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IMPERATIVE CLIMATE CHANGE ADAPTATION STRATEGIES TOWARDS FUTURE SUSTAINABLE ARCHITECTURAL DEVELOPMENT

by:
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DECLARATION OF ORIGINALITY

I declare that the mini-dissertation, Imperative Climate Change Adaptation Strategies Towards Future Sustainable Architectural Development, which has been submitted in fulfilment of part of the requirements for the module of Design Investigative Treatise, at the University of Pretoria, is my own work and has not previously been submitted by me for any degree at the University of Pretoria or any other tertiary institution.

I declare that I obtained the applicable research ethics approval in order to conduct the research that has been described in this dissertation.

I declare that I have observed the ethical standards required in terms of the University of Pretoria's ethic code for researchers and have followed the policy guidelines for responsible research.

Signature: KH Meissner-Roloff

Date: 24/07/2023

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Abstract:

The impacts of climate change are escalating worldwide, with developing nations in Southern Africa particularly vulnerable to its consequences. South African urban centers face the challenge of adapting to a changing climate and the associated heat stress on urban populations. Existing buildings must be retrofitted to accommodate these new demands and mitigate adverse environmental effects. This study explores specific architectural interventions that enhance the thermal adaptive capacity of buildings as strategies for climate change adaptation. By documenting these interventions, the study aims to establish a database for future research and reference. Sustainability and resilience are crucial concepts intertwined with adaptability in responding to climate change. The evolution of human adaptability throughout history demonstrates our ability to respond to changing conditions. However, the uncertain climate future presents varying perspectives on how to address climate change, creating tension between global influences and localized responses. South Africa's cities also face challenges associated with the global trend of urbanization. As urban areas continue to grow, they experience issues like insufficient housing, failing infrastructure, traffic congestion, and rising air pollution. Combining climate change adaptation and urban transition strategies is essential for creating climate-resilient urban ecosystems. The research question revolves around exploring the architectural building technologies implemented as climate change adaptation strategies that target thermal amelioration potential. Specific sub-questions address the methods used to assess thermal adaptive capacity and the reported outcomes, efficiencies, benefits, and shortcomings of these technologies. The research objectives aim to analyze and understand the current and future potential of thermal adaptation responses in the local Tshwane climate conditions. The study compares current and future climate change adaptation strategies, as well as Tshwane's current and projected climate conditions, to formulate a sustainable response to future climate changes. However, the study has certain limitations, particularly concerning the availability of data on climate change adaptation technologies within specific climate classifications. The scope of the study focuses on analyzing case studies within the climate classifications Cwa, Cwb, and Bsh, which restricts the available data. Consequently, the study draws conclusions based on existing literature evidence related to thermal amelioration.

1. Introduction and background

The impacts of climate change are experienced worldwide and are unparalleled in their scope and magnitude. They are becoming more frequent and intense, resulting in extreme weather events, heatwaves, and a rise in global average temperatures. Developing nations in Southern Africa, in particular, are highly susceptible to climate variations and the consequences of climate change. The heat island effect exacerbates the influence of heatwaves on both natural ecosystems and urban populations in large cities. South African urban centres have the potential to address the ongoing trend of global urbanisation and mitigate the adverse environmental effects associated with it. It is important to recognise that the cities within South Africa mostly consist of existing buildings and built infrastructure, necessitating adjustments to accommodate not only the demands of urbanisation but also the changes in local climate and the resulting heat stress on urban residents. While new constructions can incorporate such considerations into their design and development stages, retrofitting existing buildings is necessary to enhance their ability to adapt to these pressures. This is essential because the climatic conditions for which existing buildings were originally designed have shifted and continue to change (Vermeulen, 2023).

1.1 **Background**

Charles Darwin famously stated, "It's not the strongest of the species that survives, nor the most intelligent, but the one that's most adaptable to change." This quote, attributed to Darwin, serves as a profound encapsulation of the message conveyed in the book: Managing Adaptation to Climate Risk (O'Brien & O'Keefe, 2014). In the face of what is widely regarded as the most significant physical danger to humanity – the rapid climate change and growing unpredictability – it becomes increasingly clear that adapting to changing climate conditions is vital for our survival and well-being (O'Brien & O'Keefe, 2014). This study serves as a guide on our shared journey towards understanding the necessity of adaptation in the face of an uncertain and changing climate future.

1.1.1. The Challenge of Climate Change:

The magnitude of climate change poses challenges that cannot be easily fixed. While efforts to reduce emission rates may lead to some solutions, the cumulative additions of greenhouse gases already projected into the atmosphere will continue to drive changes in the climate system. Therefore, adaptation to a changing climate system becomes imperative. We (as an architectural fraternity within the built environment) currently find ourselves at a juncture where the desired destination is clear, but the path to get there remains elusive. Research indicates that what we do know is that we need each other to navigate this complex terrain.

However, there are opposing interests, as some individuals, organisations, and even whole economies still cling to a carbon-based energy model. In spite of being aware of the environmental drawbacks, carbon-emitting fuels persist as the most affordable energy source and continue to yield profits for vested parties. Unfortunately, this comes at the expense of worsening the global greenhouse gas issue and hastening the pace of climate change (O'Brien & O'Keefe, 2014).

1.1.2. Sustainability and Resilience:

Sustainability and resilience are key concepts intertwined with the adaptability required to address climate change as a response. Sustainable development, once a hopeful aspiration, has encountered significant obstacles, including the collapse of finance capital. Three interpretations of sustainability emerge: ecological sustainability, conventional economic sustainability, and an open-ended sustainability seeking to establish a new equilibrium rather than reconstructing past equilibrium (O'Brien & O'Keefe, 2014). Resilience, a buzzword of the 21st century, has also undergone various interpretations. While classical interpretations emphasize a “bounce-back” ability to return to the status quo, the authors of the book ‘Managing Adaptation to Climate Risk’ advocate for a resilience that fosters “bounce-forward” ability, enabling the creation of new opportunities in the face of adversity (O'Brien & O'Keefe, 2014).

1.1.3. The Evolution of Human Adaptability:

Throughout history, humans have demonstrated their remarkable adaptability in response to changing conditions and new opportunities. The transition from hunter-gatherer societies to agriculturalists, triggered by changing climate conditions after the Younger Dryas period, stands as a testament to humanity's ingenuity, flexibility, and adaptability (O'Brien & O'Keefe, 2014). The subsequent growth of settlements into cities and the development of systems of governance, religion, and laws exemplify our ability to respond to evolving circumstances. The industrial revolution further transformed the world, fuelled by the exploitation of fossil fuels, which simultaneously powered economic and social changes and set the stage for the climate challenges we now face (O'Brien & O'Keefe, 2014).

1.1.4. The Uncertain Climate Future:

Currently, we are faced with a dilemma that involves varying perspectives on the future. Some envision it as a postmodern era where local development takes precedence, rejecting the overarching narrative of global economic growth. On the other hand, others perceive it as a planetary phase, emphasising the need to tackle global poverty while adapting to the rapid environmental changes caused by global warming. These differing viewpoints highlight the tension between global influences and localised responses. Moreover, the complexity of climate science and the lack of political consensus contribute to uncertainty about the outcomes of climate change. Disagreements persist regarding the extent of global temperature increase and its effects on the climate system, as well as the implications for sea-level rise and extreme weather events (O'Brien & O'Keefe, 2014).

1.1.5. The Need for Adaptation:

Given the uncertainty surrounding climate change, the book 'Managing Adaptation to Climate Change' highlights the urgency to adapt to new and unknown conditions while simultaneously coping with ongoing disruptions. Adaptation encompasses both current risk reduction and planning for change in the medium (O'Brien & O'Keefe, 2014).

1.2 **Research problem**

Climate change's effects may now be seen in different elements of the global water cycle, as well as in the warming of both the atmosphere and the seas and the incidence of extreme weather events (IPCC, 2013; 2014). South Africa suffered lengthy spells of drought and heat waves between 2015 and 2020, contributing to the record-breaking six hottest years in terms of world average temperatures (WMO, 2020; 2021).

Although heatwaves lack the immediate and dramatic severity of other severe weather phenomena such as flash floods or tropical cyclones, they have serious effects for human systems, affecting health, livelihoods, and infrastructure (WMO and WHO, 2015). According to the latest "Intergovernmental Panel on Climate Change (IPCC)" assessment, such climate change consequences are anticipated to occur more frequently and fast (Agence France-Presse, 2021; IPCC, 2021).

Apart from dealing with the effects of climate change, South African cities must also deal with the challenges associated with the worldwide trend of urbanisation. It is anticipated that by 2030, around 60% of the globe's population would be residing in urban areas (UNSDG, 2019). Some studies have identified some common urban concerns, such as a lack of sufficient housing, failing infrastructure, traffic congestion, and rising air pollution (UNEP, 2019; UNSDG, 2019).

While there is growing agreement on the necessity for urban transition routes to climate change adaptation, it is crucial to explore and improve the technical viability of architectural solutions for application in South African cities. This means investigating practical and effective ways to aid in the transition to climate-resilient urban ecosystems (Vermeulen, 2023).

1.3 Research questions

The objective of this study is to document specific architectural interventions that serve as examples of building technologies utilised as strategies for adapting to climate change. These interventions aim to enhance the thermal adaptive capacity of buildings. The documentation will establish a database for future research and reference.

This study will look at the building systems and technologies that are currently being implemented as climate change adaptation techniques, with a particular emphasis on those that increase the thermal adaptive capacity of buildings. It hopes to add to the theoretical debate around climate change adaptation in urban settings by doing so. The study intends to improve understanding of the technical requirements required to improve the thermal adaptive capacity (comfort) of existing multi-story apartment buildings in South African cities. (Vermeulen, 2023).

1.3.1. *Research Question:*

“How can / do architectural building technologies implemented in selected case studies, contribute to the local climate adaptation strategies that target thermal amelioration potential (Vermeulen, 2023)?”

1.3.2. *Sub Questions:*

01 - “What methods are used to assess the thermal adaptive capacity of the building technology (Vermeulen, 2023)?”
02 - “What are the reported outcomes/ efficiencies/ benefits/ shortcomings of the building Technology (Vermeulen, 2023)?”

1.4 Research objectives

The objective is to both analyse and understand the current and future potential of thermal adaptation responses of identified adaptation strategies for application in the local Tshwane climate condition within the realm of climate change. The objective is also to compare current and future climate change adaptation strategies, as well as the current and future climate conditions of Tshwane – therefore the result of this study will aim to formulate a sustainable response towards the future climate change classification of Tshwane. The study will only look at the Köppen-Geiger climate classification of Tshwane, 2020 – 2100, as there are a variety of classifications and considerations.

1.5 Limitations, delineation and assumptions of the study

The limitations of this study deals with the climate classification of Tshwane – which is currently classified as Cwa & Cwb.It is postulated that the future classification from 2040 onwards will be Bsh – which will be discussed in more detail in this paper. There are only a few countries that share these classifications, therefore it limits the desktop study on climate change adaptation technologies. The scope of the study as outlined above, is the analysis of case studies within the climate classifications Cwa, Cwb & Bsh. Due to the limited availability of corroborating data, this study draws conclusions on the success of adaptation strategies and technologies based on the available literature evidence that has reference to thermal amelioration.

2. Literature review

2.1. Introduction + Problem definition

Over the past 10,000 years, the climate has remained relatively stable and mild, creating ideal conditions for human development. This period allowed for the growth of agriculture, the establishment of stable communities, and the rise of complex societies. Although there have been some minor local weather changes, they have typically occurred gradually, allowing living beings ample time to adjust or move to new conditions (Altomonte, 2009).

The commencement of the Industrial Revolution significantly hastened climate fluctuations. Human actions, notably the combustion of fossil fuels and other organic substances, have changed the composition of the atmosphere, resulting in potential worldwide climate alterations. The recognition of the global warming threat, driven by the accumulation of heat-trapping gases, is now widespread.

In recent times, we have become increasingly aware that our actions, possibly dating back to the Industrial Revolution, have potentially and permanently transformed the dynamic between human progress and the natural environment. This shift has fundamentally altered the conditions that once supported life's flourishing on Earth. Among numerous human activities, buildings have significantly contributed to energy consumption and CO2 emissions.

In order to tackle these challenges and promote sustainable development, it is crucial to adopt a fresh perspective on building design and construction. This new approach should take into account the limited resources of the environment as well as the requirements of contemporary societies and economies. Sustainable building design should integrate inventive energy generation and usage techniques while addressing both the reduction of human impacts on the environment and the adaptation to climate change.

Taking cues from adaptable natural systems can provide useful information. Living species in nature have evolved sensitive systems to deal with changing environments while maintaining their resources and ecological balance. With the present rate of global climate change, a 'adaptive' approach to building design and living spaces can serve as a pattern for future development. By emulating nature's efficient adaptive metabolic systems and merging ancient wisdom with modern technology, humans can achieve the most sustainable design to date (Altomonte, 2009).

2.1.1. *Greenhouse Effect*

> *“According to the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC), ‘climate’ can be defined as ‘average weather’ and is usually described in terms of the “mean and variability of temperature, precipitation and wind over a period of time, ranging from months to millions of years” (IPCC, 2007a).*

Our Earth's climate is driven through energy emitted by the Sun. This emitted energy predominantly falls within the visible part of the electromagnetic spectrum, accounting for approximately 54% of its emissions. Every second, about 1370 Watts (W) of solar radiation reaches each square meter of the Earth's atmosphere facing the Sun during daytime. Since the Earth is spherical, more solar radiation is received in the tropics due to the direct angle of sunlight, while higher latitudes receive less radiation due to the angled sunlight. This energy is distributed from tropical regions to the southern and northern latitudes through oceanic and atmospheric movement (Altomonte, 2009).

