive building strategies is rationalized. Meteonorm 7.2.1 software was used to create weather files for the city of Khartoum's 2070. Together, these make it possible to calculate the 2070 weather file for the city of Khartoum in order to evaluate how the future forecasted climate-responsive design strategies for the city would perform .See figure 4.37 gives the rate of thermal comfort in the city of Khartoum for the year 2070. ASHRAE Standard 55-2010 is again used for this research work. The result achieved for annual thermal comfort of the city of Khartoum buildings without using any design strategies is 11.7% or 1023 hours out of 8760.

With monthly thermal comfort values in mind and using ASHRAE 55-2010 as in table 4.10, the city of Khartoum's has the highest thermal comfort with December having the highest value of 30.6%. For the Hot Season, March has the highest thermal comfort with remaining months reaching 0%. The Wet Season is considered to be the hottest, and the highest thermal comfort that could be achieved is only 1.1% in October. Again the remaining months of this season have 0% thermal comfort. Based on these statistics, it will difficult to achieve thermal comfort in the Hot and Wet Seasons without using design strategies in the year 2070.



PSYCHROMETRIC CHART
ASHRAE Standard 55-2004 using PMV

LOCATION: Khartoum, KHARTOUM CITY, -
Latitude/Longitude: 15.55° North, 32.53° East, Time Zone from Greenwich 2
Data Source: MN7 0 WMO Station Number, Elevation 380 m

LEGEND
COMFORT INDOORS
100% 🟩 COMFORTABLE
0% 🟥 NOT COMFORTABLE

PLOT: COMFORT INDOORS
● Hourly ○ Daily Min/Max
● All Hours ○ Select Hours
1 a.m. through 12 a.m.
● All Months ○ Select Months
JAN through DEC
○ 1 Month JAN Next
○ 1 Day 1 Next
○ 1 Hour 1 a.m. Next
TEMPERATURE RANGE:
● -10 to 40 °C ○ Fit to Data
☑ Display Design Strategies
☐ Show Best set of Design Strategies

DESIGN STRATEGIES: JANUARY through DECEMBER
15.9% 1 Comfort(1391 hrs)
33.8% 2 Sun Shading of Windows(2961 hrs)
3 High Thermal Mass(0 hrs)
4 High Thermal Mass Night Flushed(0 hrs)
5 Direct Evaporative Cooling(0 hrs)
40.0% 6 Two-Stage Evaporative Cooling(3504 hrs)
8.8% 7 Natural Ventilation Cooling(768 hrs)
8 Fan-Forced Ventilation Cooling(0 hrs)
3.5% 9 Internal Heat Gain(306 hrs)
10 Passive Solar Direct Gain Low Mass(0 hrs)
11 Passive Solar Direct Gain High Mass(0 hrs)
12 Wind Protection of Outdoor Spaces(0 hrs)
13 Humidification Only(0 hrs)
0.3% 14 Dehumidification Only(30 hrs)
40.2% 15 Cooling, add Dehumidification if needed(3520 hrs)
16 Heating, add Humidification if needed(0 hrs)

100.0% Comfortable Hours using Selected Strategies
(8759 out of 8760 hrs)

Comfort Zones show:
Summer clothing on right,
Winter clothing on left.

Figure 4.37 : Psychometric chart with climate responsive Design strategies applied in the city of Khartoum for the year 2070. (Source;Author)

Table 4.10: Adaptive Comfort Model in ASHRAE Standard 55—2010 applied to the city of Khartoum City Sudan for the monthly thermal comfort for the year 2070

Month	Comfort (%)	Comfort (%)	Comfort (Hours)
Annual	11.7%	1023	8760
January	27.7%	206	744
February	28.3%	190	672
March	25.3%	188	744
April	0%	0	720
May	0%	0	744
June	0%	0	720
July	0%	0	744
August	0%	0	744
September	0%	0	720
October	1.1%	8	744
November	28.2%	203	720
December	30.6%	228	744

4.3.4.2 ASHRAE Standard 55 and Current Handbook of Fundamental Model

When ASHRAE Standard 55 and current Handbook of Fundamental Model is applied for the future climate of the city of Khartoum, the maximum thermal comfort that can be achieved is 15.9% compared to 11.7% which was obtained when only the ASHRAE 55-2010 model was used. This variation may be attributed to the fact that this model used global horizontal radiation and relative humidity which is likely affected by the phenomenon of climate change as justified in this research.

Classifying climate-responsive strategies on a seasonal basis table 4.11, to represent the future climate of the city of Khartoum in 2070, indicates that 36.6% thermal comfort can be achieved in the Dry Season, 13.7% in the Hot Season , and 0.9% in the Wet Season . The weather in the Dry Season is the most pleasant among all the city of Khartoum’s seasons. It is easy to achieve thermal comfort for building users by adjusting their clothing, and employing the most influential design strategies: internal heat-gain design strategies, dehumidification only and active cooling strategies. All these strategies have a direct effect on thermal comfort and they constitute 10.5 % (301 hours), 0.2% (6 hours), and 4% (116 hours) respectively. Two-stage evaporative cooling constitutes 48.5% (1396 hours) and if not used would increase active cooling from 4% (116 hours) to 37.4% (1076 hours). Natural ventilation has little direct effect on thermal comfort and contributes only about 15.4% (443 hours).

Table 4.11: Design strategies for seasonal thermal comfort for the city of Khartoum of Sudan for the year 2070 using ASHRAE Comfort model 55

Design strategies	Dry Season	Hot Season	Wet Season
Comfort	36.6%	13.7%	0.9%
Sun shading	30.6%	36.3%	34.8%
Two-stage evaporative cooling	48.5%	74.9%	12.4%
Internal heat gain	10.5%	-	-
Active cooling	4%	11.1%	86.1%

In the Hot Season, it might be difficult to achieve optimal thermal comfort without adapting active cooling; this strategy directly affects thermal comfort with an 11.1% (246 hours) improvement in thermal comfort. Also, the internal heat gain contributes about 0.2% (5 hours) to improve thermal comfort. Although two-stage evaporative cooling does not directly affect thermal comfort, if not applied, the need for active cooling will increase from 11.1% to 86.1%. Therefore it is recommended that all these strategies should be incorporated in the future design of the city of Khartoum's Wet Season buildings in order to avoid any excessive overheating that might occur.

The city of Khartoum's Wet Season has the lowest thermal comfort without using other design strategies. Compared to the other seasons, thermal comfort conditions are only met 0.9% (33 hours) in a year. In this season, cooling and dehumidification (active cooling) and dehumidification only, have direct effects on thermal comfort of 86.1% (3160 hours) and 0.7% (24 hours) respectively. Two-stage evaporative cooling has no direct effect on thermal comfort but if not used would increase the need for active cooling from 86.1% to 98.4%; therefore, it should be incorporated as an essential design strategy.

From the seasonal analysis of the 2070 hourly weather file, difficulty in achieving optimal thermal comfort for building users of the city of Khartoum in the future is conclusive. Therefore there is a need for adaptation of sustainable active-cooling in all seasons of the year. The Wet Season is projected to have the lowest thermal comfort level while the Dry Season will have the highest thermal comfort compared to other seasons. Maximizing passive-design strategies is essential for all the city of Khartoum’s buildings and should be taken as a principle design strategy. Designers should start figuring out agreeable and sustainable solutions for energy-efficient active-cooling systems in order to save costs and reduce cooling load during the long, hot months in the city of Khartoum. With maximal passive-design techniques and utilization of Sudan’s abundant renewable energy sources then reduced usage of conventional active cooling systems may be observed. For example, two-stage evaporative cooling with solar cooling, heat pumps, and desiccant cooling assisted by solar energy optimal thermal comfort may be achievable in the city of Khartoum, Sudan in the year 2070.

Chapter 5

RESULT DISCUSSION & CONCLUSION

5.1 Results Discussion

Climate has had a great influence on architecture since antiquity. Building form, building orientation, and building materials were rational consequences of local conditions. This resulted in the generation of many architectural styles and patterns; each is different from the other because of local climate peculiarities. Good examples of climate-specific architectural elements are wind towers in the Middle East, steep roof styles in cold climates, and flat roofs in hot climatic zones. All these, could be considered an intelligent solution for controlling climate effects. For a designer to successfully design, he or she should have comprehensive knowledge of the climate of the region being designed for, and how various climate-related architectural elements could be altered in order to provide optimal thermal comfort. Unfortunately, most designers do not pay enough attention to local climate and materials; instead, they follow international trends that use concrete and glass. With current trends toward sustainability, it is imperative for architects to readapt climate-responsive design strategies, which are considered the only solution to save energy. This thesis is an effort to provide climate-responsive building design strategies for the contemporary and future climate of Khartoum. In line with this, this research has paid particular attention to climate, classification, analysis, and trends analysis for the historical climate data of the city of Khartoum. Moreover, this research predicts the future resilience of climate-responsive design strategies if applied in the city of Khartoum.

The climate classification system of this research is as follows. Köppen–Geiger and ASHRAE Standard indicate the city of Khartoum has a hot/arid climate. The seasons are Hot (summer) from March to May, Wet (autumn) from June to October, and Dry (winter) from November to February. The city of Khartoum's climate is characterized by large temperature differences between day and night. Sometimes the difference can approach 20°C the Hot Season is relatively long with temperatures above 40°C and low relative humidity, which can go as low as 8%. Together, these Hot Season conditions make indoor thermal comfort levels unbearable. The Wet season is exaggerated during the month of August as it is considered the rainiest month of the season. During the Dry Season, the city experiences temperature drops most especially during the early hours of the day. Sand-dust storm occurrence is more frequent in this season than the other. The greater Sahara Desert is the main source of sand-dust storms because of pressure differences resulting from temperature fluctuations between day and night.

As mentioned in the reviewed sources, climate change has become obvious in the city of Khartoum with citizens witnessing tremendous effects. Therefore, to design a sustainable building it is essential to consider climate change analysis in building and environment design. Trends analysis of the city of Khartoum's climate data from 1981 to 2015 was conducted on a seasonal basis. The studied parameters were monthly relative humidity, average monthly temperature, average monthly wind speed, and average monthly rainfall. The climate analysis produced the following results:

- Relative humidity has been decreasing during the Dry and Hot Seasons while increasing during the Wet season.

- Temperatures have been increasing for all the three seasons of the city of Khartoum’s year.
- Wind speeds have increased in the Dry season but have decreased in the Hot and Wet Seasons.
- Rainfall’s shifts seem counterintuitive to the shifts in relative humidity since precipitation has been increasing during the Dry and Hot Seasons and decreasing during the Wet Season.

These shifts between 1981 and 2015 are proof that climate change has occurred in the city of Khartoum. Moreover, climatic shifts are expected to continue as the city of Khartoum approaches 2070:

- The already Dry and Hot Seasons will continue to exhibit decreases in humidity while the already wet season will increase in humidity.
- Temperatures will continue to rise throughout the year.
- Unfortunately, wind speeds will continue to decrease in the Hot and Wet Seasons when natural ventilation would be most desired. Likewise, continued increases in wind speed during the Dry Seasons contribute to sand-dust storms.
- Finally, due to shifts in rainfall, Wet Seasons will continue to become drier and historically Dry and Hot Seasons will receive more rain.

Table 5.1 gives comparison of Khartoum’s 2015and projected 2070 design strategies, the following results were observed:

- Thermal comfort for April through September of 2070 will be zero percent. A comfort level of zero indicates that it is impossible to achieve thermal comfort without using any design strategies.
- Annual average thermal comfort will decrease from 24.2% for 2015 to 11.7% for 2070. This decrease by more than half indicates that significant climate change effects are expected for the city of Khartoum in 2070.
- In both 2015’s and 2070’s Dry Seasons, building users experience better thermal comfort than in any other seasons while Wet season months for both years have the worst thermal comfort.
- Except for March, all other Hot Season months will have 0% thermal comfort in 2070.
- Thermal comfort in all months except December of 2070 will be lower than in 2015. December, as part of the Dry Season and having warmer temperatures in 2070 implies improved thermal comfort.

Table 5.1: Comparison between 2015 and 2070 Design Strategies

	2015 design strategies	2070 design strategies
1	Thermal Comfort without using strategy is 24.2%	Thermal Comfort without using is 11.7%
2	Zero percent thermal comfort is achieved only in June	Thermal comfort for April to September are zero percent.
3	All monthly thermal comfort are higher than 2070 except December	December is the only month in 2070 that have higher thermal comfort than 2015 months
4	Wet season have the lowest thermal comfort	Wet season have the lowest thermal comfort
5	Shading required in all season	Shading same as 2015
6	2-stage evaporative cooling efficiency is lower in Hot and Wet Season than 2070	Efficiency is same as 2070 is Lower in Dry and Hot Season and higher in Wet Season compared to 2015
7	Internal heat-gain strategy is Dry Seasons from 17.3%	Internal heat gain reduced Dry Season 2070 to 10.7%
8	Active cooling is essential in Hot and Wet Seasons	Active cooling is needed in all seasons
9	Dry season have the most favourable thermal comfort level	Dry season have the most favourable thermal comfort level
10	Natural ventilation and dehumidification are applicable in Wet season, while passive heating is required after midnight in Dry season	Natural ventilation, heating, and dehumidification are no longer applicable

Figure 5.1: Shows comparison of design strategies of 2015 and 2070 for Khartoum city, Sudan.
1= Thermal Comfort.
2= Sun shading.
3=2 stage evaporative cooling.
4= Internal heat gain.
5= Heating, Add Humidification.
6= Cooling Add dehumidification.
7= Dehumidification only.
8= Natural Ventilation

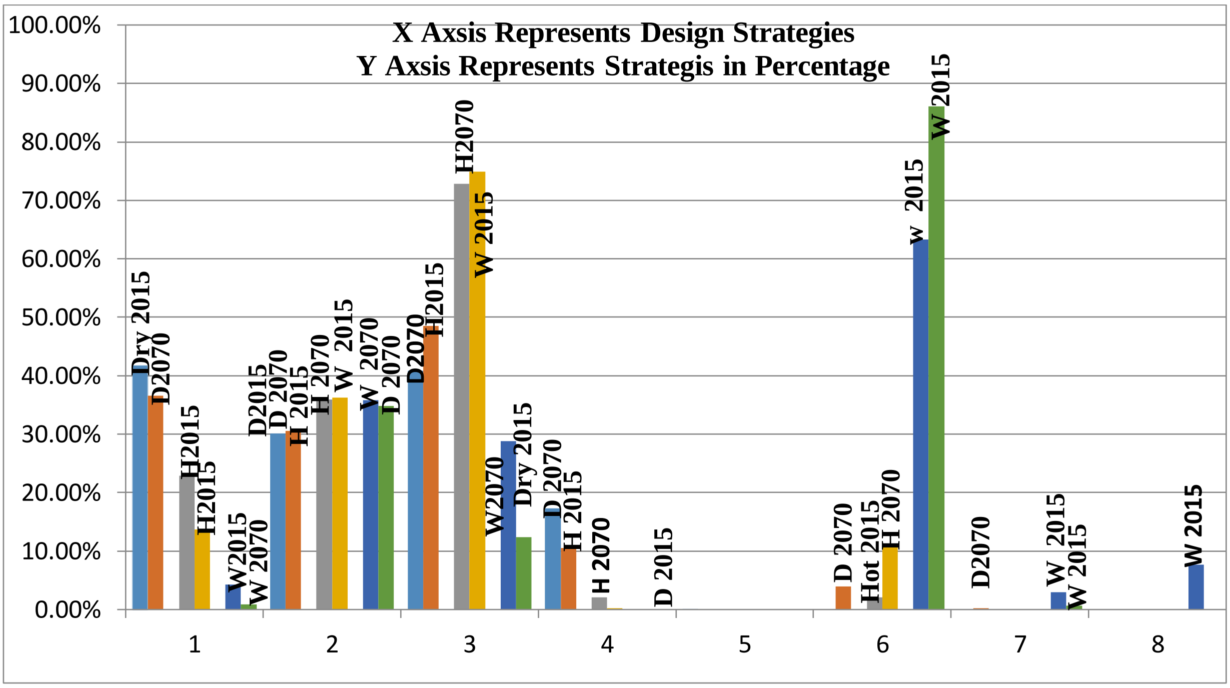


Figure 5.1: Comparison between design strategies of 2015 and 2070 for Khartoum city, Sudan.