Some of the incoming solar energy is reflected back into space by the atmosphere, and the remaining portion is absorbed by different components of the Earth's system, such as biota, land, ice caps, oceans, and gases, albeit to a lesser extent. On average, approximately 240 W/m2 of energy is absorbed by the Earth's system per second (Altomonte, 2009).

To maintain an energy balance, the earth should radiate back into space an equal quantity of energy as it absorbs. Because of the planet’s surface being cooler than the sun, energy is released at longer wavelengths, predominantly in the infrared region of the spectrum, which is known as "thermal" radiation. “Once emitted, some of this infrared radiation is absorbed by gases in the cooler upper atmosphere (CO2, water vapour and other naturally-occurring trace gases that, altogether, make up less than 0,1% of the atmosphere) and is radiated back to the surface; this is what is called the ‘greenhouse effect’ (Altomonte, 2009).” Without greenhouse gases (GHGs), the average surface temperature could be roughly 30 degrees celsius lower than the current average of +14°C, rendering life as we know it impossible due to temperatures below 0°C (Altomonte, 2009).

Human actions, notably the combustion of fossil fuels and the clearing of forests, have substantially amplified this inherent greenhouse effect. These activities have set off a chain of events that contribute to substantial climate change, a realisation we are now beginning to comprehend (Altomonte, 2009).

2.1.2. *The Earth’s Climate System*

Because the Earth's climate is governed by a complex system of interconnected subsystems, it is difficult to forecast the total response of the global climate to changes in a single subsystem, such as the atmosphere. The atmosphere’s state is influenced by other subsystems like the oceans, cryosphere, biosphere, and lithosphere. Due to these intricate interactions, significant alterations in the global climate can occur through various causes known as "climate forcing" (Altomonte, 2009).

According to the article - “Climate Change and Architecture: Mitigation and Adaptation Strategies for a Sustainable Development” by Altomonte, S (2009). These climate forcing factors include:

1) “Alteration of the Earth’s orbit and movements;
2) Variation in the intensity of solar radiation (the so-called ‘solar constant’);
3) Shift in the geological equilibrium of the planet (such as shape or position of the continents);
4) Variation in the equilibrium of oceanic currents (e.g. Gulf Stream, El Niño-La Niña cycles, etc.);
5) Modification of the Earth’s albedo (i.e. the reflectivity of the planet’s surface and atmosphere);
6) Changes in the composition of the atmosphere due to human activity (Altomonte, 2009).”

These driving factors work over a wide range of time ranges, from long geological aeons to more immediate human timelines. The climate system has complex feedback processes that can magnify (positive feedback) or lessen (negative feedback) the impacts of subsystem changes. Feedback loops generate internal reactions with complex ramifications, making it challenging to predict their effects accurately. An example of this is evidence from ice cores, which provide information on past climate changes, which reveal that the planet has undergone abrupt shifts among climate extremes due to absolute feedback systems (Altomonte, 2009).

Throughout Earth's history, which spans approximately 4.5 billion years, the climate has varied locally and globally. Famous fluctuations include the Ice Age, followed by the little Ice Age in Europe at the beginning of the Middle Ages, then the subsequent medieval warm period, and the cooling that occurred in the centuries that followed. It is understood that Carbon dioxide played a significant role in all these variations (Altomonte, 2009).

Carbon plays a fundamental role in supporting life on our planet, serving as the foundation for plants, animals, and microorganisms. The carbon cycle, which regulates the quantity of carbon in the atmosphere, has stabilised the climate through extended periods of geological time. This cycle includes processes that are chemical, biological, or physical such as carbon dioxide absorption from the atmosphere by sinks such as rocks, biota, and ocean water. Carbon is subsequently released back into the environment through processes such as living creature death and decomposition, rock weathering, and volcanic eruptions (Altomonte, 2009).

Elevated carbon dioxide levels in the atmosphere promote improved moisture retention in warmer air, resulting in a warm and humid environment. This increase in moisture facilitates enhanced rock erosion, ultimately creating a stronger sink as atmospheric carbon binds with silicate and diffuses into the oceans. Conversely, reduced levels of carbon dioxide led to colder climates and the possibility of glaciations. During such periods, ice cover shields rocks from erosion and diminishes carbon absorption. These repeated interactions contribute to the general stability of the global climate system by managing temperatures and carbon concentrations over extended periods of time (Altomonte, 2009).

In nature, the emission of CO2 is counterbalanced by carbon sinks, creating a dynamic equilibrium within the climate system, as it absorbs the energy received from the Sun. The equilibrium can be disturbed by external influences, as shown by numerous instances in the paleoclimatic history of our planet (Altomonte, 2009).

2.1.3. *Projected Impacts of climate change and evidence*

In today's world, the reality of climate change is generally acknowledged and accepted. It is stated by the ‘IPCC's Fourth Assessment Report’, that human activities have resulted in a significant and unprecedented increase in atmospheric concentrations of carbon dioxide

(CO2), methane (CH4), and nitrous oxide (N2O) over the last two centuries, surpassing pre-industrial levels. The primary causes of the rise in CO2 concentration are fossil fuel usage and changes in land use, such as deforestation. Methane and nitrous oxide emissions, on the other hand, are predominantly attributed to agricultural practices (cited in Altomonte, 2009).

The atmospheric concentration of carbon dioxide has risen from 280 parts per million (ppm) before the industrial era to 379 ppm in 2005 (cited in Altomonte, 2009). This concentration is unparalleled in at least the previous 650,000 years, according to ice core study. During glacial periods, carbon dioxide levels ranged between 180 and 300 parts per million, and 300 parts per million during mild interglacials. Concentrations higher than the present came about millions of years ago as a result of large-scale global events, such as the discharge of methane-clathrates approximately 55 million years ago. This resulted in carbon dioxide concentrations of 2000 ppm, indicating the beginning of the Eocene epoch. Based on current data and climate models, it is clear that the current concentrations cannot be attributed completely to natural sources and must take into account human impact (Altomonte, 2009).

The average annual growth rate of CO2 concentration has increased from 1.4 ppm per annum before 1960 to 1.9 ppm in the past decade. Carbon dioxide emissions have increased from 23.5 GtCO2 per year in the 1990s to 26.4 GtCO2 per year in 2004-2005 (cited in Altomonte, 2009). Methane levels within the atmosphere have jumped from around 715 parts per billion (ppb) preceding the industrial age to 1732 ppb in the early 1990s and 1774 ppb in 2005. Nitrous oxide concentrations have been steadily increasing since 1980, reaching 319 ppb in 2005, surpassing natural variations from 320 to 790 ppb. Growth rates have slowed since the early 1990s, but overall emissions remain stable. Agricultural activities primarily contribute to this increase (cited in Altomonte, 2009).

2.1.4. Radiative Forcing

Radiative forcing is a measure of how much a cause, such as rising greenhouse gas concentrations, influences climate change. It measures the impact of that factor on the energy balance of the Earth-atmosphere system and is denoted in units of Watts per square meter (Wm-2). From 1750 to 2005, CO2, CH4, and N2O concentrations increased by +2.30 Wm-2, indicating unprecedented growth in radiative forcing compared to previous 10,000 years. Other substantial anthropogenic contributors to positive radiative forcing include ozone-forming chemical emissions, halocarbon alterations, and land cover changes. Human alterations to the reflecting characteristics of ice and snow cover, on the other hand, result in a minor negative forcing, whereas aerosol emissions result in an overall negative radiative forcing (cooling impact). Since 1750, variations in solar irradiation have resulted in a little amount of positive forcing of roughly +0.12 Wm-2. In comparison to natural phenomena such as solar irradiance, human-caused cumulative radiative forcing has a significantly greater influence on current and future climate change (Altomonte, 2009).

Scientists have looked to the paleoclimatic data and studied climatically sensitive markers to explore prior climate shifts and to compare them to possible future scenarios to better comprehend the ramifications of such extreme changes. Researchers want to boost their confidence in their forecasts by comparing these scenarios to observed data (Altomonte, 2009).

2.1.5. Current & Future Climate Scenarios

According to the emission scenarios established by the “IPCC 2016 Special Report on Emission Scenarios”, the global climate system would warm by at least +0.2°C during the next two decades. If current levels of greenhouse gas emissions persist, "business as usual" will result in increased warming, resulting in massive changes in the global climate system of the twenty-first century. The IPCC predicts a +1.8°C rise by the end of the century, with a range of +1.1°C to +2.9°C. A higher emission scenario (A1F1) predicts a +4.0°C rise, with a range of +6.4°C. Sea levels are also expected to rise from 0.18m to 0.59m by the end of the century (cited in Altomonte, 2009).

While a 4°C rise may not appear to be significant, it represents the global average temperature variation between the midpoint of an ice age and the warmer periods between glacial eras (which are expected to deviate by 5-6°C on average). This shift is projected to take a century, as opposed to thousands of years as witnessed between glacial ages. Aside from the substantial local and global changes, such considerable warming would disturb the entire climate system's balance. As the planet warms, its capacity to absorb atmospheric CO2 diminishes, leading to a larger portion of carbon emissions remaining in the atmosphere. This leads to ocean acidification, further reducing CO2 absorption by the oceans and amplifying the warming effect (a positive feedback loop). Current data indicates that this process is already underway (Altomonte, 2009).

According to the IPCC Working Group II's contribution to AR4 (cited in Altomonte, 2009), evidence from various continents and oceans indicates that climate change is already impacting many natural systems, particularly through temperature increases. An examination of data from throughout the world demonstrates that human warming has had detectable consequences on physical and biological systems. Early spring events, alterations in animal and plant ranges, and extended growing seasons all indicate vulnerability in terrestrial and marine ecosystems. The Southern Ocean and sections from the North Atlantic are predicted to see the least warming (Altomonte, 2009).

A warmer globe indicates more moisture owing to more energy and greater evaporation in air movement due to the discharge of heat that remains from water vapour. Extreme heat, heatwaves, tropical cyclones, and intense precipitation events are expected to become more frequent and intense, whereas subtropical land zones are likely to see drier conditions. In the following decades, both increasing floods and drought are projected to occur. Difficulties with water shortages will grow in places already prone to droughts, wildfires, and poor rainfall. Simultaneously, the amount of individuals at risk of coastal erosion and sea-level rise will increase, particularly in densely populated and low-lying areas with limited adaptive capacity (cited in Altomonte, 2009).

Climate change is anticipated to have a detrimental influence on the future of the majority of emerging nations, since it exacerbates resource distribution and availability constraints connected with growing urbanisation, industrialisation, and economic expansion (cited in Altomonte, 2009).

2.2. Solution / Response context

2.2.1. *International Agreements*

Recognizing the significant and far-reaching effects of climate change on natural and biological systems, it is crucial to implement both adaptation and mitigation strategies to address the short-term and long-term impacts, respectively. There is a wide range of strategies available today, including technical, educational, administrative, and political measures. However, the effective implementation of these measures is still hindered by barriers, limitations, and costs that have yet to be fully estimated and understood (Altomonte, 2009).

One of the measures aimed at mitigating these substantial impacts globally was the Kyoto Protocol, signed on December 11, 1997, and fully enforced in February 2005. The protocol recognises that emissions of greenhouse gases have increased by 70% since pre-industrial times, with the energy supply sector contributing the most significant growth (+145%) between 1970 and 2004 (IPCC, 2007c).

The Kyoto Protocol requires industrialised nations to adopt legally binding limits on the 6 major greenhouse gases: CH4, CO2, N2O, PFCs, HECs, and SF6 (Altomonte, 2009).

Different countries experienced varying levels of reductions, but their collective goal was to decrease global greenhouse gas emissions by approximately 5.2% below 1990 levels between 2008 and 2012. It is important to note that developing nations, including Mexico, Brazil, India, and China, were exempt from the limitations enforced by the Protocol (Altomonte, 2009).

Because each greenhouse gas affects the climate differently and remains in the atmosphere for varying periods of time until natural removal, the Protocol grouped them and established targets for lowering specific gases by translating their impact into "CO2 equivalents." This method enables a unified representation (GtCO2-eq) of their combined effect. To determine these carbon-equivalent values, each non-carbon dioxide gas was multiplied by its global warming potential factor, which quantifies its impact in relation to carbon dioxide. For example, methane has a considerably greater warming impact than CO2 (Altomonte, 2009).

Following the signing of the Kyoto Protocol, a number of countries throughout the world enacted various programmes and laws to address sustainable development, climate change, and energy reliability. Despite these efforts, the IPCC (Intergovernmental Panel on Climate Change) anticipates that global greenhouse gas concentrations will continue to climb in the coming decades. According to the IPCC's non-mitigation scenario, estimates show an increase of greenhouse gas concentrations ranging from 9.7 to 36.7 GtCO2-eq by 2030. The majority of these concentration rises are anticipated to stem from developing economies, where per capita emissions are increasing rapidly. Even with these gains, the total statistics in poor countries remain far lower than those found in most industrialised countries (IPCC, 2007a).

The main focus right now is on determining the hazardous climate change threshold and the greenhouse gases concentration, particularly CO2, required to avert "dangerous anthropogenic interference with the climate system," as defined by the United Nations Climate Change Framework Convention. This goal should be reached in a time range that permits ecosystems to adjust naturally to climate change, assures food production stays unaffected, and promotes long-term economic development (United Nations, 1992).

“Currently, IPCC refers to stabilisation targets for CO2 between 445 and 710 ppm by 2030 (IPCC 2007c), with a general agreement at 550 ppm, double the pre-industrial level. (Altomonte, 2009).” Achieving this goal is challenging, as the limited goals set out by the Kyoto Protocol are practically insufficient due to the expected emissions growth in emerging countries. To maintain atmospheric greenhouse gas concentrations at double the pre-industrial levels, emissions would need to be reduced by approximately 70% in the coming decades, presenting a significant challenge for the global economy. When CO2 is emitted into the atmosphere, a portion is absorbed over time by carbon sinks (less than 50% over a 100 years), while the remainder continues to exist in the atmosphere. When CO2 is released into the atmosphere, a part is absorbed by carbon sinks over time (less than 50% over a century), while the remainder stays in the atmosphere (cited in Altomonte, 2009).

2.2.2. *South Africa Climate Change Projections*

As part of the study by Engelbrecht et al 2019, a series of climate model simulations were considered to analyse the current and future climate conditions in South Africa. These simulations were used to assess the impact of climate change on extreme events and the potential for renewable energy in the country. The report provides in-depth forecasts of future climate change in Africa, utilizing high-resolution data obtained by downscaling global climate models with the regional climate model CCAM. It includes both high and low mitigation scenarios (RCP4.5 and RCP8.5) and was carried out at a global resolution of 50 km, followed by a more particular downscaling to 8 km for South Africa, resulting in the most extensive and thorough forecasts available for the nation (Engelbrecht, 2019).

The estimates for South Africa at an 8 km resolution reveal considerable increases in near-surface temperatures and accompanying severe occurrences. The frequency of heat-wave days, high fire-danger days, and extremely hot days is anticipated to rise between 2021 and 2050. These modifications apply to both low and moderate-high mitigation situations. In low mitigation futures, the period from 2071 to 2099 may witness more severe effects on livestock and agriculture, particularly in the Limpopo basin and western interior. However, moderate-high mitigation efforts can significantly mitigate temperature changes and related extremes during that far-future period. Climate change may cause an increase in intense convective downpour events in the central interior areas, according to the models. This could result in higher occurrences of lightning and elevated streamflow, potentially offering benefits to water yield in the area with large dams (Engelbrecht, 2019).

3. Research methodology

3.1. Research Approach / Paradigm

A case study research method was used, together with a pragmatic approach. The study follows an in-depth inquiry into a real-life setting (Yin, 2018 in Saunders et al., 2019:196), within the realm of climate change. The topics and case studies presented, will shed light on the future sustainable built environment of Tshwane. Case studies across the globe were identified and studied, with a particular focus on the adaptation technologies and strategies that were implemented within them. These case studies were then categorised in three different climate classification, according to the Koppen-Geiger Climate Classification system, which are Cwa; Cwb; and Bsh. Gauteng is currently categorised as Cwa/Cwb, but the argument for this study is that we need to look beyond our current climate situation. It is evident that our climate is changing and argued that Tshwane (Gauteng) will be categorised as Bsh within the next 20-25 years. This study compares and analyses climate change adaptation technologies that are currently implemented, and implemented in regions similar to our future climate. The research will try to explore if there are any major differences in applications in other climates classifications and whether or not they are applicable to the future sustainable built environment of Tshwane.

3.2. Solution context / classification

3.2.1 *Köppen-Geiger climate classification*

Using threshold values and seasonal changes in temperature and precipitation, this classification (Köppen-Geiger) divides climate into 5 major classes and 30 sub-types. The classification system uses vegetation as an indicator of climate to map biomes across the globe. It groups similar regions with shared vegetation characteristics into the same class. This classification, which originated in the late 19th century, continues to be widely utilised in contemporary settings for various purposes and research concerning climatic distinctions. These applications include ecological modelling and evaluation of climate change impacts (Beck, et al., 2018).

The widespread use of the Köppen-Geiger climate classification system reflects an understanding of the importance of climate in affecting worldwide plant distribution. Climate factors are considered as the primary drivers in species distribution models, explaining species ranges on larger sizes, while habitat and terrain have a minor impact on smaller scales. This classification provides a valuable tool for simplifying complex climate gradients into an ecologically meaningful system, frequently used in analysing species distribution, growth patterns, and dynamic global vegetation models (Beck, et al., 2018).

The Köppen-Geiger climate classification has three recent versions of world maps, each derived from different precipitation and temperature datasets, with varying resolutions and the number of stations used. The maps possess relatively low resolutions (0.1° or higher) and might not fully account for topographic effects, particularly in mountainous regions. Additionally, the limited number of stations in some maps can result in misclassifications, especially in areas with sparse station coverage or notable climate variations. Moreover, these maps lack uncertainty estimates, potentially leading users to have a false sense of confidence (Beck, et al., 2018).

The study presents an enhanced Köppen-Geiger climate classification map that overcomes previous shortcomings. This new map spans the years 1980 to 2016 and has an unparalleled resolution of 0.0083° (about 1 km at the equator), allowing for a more precise depiction of diverse locations. The researchers incorporated numerous independent data sources, including WorldClim, CHELSA, and CHPclim, to increase accuracy and account for uncertainties, and made specific modifications for topographic impacts. These datasets draw from a larger number of stations, allowing for uncertainty estimation in the resulting climate classifications. The study includes future climate projections for the period 2071-2100 at the same spatial resolution using data from 32 climate change models.

> *"Seven climatic datasets were used to create the current Köppen-Geiger climate classification map, three for air temperature (WorldClim V1 and V2, and CHELSA V1.2) and four for precipitation (WorldClim V1 and V2, CHELSA V1.2, and CHPclim V1). Except for CHPclim V1.2, which has a lesser resolution of 0.05°, all of these datasets have a resolution of 0.0083°. To guarantee consistency, the CHPclim V1.2 dataset was downscaled to match the greater resolution of 0.0083° using bilinear interpolation (Beck, et al., 2018)."*

The future Köppen-Geiger classification was created using CMIP5 archived historical and future air temperature and precipitation data. The data was based on the RCP8.5 (Representative Concentration Pathway) scenario. The study used climate models that supplied data for both the 1980-2016 and the 2071-2100 time periods. From 1980 to 2016, historical data was collected by integrating historical runs (until 2005) with future runs (beginning in 2006). A single initialization ensemble represented each climate model. The data requirements were satisfied by 32 models, which were used to construct the future climate categorization map (Beck, et al., 2018).

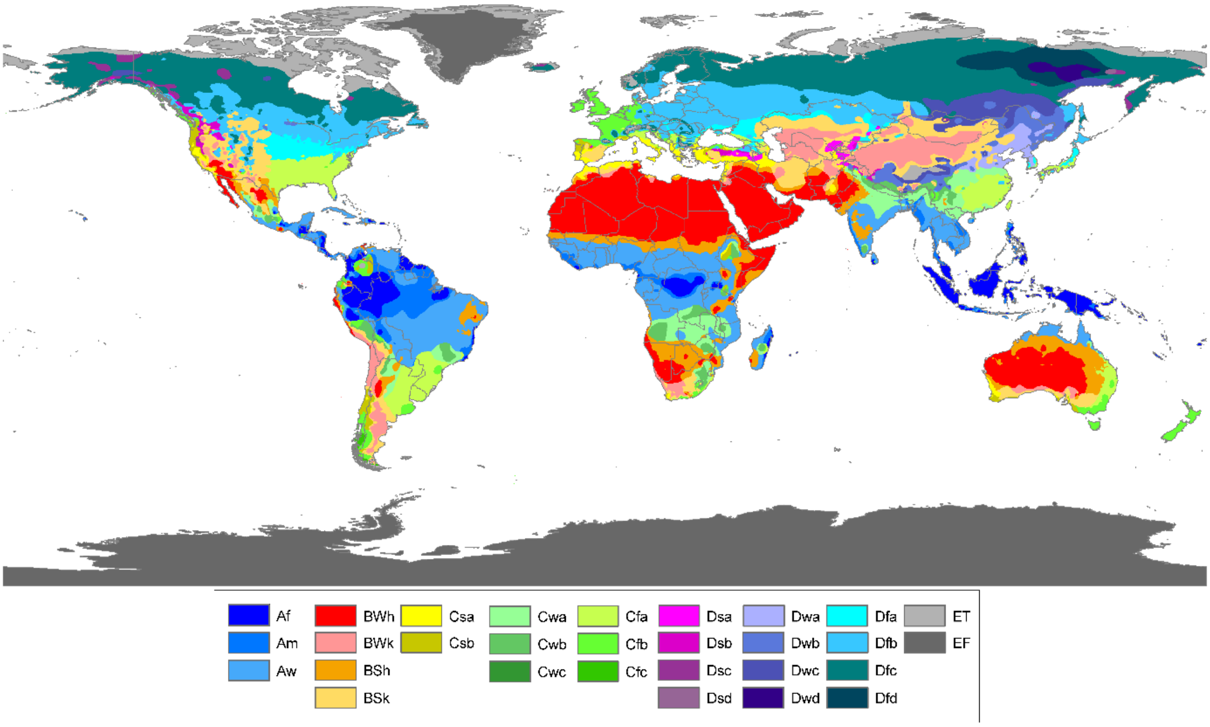
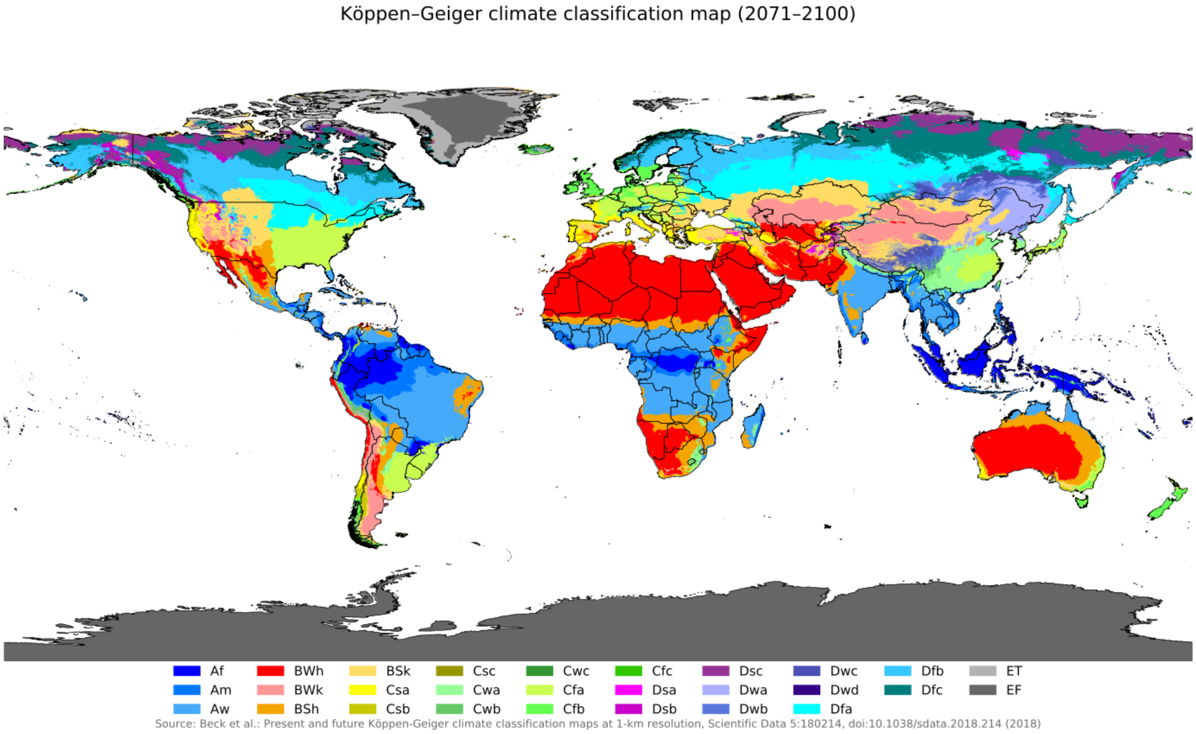
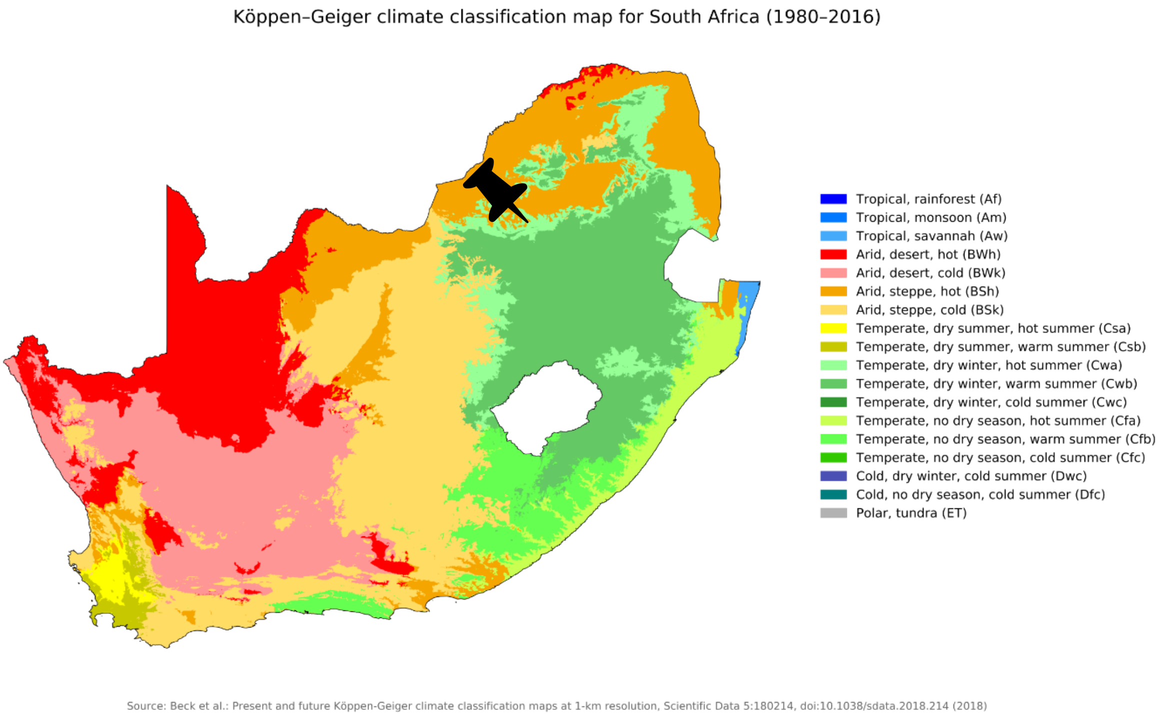


Figure 1: Köppen-Geiger Climate Classification map (1980-2016) (Beck, et al., 2018).