There are ten observations resulting from the comparison of design strategies utilized in 2015 to those projected for optimal thermal comfort in 2070 they are:

1- As of 2015, the lowest thermal comfort level (4.3%) was obtained during the wet season in the city of Khartoum. Likewise, the lowest thermal comfort level (0.9%) for 2070 also will be reached during the wet season and active cooling will remain essential.

2- Designs that shade windows from direct solar gain is an important strategy for both contemporary and future buildings.

3-Though active cooling was only needed during 2015's Hot and Wet Seasons in the city of Khartoum, it will be essential during all seasons to achieve optimal thermal comfort in the projected climatic conditions of 2070. To reduce overall energy consumption, sustainable cooling systems need to replace conventional air-conditioned cooling.

4-For the city of Khartoum's projected climate in 2070, three currently used strategies will no longer be applicable: natural ventilation, heating, and dehumidification.

5-Demand on internal heat-gain strategy is reduced in the Dry Seasons from 17.3% in 2015 to 10.7% in 2070 and should be avoided in Hot and Wet Seasons in the city of Khartoum's future.

6-As in 2015, two-stage evaporative cooling will be useful in all seasons of 2070. Its use will be partially substituted by sustainable active-cooling systems during 2070's Wet season.

7-Design strategies will adapt to have more active cooling in all seasons of 2070 except the Dry Season in which it can be minimized. In addition, design strategies will include appropriate solar control to avoid overheating when solar heating is not desired.

8-Conventional air-conditioning systems, which require a great deal of Sudan's energy supply, alongside other effects of climate change could be reduced in the city of Khartoum's future by maximizing passive-design strategies such as evaporative cooling, natural ventilation, wind towers, solar chimneys, and sustainable active cooling like desiccant and heat pump systems.

9-Because sand-dust storms have become increasingly frequent and a greater source of discomfort and health problems for building occupants, this research sought solutions to remedy both the causes and the symptoms for users in 2070.

10-Symptoms of both sand-dust storms and other façade-dependent issues may be better controlled for 2070 users by introducing bio-façades and living wall systems. As well, these systems will provide evaporative cooling.

5.2 Conclusion

This study examined Khartoum's 1981 to 2015 climate data through an extensive statistics analysis of trends on a seasonal basis. The findings proved that there has been change in Khartoum's climate. Relative humidity has decreased in dry and hot seasons, and increased in wet seasons. Temperature increased throughout the seasons of the year. Wind speed increased in dry seasons and decreased in hot and wet season. Rainfall increased in dry and hot seasons and decreased in wet seasons.

Analysis of the contemporary hourly weather file of Khartoum is calculated by Meteonorm 7.2.1 from the average climate data obtained from Khartoum Meteorological station for the years 1996 to 2015. The weather file obtained is then run in computer software called Climate Consultant 6.0. From these, contemporary design strategies are obtained. Finally, these strategies are elaborated and their adaptation criteria in Khartoum buildings are explained.

Comparison of design strategies obtained from the two time series (2015 and 2070) shows that there is need to maximize passive-cooling design strategies. However, sustainable renewable energy resources in Sudan should be appropriately utilized to provide sustainable active-cooling in order to achieve optimal thermal comfort in the future.

Two-stage evaporative cooling should be used in all seasons together with sustainable active-cooling strategies assisted by solar energy such as (desiccant cooling, and heat pumps) in order to reduce the demand on conventional air-conditioning systems. Even though natural ventilation may only be applicable to some extent in the wet season, it should be enhanced through stimulating winds through a combination of wind towers and solar chimney strategies to save energy. Window shading is also a very crucial matter in Khartoum climate in all seasons of the year. Filtration of sand and dust from storms is a very important strategy in all seasons since it occurs in all months of the year in Khartoum. This research work analyzed different alternative solutions and concluded that façade-based filtration such as active living walls and bio-façades might be a solution to control sand and dust for Khartoum’s buildings.

REFERENCES

Abbouda, S. K., & Almuhanna, E. A. (2012). Improvement of evaporative cooling system efficiency in greenhouses. *International Journal of Latest Trends in Agriculture & Food Sciences*, 2(2), 83-89.

Abdalla, K. N., & Osman, E. A. (2017). Determination of cooling load for a solar cooled building in Khartoum using a simulation method. *University Of Khartoum Engineering Journal*, 7(2).

Abed, F. M., Ahmed, O. K., & Ahmed, A. E. (2018). Effect of climate and design parameters on the temperature distribution of a room. *Journal of Building Engineering*, 17, 115-124.

Abdelmajeed, M. A., Onsa, M. H., & Rabah, A. A. (2009). Management of evaporation losses of gasoline's storage tanks. Sudan. *Eng. Soc. J*, 55(52), 39-45.

Abedini Rad, M. (2014). Creating a Future for an Ancient Sustainable City, Yazd *(Master's thesis, University of Waterloo).*

Abdelrahman, M. A., & Ahmad, A. (1991). Cost-effective use of thermal insulation in hot climates. *Building and Environment*, 26(2), 189-194.

Aboul Naga, M. M. (1990). Natural ventilation and cooling by evaporation in hot-arid climates *(Doctoral dissertation, University of Leeds).*

Ahmadikia, H., Moradi, A., & Hojjati, M. (2012). Performance analysis of a wind-catcher with water spray. *International journal of green energy*, 9(2), 160-173.

Ahmadikia, H., Moradi, A., & Hojjati, M. (2012). Performance analysis of a wind-catcher with water spray. *International journal of green energy*, 9(2), 160-173.

Ahn, Y. C., Park, S. K., Kim, G. T., Hwang, Y. J., Lee, C. G., Shin, H. S., & Lee, J. K. (2006). Development of high efficiency nanofilters made of nanofibers. Current Applied Physics, 6(6), 1030-1035.

Aida, M. (1982). Urban albedo as a function of the urban structure a model experiment. *Boundary-layer meteorology*, 23(4), 405-413.

Akande, O. K. (2010). Passive design strategies for residential buildings in a hot dry climate in Nigeria. WIT Transactions on Ecology and the Environment, 128, 61-71.

Akbari, H., Matthews, H. D., & Seto, D. (2012). The long-term effect of increasing the albedo of urban areas. *Environmental Research Letters*, 7(2), 024004.

Akbari, H., & Matthews, H. D. (2012). Global cooling updates: Reflective roofs and pavements. *Energy and Buildings*, 55, 2-6.

Akbari, H., Menon, S., & Rosenfeld, A. (2009). Global cooling: increasing world-wide urban albedos to offset CO 2. *Climatic change*, 94(3-4), 275-286.

Akbari, H., Menon, S., & Rosenfeld, A. (2007). Global cooling: effect of urban albedo on global temperature (No. LBNL-63490). Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, CA (US).

Al-Azri, N. A., Zurigat, Y. H., & Al-Rawahi, N. Z. (2013). Development of bioclimatic chart for passive building design. *International Journal of Sustainable Energy*, 32(6), 713-723.

Albatayneh, A., Alterman, D., Page, A., & Moghtaderi, B. (2017). Thermal Assessment of Buildings Based on Occupants Behavior and the Adaptive Thermal Comfort Approach. *Energy Procedia*, 115, 265-271.

Alemdağ, E. L., & Beyhan, F. (2017). A Research on Construction Systems of Double Skin Facades. *Gazi University Journal of Science*, 30(1), 17-30.

Algarni, S., & Nutter, D. (2015). Influence of dust accumulation on building roof thermal performance and radiant heat gain in hot-dry climates. *Energy and Buildings*, 104, 181-190.

Al-Homoud, M. S. (2004). The effectiveness of thermal insulation in different types of buildings in hot climates. *Journal of Thermal Envelope and Building Science*, 27(3), 235-247.

Al Huseen , A. (2014).Quantitative Assessment of Climate Change Adaptive Capacity For East Nile Locality–Khartoum State-Sudan. Faculty of Natural Sciences Department of Landscape Ecology Comenius University in Bratislava.

Al-Khasawneh, Y., Albatayneh, A., Sa’ed Althawabiah, F. A., & Bdour, M. The Application of Ground-Source Heat Pumps for a Residential Building in Jordan.

Allard, F. (1998). Natural ventilation in buildings: *a design handbook* (pp. 12-78). F. Allard (Ed.). London: James & James.

Allen, E., & Iano, J. (1989). The architect's studio companion: technical guidelines for preliminary design. John Wiley & Sons.

Almeida HS.(2010) Thermal Comfort Analysis of Buildings Using Theoretical and Adaptive Models. University of Technology, Lisbon. Portugal.

Alodan, M. A., & Al-Faraj, A. A. (2005). Design and evaluation of galvanized metal sheets as evaporative cooling pads. *J. King Saud Univ., Agric. Sci*, 18(1), 9-18.

Alonso, J. S. J., Martinez, F. R., Gomez, E. V., & Plasencia, M. A. G. (1998). Simulation model of an indirect evaporative cooler. *Energy and buildings*, 29(1), 23-27.

Altahir, E.A. (1988). Testing for the Suspected Trend in Annual Rain Fall Series in Central and West Sudan. *The Sudan Engineering Society Journal*.. Issue 30.Department of Civil Engineering. University of Khartoum. Sudan.

Alzahrani, A., Boussabaine, H., & Almarri, K. (2018). Emerging financial risks from climate changes on building assets in the UK. *Facilities*, 36(9/10), 460-475.

Ambade, A .P.(2015) Study, Design and Analysis of Two Stages Evaporative Cooling System. IJSRD - *International Journal for Scientific Research & Development*| Vol. 3, Issue 01, 2015

Aminoroayaei, N., & Shahedi, B. (2018). Study of effective factors in the design of zero energy buildings in arid climate (case of Isfahan City). *Ukrainian Journal of Ecology,* 8(1), 211-221.

Amogpai, A. (2011). LED lighting combined with solar panels in developing countries.

Ampofo, F., Maidment, G., & Missenden, J. (2006). Groundwater cooling systems in London. *International Journal of Low-Carbon Technologies,* 1(4), 336-342.

Arif, M., Katafygiotou, M., Mazroei, A., Kaushik, A., & Elsarrag, E. (2016). Impact of indoor environmental quality on occupant well-being and comfort: A review of the literature. *International Journal of Sustainable Built Environment,* 5(1), 1-11.

Arif, K. M. (2013). An assessment of climatic design strategy for low energy residential buildings in hot and arid climate.

Arking, A. (1964). Latitudinal distribution of cloud cover from tiros iii photographs. *Science,* 143(3606), 569-572.

Arola, T. (2015). Groundwater as an energy resource in Finland. *Department of Geosciences and Geography A.*

Ascione, F. (2017). Energy conservation and renewable technologies for buildings to face the impact of the climate change and minimize the use of cooling. *Solar Energy*, 154, 34-100.

Asdrubali, F., D'Alessandro, F., & Schiavoni, S. (2015). A review of unconventional sustainable building insulation materials. *Sustainable Materials and Technologies*, 4, 1-17.

ASHRAE A. Standard 55-2004, thermal environmental conditions for human occupancy, atlanta: *American society of heating, refrigerating, and air-conditioning engineers*. Inc., USA. 2004.

Ashrafian, T., Tabatabaei, J. M., & Ferdos, N. M. (2011). Sustainable energies in desert climate buildings. *International Journal on "Technical and Physical Problems of Engineering,* (6), 69-75.

Aslý, P. B.(2006). Architectural Design Based on Climatic Data. Proceeding 1st International CIB Endorsed METU *Postgraduate Conference Built Environment & Information Technologies, Ankara, 2006*.

Ashwill, M., Flora, C., & Flora, J. (2011). Building community resilience to climate change: testing the adaptation coalition framework in Latin America. *World Bank, Washington, DC.*

Assem, E. O., & Al-Mumin, A. A. (2010). Code compliance of fully glazed tall office buildings in hot climate. *Energy and buildings*, 42(7), 1100-1105.

Astel, A., Mazerski, J., Polkowska, Z. and Namiesnik, J. (2004) Application of PCA and Time Series Analysis in Studies of Precipitation in Tricity (Poland). *Advances in Environmental Research*, 8, 337-349.

Attia, S. (2012). A tool for design decision making: zero energy residential buildings in hot humid climates. *Presses univ. de Louvain*.

Awad, H. S., & Hussein, M. T. (2006). Hydrochemical appraisal of groundwater in the Khartoum region, Sudan. *Journal of Environmental Hydrology*, 14, 1-8.

Awafo, E. A., & Dzisi, K. A. (2012). Appropriate design of evaporative cooler for mango storage in the transitional and savannah zones of Ghana. *International Journal of Engineering Sciences Research-IJESR*, 3, 687-695.