Köppen–Geiger climate classification map (2071–2100)

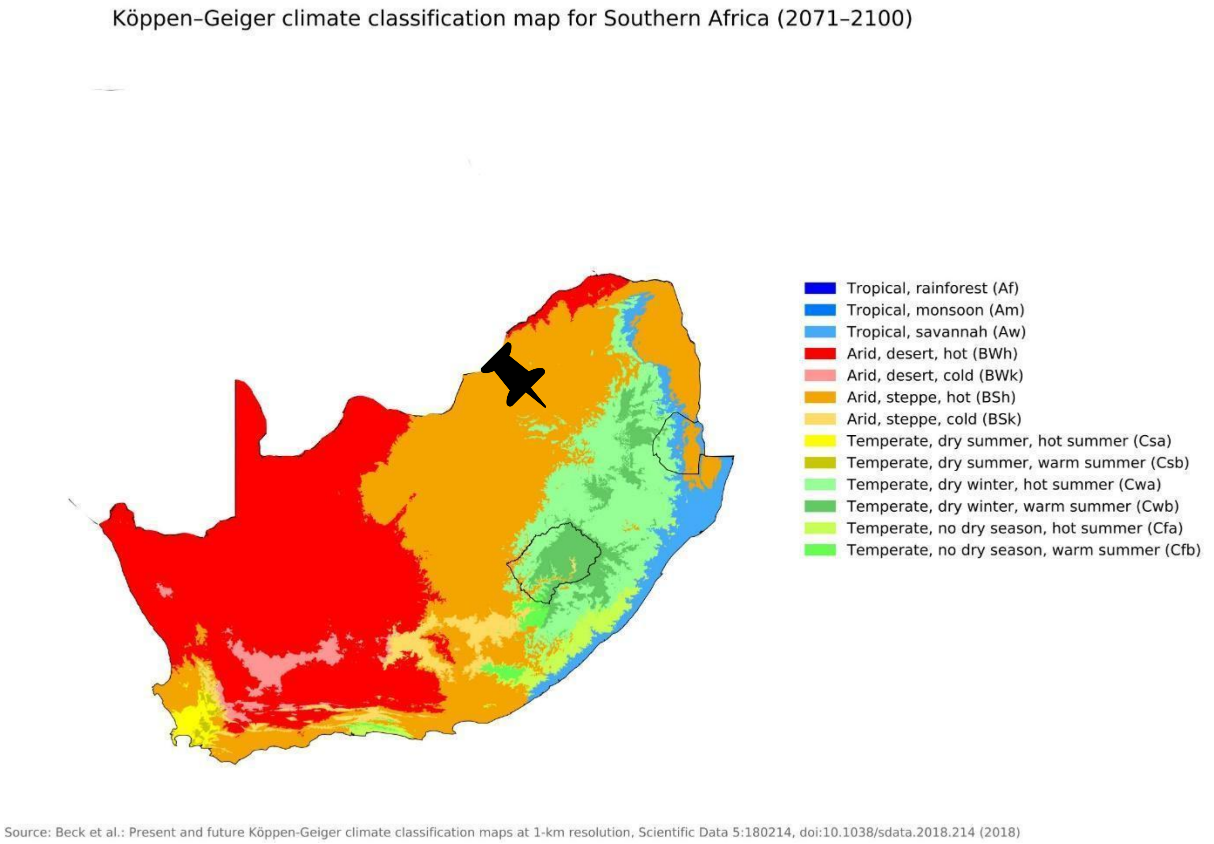
Source: Beck et al.: Present and future Köppen-Geiger climate classification maps at 1-km resolution, Scientific Data 5:180214, doi:10.1038/sdata.2018.214 (2018)

Figure 2: Köppen-Geiger Climate Classification map (2071-2100) (Beck, et al., 2018).


Köppen–Geiger climate classification map for South Africa (1980–2016)

Source: Beck et al.: Present and future Köppen-Geiger climate classification maps at 1-km resolution, Scientific Data 5:180214, doi:10.1038/sdata.2018.214 (2018)

Figure 3: Köppen-Geiger Climate Classification map for South Africa (1980-2016) (Beck, et al., 2018).


Köppen–Geiger climate classification map for Southern Africa (2071–2100)

Source: Beck et al.: Present and future Köppen-Geiger climate classification maps at 1-km resolution, Scientific Data 5:180214, doi:10.1038/sdata.2018.214 (2018)

Figure 4: Köppen-Geiger Climate Classification map for South Africa (2071-2100) (Beck, et al., 2018).

3.2.2. Present & Future Climate Classification (Cwa; Cwb; Bsh)

Cwa – Temperate, Dry Winter, Hot Summer (Tshwane Present Classification)

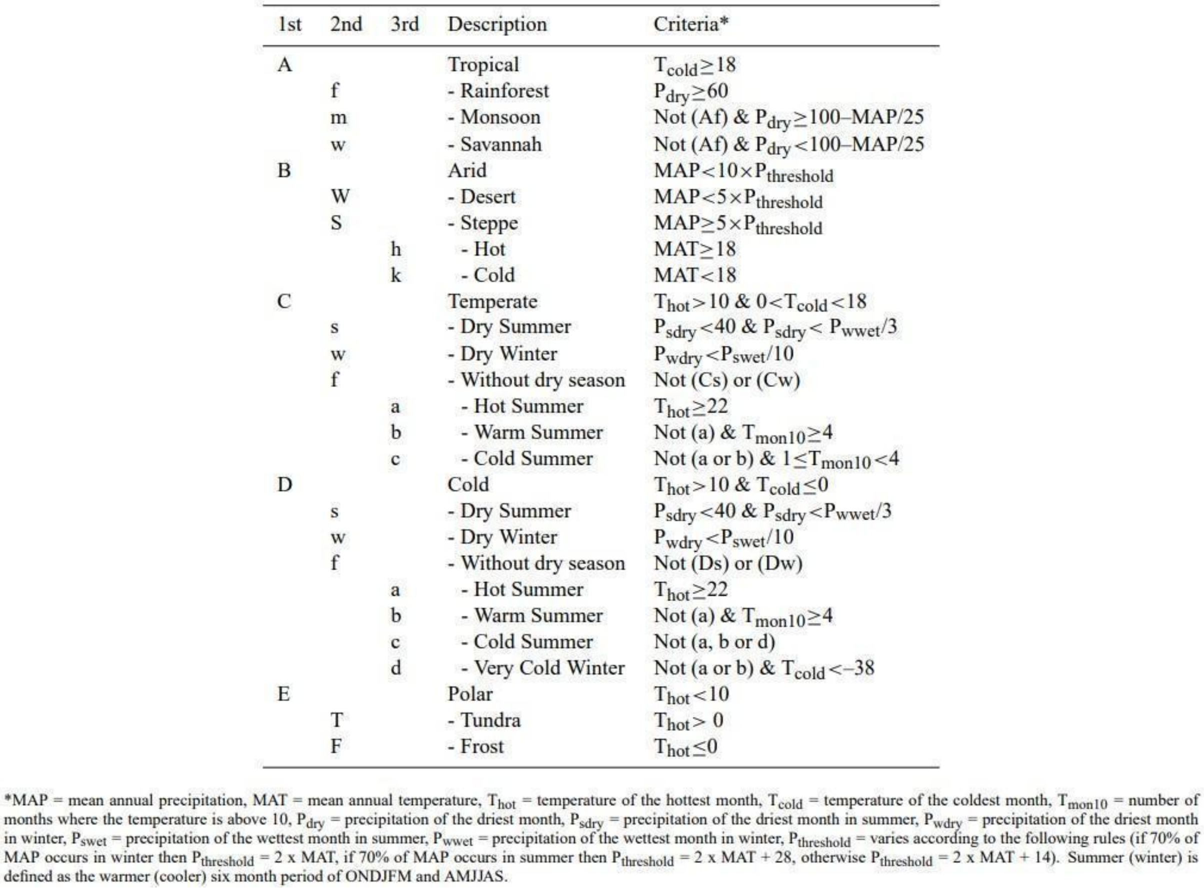
The coldest month has a temperature greater than -3 °C but less than +18 °C. The wettest month precipitation in summer is more than ten times that of the driest month precipitation in winter, while the wettest month precipitation in winter is less. The warmest month had a temperature greater than or equal to +22 °C (Chen & Chen, 2013).

Cwb – Temperate, Dry Winter, Warm Summer (Centurion/Johannesburg Present Classification)

The coldest month has a temperature greater than -3 °C but less than +18 °C. The wettest month precipitation in summer is more than ten times that of the driest month precipitation in winter, while the wettest month precipitation in winter is less. The warmest month has a temperature of less than +22 °C, while at least four months have temperatures of more than or equal to +10 °C (Chen & Chen, 2013).

BSh – Arid, Steppe, Hot (Tshwane Future Classification)

Total annual precipitation is greater than 5 times the dryness threshold. The dryness threshold is stated in millimetres and is proportional to the annual mean temperature (Tann) in degrees Celsius. It is determined as follows: if at least two-thirds of the annual precipitation falls during the winter, the dryness threshold is 2Tann; if at least two-thirds of the annual precipitation falls during the summer, the dryness threshold is 2Tann + 28; otherwise, the dryness threshold is 2Tann + 14. The annual mean temperature is more than or equal to +18 degrees Celsius (Chen & Chen, 2013).



1st	2nd	3rd	Description	Criteria*
A			Tropical	$T_{cold} \geq 18$
	f		- Rainforest	$P_{dry} \geq 60$
	m		- Monsoon	Not (Af) & $P_{dry} \geq 100 - MAP/25$
	w		- Savannah	Not (Af) & $P_{dry} < 100 - MAP/25$
B			Arid	$MAP < 10 \times P_{threshold}$
	W		- Desert	$MAP < 5 \times P_{threshold}$
	S		- Steppe	$MAP \geq 5 \times P_{threshold}$
		h	- Hot	$MAT \geq 18$
		k	- Cold	$MAT < 18$
C			Temperate	$T_{hot} > 10$ & $0 < T_{cold} < 18$
	s		- Dry Summer	$P_{sdry} < 40$ & $P_{sdry} < P_{wwet}/3$
	w		- Dry Winter	$P_{wdry} < P_{swet}/10$
	f		- Without dry season	Not (Cs) or (Cw)
		a	- Hot Summer	$T_{hot} \geq 22$
		b	- Warm Summer	Not (a) & $T_{mon10} \geq 4$
		c	- Cold Summer	Not (a or b) & $1 \leq T_{mon10} < 4$
D			Cold	$T_{hot} > 10$ & $T_{cold} \leq 0$
	s		- Dry Summer	$P_{sdry} < 40$ & $P_{sdry} < P_{wwet}/3$
	w		- Dry Winter	$P_{wdry} < P_{swet}/10$
	f		- Without dry season	Not (Ds) or (Dw)
		a	- Hot Summer	$T_{hot} \geq 22$
		b	- Warm Summer	Not (a) & $T_{mon10} \geq 4$
		c	- Cold Summer	Not (a, b or d)
		d	- Very Cold Winter	Not (a or b) & $T_{cold} < -38$
E			Polar	$T_{hot} < 10$
	T		- Tundra	$T_{hot} > 0$
	F		- Frost	$T_{hot} \leq 0$

*MAP = mean annual precipitation, MAT = mean annual temperature, T_{hot} = temperature of the hottest month, T_{cold} = temperature of the coldest month, T_{mon10} = number of months where the temperature is above 10, P_{dry} = precipitation of the driest month, P_{sdry} = precipitation of the driest month in summer, P_{wdry} = precipitation of the driest month in winter, P_{swet} = precipitation of the wettest month in summer, P_{wwet} = precipitation of the wettest month in winter, $P_{threshold}$ = varies according to the following rules (if 70% of MAP occurs in winter then $P_{threshold}$ = 2 x MAT, if 70% of MAP occurs in summer then $P_{threshold}$ = 2 x MAT + 28, otherwise $P_{threshold}$ = 2 x MAT + 14). Summer (winter) is defined as the warmer (cooler) six month period of ONDJFM and AMJJAS.

Figure 5: Description of Koppen climate symbols and defining criteria (M, et al., 2007).

3.3. Passive and Low Energy Cooling of Buildings

3.3.1. Overview and their applicability to various building typologies & climates

The strategies and technologies identified within the study should serve as a guide for designing buildings in regions that are identified as warm; hot, with semi-arid; dry winter seasonal precipitation. Architects and other designers within the built environment, designing for these specific climate types, should also be interested in providing thermal comfort for the inhabitants of the building, while reducing the consumption of conventional exhaustible energy sources. The term 'passive cooling systems' refers to cooling strategies & techniques that lower the indoor temperature of a building with the use of natural energy sources. It is important to understand that when we use the term 'passive', that it does not exclude the use of mechanical air movement systems/technologies if their participation enhances the performance of adaptation strategies (Givoni, 1994)

3.3.2. Bioclimatic Architecture and Passive Cooling

It is sometimes confused that the application and design of passive cooling systems for hot regions is the same as appropriate architectural design for these regions – termed 'tropical bioclimatic architecture'. It is important to make a distinction between these two concepts.