Aynsley, R. (2014). Natural ventilation in passive design. *Environment Design Guide*, 1-16.

Babatsikou, F. P. (2011). The sick building syndrome (SBS). *Health Science Journal*, 5(2), 72.

Babisch, W. (2008). Road traffic noise and cardiovascular risk. *Noise and Health*, 10(38), 27.

Bahadori, M. N., Dehghani-Sanij, A., & Sayigh, A. (2014). Wind towers: architecture, climate and sustainability. *Springer*.

Bahadori, M. N. (1985). An improved design of wind towers for natural ventilation and passive cooling. *Solar Energy*, 35(2), 119-129.

Bahadori, M. N., & Pakzad, A. R. (2002, January). Performance evaluation of new designs of wind towers. *In ASME 2002 Joint US-European Fluids Engineering Division Conference* (pp. 1015-1021). American Society of Mechanical Engineers.

Bahadori, M. N. (1994). Viability of wind towers in achieving summer comfort in the hot arid regions of the Middle East. *Renewable Energy*, 5(5-8), 879-892.

Bahaj, A. S., James, P. A., & Jentsch, M. F. (2008). Potential of emerging glazing technologies for highly glazed buildings in hot arid climates. *Energy and Buildings*, 40(5), 720-731.

Baird, G. (2017). Energy Performance Buildings: 0. CRC press.

Bakr, E. A. (1988). Central Sudan surface wind data and climate characteristic. Koninklijk *Nederlands Meteorologisch Instituut.*

Banks, D. (2012). An introduction to thermo-geology: ground source heating and cooling. John Wiley & Sons.

Banks, D. (2009). Thermogeological assessment of open-loop well-doublet schemes: a review and synthesis of analytical approaches. *Hydrogeology Journal*, 17(5), 1149-1155.

Bansal, N. K., Mathur, R., & Bhandari, M. S. (1993). Solar chimney for enhanced stack ventilation. *Building and environment*, 28(3), 373-377.

Bardhi, A., & Gjongecaj, B. (2014). Classification of the Climate Based on the Combination between Potential Evapotranspiration and Rainfall. International *Journal of Engineering Research and Applications,* 4(4), 188-192.

Beckett, R &, Dan Sudeyko. (2018). Technical Design Requirements Climate Resilience Study for Alberta Infrastructure *Final Report*. 2018-04-27 Technical Design Requirements Climate Resilience Study

Bekkouche, S. M. A., Benouaz, T., Cherier, M. K., Hamdani, M., Yaiche, M. R., & Benamrane, N. (2013). Influence of the compactness index to increase the internal temperature of a building in Saharan climate. *Energy and Buildings*, 66, 678-687.

Bekkouche, S. M. E. A., Benouaz, T., Cherier, M. K., Hamdani, M., Yaiche, R. M., & Khanniche, R. (2013). Influence of Building Orientation on Internal

Temperature in Saharian Climates, Building Located in Ghardaia Region (Algeria). *Thermal Science*, 17(2).

Bellia, L., Marino, C., Minichiello, F., & Pedace, A. (2014). An overview on solar shading systems for buildings. *Energy Procedia*, 62, 309-317.

Berdahl, P., Akbari, H., Levinson, R., & Miller, W. A. (2008). Weathering of roofing materials–an overview. *Construction and Building Materials*, 22(4), 423-433.

Berz, G. A. (1997). Catastrophes and climate change: Risks and (re-) actions from the viewpoint of an international reinsurer. *Eclogae Geologicae Helvetiae*, 90(3), 375-379.

Bhikhoo, N., Hashemi, A., & Cruickshank, H. (2017). Improving thermal comfort of low-income housing in Thailand through passive design strategies. *Sustainability*, 9(8), 1440.

Behling, S., Behling, S., Schindler, B., & Foster, N. (1996). Sol power: the evolution of solar architecture. Prestel.

Berglund, L. G., & Cunningham, D. J. (1986). Parameters of human discomfort in warm environments. ASHRAE Trans.;(United States), 92(CONF-8606125-)

.Berglund, L. G. (1998). Comfort and humidity. *ASHRAE journal*, 40(8), 35.

Berlatsky, N. (2010). Water and Ice. Greenhaven Publishing LLC.

Bilow, M. (2012). International façades: CROFT-Climate Related Optimized Façade Technologies (Vol. 1). *TU Delft.*

Bolduc, C. (2015). Thermal evidence for surface and subsurface water contributions to baseflow in a high Arctic river *(Doctoral dissertation).*

Bouillot, J. (2008). Climatic design of vernacular housing in different provinces of China. *Journal of environmental management*, 87(2), 287-299.

Brager GS, de Dear R. (2000) A standard for natural ventilation. *ASHRAE journal*. Vol.42 (10):21.

Brambilla, A., Bonvin, J., Flourentzou, F., & Jusselme, T. (2018). On the influence of thermal mass and natural ventilation on overheating risk in offices. *Buildings,* 8(4), 47.

Brincat, J. P., Sardella, D., Muscat, A., Decelis, S., Grima, J. N., Valdramidis, V., & Gatt, R. (2016). A review of the state-of-the-art in air filtration technologies as may be applied to cold storage warehouses. *Trends in food science & technology*, 50, 175-185.

Broersma, S., Fremouw, M., & Dobbelsteen, A. V. D. (2013). Energy potential mapping: visualising energy characteristics for the exergetic optimisation of the built environment. *Entropy*, 15(2), 490-506

Brown, W. K., & Watt, J. R. (1997). Evaporative air conditioning handbook.

Butera, F., Adhikari, R. S., & Aste, N. (2015). Sustainable Building Design for Tropical Climates. UN-Habitat-UNON, Publishing Services Section.

Calautit, J. K., Chaudhry, H. N., Hughes, B. R., & Ghani, S. A. (2013). Comparison between evaporative cooling and a heat pipe assisted thermal loop for a commercial wind tower in hot and dry climatic conditions. *Applied Energy*, 101, 740-755.

Camargo, J. R., Ebinuma, C. D., & Silveira, J. L. (2005). Experimental performance of a direct evaporative cooler operating during summer in a Brazilian city. *International Journal of Refrigeration*, 28(7), 1124-1132..

Caruso, G., & Kämpf, J. H. (2015). Building shape optimisation to reduce air-conditioning needs using constrained evolutionary algorithms. *Solar Energy*, 118, 186-196.

Caruso, G., Fantozzi, F., & Leccese, F. (2013). Optimal theoretical building form to minimize direct solar irradiation. *Solar Energy*, 97, 128-137.

Castillo, J. A., & Huelsz, G. (2017). A methodology to evaluate the indoor natural ventilation in hot climates: Heat Balance Index. *Building and Environment*, 114, 366-373.

Catalina, T., Virgone, J., & Iordache, V. (2011, November). Study on the impact of the building form on the energy consumption. *In Proceedings of building simulation* (pp. 1726-1729).

CEN Standard EN15251 (2007). Indoor environmental input parameters for design and assessment of energy performance of buildings, addressing indoor air quality, thermal environment, lighting and acoustics. Brussels: Comité Européen de Normalisation.

Chalmers, P. (2014). Climate Change: Implications for Buildings. Key Findings from the Intergovernmental Panel on Climate Change Fifth Assessment Report. World Business Council for Sustainable Development/University of Cambridge's Judge Business School/Institute for Sustainability Leadership.

Chartier, Y., & Pessoa-Silva, C. L. (2009). Natural ventilation for infection control in health-care settings. World Health Organization.

Charter, L. (2007, May). Leipzig Charter on sustainable European cities. In European Conference of Ministers Responsible for Spatial/Regional Planning, Resolution (Vol. 3).

Chatzipoulka, C. (2017). Urban geometry and environmental performance in real urban forms *(Doctoral dissertation, University of Kent,).*

Chen, Y., Tong, Z., & Malkawi, A. (2017). Investigating natural ventilation potentials across the globe: Regional and climatic variations. *Building and Environment*, 122, 386-396.

Cheng, Z., Li, L., & Bahnfleth, W. P. (2016). Natural ventilation potential for gymnasia–case study of ventilation and comfort in a multisport facility in northeastern United States. *Building and Environment*, 108, 85-98.

CIBSE, & CIBSE Guide A (1999). The chartered institution of building services engineers. London: Yale Press.

Cicerone, R. J., & Nurse, P. (2014). Climate Change Evidence & Causes: An Overview from the Royal Society and the US National Academy of Sciences.

Coch, H. (1998). —Bioclimatic in vernacular architecture. Renewable and Sustainable *Energy Reviews*, 2(1-2), 67-87.

Collins, D. C., & Avissar, R. (1994). An evaluation with the Fourier amplitude sensitivity test (FAST) of which land-surface parameters are of greatest importance in atmospheric modeling. Journal of *Climate*, 7(5), 681-703.

Concina, W., Sadineni, S., & Boehm, R. (2011, January). Solar Assisted Desiccant Cooling Simulation for Different Climate Zones. In ASME 2011 5th

International Conference on Energy Sustainability (pp. 127-136). *American Society of Mechanical Engineers*.

Crawley, D. B. (2008). Estimating the impacts of climate change and urbanization on building performance. *Journal of Building Performance Simulation*, 1(2), 91-115.

Cullen, J. M., & Allwood, J. M. (2010). Theoretical efficiency limits for energy conversion devices. *Energy*, 35(5), 2059-2069.

Dabaieh, M., Wanas, O., Hegazy, M. A., & Johansson, E. (2015). Reducing cooling demands in a hot dry climate: A simulation study for non-insulated passive cool roof thermal performance in residential buildings. *Energy and Buildings*, 89, 142-152.

Daou, K., Wang, R. Z., & Xia, Z. Z. (2006). Desiccant cooling air conditioning: a review. *Renewable and sustainable energy reviews*, 10(2), 55-77.

Daroda, K. S. (2011). Climate responsive architecture: Creating greater design awareness among architects. *Journal of Environmental Issues and Agriculture in Developing Countries*, 3(1), 33.

Davies, H. R. J., & Walsh, R. P. D. (1997). Historical changes in the flood hazard at Khartoum, Sudan: lessons and warnings for the future. *Singapore Journal of Tropical Geography,* 18(2), 123-140.

De Carli, M., Bernardi, A., Cultrera, M., Dalla Santa, G., Di Bella, A., Emmi, G., ... & Pasquali, R. (2018). A Database for Climatic Conditions around Europe for Promoting GSHP Solutions. *Geosciences*, 8(2), 71.

De Gracia, A., Castell, A., Navarro, L., Oró, E., & Cabeza, L. F. (2013). Numerical modelling of ventilated facades: A review. *Renewable and Sustainable Energy Reviews*, 22, 539-549.

Dehghani-Sanij, A. R., Soltani, M., & Raahemifar, K. (2015). A new design of wind tower for passive ventilation in buildings to reduce energy consumption in windy regions. *Renewable and Sustainable Energy Reviews,* 42, 182-195.

De Saulles, T. (2004). Free cooling systems. *BRISA.*

Dickinson, W. C., and Cheremisinoff, P. N., (1980) Solar Energy Technology Handbook (London: Butterworths).

Dickinson, E. W. (2018). Solar Energy Technology Handbook: 0. CRC Press.

Douvlou, E. D. (2004). Climatic responsive design and occupant comfort: the case of the atrium building in a Mediterranean climate *(Doctoral dissertation, University of Sheffield).*

Du, X., Bokel, R., & van den Dobbelsteen, A. (2014). Building microclimate and summer thermal comfort in free-running buildings with diverse spaces: A Chinese vernacular house case. *Building and Environment*, 82, 215-227.

Edmonds, I. R., & Greenup, P. J. (2002). Daylighting in the tropics. *Solar energy*, 73(2), 111-121.

Edwards, R. D., Jurvelin, J., Saarela, K., & Jantunen, M. (2001). VOC concentrations measured in personal samples and residential indoor, outdoor and workplace microenvironments in EXPOLIS-Helsinki, Finland. *Atmospheric Environment*, 35(27), 4531-4543.

Ekici , C A.(2013) review of Thermal Comfort and Method of Using Fanger’s PMV Equation, 2013. *5th International Symposium on Measurement, Analysis and Modeling of Human Functions 27-29 June, 2013*, Vancouver, CANADA

Elagib, N. A. (2009). Assessment of drought across central Sudan using UNEP dryness ratio. *Hydrology Research*, 40(5), 481-494.

Elagib, N. A., & Elhag, M. M. (2011). Major climate indicators of ongoing drought in Sudan. *Journal of Hydrology*, 409(3-4), 612-625.

Elagib NA. Trends in Intra-and Inter-annual Temperature Variabilities Across Sudan. *AMBIO*. 2010 Jul 1; 39(5-6):413-29.

Elagib, N. A. (2011). Evolution of urban heat island in Khartoum. International Journal of Climat Elagib, N. A., & Mansell, M. G. (2000). Recent trends and anomalies in mean seasonal and annual temperatures over Sudan. J*ournal of Arid Environments*, 45(3), 263-288.ology, 31(9), 1377-1388.

El Bakkush, A. F. M. (2016). Improving solar gain control strategies in residential buildings located in a hot climate (Tripoli-Libya) *(Doctoral dissertation, Heriot-Watt University).*

El Basyouni, M. (2017). Resilient Buildings: A Path towards Adaptability Climate Change Adaptation Strategies and Interventions for Buildings Resilience.

Eliasson, I. (2000). The use of climate knowledge in urban planning. *Landscape and urban planning*, 48(1-2), 31-44.

El-Refaie, M. F., & Kaseb, S. (2009). Speculation in the feasibility of evaporative cooling. *Building and Environment*, 44(4), 826-838.

El-Sebaii, A. A., & Trabea, A. A. (2005). Estimation of global solar radiation on horizontal surfaces over Egypt. *Egypt. J. Solids*, 28(1), 163-175.

El sheikh O, M.I.(2015). Implementation of heat pumps in Sudan. Unpublished M.Sc. thesis, Department of Mechanical Engineering University of Khartoum Sudan.

El Zein M.(2017). Solar Energy Potential in the Sudan. Master thesis in Sustainable Development. *Department of Earth Sciences, Uppsala University*

Erens, P. J., & Dreyer, A. A. (1993). Modelling of indirect evaporative air coolers. *International journal of heat and mass transfer*, 36(1), 17-26.

Evola, G., & Popov, V. (2006). Computational analysis of wind driven natural ventilation in buildings. *Energy and buildings*, 38(5), 491-501.

Exell, R. H. B. (2000). The intensity of solar radiation. *King Mongkut's University of Technology Press, Thornburi*, 549, 554.

Fanger, P. O. (1970). Thermal Comfort. Technical University of Denmark, Laboratory of heating and air conditioning.

Fanger, P. O. (1970). Conditions for thermal comfort-Introduction of a general comfort equation. Physiological and behavioral temperature regulation.

Farmahini-Farahani, M., Delfani, S., & Esmaeelian, J. (2012). Exergy analysis of evaporative cooling to select the optimum system in diverse climates. Energy, 40(1), 250-257.

Fathy, H.(1986) Natural energy and vernacular architecture. United States: N. p., 1986. Web.

Ferguson, G., & Woodbury, A. D. (2005). Thermal sustainability of groundwater-source cooling in Winnipeg, Manitoba. *Canadian Geotechnical Journal*, 42(5), 1290-1301.

Fernández, M. E., Gentili, J. O., & Campo, A. M. (2018). Sunshine Duration Analysis as a First Step to Estimate Solar Resource for Photovoltaic Electricity Production in Middle Latitudes. *Environmental Processes*, 5(2), 313-328.

Fisk, W. J., Lei-Gomez, Q., & Mendell, M. J. (2006). Meta-Analyses of the Associations of Respiratory Health Effectswith Dampness and Mold in Homes. Indoor Air, 17(LBNL-59363).

Fontanini, A., Vaidya, U., & Ganapathy Subramanian, B. (2013). A stochastic approach to modeling the dynamics of natural ventilation systems. *Energy and buil*dings, 63, 87-97.

Forsén, M., BOESWARTH, R., DUBUISSON, X., & Sandström, B. (2005). Heat pumps: technology and environmental impact. *Swedish Heat Pump Association, SVEPR.*

Foruzanmehr, A. (2017). Thermal Comfort in Hot Dry Climates: Traditional Dwellings in Iran. Routledge.

Freewan, A. A. (2014). Impact of external shading devices on thermal and daylighting performance of offices in hot climate regions. *Solar Energy*, 102, 14-30.

Frontczak, M., & Wargocki, P. (2011). Literature survey on how different factors influence human comfort in indoor environments. *Building and environment*, 46(4), 922-937

Fuliotto, R., Cambuli, F., Mandas, N., Bacchin, N., Manara, G., & Chen, Q. (2010). Experimental and numerical analysis of heat transfer and airflow on an interactive building facade. *Energy and buildings*, 42(1), 23-28.

Gabril, N. (2014). Thermal Comfort and Building Design Strategies for Low Energy Houses in Libya: Lessons from the vernacular architecture *(Doctoral dissertation, University of Westminster).*

Gagge, A. P. (1971). An effective temperature scale based on a simple model of human physiological regulatory response. *ASHRAE Trans.*, 77, 247-262.

Gan, G. (2006). Simulation of buoyancy-induced flow in open cavities for natural ventilation. *Energy and buildings*, 38(5), 410-420.

Gerth, J. J. (2013). Sky cover (Doctoral dissertation, The University of Wisconsin-Madison).

Ghattas, R., Ulm, F.J. and Ledwith, A., (2013) Mapping thermal mass benefit. Available at: https://cshub.mit.edu/sites/default/files/documents/ThermalMassBenefit_v10_13_0920.pdp. (Accessed on 22 May 2018)

Ghazi, S., Sayigh, A., & Ip, K. (2014). Dust effect on flat surfaces–A review paper. *Renewable and Sustainable Energy Reviews*, 33, 742-751.

Ghobrial, S. I., Sharif, S. M., Ateem, M. E., & El Tigani, M. (1985). Dust Storms in the Sudan: Intensity and Particles ‘characteristics. *JIEEE,* 85, 326-328.

Ghoreishi, A. (2015). Assessment of thermal mass property for energy efficiency and thermal comfort in concrete office buildings *(Doctoral dissertation, University of Illinois at Urbana-Champaign).*

Givoni, B. (1998). Climate considerations in building and urban design. John Wiley & Sons.

Givoni, B. (1976). Man, Climate and Architecture, 2nd ed. London: *Applied Science Publishers Ltd.*

Givoni, B. (1992). Comfort, climate analysis and building design guidelines. *Energy and buildings*, 18(1), 11-23.

Givoni, B. (1994). Passive low energy cooling of buildings. John Wiley & Sons.

Gładyszewska-Fiedoruk, K., & Gajewski, A. (2012). Effect of wind on stack ventilation performance. *Energy and Buildings*, 51, 242-247.

Godoy-Vaca, L., Almaguer, M., Martínez-Gómez, J., Lobato, A., & Palme, M. (2017, October). Analysis of Solar Chimneys in Different Climate Zones-Case of Social Housing in Ecuador. *In IOP Conference Series: Materials Science and Engineering* (Vol. 245, No. 7, p. 072045). IOP Publishing.

Goetzler, W., Zogg, R., Lisle, H., & Burgos, J. (2009). Ground-source heat pumps. Overview of market status, barriers to adoption, and options for overcoming barriers. Navigant Consulting, Inc., Chicago, IL (United States).

Gogtay, N. J., & Thatte, U. M. (2017). Principles of correlation analysis. *Journal of the association of physicians of India*, 65, 78-81.

Goudie, A. S., & Middleton, N. J. (2006). Desert dust in the global system. *Springer Science & Business Media.*

Goulding, J. R., Lewis, J. O., & Steemers, T. C. (Eds.). (1992). Energy conscious design: a primer for architects. London: Batsford for the Commission of the European Communities.

Gou S, Li Z, Zhao Q, Nik VM, Scartezzini JL. Climate responsive strategies of traditional dwellings located in an ancient village in hot summer and cold winter region of China. *Building and Environment*. 2015 Apr 1; 86:151-65.

Greenup, P. J., & Edmonds, I. R. (2004). Test room measurements and computer simulations of the micro-light guiding shade daylight redirecting device. *Solar Energy*, 76(1-3), 99-109.

Greening, B., & Azapagic, A. (2012). Domestic heat pumps: Life cycle environmental impacts and potential implications for the UK. *Energy*, 39(1), 205-217.

Gregory, et al . (2007). Climate change 2007: the physical science basis. *Report of Intergovernmental Panel on Climate Change (IPCC. Issued in 2007*. Cambridge University Press.

Guan, L. (2009). Preparation of future weather data to study the impact of climate change on buildings. *Building and environment*, 44(4), 793-800.

Guide, E. C. (1993). 19, Energy efficiency in offices. Energy Efficiency Office/HMSO, London.

Gut, P., & Ackerknecht, D. (1993). Climate responsive buildings: appropriate building construction in tropical and subtropical regions.

Handbook, A. F. (2009). American society of heating, refrigerating and air-conditioning engineers. Inc.: Atlanta, GA, USA.

Hansen, J., Sato, M., & Ruedy, R. (2012). Perception of climate change. *Proceedings of the National Academy of Sciences*, 109(37), E2415-E2423.

Hasan, O. A., Defer, D., & Shahrour, I. (2014). A simplified building thermal model for the optimization of energy consumption: Use of a random number generator. *Energy and Buildings,* 82, 322-329.

Hausladen, G., Liedl, P., & De Saldanha, M. (2014). Building to Suit the Climate. Munich, DE: Birkhäuser Verlag.

Hegger, M., Fuchs, M., Stark, T., & Zeumer, M. (2012). Energie Atlas: Nachhaltige Architektur. Walter de Gruyter.

Helmis, C. G., Assimakopoulos, V. D., Flocas, H. A., Stathopoulou, O. I., Sgouros, G., & Hatzaki, M. (2009). Indoor air quality assessment in the air traffic control tower of the Athens Airport, Greece. *Environmental monitoring and assessment,* 148(1-4), 47-60.

Hemsath, T. L., & Bandhosseini, K. A. (2015). Sensitivity analysis evaluating basic building geometry's effect on energy use. *Renewable Energy*, 76, 526-538.

Hensen, J. L. (1990). Literature review on thermal comfort in transient conditions. *Building and Environment,* 25(4), 309-316.

Herrera, M., Natarajan, S., Coley, D. A., Kershaw, T., Ramallo-González, A. P., Eames, M., & Wood, M. (2017). A review of current and future weather data for building simulation. *Building Services Engineering Research and Technology*, 38(5), 602-627.

Hirashima, S. D. S., Katzschner, A., Ferreira, D. G., De Assis, E. S., & Katzschner, L. (2018). Thermal comfort comparison and evaluation in different climates. *Urban Climate*, 23, 219-251.

Holmes, M. J., & Hacker, J. N. (2007). Climate change, thermal comfort and energy: Meeting the design challenges of the 21st century. *Energy and Buildings*, 39(7), 802-814.

Hoo, L. K., Lau, B., & Hung, F. C. The Adoption of Passive Cooling Strategy in Designing Public Assembly Building–A Design Typology for the Taoist Academic Centre in Tropical Climate.

Hosseini, M., & Akbari, H. (2014). Heating energy penalties of cool roofs: the effect of snow accumulation on roofs. *Advances in Building Energy Research*, 8(1), 1-13.

Hughes, B. R., Calautit, J. K., & Ghani, S. A. (2012). The development of commercial wind towers for natural ventilation: a review. *Applied energy*, 92, 606-627.

Hui, S. C., & Tsang, M. F. (2005, November). Climatic data for sustainable building design in Hong Kong. In Proc. of the Joint Symposium 2005: N*ew Challenges in Building Services* (Vol. 15, pp. 89-99).

Humphreys, M. A., & Nicol, J. F. (2002). The validity of ISO-PMV for predicting comfort votes in every-day thermal environments. *Energy and buildings*, 34(6), 667-684.

Hu, Q., Yang, N., Pan, F., Pan, X., Wang, X., & Yang, P. (2017). Adjusting sowing dates improved potato adaptation to climate change in semiarid region, China. *Sustainability*, 9(4), 615.

Hui, S. C. M. (2000). Climatic design of buildings—*an overview. Lecture Notes.*

Hui, S. C., & Cheung, M. W. (2009). Two-stage evaporative cooling systems in hot and humid climate. *In Proceedings of the Tianjin-Hong Kong Joint Symposium* (pp. 64-76).

Imbabi, M. S. E. (2006). Modular breathing panels for energy efficient, healthy building construction. *Renewable Energy*, 31(5), 729-738.

Inanici, M. N., & Demirbilek, F. N. (2000). Thermal performance optimization of building aspect ratio and south window size in five cities having different climatic characteristics of Turkey. *Building and Environment*, 35(1), 41-52.

ISO 7730 Standard (2005). Ergonomics of thermal environment analytical determination and interpretation of thermal comfort using calculation of the

PMV and PPD indices and local thermal comfort criteria. London: *International Standards Organisation*.

Iyi, D., Hasan, R., Penlington, R., & Underwood, C. (2014). Double skin façade: Modelling technique and influence of venetian blinds on the airflow and heat transfer. *Applied Thermal Engineering*, 71(1), 219-229.

Jain, S. (2008). Emulating Nature: Evaporative Cooling Systems. *ASHRAE Transactions*, 114(2).

Jentsch, M. F., James, P. A., & Bahaj, A. S. (2010, September). Climate Change adapted simulation weather data: implications for cities in hot, arid climates of the Middle East. *In proceedings of World Renewable Energy Congress* XI (pp. 25-30).

Jin, Q., Overend, M., & Thompson, P. (2012). Towards productivity indicators for performance-based façade design in commercial buildings. *Building and Environment*, 57, 271-281.

Jing, S., Li, B., Tan, M., & Liu, H. (2013). Impact of relative humidity on thermal comfort in a warm environment. *Indoor and Built Environment*, 22(4), 598-607.

Ji, W., Luo, M., Cao, B., Zhu, Y., Geng, Y., & Lin, B. (2018). A new method to study human metabolic rate changes and thermal comfort in physical exercise by

CO2 measurement in an airtight chamber. *Energy and Buildings*, 177, 402-412.

Jiang, Y., & Lei, Y. (2017). Analysis of influencing factors of ground-source heat pump applications in China using partial least squares regression. *Polish Journal of Environmental Studies*, 26(6).

John, W., & Reischl, G. (1978). Measurements of the filtration efficiencies of selected filter types. *Atmospheric Environment* (1967), 12(10), 2015-2019.

Judson, R., Houck, K., Martin, M., Knudsen, T., Thomas, R. S., Sipes, N., ... & Crofton, K. (2014). In vitro and modelling approaches to risk assessment from the US Environmental Protection Agency Tox Cast programme. *Basic & clinical pharmacology & toxicology*, 115(1), 69-76.

Khanal, R., & Lei, C. (2011). Solar chimney—A passive strategy for natural ventilation. *Energy and Buildings*, 43(8), 1811-1819.

Khani, S., Bahadori, M., Dehghani-Sanij, A., & Nourbakhsh, A. (2017). Performance evaluation of a modular design of wind tower with wetted surfaces. *Energies*, 10(7), 845.

Kahrl, F., & Roland-Holst, D. (2009). Growth and structural change in China's energy economy. *Energy*, 34(7), 894-903.

Keller, A., Petrus, C., & Mosoarca, M. (2016, April). The impact of climate change on the energy performance of historical buildings. *In Proceedings of the 3rd International Academic Conference on Places and Technologies* (pp. 14-15).

Khalfan, M, and Steve, S. The Present and Future Energy Performance of the First Passivhaus Project in the Gulf Region. *Sustainability Journal*. 2016. Volume 8, no. 2, pp: 1- 17. DOI: 10.3390/su8020139.

Khlebnikova, E. I., & Shkol'nik, I. M. (2012). Regional climate changes as the factors of impact on the objects of construction and infrastructure. *Russian meteorology and hydrology*, 37(11-12), 735-745.

Kim, T., Lee, D. H., Ahn, K., Ha, H., Park, H., Piao, C. X., & Seo, J. (2007). Characteristics of rain penetration through a gravity ventilator used for natural ventilation. *Annals of Occupational Hygiene*, 52(1), 35-44.

Kim, J., & Nam, Y. (2016). A numerical study on system performance of groundwater heat pumps. *Energies*, 9(1), 4.

Kleiven, T. (2003). Natural ventilation in buildings: architectural concepts, consequences and possibilities. *Institutt for byggekunst, historie og teknologi*.

Klote, J. H., & Evans, D. H. (2007). A Guide to Smoke Control in the 2006 IBC: An Interpretation and Applications Guide. *International Code Council*.