Buildings experience daytime heating and nighttime cooling, with the latter happening due to the outdoor air's radiant loss to the sky. Specialised passive cooling systems are not necessary for these natural processes to take place. Because of this heating and cooling cycle, the average inside temperature is greater than the average outside temperature. This difference is attributed to the building absorbing solar radiation through its envelope and windows, allowing it to retain heat throughout the day and gradually releasing it at night. A building will have higher solar gain when its envelope has darker colours and heat is generated by the occupants through cooking, lighting, etc. This higher solar gain increases the indoor temperature elevation. Sol-air temperature elevation refers to the increase in indoor average temperature resulting from both direct and indirect solar energy gain. Bioclimatic architectural design, with a focus on cooling during summer, aims to reduce this sol-air elevation. This requires the input of cooling energy that is obtained through the use of renewable natural sources with the help of and implementation of passive systems. The book, Passive and Low Energy Cooling of Buildings by Baruch Givoni, describes the above mentioned as the operational definition of passive cooling systems (Givoni, 1994).

Bioclimatic architecture can be described as architectural design that utilises the design and choice of materials that aim to provide thermal comfort, and reducing the demand for energy that is used to cool a building. The aim of bioclimatic architecture is to minimise the heat gain of the building, minimise solar penetration through windows and solar heating of the envelope, and to provide comfort through natural ventilation. Design elements for bioclimatic architecture include – orientation; size; layout; shading devices; window details and thermal resistance. Their average indoor temperature can be reduced if the application of these design elements is used appropriately. The average indoor temperature can get close to the average outdoor temperature, but never really below (Givoni, 1994).

It is recognised that passive cooling systems employ passive techniques to provide dynamic cooling. Passive technologies and strategies utilise heat-flow paths, these paths will be absent in buildings that do not incorporate these strategies and technologies. Appropriate ‘architectural bioclimatic design’ and ‘passive cooling systems’ reinforce and supplement one another, as architectural bioclimatic design can be considered as a precondition for the application of passive cooling systems (Givoni, 1994). The tandem of these two practices can be viewed as ideal circumstances, but is not always possible. This study only focuses on passive cooling systems, as the research problem lies within the realm of adaptation to existing buildings in the urban environment. The aim is to identify adaptation strategies and technologies that are sustainable towards a changing climate.

3.3.3. Classification of Passive Cooling Systems

Passive cooling systems for buildings heavily rely on natural heat sinks, which include ambient air, water, the upper atmosphere, and the undersurface soil. These cooling systems utilise the cooling energy derived from these sources in various ways. The classification of different passive cooling systems is based on the source from which their cooling energy is derived (Givoni, 1994):

- **Comfort Ventilation -** during the day, it delivers immediate human comfort;
- **Direct Evaporative Cooling** is cooling of air by means of mechanical or nonmechanical evaporation. The air that is cooled and humidified is then distributed through the building;
- **Soil Cooling** occurs when the soil is cooled below its natural temperature, which is then used as a source to cool down the building;
- **Cooling of Outdoor Spaces** is a cooling method suited to patios and courtyards close to or within a building (Givoni, 1994).

These cooling systems still depend on specific limits when applicable. Some of the systems can only be applied to specific building typologies or under certain climatic conditions. It is important to always have a regional approach when designing or applying these systems, so that when the system or technology is implemented, it can be utilised to its maximum potential. Building typologies and climatic conditions vary significantly between regions and countries. In hot regions of developing countries, people often tolerate higher temperatures and humidity levels due to lower expectations and natural acclimatisation. When studying specific values for the applicability of systems, it's crucial to interpret them as a range instead of fixed values. This is because the concept of comfort differs in various climatic regions and countries, making flexibility and adaptability essential considerations (Givoni, 1994).

3.3.4. Comfort Ventilation

Under still air circumstances, this is arguably the easiest overarching method for improving indoor thermal comfort with midday ventilation by increasing interior air speed. The term 'comfort ventilation' refers to the practice of allowing outside air to flow through a building, hence expanding the top limit of the comfort zone beyond what is feasible with still air conditions. Even though the outside air is quite warm, this external air movement can have a physiological cooling effect. When cross-ventilation is employed all day, the ambient temperature of the inside air and surfaces nearly mimics the temperature of the external environment. As a result, midday ventilation is only appropriate when interior comfort is comparable to external air temperature (Givoni, 1994). Outdoor air flow affects indoor daytime temperature, which depends on the building's design, internal heat generation, and solar energy penetration. In buildings with high insulation and thermal mass, indoor daytime temperature may be below outdoor levels without ventilation. Daytime ventilation raises indoor air and radiant surface temperature (Givoni, 1994:5).

In warm regions, the most straightforward approach for ensuring comfort is through comfort ventilation. This method is suitable when the outdoor maximum temperature remains below approximately 32 degrees Celsius and there is an indoor air speed of 1.5-2.0 m/s. The effectiveness of this approach is also influenced by the adaptation of the individuals. To mitigate the impacts of high heat and humidity, daytime ventilation becomes essential, as it also improves the body's ability to dissipate heat through convective processes (Givoni, 1994).

Comfort Ventilation is applicable to all building typologies and requires large windows that are well shaded, with the preferred structural materials being lightweight concrete, wood and perforated bricks. In areas where proper cross ventilation is challenging due to low wind speeds, or not possible, a mechanical fan can be employed to exhaust indoor air. Simultaneously, fresh exterior air is drawn into the interior through open windows to facilitate air movement and ventilation (Givoni, 1994).

3.3.5. Direct Evaporative Cooling

This is a cooling system where evaporative water is utilised to cool outdoor air before it enters the building. Mechanic or passive methods can be used to induce the air flow. A passive system of direct evaporative cooling is – humidification of the ambient air via evaporative cooling towers (Givoni, 1994:12). Indirect examples are – a roof is cooled through a pond of water body; or a ceiling that is transformed into a cooling element. This reduces the temperature of the space below through long-wave radiation and convection, without raising the indoor humidity (Givoni, 1994:12). When examining the applicability for a certain climate or location, direct evaporative cooling should be carefully evaluated. In low-humidity areas, such as deserts, this cooling system can be a cheap, attractive, and physiologically beneficial alternative. Regions that are more humid will see the efficiency of the system reduced with an undesired humidity. An indirect system would be more appropriate in this region, as it has no effect on the indoor humidity (Givoni, 1994:12).

3.3.6. The Soil as a Cooling Source

During the summer, the inherent temperature of soil in temperate areas may be low enough to function as a cooling source. In contrast, the natural temperature of the earth in hot locations during the summer is usually too high to be used as a cooling source. In hot places, it is feasible to lower the earth's temperature, and after the soil has cooled sufficiently, it may be used in a variety of ways to efficiently cool structures. Earth covered buildings are a successful method in regions that are hot with mild winters. Direct conductive passive cooling is provided by the cool earth mass (Givoni, 1994:19).

3.3.7. Discussion of Adjacent Outdoor Spaces

In hot regions it is very common to see open spaces adjacent to buildings and enclosed by walls, widely known as internal patios and courtyards. The detail of their design is a key factor when considering their performance. Some courtyards can improve the indoor thermal conditions of a building and provide a pleasant outdoor environment, while others can increase the indoor temperature of the building around them which can also result in poor ventilation in the adjacent rooms. It is possible to lower the air and radiant temperatures within the courtyard below the level of the ambient air, by applying specific design details and cooling systems to courtyards adjacent to buildings. A simple way to minimise the radiant temperature within a courtyard is by using plants to shade or pergolas. The adjacent walls and windows of a courtyard will also experience less radiant load, when these systems are applied and design accordingly. Shading alone is not enough to significantly lower the air temperature in an open area. Plant selection is also critical as it is important to make use of deciduous trees and vines that are bare in winter, because a sunny courtyard is much more desirable in winter than a shaded one. It should be made clear that when one attempts to modify the climatic conditions next to the skin of a building, like a courtyard, can only be done and be successful when the courtyard is separated from the outside environment. This can be done by enclosing the courtyard with high walls, and a built element of canopy from above, so that the space is enclosed from all sides. This separates the confined cool air in the courtyard from the warmer air above (Givoni, 1994:253).

3.4. Adaptation Strategies

The following adaptation strategies and technologies were identified by the RFS 701 group of 2022. These strategies are further classified from the above information and served as the baseline for the study. The technologies and their implication were adapted to a degree, to accommodate the case studies and argument for this study. Some technologies and strategies were also added as they became evident through the selected case studies.

Active Ventilation

- Mechanical Air Movement Equipment

Passive Ventilation

- Openable Clerestory windows to provide convectional air current.
- Openings that can be completely opened enable cross ventilation.
- Stack ventilation to induce natural air flow and extract hot air
- Louvered intake provides a turbulent loop for air circulation.

Shading

- Planting and/or green space in proximity to buildings.
- Screen / brise soleil of perforated wall that provides shades
- PV panels used as window shading devices

Thermal Inertia

- Thermal mass acts as an insulator to regulate interior cooling retention.

Alternative Strategies & Technologies

- Courtyard enhances air flow and minimises internal temperature of the building.
- Evaporative cooling reduces internal temperature.
- Wind towers induce air flow and reduce interior temperature.
- Perforated ceiling diffuses indirect sunlight while avoiding direct radiation.
- Mashrabiya / celosia: Similar to a screen, used for wind penetration. Traditional methods for passive cooling.
- Thermoacoustic roof tiles enhance thermal comfort.
- Double Glazing provides insulation and reduces energy use
- Double Façade System increases energy efficiency and natural ventilation.
- Ribbed Façade reducing heat generated on walls

4. **Results**

4.1. Cwa Climate Classification

The following table illustrates the case studies with their findings within the climate classification Cwa – Temperate, Dry Winter, Hot Summer. This is the current climate classification for Tshwane, and the technologies and systems presented can be seen as the current discourse for climate change adaptation within the region.

Case Studies – CWA (Present Climate Classification of Tshwane)

			Active Ventilation	*Passive Ventilation*				*Shading*			*Thermal Inertia*	*Other*	
Project	**Location**	**Building Typology**	**Mechanical Equipment**	**Clerestory Windows**	**Cross Ventilation**	**Stacked Ventilation**	**Louvered Intake**	**Planting**	**Screens**	**PV Panels**	**Thermal Mass**	**Alternative Strategies & Technologies**	***Score (x/10) 5 Av.***
Lee House – Studio mk27	Porto Feliz, Brazil	Single-Storey; Residential			🟩		🟩	🟩	🟩		🟩		5
Harmonia 1250 - Triptyque Architecture	Sao Paulo, Brazil	Multi-Storey; Commercial			🟩			🟩	🟩				3
Casa Azul - Delfino Lozano	Zapopan, Mexico	Multi-Storey; Residential		🟩	🟩	🟩			🟩		🟩	🟩	6
Casamirador Savassi - Gisele Borges Architecture	Belo Horizonte, Brazil	Multi-Storey; Residential	🟩		🟩				🟩		🟩	🟩	5
Panda Pavilions Zoo - EID Architecture	Chengdu, China	Single-Storey; Commercial	🟩	🟩	🟩	🟩		🟩	🟩			🟩	7
FBV WP House - Gabriel Garbin Architecture	Porto Feliz, Brazil	Single-Storey; Residential	🟩		🟩			🟩	🟩		🟩	🟩	6
Casa Mantiqueira - ARKITITO Architecture	Delfim Moreira, Brazil	Single-Storey; Residential			🟩			🟩			🟩	🟩	4
Edificio Tico RV - Terra e Tuma Architects	Sao Paulo, Brazil	Multi-Storey; Residential			🟩	🟩		🟩			🟩	🟩	5
Qianhai Prisma Towers - BIG	Shenzhen, China	Multi-Storey; Commercial			🟩	🟩	🟩	🟩		🟩		🟩	6
Shenzhen Energy Mansion - BIG	Shenzhen, China	Multi-Storey; Commercial	🟩						🟩		🟩	🟩	4
Macao Bridge Hong Kong *Port* - RSHP	Hong-Kong, China	Multi-Storey; Commercial			🟩	🟩		🟩	🟩			🟩	5
Vertical Itaim - *Studio mk27*	Sao Paulo, Brazil	Multi-Storey; Residential			🟩	🟩			🟩		🟩		4
Frequency of Use (x/12)			4	2	11	6	2	8	9	1	8	9	

Figure 6: Table showing results from Cwa climate classification (Author, 2023).