Kong, D., Liu, H., Wu, Y., Li, B., Wei, S., & Yuan, M. (2019). Effects of indoor humidity on building occupants' thermal comfort and evidence in terms of climate adaptation. *Building and Environment.*

Kothe, S., Pfeifroth, U., Cremer, R., Trentmann, J., & Hollmann, R. (2017). A satellite-based sunshine duration climate data record for Europe and Africa. *Remote Sensing*, 9(5), 429.

Kottek, M., Grieser, J., Beck, C., Rudolf, B., & Rubel, F. (2006). World map of the Köppen-Geiger climate classification updated. *Meteorologische Zeitschrift*, 15(3), 259-263.

Krishan, A. (Ed.). (2001). Climate responsive architecture: *a design handbook for energy efficient buildings*. Tata McGraw-Hill Education.

Krautheim, M., Pasel, R., Pfeiffer, S., & Schultz-Granberg, J. (2014). City and wind: climate as an architectural instrument. Dom Publishers.

Kuchen, E. R. N. E. S. T. O. (2016). Variable Thermal Comfort Index for Indoor Work Space in Office Buildings: A Study in Germany. *Open J Civ Eng*, 6, 670-84.

Kudoda, A. M., & Abdalla, O. A. (2015). Hydrochemical characterization of the main aquifers in Khartoum, the capital city of Sudan. *Environmental Earth Sciences*, 74(6), 4771-4786.

Lam, J. C., Yang, L., & Liu, J. (2006). Development of passive design zones in China using bioclimatic approach. *Energy Conversion and management*, 47(6), 746-762.

Lam, J. C., Tang, H. L., & Li, D. H. (2008). Seasonal variations in residential and commercial sector electricity consumption in Hong Kong. *Energy*, 33(3), 513-523.

Lam, J. C., Wan, K. K., Lam, T. N., & Wong, S. L. (2010). An analysis of future building energy use in subtropical Hong Kong. *Energy*, 35(3), 1482-1490.

Lavafpour, Y., & Surat, M. (2011). Passive low energy architecture in hot and dry climate. *Australian Journal of Basic and Applied Sciences*, 5(8), 757-765.

Lee, E. S., DiBartolomeo, D. L., & Selkowitz, S. E. (2006). Daylighting control performance of a thin-film ceramic electrochromic window: field study results. *Energy and Buildings*, 38(1), 30-44.

Lemouari, M., Boumaza, M., & Kaabi, A. (2009). Experimental analysis of heat and mass transfer phenomena in a direct contact evaporative cooling tower. *Energy conversion and management*, 50(6), 1610-1617.

Lewtas, J. (2007). Air pollution combustion emissions: characterization of causative agents and mechanisms associated with cancer, reproductive, and cardiovascular effects. *Mutation Research/Reviews in Mutation Research*, 636(1), 95-133.

Li, D. H., Yang, L., & Lam, J. C. (2012). Impact of climate change on energy use in the built environment in different climate zones–a review. *Energy*, 42(1), 103-112.

Lien, J., & Ahmed, N. (2011). Wind driven ventilation for enhanced indoor air quality. In Chemistry, Emission Control, Radioactive Pollution and Indoor Air Quality. InTech.

Liu, J., Shui, T. T., & Ma, F. (2013). Analysis of natural cross-ventilation in buildings driven by wind and buoyancy forces. *In Applied Mechanics and Materials* (Vol. 353, pp. 3001-3004). Trans Tech Publications.

Liu, L. (2017, May). Principle and characteristics of heat pump air conditioning system. *In AIP Conference Proceedings* (Vol. 1839, No. 1, p. 020031). AIP Publishing.

Liu, G., Xiao, M., Zhang, X., Gal, C., Chen, X., Liu, L., & Clements-Croome, D. (2017). A review of air filtration technologies for sustainable and healthy building ventilation. *Sustainable cities and society*, 32, 375-396.

Liu, L., Wu, D., Li, X., Hou, S., Liu, C., & Jones, P. (2017, October). Effect of geometric factors on the energy performance of high-rise office towers in Tianjin, China. *In Building Simulation* (Vol. 10, No. 5, pp. 625-641). Tsinghua University Press.

Looman, R. (2017). Climate-responsive design: A framework for an energy concept design-decision support tool for architects using principles of climate-responsive design. A+ BE| *Architecture and the Built Environment*, (1), 1-282.

Lorenz, A. (2012). Uncertainty & Learning in Global Climate Analysis. Available at: https://www.depositonce.tu-berlin.de/handle/11303/3442 (Accessed on 11 March 2019)

Lovatt, J. E., & Wilson, A. (1995). Stack effect in tall buildings. *In Fuel and Energy Abstracts* (Vol. 4, No. 36, p. 289).

Luo, T., Yan, D., Lin, R., & Zhao, J. (2015). Sky-luminance distribution in Beijing. *Lighting Research & Technology*, 47(3), 349-359.

MacKay, D. (2008). Sustainable Energy-without the hot air. UIT Cambridge.

Magzoub, E. E., & Osman, E. A. (1998). Computer simulation of solar cooled buildings in Khartoum. *Renewable energy*, 14(1-4), 373-379.

Maheshwari, G. P., Al-Ragom, F., & Suri, R. K. (2001). Energy-saving potential of an indirect evaporative cooler. *Applied Energy*, 69(1), 69-76.

Mahmoud, W. H., Elagib, N. A., Gaese, H., & Heinrich, J. (2014). Rainfall conditions and rainwater harvesting potential in the urban area of Khartoum. *Resources, Conservation and Recycling*, 91, 89-99

Manioğlu, G., & Yılmaz, Z. (2008). Energy efficient design strategies in the hot dry area of Turkey. *Building and Environment*, 43(7), 1301-1309.

Manteghi, G., & Remaz, D. (2015). Water bodies an urban microclimate: a review. Modern *Applied Science*, 9(6), 1.

Manzano-Agugliaro, F., Montoya, F. G., Sabio-Ortega, A., & García-Cruz, A. (2015). Review of bioclimatic architecture strategies for achieving thermal comfort. *Renewable and Sustainable Energy Reviews*, 49, 736-755.

Manzella A.(2017). Geothermal energy. In EPJ Web of Conferences. Vol. 148, p. 00012). EDP Sciences.

Matsumoto, H., Tsuzuki, K., & Susanti, L. (2017). Bioclimatic Analysis in Pre-Design Stage of Passive House in Indonesia. *Buildings*, 7(1), 24.

Matuszko, D.(2012). Influence of cloudiness on sunshine duration. *International Journal of Climatology*, 32 no 10. 2012: 1527–1536.

Mazria, E. (1980). The passive solar energy book .Rodale Press.McIntyre, D. A. (1980). Indoor climate. *Elsevier.*

McMichael, A. J., Woodruff, R. E., & Hales, S. (2006). Climate change and human health: present and future risks. *The Lancet*, 367(9513), 859-869.

Mc Pherson, E. G., Scott, K. I., & Simpson, J. R. (1998). Estimating cost effectiveness of residential yard trees for improving air quality in Sacramento, California, using existing models. *Atmospheric Environment*, 32(1), 75-84.

McTainsh, G. H., & Pitblado, J. R. (1987). Dust storms and related phenomena measured from meteorological records in Australia. Earth Surface Processes and Landforms, 12(4), 415 Meehl, G. A., Covey, C., Delworth, T., Latif, M., McAvaney, B., Mitchell, J. F., ... & Taylor, K. E. (2007). The WCRP CMIP3 multimodel dataset: *A new era in climate* change research. Bulletin of the American Meteorological Society, 88(9), 1383-1394.-424.

Mehani, I., & Settou, N. (2012). Passive cooling of building by using solar chimney. World Academy of Science, Engineering and Technology .*International Journal of Civil, Environmental, Structural, Construction and Architectural Engineering*, 6(9), 735-736.

Meir, I. A., & Roaf, S. C. (2002). Thermal comfort–thermal mass: housing in hot dry climates. *In Proc. 9th Int. Conf. on 'Indoor air quality and climate'*,(ed. H. Levin) (Vol. 1, pp. 1050-1055).

Meir, I. A. (2000). Integrated Approach to the Design of Sustainable Desert Architecture a Case Study. *Open House International*, 25(3), 47-57.

Meteonorm 7.3 (2018) 'Handbook part II: Theory Version 7.3. Available at: https://meteonorm.com/en/meteonorm-documents. (Accessed on 16 July 2019)

Middleton, N., & Kang, U. (2017). Sand and dust storms: impact mitigation. *Sustainability*, 9(6), 1053.

Middleton, N. J., & Sternberg, T. (2013). Climate hazards in drylands: A review. *Earth-Science Reviews*, 126, 48-57.

Middleton, N. J. (2017). Desert dust hazards: A global review. *Aeolian research*, 24, 53-63.

Midgley, G. F., Chapman, R. A., Hewitson, B., Johnston, P., De Wit, M., Ziervogel, G., & Kgope, B. (2005). A status quo, vulnerability and adaptation assessment of the physical and socio-economic effects of climate change in the Western Cape.

Miller, S. D., Kuciauskas, A. P., Liu, M., Ji, Q., Reid, J. S., Breed, D. W., ... & Mandoos, A. A. (2008). Haboob dust storms of the southern Arabian Peninsula. *Journal of Geophysical Research: Atmospheres*, 113(D1).

Mirza, M.Q., Warrick, R.A., Ericksen, N.J. and Kenny, G.J. (1998) Trends and Persistence in Precipitation in the Ganges, Brahmaputra and Meghna River Basins. *Hydrological Sciences Journal*, 43, 845-858.

Mishra, A. K., & Ramgopal, M. (2013). Field studies on human thermal comfort—an overview. *Building and Environment*, 64, 94-106.

Mohamed, N. A. H., Osman, H. M. F., & el Deen, S. Z. (2014). Rainfall changes in central Sudan between 1960-2010. *International Journal of Geosciences and Geomatics*, 2, 61-67.

Montazeri, H. (2011). Experimental and numerical study on natural ventilation performance of various multi-opening wind catchers. *Building and Environment*, 46(2), 370-378.

Mora-Pérez, M., Guillen-Guillamón, I., López-Patiño, G., & López-Jiménez, P. A. (2016). Natural Ventilation Building Design Approach in Mediterranean Regions—A Case Study at the Valencian Coastal Regional Scale (Spain). *Sustainability*, 8(9), 855.

Morgan. H., Trans. (1960). The ten books on architecture. New York: Dover Publication.

Mumtahana, F., Admiranto, A. G., Sungging, E., Nurzaman, M. Z., Priyatikanto, R., & Dani, T. (2016, November). Tutulemma of near equator Partial Solar Eclipse 2016. *In Journal of Physics: Conference Series* (Vol. 771, No. 1, p. 012021). IOP Publishing.

Muangnoi, T., Asvapoositkul, W., & Wongwises, S. (2008). Effects of inlet relative humidity and inlet temperature on the performance of counterflow wet cooling tower based on exergy analysis. *Energy Conversion and Management*, 49(10), 2795-2800.

Mujeebu, M. A., & Alshamrani, O. S. (2016). Prospects of energy conservation and management in buildings–The Saudi Arabian scenario versus global trends. *Renewable and Sustainable Energy Reviews*, 58, 1647-1663.

Muselli, M. (2010). Passive cooling for air-conditioning energy savings with new radiative low-cost coatings. *Energy and Buildings*, 42(6), 945-954.

Nakayama, T., & Fujita, T. (2010). Cooling effect of water-holding pavements made of new materials on water and heat budgets in urban areas. Landscape and Urban Planning, 96(2), 57-67.

Nasrollahi, N., & Salehi, M. (2015). Performance enhancement of double skin facades in hot and dry climates using wind parameters. *Renewable energy,* 83, 1-12.

Nematchoua, M. K., Tchinda, R., & Orosa, J. A. (2014). Thermal comfort and energy consumption in modern versus traditional buildings in Cameroon: A questionnaire-based statistical study. *Applied Energy*, 114, 687-699.

Nguyen, A. T., Tran, Q. B., Tran, D. Q., & Reiter, S. (2011). An investigation on climate responsive design strategies of vernacular housing in Vietnam. *Building and Environment*, 46(10), 2088-2106.

Nguyen, A. T., & Reiter, S. (2014). A climate analysis tool for passive heating and cooling strategies in hot humid climate based on Typical Meteorological Year data sets. *Energy and buildings*, 68, 756-763.

Nicol, J. F. (1974). An analysis of some observations of thermal comfort in Roorkee, India and Baghdad, Iraq. *Annals of human biology*, 1(4), 411-426.

Nicol, J. F. (2008). A handbook of adaptive thermal comfort towards a dynamic model. University of Bath: Bath, UK.

Nicol, J. F., & Humphreys, M. (1998). Understanding the adaptive approach to thermal comfort. *ASHRAE transactions*, 104, 991-1004.

Nowak, D. J., Crane, D. E., Stevens, J. C., & Ibarra, M. (2002). Brooklyn’s Urban Forest. USDA Forest Service Gen. Tech. Rep. 290.

Oliver, J. (1965). Evaporation losses and rainfall regime in central and north Sudan. *Weather*, 20(2), 58-64.

Olgyay, V. (2015). Design with Climate: Bioclimatic Approach to Architectural Regionalism-New and expanded Edition. Princeton university press.

Olotuah, A. O. (2015). Climate-Responsive Architecture and Sustainable Housing in Nigeria. *Global Journal of Research and Review*, 24, 094-099.

Omer, A. M. (2000). Wind energy in Sudan. Renewable energy, 19(3), 399-411.

Omer, A. M. (2002). Overview of renewable energy sources in the Republic of the Sudan. *Energy*, 27(6), 523-547.

Omer, A. M. (1997). Compilation and evaluation of solar and wind energy resources in Sudan. *Renewable Energy*, 12(1), 39-69.

Omer, G. E., Elhassan, B. A., & Mohammed, F. A. (2015). Assessing the impact of different land use activities on the vegetation cover and sustainable livelihoods along the Banks of Niles at Khartoum State, Sudan. *Journal of Geoscience and Environment Protection*, 3(03), 52.

Osman, M. M., & Alibaba, A. (2015). Comparative studies on integration of photovoltaic in hot and cold climate. *Scientific Research Journal (SCIRJ).*

Osman, M. M., & Sevinc, H. (2019). Adaptation of Climate-Responsive Building Design Strategies and Resilience to Climate Change in the Hot/Arid Region of Khartoum, Sudan. *Sustainable Cities and Society, 101429*.

Osman, M.M; Sevinc, H & Hancer.P.(2017).Passive Cooling Strategies for Low rise Buildings in Hot and Arid/Climate (A case study of Khartoum city of Sudan).*Proceeding of International Congress on World Contemporary in Civil Engineering, Architecture & Urban Development 6&7 Mrach 2017. Dubai*.

Omondi, P. A. O., Awange, J. L., Forootan, E., Ogallo, L. A., Barakiza, R., Girmaw, G. B., ... & Kilavi, M. (2014). Changes in temperature and precipitation extremes over the Greater Horn of Africa region from 1961 to 2010. *International Journal of Climatology*, 34(4), 1262-1277.

Onsa EH, Onsa MH, Zamil TA, Elzein OA. (2015) Editing the Solar Radiation values during all Stages of Building Projects in Sudan. *International Journal of Scientific & Engineering Research*, Volume. ISSN 2229-5518.

Ourghi, R., Al-Anzi, A., & Krarti, M. (2007). A simplified analysis method to predict the impact of shape on annual energy use for office buildings. *Energy Conversion and Management*, 48(1), 300-305.

Ozay, N. (2005). A comparative study of climatically responsive house design at various periods of Northern Cyprus architecture. *Building and Environment*, 40(6), 841-852.

Pacheco, R., Ordóñez, J., & Martínez, G. (2012). Energy efficient design of building: A review. *Renewable and Sustainable Energy Reviews*, 16(6), 3559-3573.

Pagano, T., & Sorooshian, S. (2002). Hydrologic Cycle. Encyclopedia of Global Environmental Change. Vol. 1, the Earth System: *Physical and Chemical Dimensions of Global Environmental Change*, 450-464.

Pathirana, S., Rodrigo, A., & Halwatura, R. (2019). Effect of building shape, orientation, window to wall ratios and zones on energy efficiency and thermal comfort of naturally ventilated houses in tropical climate. *International Journal of Energy and Environmental Engineering*, 1-14.

Peel, M. C., Finlayson, B. L., & McMahon, T. A. (2007). Updated world map of the Köppen-Geiger climate classification. *Hydrology and earth system sciences discussions*, 4(2), 439-473.

Pérez-Urrestarazu, L., Fernández-Cañero, R., Franco, A., & Egea, G. (2016). Influence of an active living wall on indoor temperature and humidity conditions. *Ecological engineering*, 90, 120-124.

Perry, R. H., Green, D. W., & Maloney, J. O. (2015). Perry's chemical engineers' handbook. New York: McGraw-Hill.

Podgórski, A., Bałazy, A., & Gradoń, L. (2006). Application of nanofibers to improve the filtration efficiency of the most penetrating aerosol particles in fibrous filters. *Chemical Engineering Science,* 61(20), 6804-6815.

Poortinga, W., Aoyagi, M., & Pidgeon, N. F. (2013). Public perceptions of climate change and energy futures before and after the Fukushima accident: A comparison between Britain and Japan. *Energy Policy*, 62, 1204-1211.

Poudyal, K. N., Bhattarai, B. K., Sapkota, B. K., & Kjeldstad, B. (2012). Estimation of global solar radiation using sunshine duration in Himalaya Region. *Research Journal of Chemical Sciences,* 2(11), 20-25.

Prueksakorn, K., Piao, C. X., Ha, H., & Kim, T. (2015). Computational and Experimental Investigation for an Optimal Design of Industrial Windows to Allow Natural Ventilation during Wind-Driven Rain. *Sustainability*, 7(8), 10499-10520.

Qureshi, B. A., & Zubair, S. M. (2006). A comprehensive design and rating study of evaporative coolers and condensers. Part I. Performance evaluation. *International journal of refrigeration,* 29(4), 645-658.

Rabah, K., & Tamakan, Z. (2002). Application of ARCHIPAK for development of passive solar energy-efficient building in North Cyprus. Architectural Science Review, 45(3), 219-229.

Rasmussen, T. V. (2012). A Strategic Approach for Existing Buildings to Withstand Climate Change. *Open House International*, 37(4).

Reid, E. (1988). Understanding buildings: a multidisciplinary approach. MIT Press.Rendall, C. (2017). Sun/Water/Wind: Art and the Aesthetics of Ecology in the Built Environment *(Doctoral dissertation, Fashion Institute of Technology, State University of New York).*

Remund, J., Lang, R., & Kunz, S. (1999). Meteonorm software v4. 0. Bern-Switzerland: Meteotest.

Rahimzadeh, F., Renwick, J., Rusticucci, M., Soden, B., and Zhai, P. (2007). Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment *Report of the Intergovernmental Panel on Climate Change*, chapter Observations: Surface and Atmospheric Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Rasmussen, T. V. (2012). A strategic Approach for Existing Buildings to Withstand Climate Change. *Open House International*, 37(4).

Remund, J., Müller, S. C., Schilter, C., & Rihm, B. (2010, September). The use of Meteonorm weather generator for climate change studies. *In 10th EMS Annual Meeting, 10th European Conference on Applications of Meteorology (ECAM) Abstracts, held Sept. 13-17, 2010 in Zürich, Switzerland*..

Ring, M. J., Lindner, D., Cross, E. F., & Schlesinger, M. E. (2012). Causes of the global warming observed since the 19th century. *Atmospheric and Climate Sciences*, 2(04), 401.

Roaf, S., Roaf, S., Crichton, D., & Nicol, F. (2009). Adapting buildings and cities for climate change: *a 21st century survival guide*. Routledge.

Robert, A., & Kummert, M. (2012). Designing net-zero energy buildings for the future climate, not for the past. *Building and Environment*, 55, 150-158.

Roberts, S. (2008). Effects of climate change on the built environment. Energy Policy, 36(12), 4552-4557.

Ross, B. M. (2009). Design with energy in mind: Toward a low-load and high satisfaction civic architecture in the great lakes basin. *Master of Architecture thesis, University of Waterloo.*

Ross, C.(2008). Air Source Heat Pump Installation Performance Review. Unpublished Master thesis submitted in partial fulfilment for the requirement of degree in

Master of Science in Energy Systems and the Environment. University of Strathclyde. United Kingdom.

Roulet, C. A., Johner, N., Foradini, F., Bluyssen, P., Cox, C., de Oliveira Fernandes, E., & Aizlewood, C. (2006). Perceived health and comfort in relation to energy use and building characteristics. *Building research and informati*on, 34(5), 467-474.

Rubio-Bellido, C., Pulido-Arcas, J., & Cabeza-Lainez, J. (2015). Adaptation strategies and resilience to climate change of historic dwellings. *Sustainability*, 7(4), 3695-3713.

Rupp, R. F., Vásquez, N. G., & Lamberts, R. (2015). A review of human thermal comfort in the built environment. *Energy and Buildings*, 105, 178-205.

Saadatian, O., Haw, L. C., Sopian, K., & Sulaiman, M. Y. (2012). Review of windcatcher technologies. *Renewable and Sustainable Energy Reviews*, 16(3), 1477-1495.

Sadek, A. H., & Mahrous, R. (2018). Adaptive glazing technologies: Balancing the benefits of outdoor views in healthcare environments. *Solar Energy*, 174, 719-727.

Samuel, D. L., Nagendra, S. S., & Maiya, M. P. (2013). Passive alternatives to mechanical air conditioning of building: A review. *Building and Environment*, 66, 54-64.

Sanders, C. H., & Phillipson, M. C. (2003). UK adaptation strategy and technical measures: the impacts of climate change on buildings. *Building Research & Information*, 31(3-4), 210-221.

Santamouris, M., & Kolokotsa, D. (2013). Passive cooling dissipation techniques for buildings and other structures: The state of the art. *Energy and Buildings*, 57, 74-94.

Santamouris, M., Pavlou, K., Synnefa, A., Niachou, K., & Kolokotsa, D. (2007). Recent progress on passive cooling techniques: Advanced technological developments to improve survivability levels in low-income households. *Energy and Buildings*, 39(7), 859-866.

Santillán-Soto, N., García-Cueto, R., Haro-Rincón, Z., Ojeda-Benítez, S., Quintero-Núñez, M., & Velázquez-Limón, N. (2015). Radiation balance of urban materials and their thermal impact in semi-desert region: Mexicali, México study case. *Atmosphere,* 6(10), 1578-1589.

Sassi, P. (2006). Strategies for sustainable architecture. Taylor & Francis.

Sayigh, A., & Marafia, A. H. (1998). -Thermal comfort and the development of bioclimatic concept in building design. *Renewable and Sustainable Energy Reviews*, 2(1-2), 3-24.

Sayed,M,A and Abdala,B.(2010). SUDAN Environmental and Climate Change Assessment: Prepared for IFAD's Country Strategic Opportunities Programme 2013-2017. All rights reserved. © 2010 by the *International Fund for Agricultural Development (IFAD)*

Schittich, C. (Ed.). (2003). Solar architecture: strategies, visions, concepts. Walter de Gruyter.

Schlosser, C. A., & Houser, P. R. (2007). Assessing a satellite-era perspective of the global water cycle. *Journal of climate*, 20(7), 1316-1338.

Shakurov, I., Elamin, A., & Zebilila, M. (2016). Development and metabolism of the city of Khartoum (Republic of Sudan): spatial designing of the coastal territory of the Blue and White Nile. *In E3S Web of Conferences* (Vol. 6, p. 01010). EDP Sciences.

Shameri, M. A., Alghoul, M. A., Sopian, K., Zain, M. F. M., & Elayeb, O. (2011). Perspectives of double skin façade systems in buildings and energy saving. *Renewable and Sustainable Energy Re*views, 15(3), 1468-1475.

Sharma, A., Dhote, K. K., & Tiwari, R. (2003). Climatic responsive energy efficient passive techniques in buildings. *IE (I) Journal*. AR, 84.

Sharag-Eldin, A. M. K. (1988). The architectural implications of passive solar cooling systems in hot-arid climates *(Doctoral dissertation, Massachusetts Institute of Technology).*

Sheffield, J., Wood, E. F., & Roderick, M. L. (2012). Little change in global drought over the past 60 years. *Nature*, 491(7424), 435.

Sherif, A., Sabry, H., & Rakha, T. (2012). External perforated Solar Screens for daylighting in residential desert buildings: Identification of minimum perforation percentages. *Solar Energy,* 86(6), 1929-1940.

Snow, M., & Prasad, D. (2011). Climate change adaptation for building designers: an introduction. *Environment Design Guide,* 1-11.

Silva, H. D. C., Kinsel, L. S., & Garcia, S. T. (2008). Climate analysis and strategies for bioclimatic design purposes. *In 25th conference on passive and low energy architecture* (pp. 22-24).

Silva, H. D. C., & Kinsel, L. S. (2006). Região climática de Porto Alegre: revisão para um desenho inteligente e uma arquitetura adequada. Arqtexto. n. 9 (2006), p. 124-133.

Spence, A., & Pidgeon, N. (2009). Psychology, climate change & sustainable bahaviour. Environment: *Science and Policy for Sustainable Development*, 51(6), 8-18.

Staffell, I., Brett, D., Brandon, N., & Hawkes, A. (2012). A review of domestic heat pumps. *Energy & Environmental Science*, 5(11), 9291-9306.

Stephen S. Szoke, et al, LEED/AP, CSI-CDT, 2014, National Institute of Building Sciences, Washington, DC. Available at: http://buildingsciences.nibs.org/2014June.html (Accesed on 23 May 2018).

Street, M. A. (2013). Comparison of simplified models of urban climate for improved prediction of building energy use in cities *(Doctoral dissertation, Massachusetts Institute of Technology).*

Straube, J. F., & van Straaten, R. (2001). The technical merit of double facades for office buildings in cool humid climates. *Building Engineering Group, University of Waterloo, Canada.*

Suehrcke, Harry, Eric L. Peterson, and Neville Selby. "Effect of roof solar reflectance on the building heat gain in a hot climate. *Energy and Buildings* 40, no. 12 (2008): 2224-2235.

Sukhera, M. B., & Pasha, M. A. R. (1987). Solar radiation maps for Pakistan. *Solar & wind technology*, 4(2), 229-238.

Szokolay, S. "Introduction to Architectural Science (ed.)." (2008). an imprint of Elsevier Science Linacre House, Jordan Hill, Oxford OX2 8DP .200 Wheeler Road, Burlington, MA01803.

Szokolay, S. V. (1986). Climate analysis based on the psychometric chart. *International journal of ambient energy,* 7(4), 171-182.

Szokolay, S. V. (1996). Solar geometry. Published by: Passive and Low Energy Architecture International in association with Department of Architecture, The University of Queensland Brisbane 4072.

Taha, H., Sailor, D. J., & Akbari, H. (1992). High-albedo materials for reducing building cooling energy use. *Energy and Environment Division Lawrence Berkeley Laboratory* University of California Berkeley, CA 94720.

Tahir, H. M., & Yousif, T. A. (2013). Modeling the effect of urban trees on relative humidity in Khartoum State. *Journal of Forest Products and Industries,* 2(5), 20.

Taleb, H. M. (2014). Using passive cooling strategies to improve thermal performance and reduce energy consumption of residential buildings in UAE buildings. *Frontiers of Architectural Research,* 3(2), 154-165.

Taleghani, M., Tenpierik, M., van den Dobbelsteen, A., & Sailor, D. J. (2014). Heat mitigation strategies in winter and summer: Field measurements in temperate climates. *Building and environment,* 81, 309-319.

Tamura, G. T. (1994). Smoke movement and control in high-rise buildings. National Fire Protection Association: Quincy, MA, USA,

Tan, A., & Wong, N. (2013). Parameterization studies of solar chimneys in the tropics. *Energies,* 6(1), 145-163.

Theeuwes, N., Solcerová, A., & Steeneveld, G. (2013). Modeling the influence of open water surfaces on the summertime temperature and thermal comfort in the city. Journal of Geophysical Research: *Atmospheres*, 118(16), 8881-8896.

Tong, S., Li, H., Zingre, K. T., Wan, M. P., Chang, V. W. C., Wong, S. K., ... & Lee, I. Y. L. (2014). Thermal performance of concrete-based roofs in tropical climate. *Energy and Buildings,* 76, 392-401.

Trenberth, K. E. (2011). Changes in precipitation with climate change. *Climate Research,* 47(1-2), 123-138.