**Score: 0-2 (Inadequate); 3-4 (Adequate); 5-7 (Good); 8-10 (Exceptional)*

**The score is an indicator of how well the building deals with the factors influencing thermal comfort and not necessarily the building's success. It is assumed that a higher score indicates a greater experience of thermal comfort.*

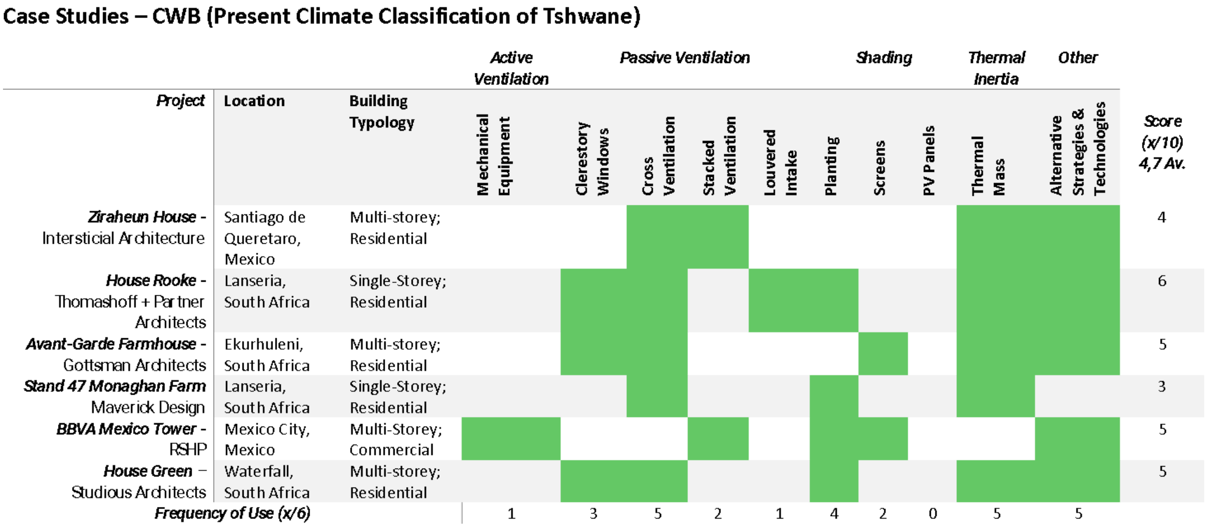
**Frequency of Use: An indicative amount of times a strategy or technology has been implemented. This is not to be understood as final, and that the strategy or technology is successful. It can be implied that a specific technology of strategy is more popular or has somewhat greater influence on thermal comfort. The success of each strategy would be finalised in a further study, where the technical abilities will be measured.*

Alternative Strategies & Technologies identified within case studies from Cwa Climate classification

- Mashrabiya
- Courtyards
- Thermoacoustic Roof Tiles
- Double Façade System

4.2. Cwb climate classification

The following table illustrates the case studies with their findings within the climate classification Cwb - Temperate, Dry Winter, Warm Summer. This is the current climate classification for Centurion and Johannesburg.



Case Studies – CWB (Present Climate Classification of Tshwane)

			Active Ventilation	*Passive Ventilation*				*Shading*			*Thermal Inertia*	*Other*	
Project	**Location**	**Building Typology**	**Mechanical Equipment**	**Clerestory Windows**	**Cross Ventilation**	**Stacked Ventilation**	**Louvered Intake**	**Planting**	**Screens**	**PV Panels**	**Thermal Mass**	**Alternative Strategies & Technologies**	***Score (x/10) 4,7 Av.***
Ziraheun House **-** Intersticial Architecture	Santiago de Queretaro, Mexico	Multi-storey; Residential			🟩	🟩					🟩	🟩	4
House Rooke **-** Thomashoff + Partner Architects	Lanseria, South Africa	Single-Storey; Residential		🟩	🟩		🟩	🟩			🟩	🟩	6
Avant-Garde Farmhouse **-** Gottsman Architects	Ekurhuleni, South Africa	Multi-storey; Residential		🟩	🟩				🟩		🟩	🟩	5
Stand 47 Monaghan Farm Maverick Design	Lanseria, South Africa	Single-Storey; Residential			🟩			🟩			🟩		3
BBVA Mexico Tower **-** RSHP	Mexico City, Mexico	Multi-Storey; Commercial	🟩			🟩		🟩	🟩			🟩	5
House Green – Studious Architects	Waterfall, South Africa	Multi-storey; Residential		🟩	🟩			🟩			🟩	🟩	5
Frequency of Use (x/6)			1	3	5	2	1	4	2	0	5	5	

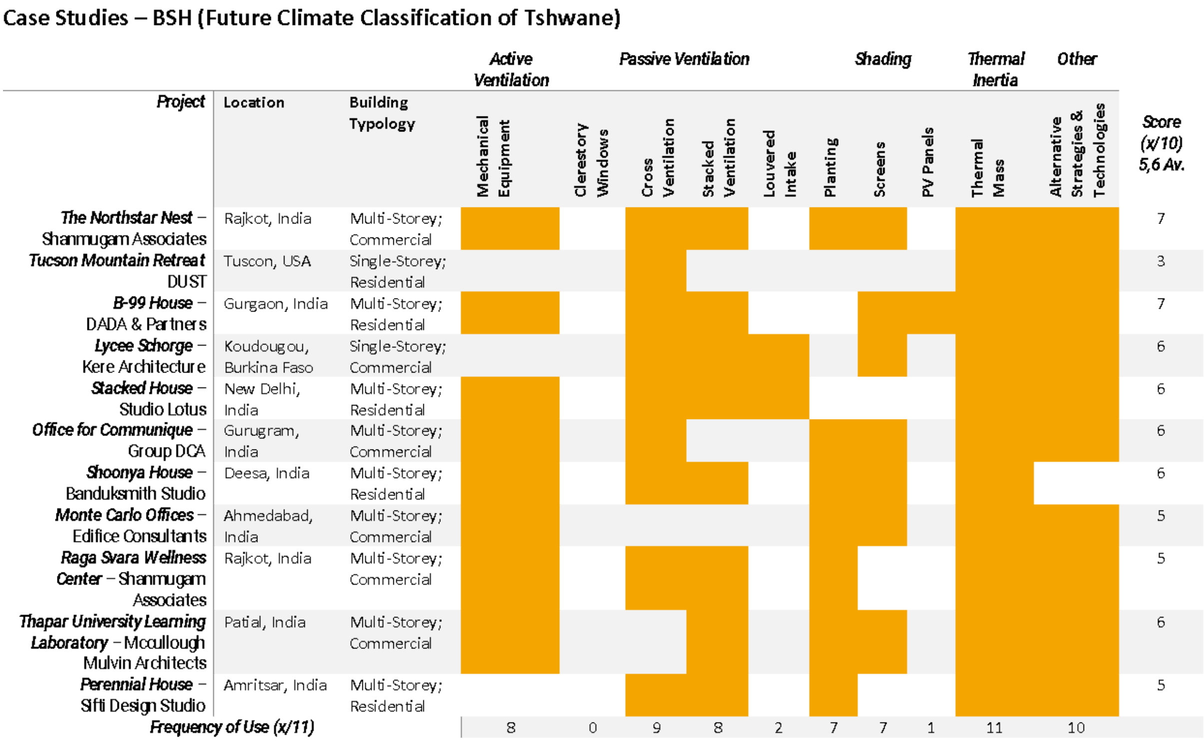
Figure 7: Table showing results from Cwb climate classification (Author, 2023).

Other Strategies identified within case studies from Cwb Climate classification

- Evaporative Cooling
- Courtyard
- Double Glazing

4.3. BSh Climate Classification

The following table illustrates the case studies with their findings within the climate classification BSh - Arid, Steppe, Hot. It is projected that this will be the future climate classification of Tshwane, Centurion, and Johannesburg in about 20 years.



Case Studies – BSH (Future Climate Classification of Tshwane)

			Active Ventilation	*Passive Ventilation*				*Shading*			*Thermal Inertia*	*Other*	
Project	**Location**	**Building Typology**	Mechanical Equipment	Clerestory Windows	Cross Ventilation	Stacked Ventilation	Louvered Intake	Planting	Screens	PV Panels	Thermal Mass	Alternative Strategies & Technologies	***Score (x/10) 5,6 Av.***
The Northstar Nest – Shanmugam Associates	Rajkot, India	Multi-Storey; Commercial	●		●	●		●	●		●	●	7
Tucson Mountain Retreat DUST	Tuscon, USA	Single-Storey; Residential			●						●	●	3
B-99 House – DADA & Partners	Gurgaon, India	Multi-Storey; Residential	●		●	●			●	●	●	●	7
Lycee Schorge – Kere Architecture	Koudougou, Burkina Faso	Single-Storey; Commercial			●	●	●		●		●	●	6
Stacked House – Studio Lotus	New Delhi, India	Multi-Storey; Residential	●		●	●	●				●	●	6
Office for Communique – Group DCA	Gurugram, India	Multi-Storey; Commercial	●		●			●	●		●	●	6
Shoonya House – Banduksmith Studio	Deesa, India	Multi-Storey; Residential	●		●	●		●	●		●		6
Monte Carlo Offices – Edifice Consultants	Ahmedabad, India	Multi-Storey; Commercial	●					●	●		●	●	5
Raga Svara Wellness Center – Shanmugam Associates	Rajkot, India	Multi-Storey; Commercial	●		●	●		●			●	●	5
Thapar University Learning Laboratory – Mccullough Mulvin Architects	Patial, India	Multi-Storey; Commercial	●			●		●	●		●	●	6
Perennial House – Sifti Design Studio	Amritsar, India	Multi-Storey; Residential			●	●		●			●	●	5
		Frequency of Use (x/11)	8	0	9	8	2	7	7	1	11	10	

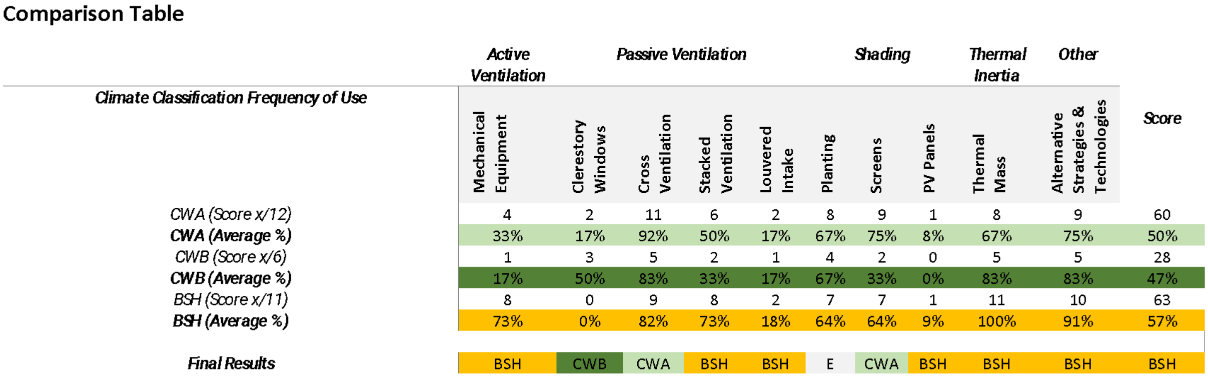
Figure 8: Table showing results from BSh climate classification (Author, 2023).

Other Strategies identified within case studies from BSh Climate classification

- Brise Soleil
- Ribbed Facade
- Courtyard
- Perforated Ceiling
- Wind Towers
- Double Façade
- Double Glazing
- Evaporative Cooling

4.4. Climate Classification Findings & Comparison

By studying the results in the tables presented, it is evident that some adaptation strategies and technologies are more popular than others. The technologies, strategies, and systems from the climate classification BSh have received the highest score – meaning that the buildings within those climate regions, implemented the most strategies that target thermal amelioration. It is thus evident that a warmer climate (future scenario) requires that more adaptation strategies are implemented within a building to lower the interior temperature and enhance thermal comfort.



Comparison Table

	Active Ventilation	Passive Ventilation				Shading			Thermal Inertia	Other	
Climate Classification Frequency of Use	Mechanical Equipment	Clerestory Windows	Cross Ventilation	Stacked Ventilation	Louvered Intake	Planting	Screens	PV Panels	Thermal Mass	Alternative Strategies & Technologies	Score
CWA (Score x/12)	4	2	11	6	2	8	9	1	8	9	60
CWA (Average %)	33%	17%	92%	50%	17%	67%	75%	8%	67%	75%	50%
CWB (Score x/6)	1	3	5	2	1	4	2	0	5	5	28
CWB (Average %)	17%	50%	83%	33%	17%	67%	33%	0%	83%	83%	47%
BSH (Score x/11)	8	0	9	8	2	7	7	1	11	10	63
BSH (Average %)	73%	0%	82%	73%	18%	64%	64%	9%	100%	91%	57%
Final Results	BSH	CWB	CWA	BSH	BSH	E	CWA	BSH	BSH	BSH	BSH

Figure 9: Table comparing results from all three climate classifications.

The comparison chart and table, presents that ‘clerestory windows’, ‘PV panels’, and ‘louvered intake’ are not the most popular or successful adaptation strategies. By comparing the results from all three climate classifications, it is evident that future sustainable development within Tshwane, will require more implementations of ‘mechanical equipment’, ‘stacked ventilation’, ‘alternative strategies and technologies’, and fewer ‘clerestory windows’ as adaptation strategies. Is it important to understand that one or two adaptation strategies is not enough to target thermal amelioration. The more strategies implemented within a building, will see greater success in terms of thermal comfort. It is also important to note that when designing or incorporating these strategies, one should aim for them to work in tandem and not in isolation. The results indicate that buildings within our future climate classification, utilises more alternative strategies & technologies and not just the conventional ones.

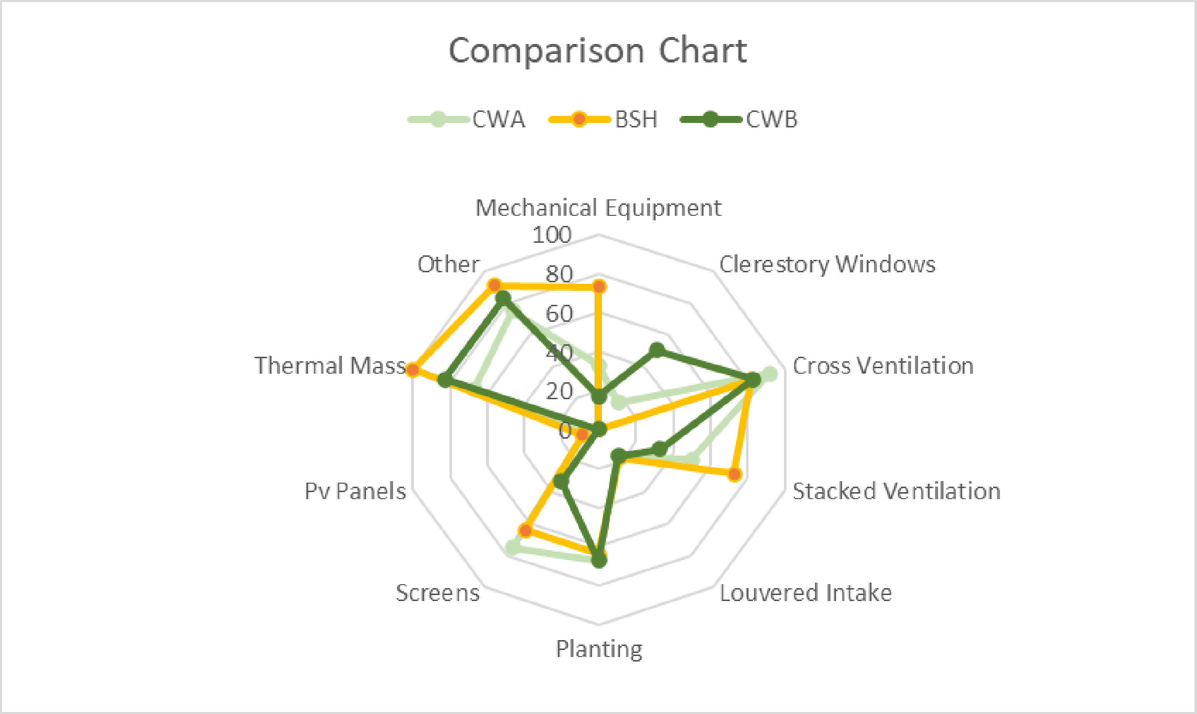


Figure 10: Chart comparing results from all three climate classifications.

5. Discussion

5.1. Research Question & Imperative Adaptation Technologies

"How can / do architectural building technologies implemented in selected case studies, contribute to the local climate adaptation strategies that target thermal amelioration potential (Vermeulen, 2023)?"

By enhancing thermal amelioration potential, architectural building technologies that include diverse passive cooling measures can greatly contribute to local climate adaptation tactics. These technologies can help reduce energy consumption, improve indoor comfort, and mitigate the urban heat island effect. Let's examine how each of the mentioned strategies can play a role in this context:

- Fully openable openings enable cross ventilation: By allowing natural airflow through the building, fully openable openings promote cross ventilation, which helps dissipate heat and maintain a comfortable indoor environment without relying heavily on mechanical cooling systems.

- Stack ventilation: This natural ventilation technique involves using temperature and pressure differences to induce air movement. It allows warm air to rise and escape through higher openings while drawing in cooler air from lower openings, promoting efficient air circulation and cooling.

- Planting and/or green space in proximity to the building: Green spaces and vegetation can act as a natural cooling mechanism. They absorb solar radiation, provide shade, and release moisture through transpiration, reducing the overall ambient temperature in the surrounding area.

- Screen / brise soleil of perforated wall that provides shades: These shading devices help block direct sunlight while still allowing airflow and natural light to penetrate. They prevent excessive heat gain and reduce the need for mechanical cooling.

- Thermal mass: Incorporating thermal mass materials like concrete or stone in the building's construction helps regulate interior cooling retention. These materials absorb and store heat during the day and release it slowly during cooler periods, stabilising indoor temperatures.

- Courtyard: A courtyard can act as a central open space that enhances air circulation within the building. It facilitates natural ventilation and minimises internal temperatures, especially when combined with shading elements and greenery.

- Evaporative cooling: This technique involves using water to cool the air, which is particularly effective in dry climates. By evaporating water, the surrounding air temperature is lowered, providing a natural and energy-efficient cooling solution.

- Wind towers: Wind towers, also known as windcatchers, are traditional architectural elements that induce air flow. They harness prevailing winds and direct them into the building, promoting natural ventilation and reducing the interior temperature.

- Mashrabiya / celosia: These latticed screens are traditional elements used for wind penetration and passive cooling in hot climates. They allow airflow while providing privacy and shade, contributing to thermal amelioration.

- Double glazing: Double glazing offers better insulation than single-pane windows, reducing heat transfer between the interior and exterior of the building. This helps to keep the interior temperature more consistent and minimises the demand for heating or cooling.

- Double Façade System: This system involves creating two layers of building envelopes with a gap in between. The outer layer provides shading and thermal insulation, while the inner layer facilitates natural ventilation, leading to increased energy efficiency.

Implementing these architectural building technologies in selected case studies can result in improved thermal comfort, reduced energy consumption, and enhanced resilience to local climate conditions. They contribute to climate adaptation strategies by mitigating heat stress and supporting sustainable building practices that align with the local climate's characteristics and challenges.

5.2. Future Sustainable Development

Sustainability is a crucial aspect of building cooling systems, along with sustainability, energy efficiency, and economic affordability. Cooling strategies that are energy efficient do not necessarily equal sustainable cooling strategies, as excessive energy-saving efforts might jeopardise a building's capacity to sustain appropriate thermal conditions in adverse weather scenarios. The Köppen-Geiger climate classification connects climate and vegetation by offering a basic framework within which climatic variability and climate may be represented in an integrated manner (Chen & Chen, 2013).

In reaction to climate change, several international accords, national and local policies have been formed, with the goal of limiting the future effect of climate change while simultaneously preparing for it. South Africa is predicted to experience higher average temperatures in the predicted future, and the country must establish city response methods that can be carried out by both big governmental agencies and smaller groups or people. To successfully prevent long-term consequences and adapt to unavoidable climate changes in the short term, the issue is to find and effectively implement design techniques that incorporate sustainable technology with present construction patterns (Altomonte, 2009).

The entire design of buildings - their structure, exterior, interiors, and services - regulates the delicate balance among the aspects defining the circumstances within (and outside) constructed spaces, rather than the sheer use of innovative technology per se. By employing a strategic integrated design approach and effectively applying existing and upcoming knowledge, buildings should effectively harmonize their main functions and needs with the dynamic environmental factors. This will ensure the comfort of their occupants while minimizing energy usage and reducing harmful waste and emissions (Altomonte, 2009)

A new comprehensive design technique that may pave the way for progressive and innovative architecture which responds sustainably and fast to present and future climatic conditions and spatial surroundings must be devised. This innovative new design method is ironically tied to the well-known norms of the natural world in which we all live (Altomonte, 2009).

A conceptual design framework refers to a set of methodologies and criteria that need to be meticulously studied and developed during the architectural design process to effectively reduce the environmental impact of constructed buildingsThe author (Altomonte and Luther, 2006) conducted earlier research that introduced a novel integrated building design methodology founded on a thorough and iterative examination of interconnected architectural categories and principles:

1) Analysing site, exposure, temperature, orientation, topography, local restrictions, natural resource availability, and environmentally appropriate energy consumption are all factors to consider for optimal energy usage duration and intensity (cited in Altomonte, 2009).
2) Adaptable and Versatile Structural Systems: Analyzing the structure's attributes, durability, integration with other building elements, and aesthetic impact.
3) Sustainable & Eco-friendly Building Materials: Assessing the competency, size, standardization, structural suitability, complexity, suitability, cost, labor, origin from renewable sources, growth method, embodied energy, recycled content, and level of toxicity.
4) Modular Building Systems: Exploring construction and assembly methods that facilitate faster building processes, reduce energy consumption, offer flexibility, simplify maintenance, and allow for easy replacement.
5) Building Envelope Systems: Investigating devices, components, and systems acting as interfaces and dynamic filters between indoor and outdoor environments, effectively managing energy flows within enclosed spaces.
6) Renewable and non-conventional energy systems integrated into existing structures, supplying energy without depleting their source, and capable of being harnessed on-site or in centralized locations with minimal environmental impact.
7) Innovative HVAC systems provide comfortable interior conditions using mechanically-regulated, hybrid, or passive systems, ensuring thermo-hygrometric and air quality comfort for occupants.
8) Investigating water collection and storage systems for efficient use, distribution, and recycling in inhabited structures, ensuring lifelong resource utilization (Altomonte, 2009).

6. **Conclusion**

This study delves into the urgent need for climate change adaptation in South African cities, particularly focusing on enhancing the thermal adaptive capacity of existing buildings. The impacts of climate change, including extreme weather events and rising temperatures, are already being felt worldwide, and Southern Africa, in particular, is vulnerable to its consequences.

The report emphasizes the importance of recognizing the challenges posed by climate change and the growing trend of urbanization. With a significant portion of the global population projected to reside in urban areas by 2030, there is a pressing need to develop sustainable and climate-resilient urban ecosystems.

Through a comprehensive analysis of architectural building technologies and interventions, the research explores ways to improve the thermal adaptive capacity of buildings in South African cities. By implementing passive cooling measures, green spaces, shading devices, and innovative ventilation systems, buildings can reduce energy consumption, enhance indoor comfort, and mitigate the urban heat island effect.

Sustainability and resilience emerge as critical components intertwined with climate change adaptation. The report highlights the importance of fostering resilience that enables "bounce-forward" abilities, creating new opportunities despite adversities. Moreover, the study recognizes the uncertainty surrounding the future climate, which necessitates both current risk reduction and planning for future changes.

The research also acknowledges the significance of adaptability in human history, from the transition of hunter-gatherer societies to modern urban centers. It emphasizes the need to adapt to new and unknown conditions while coping with ongoing disruptions to address the challenges of climate change.

Moving forward, the report emphasizes the importance of formulating a sustainable response to future climate change classifications in South Africa, particularly in Tshwane. It calls for strategic integrated design that aligns with the natural world, utilizing renewable energy systems, modular building approaches, and innovative HVAC solutions to ensure both comfort and energy efficiency.

In conclusion, the research report highlights the urgency of taking action to adapt to climate change and improve the thermal adaptive capacity of buildings in South African cities. By embracing sustainable architectural solutions and learning from adaptive natural systems, it is possible to secure a prosperous and resilient future for current and future generations. The report emphasizes the importance of collective efforts from policymakers, professionals, and communities in mitigating and adapting to the challenges of climate change for a sustainable and thriving future.

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8. Appendices (if necessary)

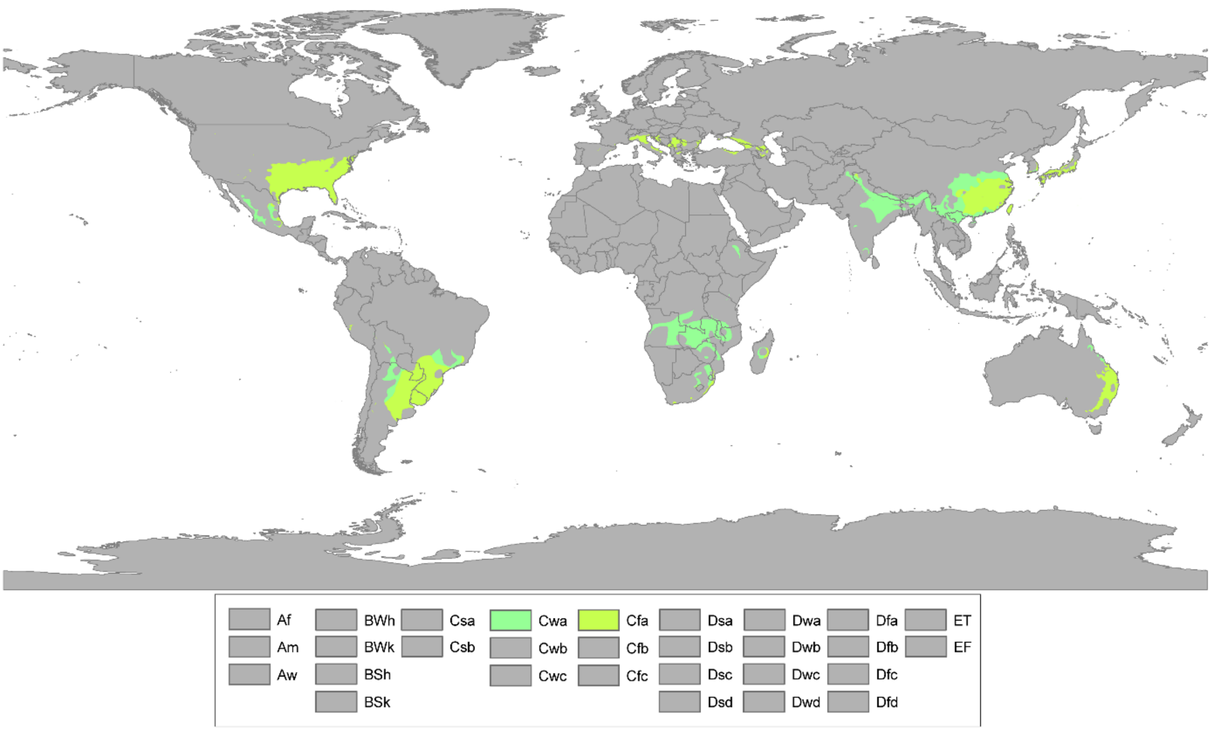

Figure 11: World Map showing Cwa climate regions (Beck, et al., 2018).