Trenberth, K., Jones, P., Ambenje, P., Bojariu, R., Easterling, D., Tank, A. K., Parker, D.,

Trenberth, K. E., Dai, A., Van Der Schrier, G., Jones, P. D., Barichivich, J., Briffa, K. R., & Sheffield, J. (2014). Global warming and changes in drought. *Nature Climate Change,* 4(1), 17.

Tschakert, P., Sagoe, R., Ofori-Darko, G., & Codjoe, S. N. (2010). Floods in the Sahel: an analysis of anomalies, memory, and anticipatory learning. *Climatic Change*, 103(3-4), 471-502.

Turner, L. (2003). Climate and Architecture. *A lecture note of MET1010 Introduction to the Atmosphere.* Florida State University. USA.

Tzikopoulos, A. F., Karatza, M. C., & Paravantis, J. A. (2005). Modeling energy efficiency of bioclimatic buildings. *Energy and buildings*, 37(5), 529-544.

Vale, B., Vale, R., & Doig, R. (1991). Green architecture: design for a sustainable future (pp. 1-126). London: Thames and Hudson.

Valizadeh, L.(2013). Ground Source Heat Pumps. *Journal of Clean Energy Technologies*.. Vol. 1, No. 3

Van Den Wymelenberg, K., Djunaedy, E., Brown, G.Z. and Kline, J.,.(2009) A climate Responsive Design Tool to Promote Passive and Low Energy Design . *Proceedings American Solar Energy Society, Annual Conference, May 2009. United State of America*.

Van Hoof, J., Mazej, M., & Hensen, J. L. (2010). Thermal comfort: research and practice. *Frontiers in Bioscience*, 15(2), 765-788.

Visitsak, S. (2007). An evaluation of the bioclimatic chart for choosing design strategies for a thermostatically-controlled residence in selected climates. Texas A&M University.

Waithaka, M., Nelson, G. C., Thomas, T. S., & Kyotalimye, M. (Eds.). (2013). East African agriculture and climate change: A comprehensive analysis. *Intl Food Policy Res Inst*.

Wang, Y., Zhao, F. Y., Kuckelkorn, J., Liu, D., Liu, J., & Zhang, J. L. (2014). Classroom energy efficiency and air environment with displacement natural ventilation in a passive public school building. *Energy and Buildings*, 70, 258-270.

Wang, N., Raza, A., Si, Y., Yu, J., Sun, G., & Ding, B. (2013). Tortuously structured polyvinyl chloride/polyurethane fibrous membranes for high-efficiency fine particulate filtration. *Journal of colloid and interface science*, 398, 240-246.

Watkins, R., Palmer, J., Kolokotroni, M., & Littlefair, P. (2002). The balance of the annual heating and cooling demand within the London urban heat island. *Building Services Engineering Research and Technology*, 23(4), 207-213.

Watson, D. (1983). Climatic design: Energy efficient building principles and practices. United States: N. p., 1983. Web.

Weihe, W. H. (1984). Life expectancy in tropical climates and urbanization. In Life expectancy in tropical climates and urbanization.

Weng, Q., & Yang, S. (2004). Managing the adverse thermal effects of urban development in a densely populated Chinese city. *Journal of Environmental Management*, 70(2), 145-156.

Widatalla, A. M., & Zinko, H. (2011, November). Designing a Photovoltaic Solar Energy System for a Commercial Building. Case Study: Rosa Park Hotel in Khartoum-Sudan. In World Renewable.

Energy Congress-Sweden; 8-13 May; 2011; Linköping; Sweden (No. 057, pp. 2899-2906). Linköping University Electronic Press.

Wilcock, A. A. (1968). Köppen after fifty years. *Annals of the Association of American Geographers*, 58(1), 12-28.

Wood, A., Bahrami, P., & Safarik, D. (2014). Green walls in high-rise buildings: An output of the CTBUH sustainability working group. Images Publishing.

Xia, X. (2010). Spatiotemporal changes in sunshine duration and cloud amount as well as their relationship in China during 1954–2005. *Journal of Geophysical Research: Atmospheres*, 115(D7).

Xia, B. (2013). Thermal comfort and the Mahoney tables in Shanghai building bioclimatic design. *Advances in Information Sciences and Service Sciences*, 5(9), 27.

Xu, H., Huang, Q., Liu, G., & Zhang, Q. (2016). A quantitative study of the climate-responsive design strategies of ancient timber-frame halls in northern China based on field measurements. *Energy and Buildings*, 133, 306-320.

Yang, X., Qin, Q., Grussenmeyer, P., & Koehl, M. (2018). Urban surface water body detection with suppressed built-up noise based on water indices from Sentinel-2 MSI imagery. *Remote Sensing of Environment*, 219, 259-270.

Yau, Y. H. (2008). A preliminary thermal comfort study in tropical buildings located in Malaysia. *International Journal of Mechanical and Materials Engineering*, 3(2), 119-126.

Yu, T., Heiselberg, P., Lei, B., Pomianowski, M., & Zhang, C. (2015). A novel system solution for cooling and ventilation in office buildings: A review of applied technologies and a case study. *Energy and Buildings*, 90, 142-155.

Zakieldeen, S. A. (2009). Adaptation to climate change: A vulnerability assessment for Sudan. Gatekeeper series/*International Institute for Environment and*

Development, Sustainable Agriculture and Rural Livelihoods Programme; 142.

Zaki, A. K., Amjad, A. M., & Almssad, A. (2007, September). Cooling by underground earth tubes. In Second PALENC Conference and 28th AIVC Conference on Edification Low Energy Cooling and Advanced Ventilation Technologies in the 21st Century, Crete Island, Greece, Sept (pp. 27-29).

Zareaian, S., & Zadeh, K. A. (2013). The role of climate factors on designing and constructing buildings (from urbanization architecture approach). *Bulletin of Environment, Pharmacology and Life Sciences*, 31, 197-200.

(URL.1). Thermal Comfort Parameters: Tropical Bioclimatic Architecture .Available at: https://tropical-architecture.blogspot.com/2011/07/thermal-comfort-parameters.html (Accessed on 31 March 2019).

(URL.2) Heath and comfort in buildings. By Jan Sundell International Centre for Indoor Environment and Energy, Technical University of Denmark, Lyngby, Denmark. Available at:

https://www.researchgate.net/publication/268428469_HEALTH_AND_COMFORT_IN_BUILDINGS (Accessed on 13 Oct. 18).

(URL.3) World Health Organization (WHO) definitions of health/ wellness. Available at: http://pnf.org/Definitions_of_Health_C.pdf / (Accessed on 2 April 1, 2019).

(URL.4) Architecture for Well-being and Health: text by Koen Steemers : Availble at: http://thedaylightsite.com/architecture-for-well-being-and-health/. (Accessed on 14 October 2018).

(URL.5) what makes the wind blow? Factors Affecting Winds & Patterns. Available at: https://schoolworkhelper.net/what-makes-the-wind-blow-factors-affecting-winds-patterns/ (Accessed on 18 November 2018).

(URL.6) Climate Change: Impacts, Vulnerabilities and Adaptation in Developing Countries. 2007 UNFCCC United Nations Framework Convention on Climate ChangeAvailable at: https://unfccc.int/resource/docs/publications/impacts.pdf (Accessed on 13 March 2019).

(URL.7) Intergovernmental Panel on Climate Change **(IPCC)** Printed October 2018 by the IPCC, Switzerland. Electronic copies of this Summary for Policymakers are available from the IPCC website https://report.ipcc.ch/sr15/pdf/sr15_spm_final.pdf (Accessed on 11 Mar. 19).

(URL.8). Quantitative Assessment of Climate Change Adaptive Capacity for East Nile Locality – Khartoum State-Sudan Ahmed Al-Huseen. Available at: https://mnet.mendelu.cz/mendelnet2014/articles/56_alhuseen_1021.pdf?id=1021&file=56_alhuseen_1021.pdf (Accessed on 12 March 2019).

(URL.9) Global Warming and Its Impacts on Climate of India. By Theodore C. Sorensen. Available: at: file:///C:/Users/mubarak123/Desktop/phd%20c.change/resilient/GLOBAL_WARMING_AND_ITS_IMPACTS_ON_CLIMATE_OF_INDIA.pdf (Accessed on 18 March 17, 2019).

(URL.10). Global Warming Effects on Drought - climatehotmap.org .Available at: https://www.climatehotmap.org/global-warming-effects/drought.html (Accessed on 19 March 19, 2019).

(URL.11) United Nations, 2011. World Urbanization Prospects, the 2011 Revision. Department of Economic and Social Affairs, New York, New York Accessed from:http://www.un.org/en/development/desa/population/publications/pdf/urbanization/WUP2011_Report.pdf (Accessed on 27 October 2018)

(URL.12) Green Passive Solar Magazine: Highlighting the Sustainable, Renewable, Green Building Technologies of Passive (and Active!) Solar Design Available at: https://greenpassivesolar.com/. (Accessed on 13 November 2018).

(URL.13) What are the Factors affecting the distribution of insolation? By Rajan, D.Available at: http://www.preservearticles.com/2011111217104/what-are-the-factors-affecting-the-distribution-of-insolation.html. (Accessed on 15 November 2018).

(URL.14) natural ventilation and air movement - CED Engineering. By Bhatia , A . Available at: https://www.cedengineering.com/userfiles/HVAC%20-%20Natural%20Ventilation%20Principles%20.pdf (Accessed on 27 March 2019).

(URL.15) Building Science: Designing Energy Efficient Buildings in Hot Climates Available at: https://www.bautexsystems.com/blog/hot-climate-building-design (Accessed on 22 March 2019).

(URL.16) Climate-Based design approach for facades. Available at: http://www.beck-shop.de/fachbuch/leseprobe/9781118458600_Excerpt_001.pdf. (Accessed on 8 January 2019).

(URL.17) METEONORM 7 SOFTWARE. Available at: file:///C:/Users/mubarak123/Desktop/phd%20c.change/manual-usuario-part-1-meteonorm.pdf . (Accessed on 12 February 2017).

(URL.18) Climate tech wiki: clean research platform. Available at: http://www.climatetechwiki.org/technology/heat-pumps. (Accessed on 12 May 2018).

(URL.19) Air-Source Heat Pumps. DOE/GO-102001-1113 FS143.June 2001. Available at:https://www.google.com/search?q=air+to+air+air+source+heat+pumps.pdf &oq=air+to+air+air+source+heat+pumps.pdf&aqs=chrome..69i57.32816j0j8 &sourceid=chrome&ie=UTF-8#. (Accessed on 23 May 2018).

(URL.20) Engineering Standard for Venting, Ventilation and Pressurizing System. Original Edition. http://igs.nigc.ir/STANDS/IPS/e-ar-160.PDF. (Accessed on 15 January 2018).

APPENDICES

Appendix A: Khartoum Meteorological Station Climate Data

Station-Khartoum. Elevation 380 metre Monthly Average Relative Humidity (%)

Period 1981-2015

YEAR	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**	**NOV**	**DEC**
1981	19	17	15	13	18	25	47	41	42	26	22	30
1982	25	18	12	13	14	20	31	48	41	29	22	24
1983	23	17	13	11	14	29	37	38	31	18	21	28
1984	25	22	14	10	20	17	24	26	29	20	22	27
1985	25	17	15	13	25	30	41	39	37	23	23	31
1986	24	16	13	12	12	27	42	42	41	28	24	24
1987	25	17	13	11	30	30	34	49	32	29	26	31
1988	29	27	21	15	19	30	47	59	51	27	25	29
1989	24	19	14	14	24	27	36	44	44	25	23	25
1990	25	19	13	13	13	18	36	25	31	25	24	30
1991	23	18	15	18	26	21	37	47	35	31	30	32
1992	33	26	21	19	19	28	41	56	42	31	27	30
1993	30	25	15	16	25	24	36	45	37	31	31	32
1994	32	27	22	20	25	32	49	55	51	37	29	30
1995	23	27	20	15	21	30	52	52	45	26	24	22
1996	25	22	14	16	29	29	37	51	52	32	26	27
1997	29	20	20	21	22	29	48	50	36	28	38	30
1998	24	20	15	14	22	21	43	58	58	37	26	30
1999	27	21	16	13	20	21	49	57	46	40	26	30
2000	25	19	14	15	21	23	37	43	42	30	23	30
2001	27	19	15	12	17	22	42	55	42	29	23	27
2002	28	27	18	20	22	24	32	52	65	31	25	35
2003	24	15	12	13	17	30	49	58	43	29	28	31
2004	25	24	16	13	16	33	42	54	43	31	28	33
2005	27	20	13	13	21	29	57	60	48	30	25	35
2006	20	18	14	11	26	31	43	63	61	39	22	30
2007	24	18	15	15	14	33	69	72	80	29	30	36
2008	31	25	14	23	17	30	44	59	53	33	23	25
2009	22	23	22	17	14	21	43	49	39	23	23	23
2010	25	19	15	11	13	25	44	51	41	26	22	25
2011	24	15	12	9	19	17	33	49	39	30	24	30
2012	23	21	11	8	14	26	44	54	34	24	19	25
2013	24	17	10	8	11	22	28	56	33	19	22	28
2014	25	21	14	16	17	21	45	54	45	27	21	29
2015	25	16	14	9	15	20	27	41	37	27	21	23

MINISTRY OF ENVIRONMENT, FORESTRY AND PHYSICAL DEVELOPMENT

METEOROLOGICAL AUTHORITY

WEATHER-CLIMATE DATA

Station-Khartoum. Elevation 380 metre

Monthly Average Temperature (^{O}C)

Period 1981-2015

Month	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
JAN	25.03	21.5	20.8	24.3	25.1	23.9	22.6	21.7	22.2	23.0
FEB	22.2	22.0	24.0	21.6	24.9	26.8	25.7	23.0	21.8	24.9
MAR	27.9	26.8	28.2	30.1	30.8	29.2	29.2	28.3	26.7	27.1
APR	31.5	30.73	31.5	31.9	31.0	31.1	32.2	32.1	32.5	33.2
MAY	33.7	34.2	34.7	34.3	33.9	32.7	34.9	34.7	35.5	35.3
JUN	34.3	33.8	34.3	33.8	33.8	33.8	34.3	35.3	34.9	35.3
JUL	33.1	32.9	33.9	32.4	31.9	32.9	32.7	32.8	33.7	33.1
AUG	31.5	32.5	33.6	33.4	32.8	31.9	30.2	31.4	33.5	33.2
SEP	30.7	33.6	33.6	33.5	32.4	33.8	32.9	32.8	33.5	34.0
OCT	32.2	32.8	32.8	33.0	32.8	32.4	32.1	32.7	32.9	33.9
NOV	25.8	27.4	27.8	27.5	28.3	28.7	28.4	28.8	29.7	29.7
DEC	23.4	24.2	25.1	24.3	23.8	22.9	25.3	24.7	25.8	25.7