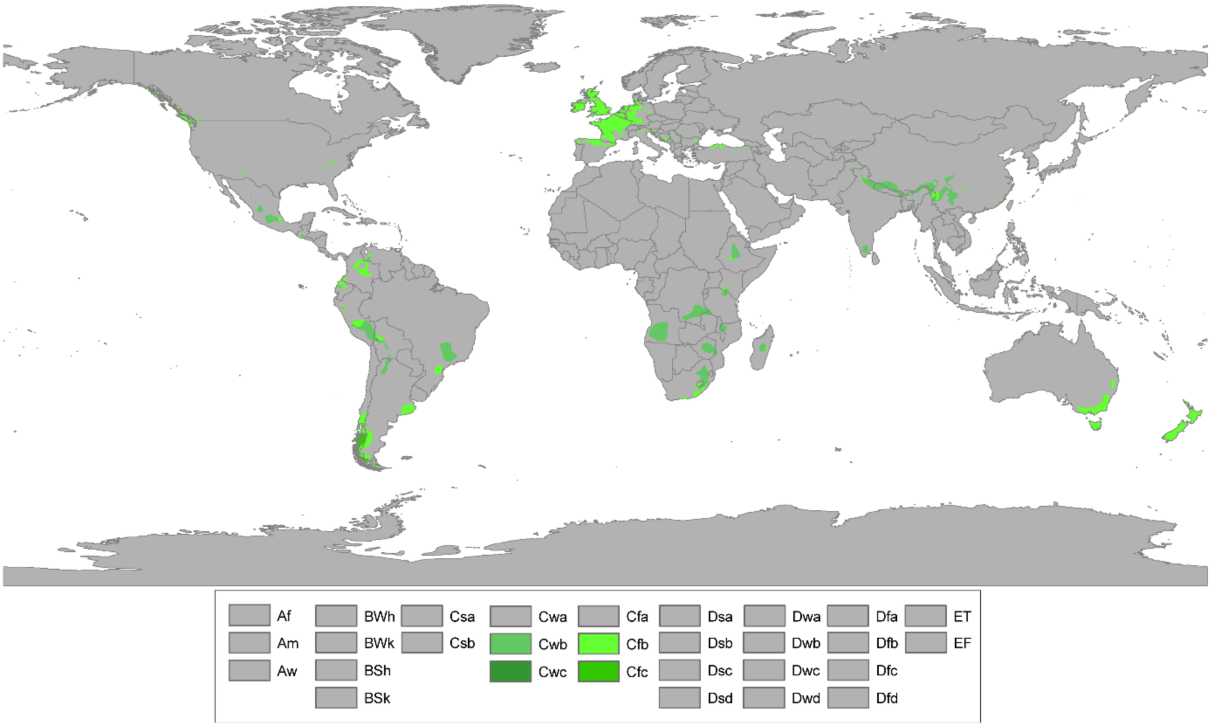

Figure 12: World map showing Cwb climate regions (Beck, et al., 2018).

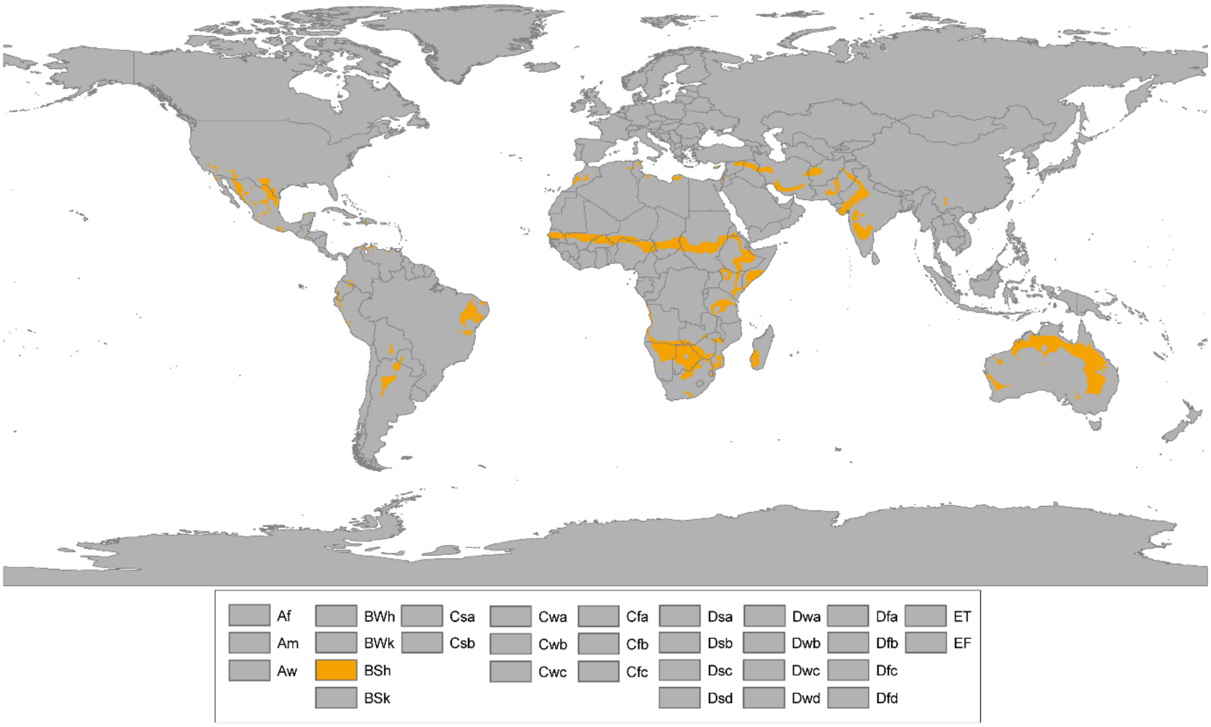

Figure 13: World Map showing BSh climate regions (Beck, et al., 2018).

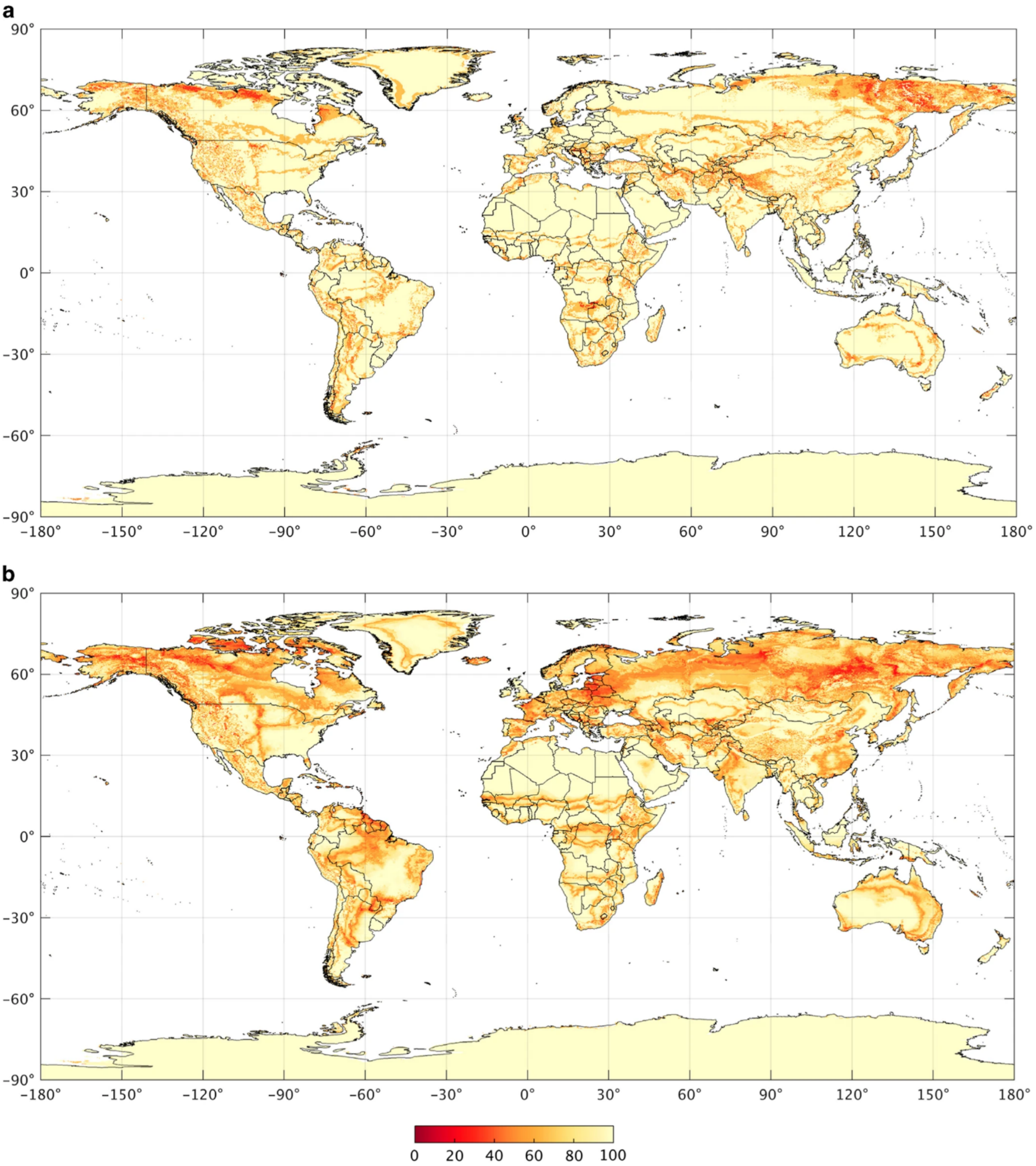

Figure 14: Part (a) shows the present-day confidence map (1980–2016) and panel (b) the future confidence map (2071–2100). These maps provide an indication of classification accuracy (Beck, et al., 2018).

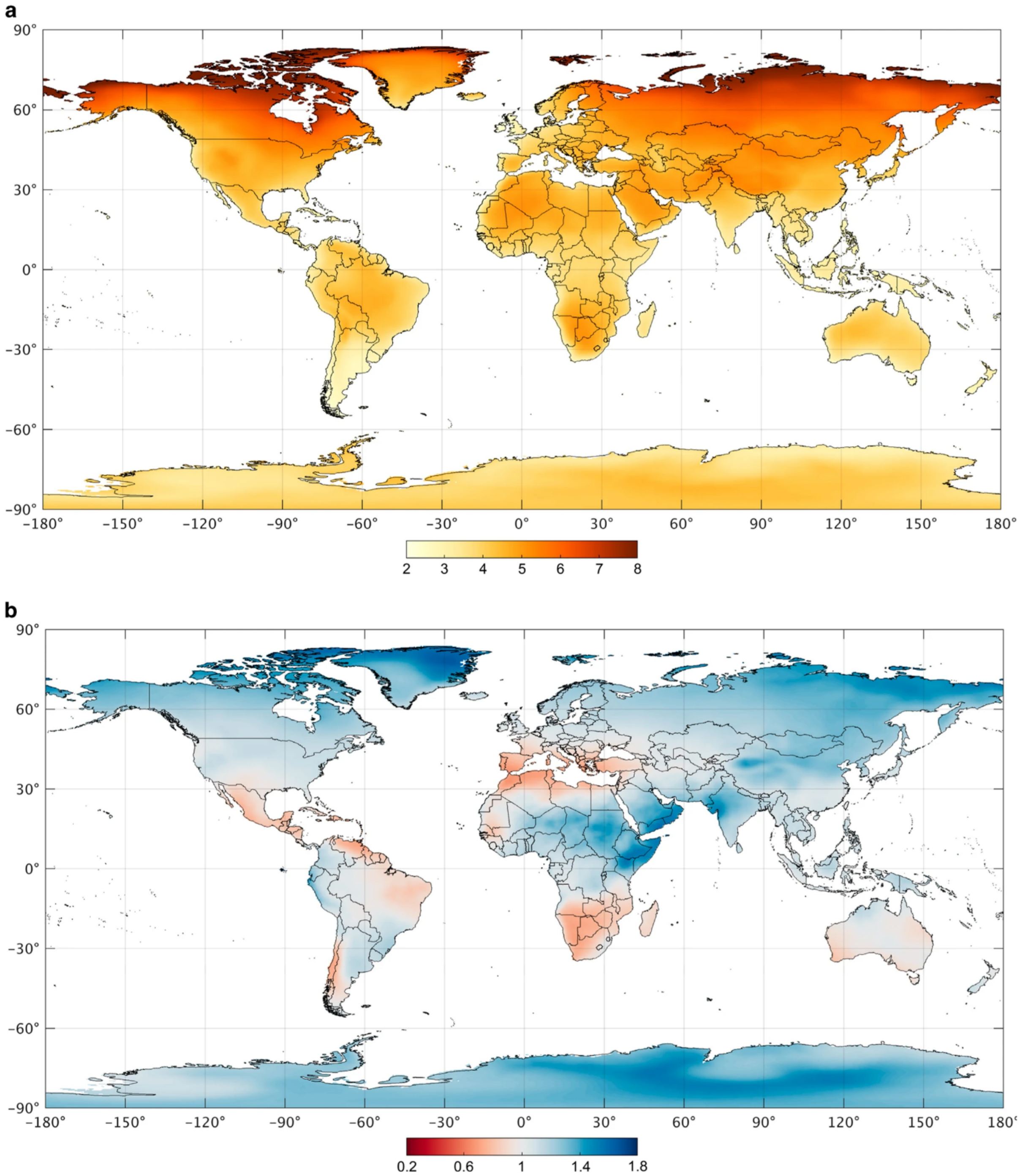

Figure 15: Part (a) presents air temperature change offsets and part (b) precipitation change factors. The values represent the mean over all models and months (Beck, et al., 2018).