Month	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
JAN	21.8	21.7	24.1	25.7	24.0	23.2	24	21.9	25.1	23.7
FEB	22.6	22.2	23.9	24.0	25.6	26.5	22.2	24.2	29.9	25.2
MAR	28.2	28.9	27.6	27.8	29.5	30	27.9	27.9	28	27.5
APR	33.5	32.5	33.0	32.3	31.7	32	32.7	33.5	32.2	32.9
MAY	35.5	34.4	34.3	34.2	34.2	34.5	34	35.9	36	35.3
JUN	35.2	35.1	34.3	34.9	34.3	33.9	34.7	35.8	35	34.9
JUL	32.9	33.4	32.5	31.4	32.1	33.4	34	33.6	31.4	32.8
AUG	31.2	31.8	31.2	30.9	30.8	31.2	34.7	30.6	30.4	32.7
SEP	33.0	32.0	32.3	32.0	31.2	31	31.9	31.1	31.8	32.5
OCT	33.1	33.1	32.9	33.5	33.2	32.7	31.7	32.7	31.5	30.9
NOV	28.5	28.7	28.6	27.5	27.6	27.6	34.7	30.2	28.7	28.1
DEC	22.7	24.4	24.4	23.4	24.7	25.3	32.5	26.5	25.7	23.7

Month	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
JAN	22.5	21	24.9	24.5	22.2	24.7	21.5	24.2	25.9	26.2
FEB	24.5	27.7	26.1	24.7	29.3	24.6	25.2	25.3	28.2	28
MAR	29.3	28.9	28.4	29	29.6	24.9	29.4	30.4	29.1	29.6
APR	33.1	32.6	32.9	32.7	33.1	27	32.8	31.4	34.5	33.6
MAY	35	32.8	34.7	35.8	33.2	31.5	35.9	31.3	34.7	35.9
JUN	34.1	35.1	34.6	34.6	35.5	34.9	34.9	31.5	36	35.8
JUL	32.1	33.9	31.6	33.8	32.4	34.7	31.1	30.3	32.3	32.3
AUG	30.5	31.3	30.3	32.4	32	37.8	30.4	28.4	32.8	31.8
SEP	32.2	33.2	32.5	33.7	33.4	34.5	32.5	27.9	34.5	33
OCT	32.9	33.4	33.8	33.2	33.3	30.4	33.9	29.1	33.7	34.6
NOV	29.1	30.3	29.8	29.4	28.6	27.5	30.4	28.6	28.5	31.4
DEC	25.6	24.2	25.4	24.6	27.5	23.7	26.7	27.6	24.4	26.4

Month	2011	2012	2013	2014	2015
JAN	25	22.5	25.8	24.5	23
FEB	27.8	27.8	28.3	24.9	28.3
MAR	26	28.5	30.9	30.3	31.4
APR	32.5	32.4	32.4	34.2	31
MAY	34.4	35.9	35.6	34.7	35.5
JUN	36	35.1	35.4	33.5	35.5
JUL	34.2	32.7	30.2	31.5	34.8
AUG	32.3	31	33.4	30.1	32.3
SEP	33.3	33.9	31.6	31.8	33.3
OCT	33.7	33.7	31.6	32.3	34.8
NOV	26.4	29.7	28.2	28.4	28.8
DEC	25.4	25	25.1	26.3	22.6

MINISTRY OF ENVIRONMENT, FORESTRY AND PHYSICAL DEVELOPMENT

METEOROLOGICAL AUTHORITY

WEATHER-CLIMATE DATA

Station-Khartoum. Elevation 380 metre

Monthly Average wind speed (m/sec)

Period 1981-2015

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1981	5	5.5	5	5	4	4.5	4.5	4.5	4	3.5	5	3
1982	3	4	4	3.5	3	4.5	4.5	4	3	4	4	4
1983	7.5	8	8	6.5	5	6.5	8	5.5	8.5	6.5	6	7.5
1984	5.5	5.5	4.5	5	3.5	4	3	3.5	3.5	3	3	4.5
1985	5	5.5	4	5	4	4.5	5	5.5	5	3	4	4.5
1986	2.5	2.5	3	3	4.5	4	4	3.5	3.5	4	4.5	4.5
1987	3.5	5	4.5	4.5	4.5	3.5	4.5	5.5	5	5	3.5	4
1988	4	1.5	5	3	2.5	4	4	3	3.5	1.5	4.5	3.5
1989	6.5	5	3.5	3.5	3.5	3.5	4	4	4	3.5	4	3.5
1990	4.5	4	3.5	2.5	5	3.5	4	3	3.5	3	5	0.5
1991	3.5	4	5.5	3.5	4.5	4.5	4.5	4	3	2.5	5.5	3.5
1992	3.5	3.5	4.5	4.5	4	5.5	6	6	3.5	3	3.5	3.5
1993	4.5	4	5.5	5	4	5	6	5	5	3.5	4	3.5
1994	4	5.5	5	5.5	5	4	6	5.5	4	3.5	6	6
1995	5.5	6	5.5	5	5	5	5	5	3.5	3.5	5.5	5.5
1996	4	4	5	4.5	3.5	3.5	4.5	5	4	3.5	4	4
1997	4	5	4.5	3.5	3.5	4	4.5	4	2.5	2	3	3.5
1998	3.5	4	4	3.5	4	3.5	5	4.5	3	2	3.5	4
1999	5	5.5	5.5	5	3.5	3	5	3	3	2.5	4	4
2000	4.5	4.5	5	2.5	2.5	2.5	4.5	4.5	2.5	3	3	4
2001	3	4	2.5	4	3.5	2	3	3	2	2.5	2.5	2.5
2002	3.5	3.5	3.5	3	3	3.5	4.5	4.5	2.5	3	3	3
2003	3	4.5	4.5	4	3.5	3.5	5	5	4	3.5	4.5	5
2004	4.5	5.5	5	4	4	4.5	5	5	4	3.5	4.5	4.5
2005	5	5.5	4.5	5	4	5	5	5	4	3.5	5	4
2006	5.5	4.5	4.5	4.5	3.5	4	4	4.5	4	3.5	5	6
2007	5	4.5	5	4.5	4	4.5	5.5	5	4	3	4	4.5
2008	5	5.5	4.5	4.5	4	4.5	4.5	5.5	3.5	3	4	4
2009	4.5	4.5	4.5	4	5	4	5	4.5	4	3.5	4.5	4
2010	4.5	4	3.5	4.5	4	4.5	4.5	5	4	3	4	4.5
2011	4.5	5.5	5.5	5	4.5	4	5	4.5	4	3.5	4.5	4.5
2012	5	5.5	5.5	4	4.5	4.5	5	5	4	3	4	4.5
2013	4.5	4.5	4.5	3.5	3	3.5	4.5	4	4.5	4	4	4.5
2014	4.5	4.5	5	4.5	4	3	5	4.5	4	4	4.5	4
2015	5	4.5	5	5.5	4	3.5	4	5	3.5	4	4.5	5.5

MINISTRY OF ENVIRONMENT, FORESTRY AND PHYSICAL DEVELOPMENT

METEOROLOGICAL AUTHORITY

WEATHER-CLIMATE DATA

Station-Khartoum. Elevation 380 metre Period 1981-2015 Monthly Average Rainfall (mm)

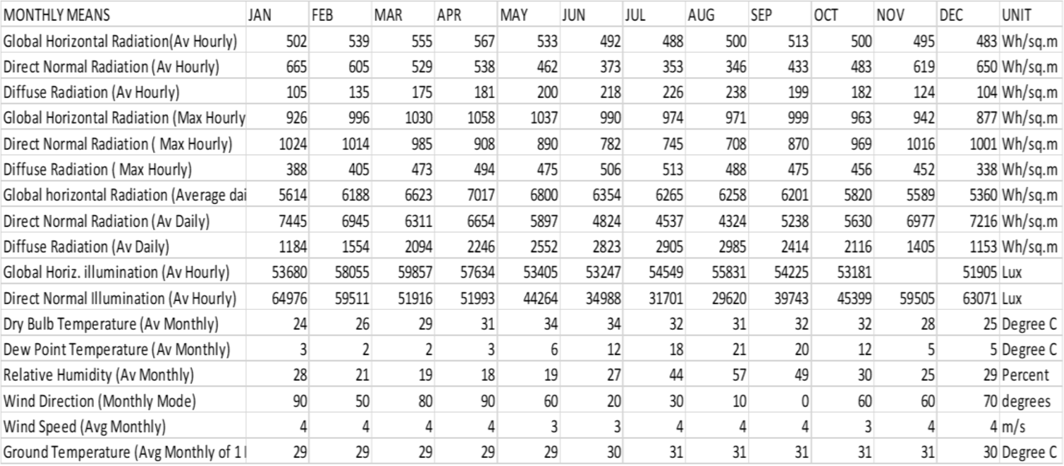
YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1981	0	0	1.4	0	1.2	1.7	86.9	30.7	12.9	6.3	0	0
1982	0	0	1.6	0	5	0	9.4	46.9	39.8	0	0	0
1983	0.6	0	0	0	1.1	46.5	23.2	6.8	5.8	0	0	0
1984	0	0	0	0	1.4	0	0	0	3.3	0	0	0
1985	0	0	0	0	9.1	3.1	16.4	0.3	9.9	0	0	0
1986	0	0	0	0	0	0	9.1	21.9	16.3	10.4	0	0
1987	0	0	0	0	21.1	23	22	48.9	0	0.6	0	0
1988	0	0	0	0	0	0	65.9	301.4	46.3	1.9	0	0
1989	0	0	0	0	5.8	1.3	0	24.7	48	0	0	0
1990	0	0	0	0	0	0	2	0	2.4	0	0	0
1991	0	0	0	0	2.3	0	4.3	37.7	0	0.6	0	0
1992	0	0	0.6	0	10.8	4	6.9	89	38.6	0	0	0
1993	0	0	0	0	3.8	0	1	33.4	0	1.6	0	0
1994	0	0	0	0	12.7	0	51.3	48	101.2	19.4	0	0
1995	0	0	0	0	0	0.3	83.9	52.9	46.5	11.4	0	0
1996	0	0	0	0	19.5	0.4	32	55	91.9	0.5	0	0
1997	0	0	0	0	0	3.1	50.9	35	9.2	42.8	0	0
1998	0	0	0	0	0	0	0	21.3	85.4	4	0	0
1999	0	0	0	0	0	1.9	26.9	47.3	25.5	29	0	0
2000	0	0	0	0	0	0	1.4	8.5	15.3	34.8	0	0
2001	0	0	0	0	0	0	37.4	73.7	13.5	3.2	0	0
2002	0	0	0	0	0	0	7.7	82.6	13.7	3.5	0	0
2003	0	0	0	0	23.5	44.3	27.2	39.4	11	8.4	7.6	0
2004	0	0	0	0	0	0.3	6	88.8	9.6	5	0	0
2005	0	0	0	0	32.8	0	77.6	30.3	0	0	0	0
2006	0	0	0	0	8	1.8	1.5	37.2	85.2	0	0	0
2007	0	0	0	2.1	0	0.8	25.8	145.9	0.5	5.8	0	0
2008	0	0	0	13	0	8.1	8.4	42.3	7.4	3	0	0
2009	0	0	0	0	0	0	34.5	101.2	4.8	0.5	0	0
2010	0	0	0	0	0.2	1.4	0	34.2	18	1	0	0
2011	0	0	0	0	5.6	0	22	20	0	2.3	0	0
2012	0	0	0	0	0	0	20.9	62.9	0	0	0	0
2013	0	0	0	0	1.5	1.3	14.4	61.3	3.2	0	0	0
2014	0	0	0	0	4	0.6	78.3	52.3	29.4	1.6	0	0
2015	0	0	0	0	8.5	0	0.4	32.9	13.9	29.3	0	0

Appendix B: Data Acquired from Meteonorm Company

WEATHER DATA LOCATION: KHARTOUM SUDAN

15°33'6.37''N, 32°31'56.68''E

Elevation: 380 m



MONTHLY MEANS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	UNIT
Global Horizontal Radiation(Av Hourly)	502	539	555	567	533	492	488	500	513	500	495	483	Wh/sq.m
Direct Normal Radiation (Av Hourly)	665	605	529	538	462	373	353	346	433	483	619	650	Wh/sq.m
Diffuse Radiation (Av Hourly)	105	135	175	181	200	218	226	238	199	182	124	104	Wh/sq.m
Global Horizontal Radiation (Max Hourly	926	996	1030	1058	1037	990	974	971	999	963	942	877	Wh/sq.m
Direct Normal Radiation (Max Hourly)	1024	1014	985	908	890	782	745	708	870	969	1016	1001	Wh/sq.m
Diffuse Radiation (Max Hourly)	388	405	473	494	475	506	513	488	475	456	452	338	Wh/sq.m
Global horizontal Radiation (Average dai	5614	6188	6623	7017	6800	6354	6265	6258	6201	5820	5589	5360	Wh/sq.m
Direct Normal Radiation (Av Daily)	7445	6945	6311	6654	5897	4824	4537	4324	5238	5630	6977	7216	Wh/sq.m
Diffuse Radiation (Av Daily)	1184	1554	2094	2246	2552	2823	2905	2985	2414	2116	1405	1153	Wh/sq.m
Global Horiz. illumination (Av Hourly)	53680	58055	59857	57634	53405	53247	54549	55831	54225	53181		51905	Lux
Direct Normal Illumination (Av Hourly)	64976	59511	51916	51993	44264	34988	31701	29620	39743	45399	59505	63071	Lux
Dry Bulb Temperature (Av Monthly)	24	26	29	31	34	34	32	31	32	32	28	25	Degree C
Dew Point Temperature (Av Monthly)	3	2	2	3	6	12	18	21	20	12	5	5	Degree C
Relative Humidity (Av Monthly)	28	21	19	18	19	27	44	57	49	30	25	29	Percent
Wind Direction (Monthly Mode)	90	50	80	90	60	20	30	10	0	60	60	70	degrees
Wind Speed (Avg Monthly)	4	4	4	4	3	3	4	4	4	3	4	4	m/s
Ground Temperature (Avg Monthly of 1 I	29	29	29	29	29	30	31	31	31	31	31	30	Degree C